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DEVELOPMENTS IN ECONOMIC GEOLOGY, 19

empirical metallogeny

Depositional Environments, Lithologic Associations and Metallic Ores

Vol. 1: Phanerozoic Environments, Associations and Deposits

PART B

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"Broadly regarded, the depth to which a metalliferous region has been eroded affects its present characteristics as a mineral province, because of the exposure of the various depth zones in which the ores were formed".
E. Sherbon Hills in Geology of Australian Ore Deposits, 1953, p. 57.

CHAPTER 27

Intracrustal and Subcrustal Environments (Introduction to Chapters 28-32)

The depositional environments treated so far, and the lithologic associations generated in them, have either been wholly surficial (supracrustal) or they have had a significant supracrustal component. In contrast, the environmemts in which the rocks treated in Chapters 9,28,29,32 formed, were intracrustal. The lithologic associations described in Chapters 4,5,7, 11-14, 31,33, are partly intracrustal.

Because the active intracrustal environments are not directly accessible and consequently they cannot be observed and summarized in empirical terms, they will not be discussed further in this book (but their products, lithologic associations formed at a greater depth, are). The reader is referred to the theoretical literature based on geophysical, geochemical and other data (e.g. Condie, 1982; Ringwood, 1975; Turner, 1980). Figures 27-1 to 27-5 show diagrammatically the depth setting of intracrustal lithologic associations and orebodies, at their time of origin.

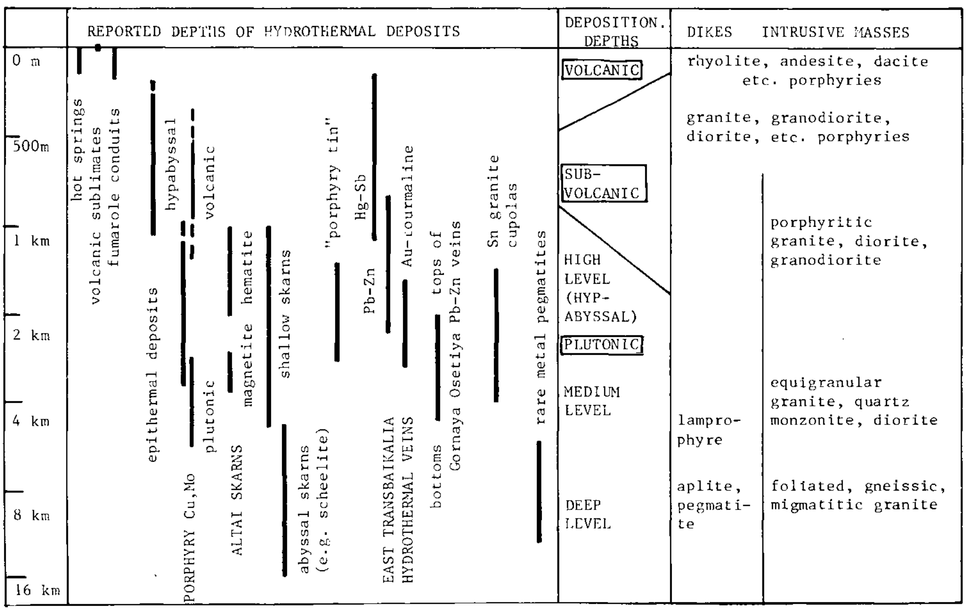


Fig. 27-1. Depths of formation of hydrothermal deposits and associated intrusives.

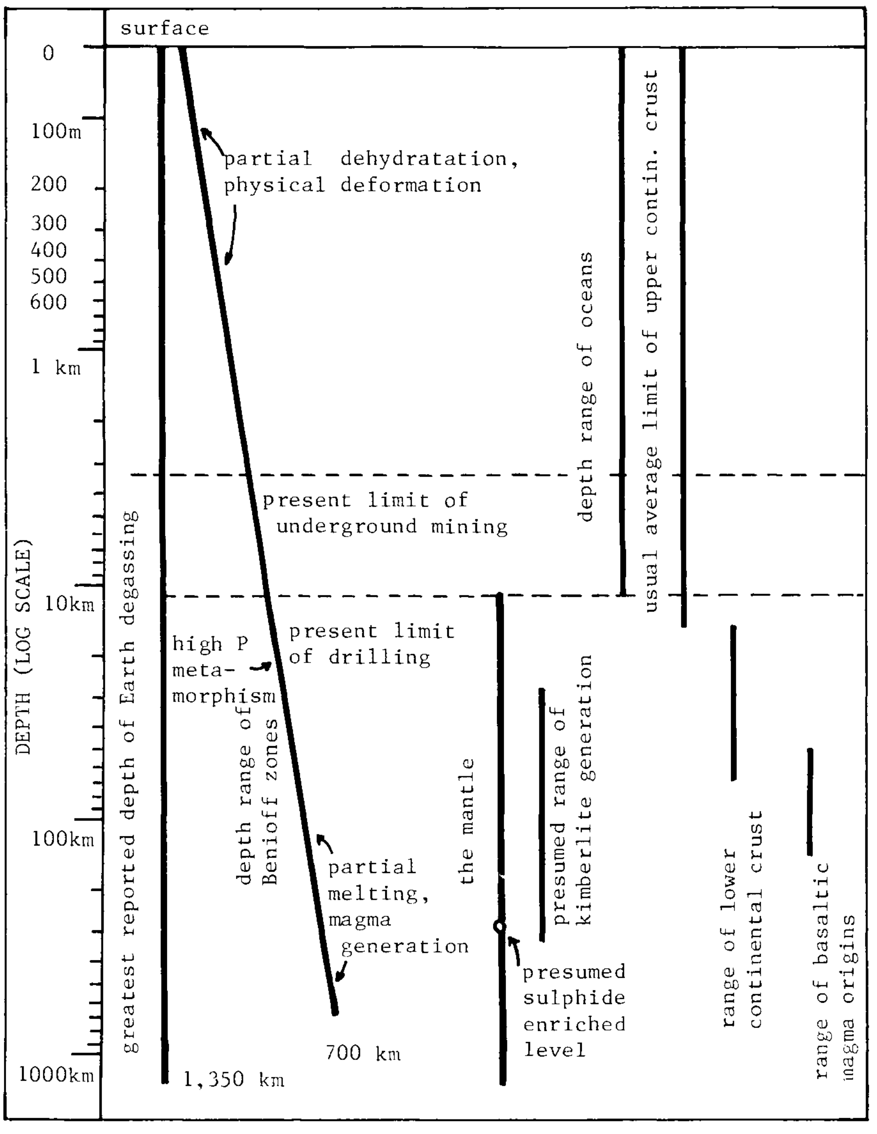


Fig. 27-2. Depth ranges of selected rock and ore-forming zones, planes and processes.

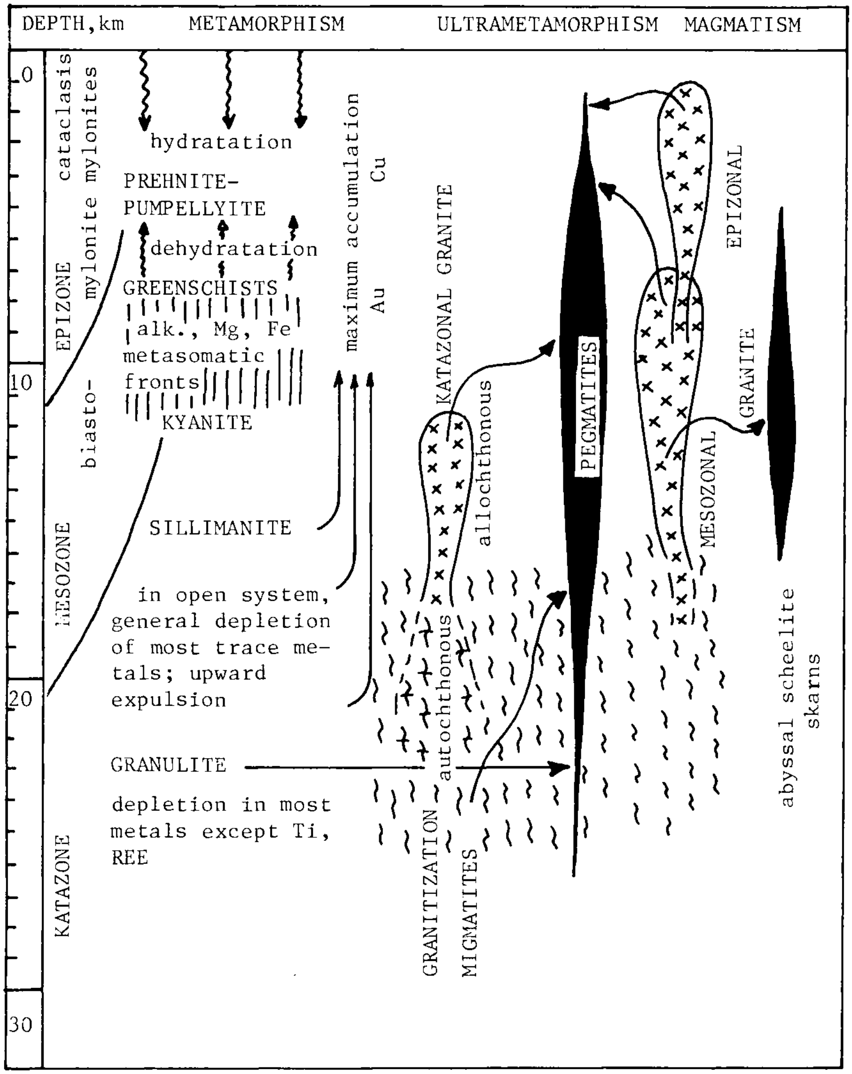


Fig. 27-3. Interpreted depth levels of metamorphism, ultrametamorphism and granite magmatism.

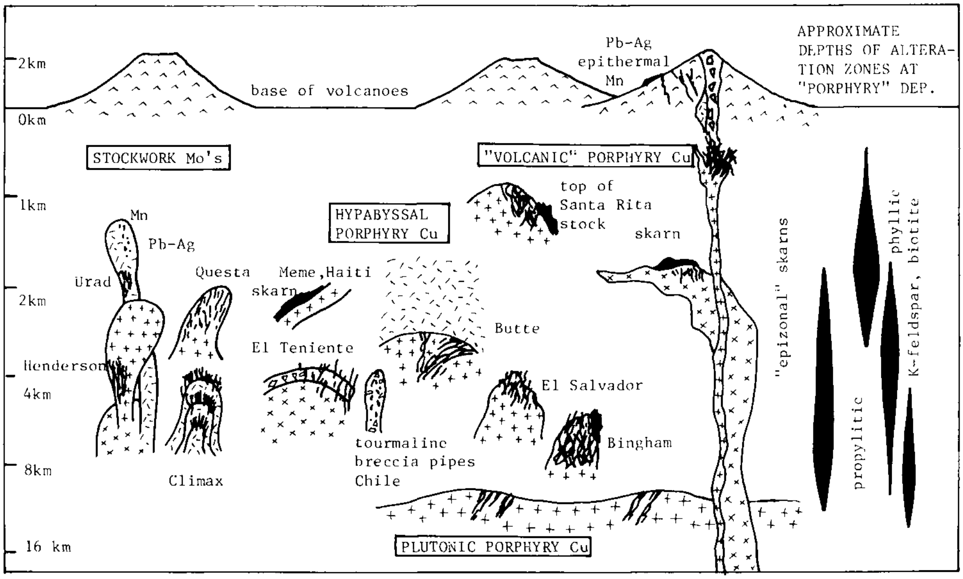


Fig. 27-4. Porphyry Cu and Mo deposits, interpreted depths of origin.

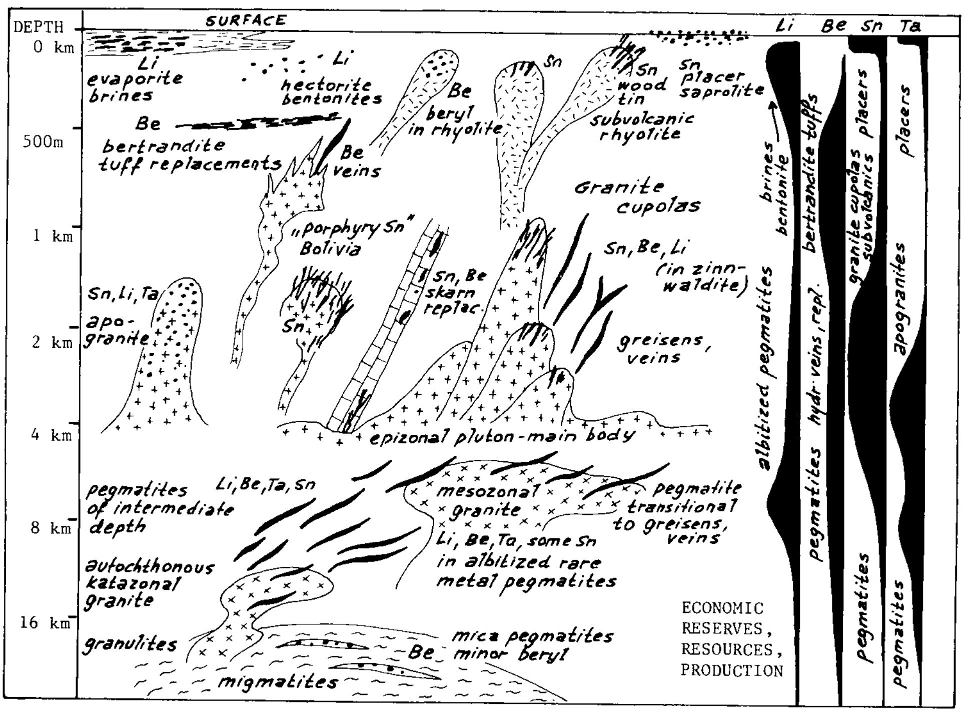


Fig. 27-5. Depth variation in genetic association and mineralization style of rare element deposits.

"Granite is the balance of what was there originally, plus what has migrated in, minus what has been driven out".
Arthur Holmes, 1937.

"Porphyry copper deposits are not found, they are made".
Donald K. Mustard, 1976.

"The economic geology of the (S.E. Asian) tin belt is still a riddle wrapped in a mystery inside an enigma despite certain naïve utterances to the contrary".
K. F. G. Hosking (paraphrasing Sir Winston Churchill) in 2nd Tech. Conf. on Tin, 1970.

CHAPTER 28

Plutonic Granite, Diorite, (Gabbro) Association (GDG) and its Aureole

28.1. INTRODUCTION

Granite, diorite, (gabbro) associations abbreviated GDG are also known as "granites", granites sensu lato, granitic rocks or granitoids because of the granitic or hypidiomorphic-granular texture characteristic of these rocks regardless of their colour index. This is, without doubt, the most complex lithologic association to be handled from the point of affiliated orebodies. It is so because few of the affiliated ores are directly hosted by these rocks, and even when this is the case such ores are almost always "epigenetic", that is, younger than the adjacent rock and generally emplaced when the host was a "dead" (solidified, lithified, fractured) recipient only. With the exception of some gabbros, syn-magmatic and orthomagmatic metal accumulations generated during the magmatic crystallization and hosted by the parent rock in the same manner in which detrital heavy minerals in placers are enclosed in the sediments with which they formed, are rare and of little importance, economically. The bulk of ores is post-magmatic, that is, formed from highly mobile fluids released in the latest development stages of a magmatic body and migrating generally upward, or even generated outside of the intrusion, for example, from the pore waters in the rocks present in the GDG roof or from downward percolating meteoric waters.

In the latter case, the evolving GDG intrusion could have supplied heat only, the principal driving energy. Yet, without the heat, the ore depositing process would not have taken place so the presence of a GDG system is genetically important, causal and indispensable for most hydrothermal mineralizations, even if the orebodies themselves (e.g. hydrothermal veins) are actually located outside the intrusions, often far outside, in an endless variety of host lithologic associations.

No parent (driving, generating) intrusive body is known for many hydrothermal veins at the present level of exposure. Even when veins do occur within or in the proximity of a "granite", the genetic affiliation of both should not automatically be assumed without conclusive evidence, as was the case in the past. To bypass the problem of uncertain affiliation, Stanton (1972) in his book in which he pioneered the treatment of ore deposits in the framework of lithologic associations, coined a category, "ores in vein association". Such association is neutral, truly independent of the nature of the host rocks and one does not need a "granite" in sight to search for such orebodies. But veins themselves are extremely rare rock bodies seldom cropping over more than 0.001% of an area surface, so the "vein association" is of little assistane to a prospector who needs a regionally widespread lithologic association to start looking for the veins. For this purpose the GDG association is useful, because most postmagmatic hydrothermal deposits do occur in the proximity, in the aureole of igneous intrusions, and this aureole is more or less definable by the effects of thermal metamorphism.

When exploring in GDG terrains and their aureoles, one cannot avoid genetic speculation and reasoning no matter how imperfect. In doing so, however, an exploration geologist should always try to differentiate the recipient and generator rocks or units. The former actually host the orebodies, but they did not set into motion the processes that produced or drove the ore-bearing fluids that came from the outside (however, they caused the ores to precipitate and in some instances even supplied the metals). The latter provided the heat (energy) to drive the hydrothermal system and in many cases are still considered to have supplied the ore-forming fluids and metal as well. In some instances a rock may be both reservoir and generator rock (e.g. gabbros containing accumulations of ilmenite crystallized from an immiscible liquid). In others, both functions are close to each other in space and time so that they overlap and cannot be separated (e.g. certain cassiterite disseminations in endocontacts of granite cupolas). The simple empirical observation that an ore is hosted by an intrusion, however, does not necessarily indicate that the host rock is both reservoir and concentrator medium. In most cases (as in the porphyry copper, stockwork molybdenum or tin cupola complexes) we are dealing with multiphase, magmatic systems and typically the older phases, more visible and volumetrically abundant, provide reservoirs to fluids generated by younger (often the youngest) phases that are usually volumetrically insignificant (stocks, dikes, sills), if they are exposed in outcrop or in the mine workings at all. The Climax Mo complex is the best known example. Here three generations of orebodies appear above their generator intrusions hosted by sequentially earlier intrusions forming the roof in the time of ore deposition. The plutonic GDG association treated in this chapter includes the "most typical granites" formed at intermediate (mesozonal) and shallow (epizonal) crustal levels by solidification of introduced melts. There is a gradual upward transition and overlap between this association and the continental volcanic and subvolcanic terrains treated in Chapters 5 (Recent) and 26 (pre-Quaternary). The transition into the "marine" volcanic-sedimentary associations

(Chapters 10-14) is less typical and more controversial. With increasing depth, the mesozonal granites treated here change into katazonal granites, that are set in or coincide with the level of high-grade metamorphism and ultrametamorphism (partial melting), treated in Chapter 29. The latter is a zone of generation of at least some of the granites treated here, so some of the petrogenetic principles applicable to the generation of granitic magmas are discussed there. The GDG-affiliated metallogeny depends to a considerable degree on interaction with the outside rocks, so it is transitional with the metallogeneses of almost all the ancient lithologic associations treated in this book.

28.2. PETROGRAPHY, ORIGIN AND SETTING OF GDG PLUTONIC ROCKS

28.2.1. General

Examples of exposed "granitic" batholiths or plutons are known from almost the entire range of ages measured in the outcropping rocks (about 3.6 b.y. to 1.2 m.y.) and are among the most widespread rock types. Granites, granodiorites and diorites account for 21.6% of the total volume of the crust (Ronov and Yaroshevsky, 1969). Tonalite (light quartz diorite) "is the dominant rock type in the continental crust and the average composition of the continents is virtually tonalite" (Brown, 1979). The above statement, however, is applicable in the compositional rather than textural sense because the bulk of Brown's "tonalites" are the Precambrian "granite gneisses" treated in Volume 2 of this book.

GDG rocks occur as composite batholiths (gabbro, diorite, tonalite, granodiorite, quartz monzonite, granite) having a total silica content ranging from 45 to 78% (as in the Andean Batholith, Peru), or as homogeneous bodies composed virtually of a single rock type. "Granites" are perhaps most famous for the periodic genetic controversies they generate, the most notable having been one in the 1950s (magmatic versus metasomatic origin of "granites"). The controversies are the inevitable consequence of the fact that nobody has actually observed and measured a granite in the process of formation so that our interpretation is based on hypotheses gradually improving by the addition of constraints obtained in the field and in the laboratory. The granite controversy is not yet settled, as comparison of two recent statements indicates: (1) "Production of melts of the granite class is a natural culmination of metamorphic processes in the crust" (Fyfe, 1973); and (2) "Calc-alkaline batholiths are furnished by between a 70-100% contribution from melts derived from the upper mantle above subduction zones" (Brown, 1979).

To an exploration geologist, the origin of "granite" is of some importance, because it is at the core of a predictive philosophy of where to find the "granite"-related ore deposits. In view of "the simplistic (and one-sided; my remark) models in which petrologists are prone to indulge" (Hughes, 1982), the existing models should be used with utmost care, opposing opinions compared and the empirically observable facts given the highest priority. The basic aspects of petrology, origin and setting of GDG rocks relevant to the associated metallic ores are reviewed briefly in the following paragraphs In-depth coverage can be found in the petrographic and petrologic literature, e.g. Marmo (1971), Carmichael et al. (1974) and Hughes (1982).

An explorationist trying to find ores has to go farther than a petrologist in regional geological interpretations, and take into consideration the lithologic associations surrounding the "granite" as well as the regional structure and alterations, as clues to mineralization.

The bulk of "granites" occur in moderately to deeply eroded orogenic belts marking the former continental margins. The present is a "prime time" of exposure of the lower Tertiary and late Mesozoic high-level (epizonal) granites, because the plutons have been sufficiently erosion dissected yet remnants of their locally comagmatic ejecta roofs are still preserved. It is also a "prime time" of exposure of the late Paleozoic to early Mesozoic medium-level (mesozonal) granites. These terrains are characteristically calc-alkaline and subsurficial equivalents of the continental volcanics (Chapters 5, 26) when such were developed. Granitoids with tholeiitic affinities (the gabbro-plagiogranite suite) occur in orogenic belts formed in evolutionarily primitive island arcs, e.g. in the Izu Peninsula, Japan and elsewhere; compare Chapters 7, 10 and 12. Alkaline granitic rocks within orogenic belts (compare Brown, 1979) usually formed along intraplate reactivated terrains, in collision belts and along intermontane or interarc extensional structures.

A proportion of "granites" constituting a very small volume is affiliated with intra- and inter-continental ("rift") structures and systems and this association is dominated by alkaline members although calc-alkaline rocks (such as biotite granites) are also present. This association is largely treated in Chapter 33.

Intrusive rocks are conventionally subdivided into hypabyssal and plutonic (Hughes, 1982). The hypabyssal rocks include small near-surface dikes, sills and plugs that have cooled quickly and are fine-grained. Plutonic rocks are coarse-grained, because they have cooled slowly at generally deeper levels. The most common large bodies of intrusive rocks are almost equidimensional or elongated plutons, batholiths or massifs. These terms are usually used interchangeably although the prevalent application is as follows (based on the A.G.I. Glossary of Geology): (1) Batholiths are large, generally discordant plutonic masses, having a surface exposure of over 100 km^2, and lacking a visible floor. (2) Pluton is a general term, used as a synonym for "igneous intrusion", as well as for a body of rocks formed by metasomatic replacement. (3) Massif is an alternative general term for a plutonic rock body and its underlying area. Small stocks and plugs are also common and largely self-explanatory. Additional varieties of intrusive bodies will be discussed later.

In a "most normal" GDG terrain (within a core of an orogen, eroded to a depth of 5 km), the dominant rock type is an equigranular, hypidiomorphic granodiorite composed of white, creamy or greenish plagioclase; creamy to pink or also white potash feldspar; gray translucent quartz and biotite and/or hornblende. Changing proportions of the five rock-forming minerals result in granite (sensu stricto) containing at least twice the volume of K-feldspar and above 20% of quartz, diorite, gabbro and syenite. At present, the nomenclature of Streckeisen (1976) is most widely used (Fig. 28-1).

The equigranular rocks grade readily into porphyritic equivalents, in which feldspar tablets are the most common phenocrysts. The homogeneity of the plutonic rocks is often interrupted by the presence of autoliths, xenoliths, schlieren, mineral nodules and intrusive dikes, and many granitic bodies are lightly to strongly foliated. Autoliths (or cognate xenoliths) are usually rounded inclusions or fragments of older intrusive rocks genetically related to the host. They tend to be more melanocratic, but mineralogically equilibrated with the surrounding intrusion. The rest of the xenoliths are fragments of country rocks ranging from sharply-outlined to almost-digested end members.

Didier (1973) prepared a definitive work on the enclaves in granites and their variety. The term schlieren is used to describe usually streaky, irregular masses or trains of inhomogeneities (minerals or inclusions) in granites. Mineral nodules are defined by Didier (1973) as more or less diffuse, heterogeneous patches not as sharply outlined as xenoliths, nor linear as the schlieren. Tourmaline and cordierite nodules tend to be the most common.

Frequent dikes in "granites" often occur in several mutually crosscutting generations and are controlled by joints. In the meso- and epizonal granites virtually all dikes have sharp boundaries. Compositionally, the dikes are: (1) porphyritic equivalents of the plutonites they transect (e.g. granodiorite porphyry); (2) leucocratic equivalents, polymineralic (e.g. aplite, pegmatite) or monomineralic (vein quartz); and (3) lamprophyres (minette, kersantite, spessartite or vogesite).

The field relations in plutonic terrains and in particular their interaction with the country rocks are, to a considerable degree, influenced by the depth level of emplacement. Buddington (1959) in his classical paper on the North American granites, proposed a three-fold depth subdivision of plutons and batholiths into epizonal, mesozonal and katazonal varieties. This division and terminology is "alive" and widely used in igneous petrology, although the same terms applied to metamorphic assemblages are now generally considered obsolete.

28.2.2. Epizonal plutons

Buddington (1959) characterized epizonal (epizone) "granites" as emplaced at depths of 1-6 km; having sharp, discordant contacts with

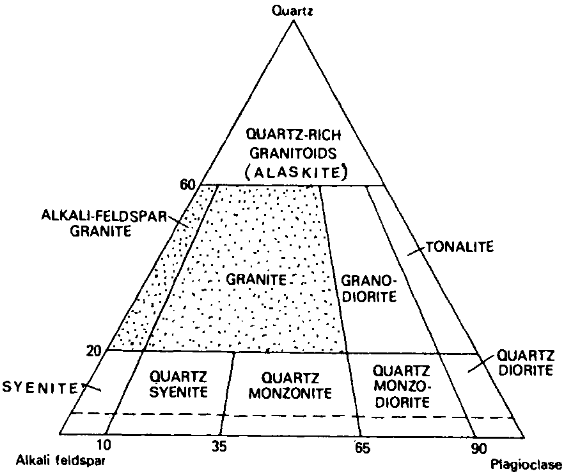


Fig. 28-1. Nomenclature of granite, diorite, syenite association, proposed by Streckeisen (1976).

their surroundings; composed of nonfoliated rocks; emplaced by large-scale magmatic stoping and as ring dikes or cone sheets. Additional characteristics contributed by Hutchison (1977) and Hughes (1982) include: extreme temperature difference between "granite" and its country rocks expressed in the well-developed contact metamorphic aureole (hornfelsing); frequently documented relationship to comagmatic volcanics and sub-volcanics; structurally unstable feldspars (e.g. mesoperthite) due to rapid loss of water; "post orogenic" and "orogenic" setting; predominance of equigranular to micro-porphyritic rocks; virtual absence of "typical" pegmatites; general concordance of Rb:Sr and K:Ar dates and other properties. Excluding alkaline and peralkaline complexes, the most frequent epizonal plutonites are granodiorites, quartz monzonites and granites commonly emplaced into their slightly earlier dacite, rhyodacite, quartz latite and rhyolite equivalents.

Both vented (=communicating with the surface) and unvented varieties of epizonal "granites" are known. Cunningham (1976) tabulated criteria indicative of former vents: (1) clastic texture; (2) partly aphanitic groundmass; (3) vertical pipe-like form located at the centre of the youngest plutonic rock; (4) pervasive alteration and disseminated Fe oxides; (5) evidence of a high content of volatile material as indicated by miarolic cavities; (6) fluid inclusions: zonality and increasing proportion of gas-rich inclusions. Most of the mineralized volcanic-subvolcanic terrains are underlain by epizonal "granites" some of them in the initial stages of unroofing, others still buried. There, caldera collapse, ring dikes and stratovolcanoes, are considered as surface expressions of near-surface plutons.

Examples of epizonal plutons associated with mineralization are numerous. Two of them, the Coastal (Andean) Batholith of Peru and the

Boulder Batholith, Montana, have recently been studied in some detail and have been included here as two representative examples.

COASTAL (ANDEAN) BATHOLITH OF PERU

This intrusive body has an extensive literature summarized in the recent memoir by Cobbing et al. (1981) and reviewed briefly in Hughes (1982); Fig. 28-2. The batholith, in its uninterrupted and dominantly plutonic portion, forms an elongated belt over 1,600 km long and 50 km wide. Minor isolated intrusive bodies believed to be connected with the main batholith at a depth, however, occur within an additional width of 150-200 km and are up to 15 km thick. The entire complex is composed of over 800 mappable plutons and small intrusions emplaced in two periods (105 to 55 m.y. and 33 to 12 m.y.) separated by a 20 m.y. hiatus. The batholith includes phases formed at both the epizone and mesozone levels and sharp demarcation is impossible. The intrusive rocks comprise 58% tonalite and granodiorite, 25.5% quartz monzonite, 16% gabbro and diorite and 0.5% granite. The plutons were emplaced by stoping or cauldron subsidence into a passive upper crust comprising (1) marine "eugeoclinal" volcanic-sedimentary association dominated by pyroxene andesite; (2) Precambrian metamorphics; (3) Paleozoic and Mesozoic (meta)sediments including abundant "black slates" and carbonates and (4) its own ejecta of subaerial andesites, dacites and rhyolites. Although the magmatism was contemporary with, and presumably related to, subduction the structural history and intrusive emplacement in western Perú was dominated by vertical tectonics. The batholith, together with its surrounding supracrustals, is transversely segmented and this segmentation appears to control the metallogeny to a considerable degree.

The excellent outcrops along the arid Peruvian coast and in the numerous quebradas (dry canyons) illustrate convincingly, in three dimensions, the intrusive morphology and composition which makes a fairly detailed interpretation possible. Myers (1975) and Cobbing et al., (1981); Fig. 28-3, interpreted four distinct mechanisms of intrusion in the Lima segment, marked by mostly permissive emplacement and a lack of metasomatism:

(1) Piecemeal stoping. This is illustrated by pluton apophyses "frozen" in the process of prying-off slabs of andesite from the roof, blocks of andesite "showering down from a roof of volcano" and trains of angular wallrock blocks enclosed in "granite", showing a gradual reduction in size and progressive rounding, recrystallization and dispersion. Despite the overwhelming evidence for stoping along the intrusive margins, the interiors of most plutons are clear of inclusions indicating that stoping was only a secondary process in creating space for magma.

(2) Cauldron subsidence is demonstrated by the "bell-jar" shape of the majority of plutons in which flat-lying roofs pass into steep walls. Some such intrusions are multiphase, nested, and include a subsidence of the central block and the downward passage of tabular plutons into

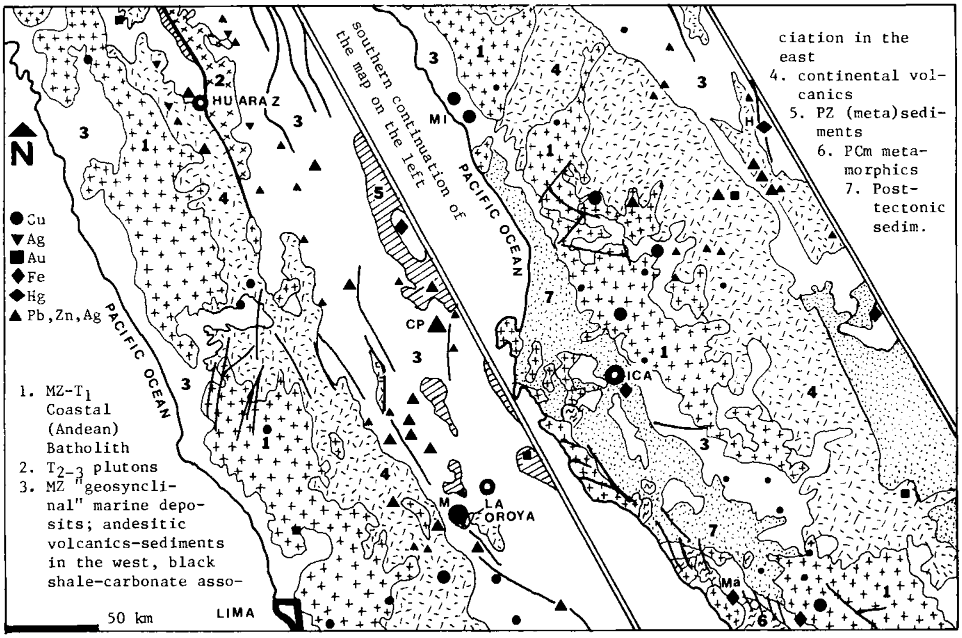


Fig. 28-2. Coastal (Andean) Batholith of Perú, map and distribution of ore deposits in the central sector. Based on the Mapa Metalogénico del Perú (Bellido E., Girard D., and Paredes J.) in Bellido and de Montreuil (1972). Abbreviations: CP=Cerro de Pasco; M=Morococha; Ml=Mala, Cu; Ma=Marcona, Fe; H=Huancavelica, Hg.

ring dikes.
(3) Fluidization and entrainment resulted in intrusive breccias that form some ring dikes. Such breccias comprise large blocks of volcanics, gabbros and earlier plutonic phases, enclosed in a "fluidized" matrix. Tuffisitic breccia dikes are considered to represent fluidized magmas rising ahead of a pluton.
(4) Uplift of the roof.

The distribution of ore deposits within and around the Andean Batholith of Peru (Bellido and de Montreuil, 1972; Putzer, 1976; Hollister, 1978) is quite characteristic of the overall batholithic metallogeny worldwide. The most striking feature is that the intrusive mass itself is virtually barren, almost devoid of economic orebodies (Fig. 28-2). This also correlates with the scarcity of metasomatism and hydrothermal alteration. The ores, however, start to appear in force along the contact. Some conformable orebodies in the hornfelsed exocontacts (e.g. the Cu "mantos" near Mala; Chapter 13) are probably thermally modified, volcanic-sedimentary relicts. Other

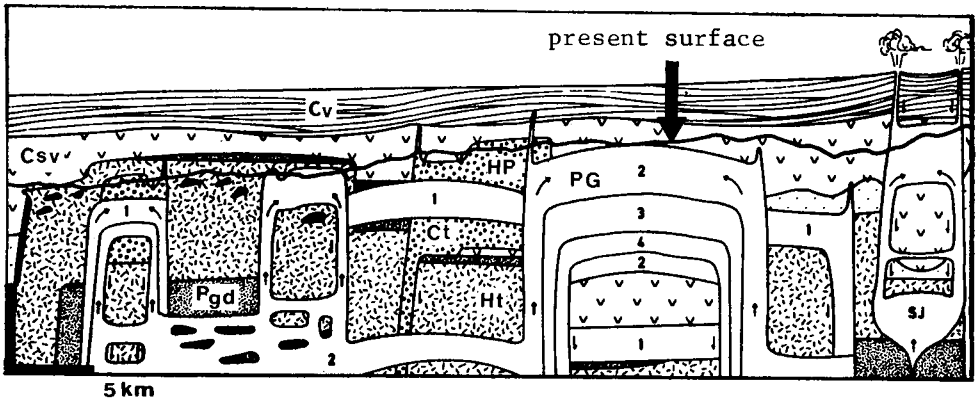


Fig. 28-3. Generalized section showing the major structures of the Coastal (Andean) Batholith of Peru during the latest intrusive episode about 50 m.y. ago. The batholith is composed of numerous plutons emplaced by repeated cauldron subsidence into their own volcanic ejecta. Abbreviations: SJ=San Jeronimo Granite; PG=Puscae Granite; half arrow=movement of block; arrow=movement of magma, during intrusion of SJ and PG; HP=Huampi Piruroc Granodiorite; Ct=Corralillo Tonalite; Ht=Huaricanga Tonalite; Pgd=Patap Gabbrodiorite; CV=Calipuy Volcanics; Csv=Casma Volcanics. From Myers (1975), reprinted with permission of the author.

localities (e.g. the large Marcona zone of magnetite bodies replacing Jurassic marine limestones at contact with an earlier Jurassic deeper-seated granodiorite batholith in an area underlain by Precambrian metamorphics; Putzer, 1976) are also relicts, partly modified. At Marcona, subvolcanic andesite and dacite dikes, probably related to the Coastal Batholith and intersecting the magnetite orebodies, produced magnetite, actinolite, minor calcite, quartz, chalcopyrite, talc, etc. possibly mobilization veins.

The major porphyry copper deposits that have so far been recognized in three areas in Peru (in the south-eastern corner of the Coastal Batholith near Arequipa, Toquepala-Cerro Verde district; in the centre, Morococha and in the north, Michiquillay) straddle the intrusive contacts and are related to "Laramide", Pliocene and Miocene subvolcanic dacite and high-level quartz monzonite porphyry intrusions, respectively.

The bulk of the Peruvian base and precious metal deposits occur along the fringe of the subaerial, late Tertiary volcanic pile topping the "miogeoclinal" and transitional basement megafacies. Both are intruded by sparse (under 20% by area) high-level plutonic bodies. The ores include major Pb,Zn,Ag replacements and veins (e.g. Cerro de Pasco, Casapalca; Chapter 26), all marked by intensive hydrothermal alteration. A strong basement metal source heritage is suspected (Chapter 19). These high-level orebodies, however, postdate emplacement of the major phase of the orogenic belt granites as in many other regions of the world (Colorado Mineral Belt, Great Basin, W. Rumania, etc.). The regional metal zoning pattern across the batholith based on the metals most conspicuously accumulated in ore deposits is (from west to east) approximately Fe,Cu-Pb,Zn,Ag and to a lesser extent Cu,W-Zn,Pb.

BOULDER BATHOLITH, S.W. MONTANA

This is a composite batholith 120 km long and 50 km wide, composed of coalesced epizonal plutons compositionally ranging from gabbro to alaskite (Hamilton and Myers, 1967; Klepper et al., 1971; Miller, ed.,1973; Fig. 28-4). The batholith was emplaced syn- and post-tectonically during an interval from 78-68 m.y. ago (late Cretaceous) in a basement of steeply dipping Proterozoic metamorphics covered by "miogeoclinal" Paleozoic and Mesozoic sediments, and into and under the roof of its own ejecta, the late Cretaceous Elkhorn Volcanics.

These volcanics are entirely continental and consist of dacite, rhyodacite and quartz latite flows and especially felsic welded tuffs. The "granite" / volcanics contacts range from horizontal (predominant) to steep faulted ones (in the east), and the intrusive emplacement was predominantly permissive but forceful in the east where wallrocks were locally sheared and vertically stretched. Hamilton and Myers (1967, Fig. 28-4) envisage emplacement of the batholith as a "gigantic mantled lava flow across a broad basin whose subsidence may have been due to the withdrawal of magma from depth". Portions of the batholith solidified within 1,600 m of the surface.

The constituent plutons formed over a 10 m.y. period, generally in order of increasing SiO_2 content, and can be placed into one of the four major compositional groups resulting from mixing of two different magma series ("normal" and sodic). These comprise (1) early mafic rocks (syenogabbro, syenodiorite, monzonite), (2) granodiorite, (3) Butte quartz monzonite (predominant phase) and (4) late leucocratic quartz monzonite, granodiorite, granite, quartz feldspar porphyry, aplite, alaskite, etc. The batholith is notable for the presence of a relatively widespread pegmatite, an unusual member of epizonal plutons.

Boulder Batholith and its aureole are densely mineralized. Several hundred of vein deposits, mostly small, produced Pb,Zn,Ag,Au and small quantities of U. There are small skarn orebodies, stockwork Mo occurrence, and the great Butte ore field in the southern part of the batholith. In contrast to the Peruvian Coast batholith, most of the deposits are within the granitic intrusive rocks, although relatively close to its former roof.

Hydrothermal epigenetic veins occur along joints, fractures and faults, often in swarms, trending E.-W. in the north-eastern portion of the batholith. They are parallel with the local alaskite, porphyry and quartz latite dikes replacing fault gouge or fractured wallrocks,

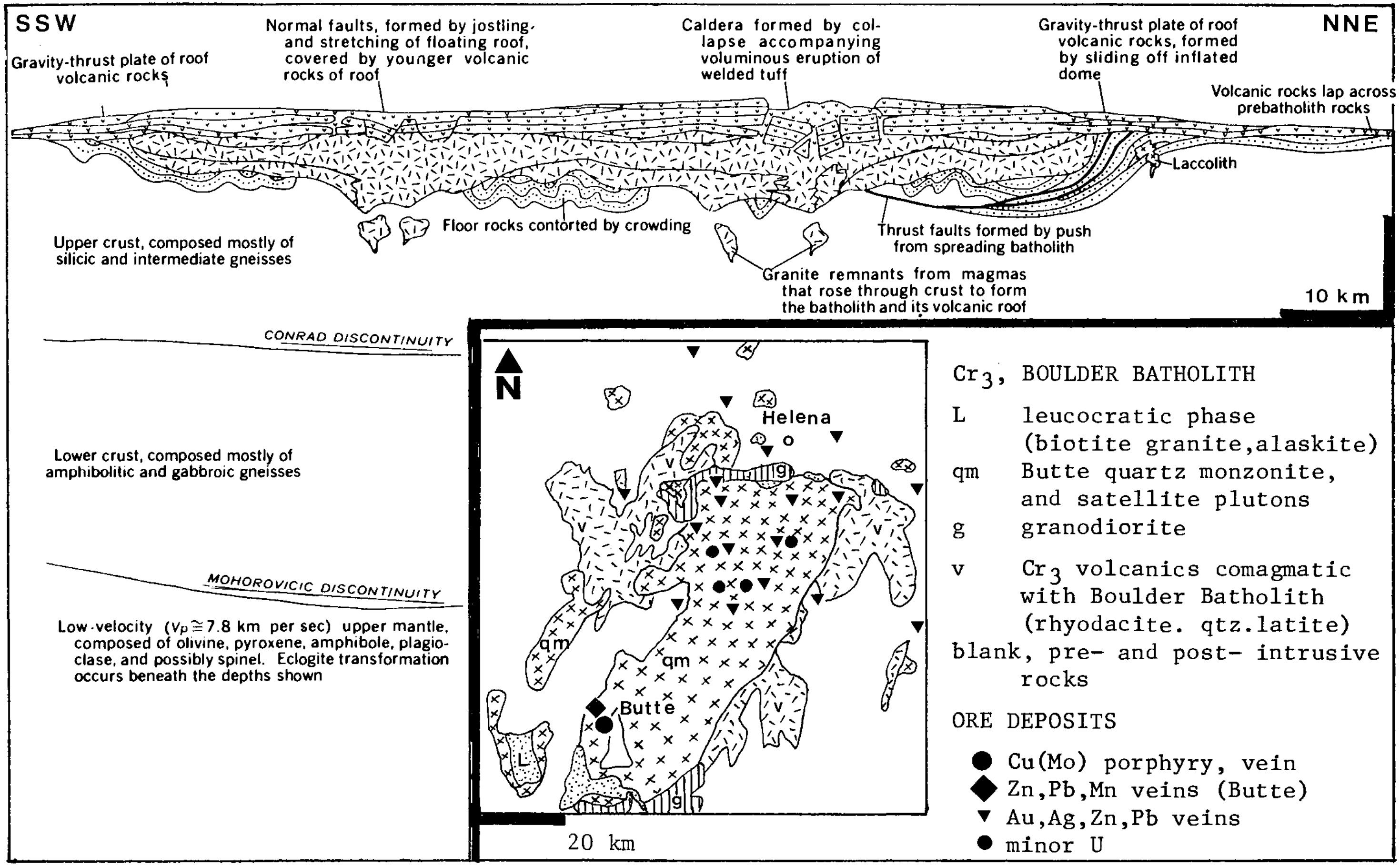


Fig. 28-4. Boulder Batholith, western Montana. TOP LEFT: Diagrammatic longitudinal geologic and crustal section, from Hamilton and Myers (1967). BOTTOM RIGHT: Simplified geological map and major ore deposits, from LITHOTHEQUE.

and some veins were repeatedly sheared and then healed. The gangue is almost exclusively silica, either gray quartz or chalcedony. The mineralization consists of disseminated , scattered to banded pyrite, sphalerite, galena, arsenopyrite, minor tetrahedrite, frequently accompanied by Ag-sulphosalts, gold or pitchblende. The total production has been about 120 Tt Pb, 476 t Au (much of it from gulch placers) and 2.5 Tt Ag, from about 15 ore fields or districts. Rimini was the most productive field. The wallrock alteration ranges from light to strong, and quartz, sericite, pyrite assemblage is most common.

Several mineralized breccia pipes and "pebble dikes" are known (e.g. the Montana Tunnels deposit, Obelisk Mine). The former locality contains disseminated pyrite and minor sphalerite and galena coating bleached rounded cobbles and pebbles resting in a tuff matrix, probably formed at base of the Elkhorn Volcanics. Most recently, a large tonnage of a very low-grade material has been established there (58.5 Mt ore with 0.93 ppm Au, 8.5 ppm Ag, 0.7% Zn, 0.3% Pb; Engineering and Mining Journal, November 1984).

The Butte ore field contains a multistage mineralization hosted by the Butte quartz monzonite in an area conspicuous for the abundance of late stage quartz-feldspar rocks (aplite, alaskite, pegmatite) apparently transitional into hydrothermal metasomatites and hydrothermal open space fillings. The recent results quoted repeatedly in the guidebook of Miller, ed., (1973), however, suggest a discontinuity between the process of batholith crystallization and ore deposits, representing a hiatus of some 10-15 m.y. This hiatus may have been accompanied by a partial de-roofing and initiate groundwater circulation through the completely crystallized and fractured quartz monzonite.

Butte (Brimhall, 1977; Meyer et al., 1968; Fig. 28-5) has been famous for almost a century as an example of numerous high-grade Cu-Ag veins, metal zoning, chalcocite supergene blankets and the overall richness. The veins formed during the Main Stage (58-57 m.y.) show an ore field-wide zoning of its mostly E.-W, N.E. and N.W.-striking fissure veins and branching vein sets from a central copper zone (with a small segment rich in quartz-molybdenite veins at its outer edge) to Zn and Mn zone on the periphery. The veins in the Cu zone can be subdivided into several varieties that differ by the degree of sulphurization of the copper minerals. The high-sulphur assemblage also rich in silver has mainly hypogene chalcocite and enargite, lesser tetrahedrite in quartz-pyrite gangue, and it is gradational into covellite, digenite, colusite and bornite-chalcopyrite veins. The wallrock alteration is mainly sericitization, quartz-sericitization or locally advanced argillization (dickite-kaolinite). The Zn-Mn zone has mostly sphalerite veins with rhodochrosite gangue.

An earlier (62 to 63 m.y.; Fig. 28-6) Pre-Main Stage porphyry Cu-Mo mineralization was recognized and economically utilized later. It consists of a stockwork, containing veinlets less than 3 cm wide and composed of quartz, K-feldspar, chalcopyrite, lesser anhydrite,

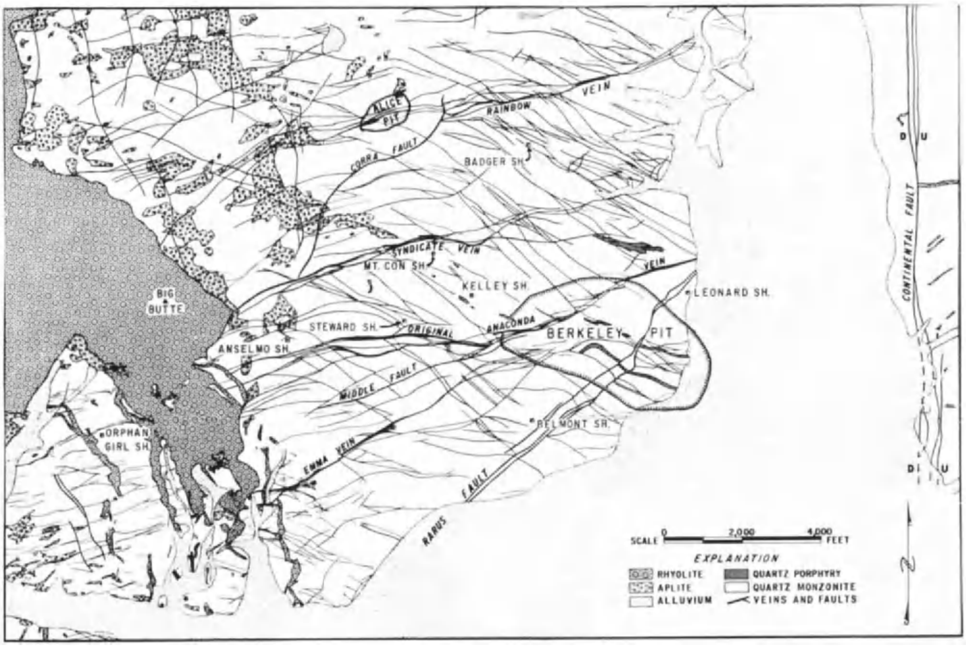


Fig. 28-5. Butte ore field, Montana. From Meyer et al. (1968), courtesy of the Society of Mining Engineers of A.I.M.E.

molybdenite, magnetite and biotite, surrounded by alteration envelopes of overlapping potassic (K-feldspar, biotite, anhydrite) and advanced argillic (andalusite, corundum, muscovite) assemblage. This represents a considerable resource of low-grade ore (min. 3 Mt Cu) and appears shortly to postdate (or possibly overlap with) emplacement of quartz porphyry and a biotite igneous breccia. In this breccia, fragments of quartz monzonite, aplite, vein quartz, sulphides, etc. are enclosed in biotite and K-feldspar matrix.

Although the Butte field has recently been considered to be located in the vicinity of a "root zone" of the Boulder Batholith, the reason for its existence and its metal sources remains as enigmatic as ever. Following ore deposition and partial unroofing, Boulder Batholith and portions of the Butte field have been intruded by post-ore rhyolite and rhyodacite dikes and blanketed by Eocene quartz latite continental volcanics. These rocks are virtually unmineralized.

NORTH LAKE BALKHASH (PRIBALKHASH) REGION, KAZAKHSTAN, U.S.S.R.

This is an outstanding region of Permo-Carboniferous continental volcanism and comagmatic plutonism so little eroded that several hundred paleovolcanic remnants (stratovolcanoes, calderas, cauldrons, volcano-tectonic depressions) are still recognizable. These are

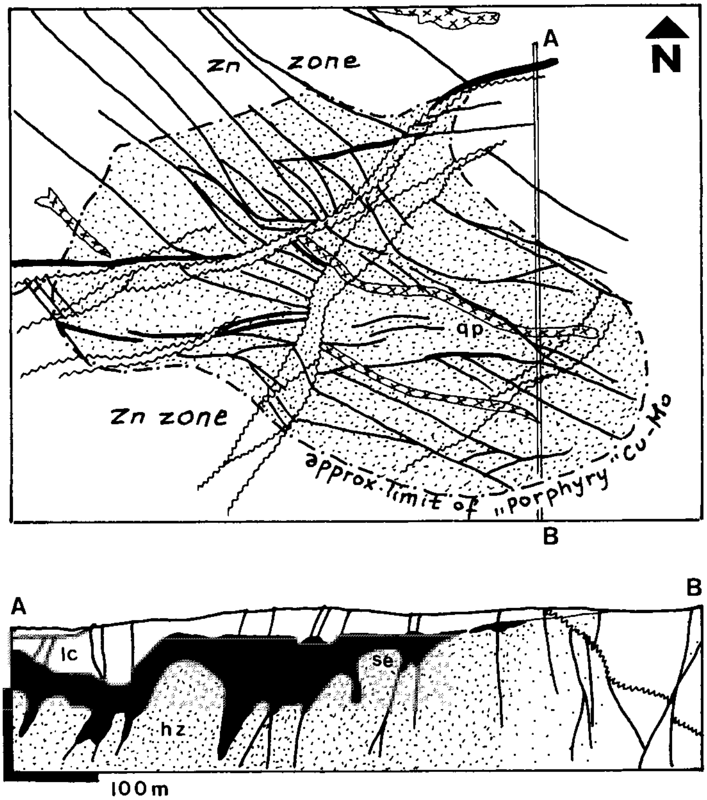


Fig. 28-6. Butte, Berkeley pit, the early stage "porphyry" Cu-Mo mineralization intersected by "main stage" chalcocite and enargite veins. Butte Quartz Monzonite is the host rock throughout. lc=leached capping; qp=quartz porphyry; hz=hypogene zone; se=secondary sulphides zone. From LITHOTHEQUE, based on data in Miller, ed. (1973)

interspersed with numerous epizonal plutons (Yesenov, ed., 1972; Nakovnik, 1968; Fig. 28-7).

Central Kazakhstan is extremely complex in geological terms. It remains an enigmatic accumulation of several crustal megablocks, comprising blocks of thickened (50-55 km) Proterozoic to Permian transitional to continental crust forming structural highs, alternating with thinner (40-45 km) synclinoriums. In the Permo-Carboniferous period, this was probably an "Andean-type" continental margin with a northward polarity which later collided. Basalt, andesite, rhyolite volcanism started in the middle-upper Devonian and lavas, pyroclastics and volcaniclastics were deposited over the immediate basement of Silurian marine sediments, in both subaqueous and subaerial environments. Of the several phases of "orogenic" volcanism, the middle-upper Carboniferous was most intensive and increasingly subaerial. In the Tokrau-Bakanass volcanic belt a number of eruptive centres produced andesites and basalts in downwarps adjacent to deep faults, and dacites-rhyolites along uplifts.

The upper Carboniferous to Permian interval was dominated by "subsequent" (post-orogenic) continental volcanism, and andesite, dacite, rhyolite lavas and pyroclastics issued from numerous centres controlled by block faults. The Permo-Carboniferous volcanism was cyclic and closely comparable with the Tertiary cycles reviewed (as in the San Juan Mts.) in Chapter 26. Each cycle (duration 20-25 m.y. in the earlier cycles, 10-15 m.y. in the later cycles) was initiated by (1) deposition of coarse dacite tuffs containing basement rock fragments on an eroded fundament. This was followed by (2) andesite and dacite lavas and subvolcanic andesite bodies, sometimes postdated by granodiorite intrusions. (3) After a break marked by deposition of conglomerate and sandstone, widespread deposition of rhyolite, dacite and latite lavas, ignimbrites and ash-flow tuffs was contemporary with caldera and volcano-tectonic depression development. This was shortly followed by consolidation, in depth, of granodiorite-quartz monzonite massifs. The closing stages (4) produced mostly felsic dike complexes and a variety of hydrothermal metasomatites dominated by "secondary quartzites" (relict-free zones of silicification; compare Fig. 28-7a). The late magmatism frequently had alkaline tendencies (trachybasalts, trachytes, monzonites, syenites).

In the North Balkhash area, intrusive Permo-Carboniferous plutons are now exposed over about 30% of the territory. 40% is occupied by the comagmatic volcanics, and the rest are rocks of the basement, Permo-Carboniferous sediments and Mesozoic-Cainozoic sediments of the platformic and para-platformic covers. The intrusions range from usually elongated large plutons of irregular outline to subrounded small massifs and rounded to irregular stocks, dikes, vent breccias and ring dikes, scattered within and on flanks of a former caldera. The small massifs are often interpreted as marking the cores of stratovolcanoes.

The region is densely mineralized and contains the principal Soviet porphyry Cu-Mo province estimated to represent some 15 Mt Cu and 200 Tt Mo. Most of these metals are in the large Kounrad (Cu-Mo) and East Kounrad (Mo-W) fields. There are two or three additional large porphyry Cu and skarn/porphyry deposits (Karatas, Sayak, Borly), one large Zn-Pb replacement in Paleozoic carbonates (Kyzyl-Espeh), and 116 Cu, 112 Zn,Pb,Ag, 75 Mo, W, Sn and 17 Au medium-to-small deposits and occurrences. Unfortunately, no size or tonnage figures are available. Neither, in most cases, are the exact locations of the deposits.

The absolute majority of the North Balkhash ore deposits (and all the economically important ones) are hydrothermal-epigenetic, postmagmatic mineralizations formed during stage (4) of the magmatic development mentioned above. All appear to be high-level occurrences, formed at the subvolcanic to uppermost plutonic levels, in the roof

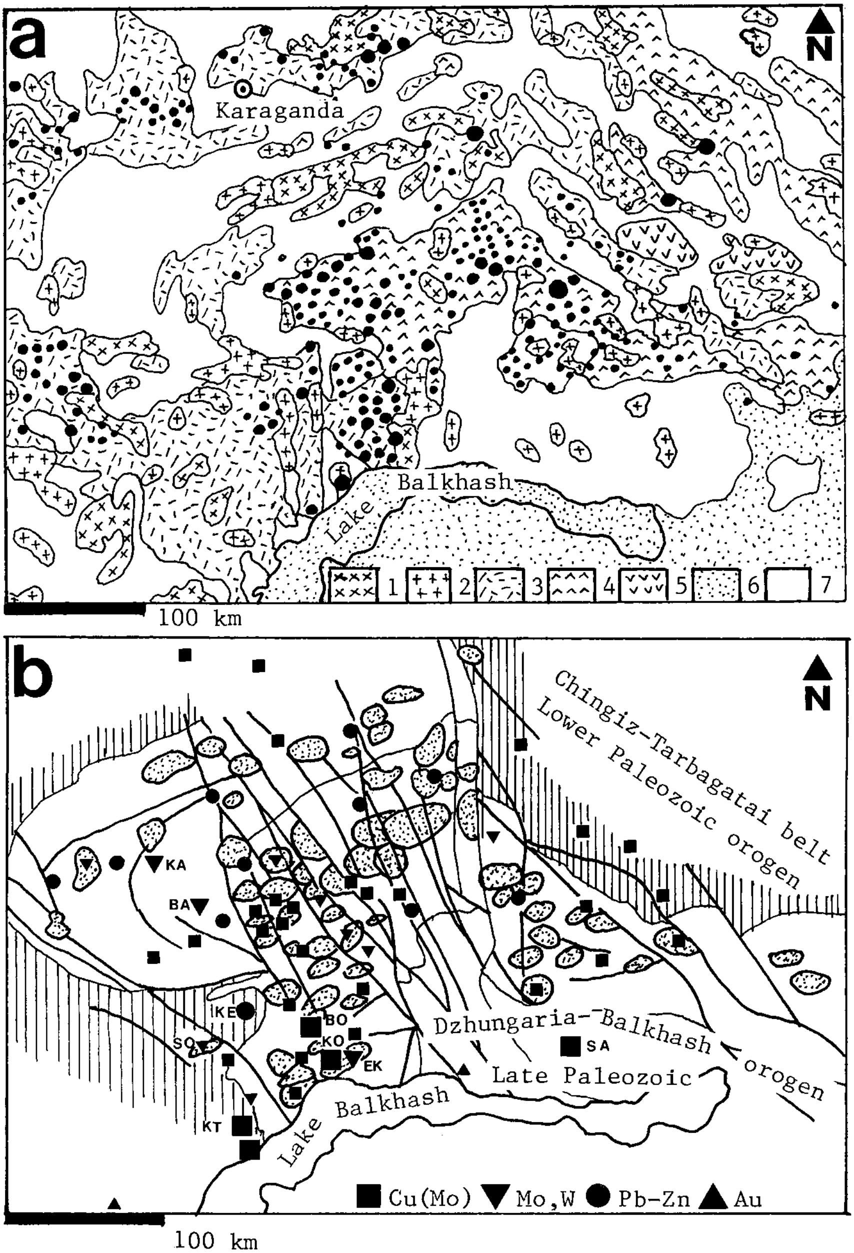


Fig. 28-7. North Lake Balkhash (Kazakhstan) late Paleozoic mineralized region.
a) Simplified geological map, showing the distribution of massifs of "secondary quartzites" (black dots; a hydrothermal silicification usually associated with aluminous products of sericitic and advanced

and above-roof zones of the intrusive bodies formed under volcanic centres. Because of the magmatic cyclicity (at least 3 major cycles), virtually identical ores are associated with upper Devonian to upper Permian (or even lower Triassic) magmatism, although the importance with regard to Mo, W and Sn increases with the decreasing age (maximum in upper Permian), while Cu had reached its peak of accumulation during the middle Carboniferous period.

The best guide to the location of ores on the gently rolling surface of the semiarid Kazakh Steppe are the topographically positive zones of intensive silicification ("secondary quartzites"), often gradational into quartz-sericite and advanced argillic (andalusite, diaspore, corundum) alterites. The "secondary quartzites" and even more the adjacent silicate alterites host most of the orebodies: porphyry Cu-Mo stockworks and pervasive disseminations; gold-quartz veins grading to "linear stockworks" (some reminescent of the Butte "horsetail" veins); quartz, molybdenite, wolframite veins to stockworks (East Kounrad) and a variety of vein Pb-Zn deposits. Yesenov, ed., (1972) reported 500 major occurrences of "secondary quartzites" in the North Balkhash region, of which 60 are associated with porphyry Cu deposits or occurrences. Additional Cu porphyries (and Sn,W,Mo "cupola" stockworks, veins and disseminations) have been discovered in the more recent phase of exploration, affiliated with K-silicate-altered and greisenized granitoids lacking the conspicuous silicification.

The Sary-Oba ore field described by Laumulin et al. (1973; Fig. 28-8) is a rather typical example of a mineralized North Balkhash volcanic-intrusive centre. It is located 110 km W.N.W. of the city of Balkhash, in the Tasaral-Kyzyl Espeh Anticlinorium. There, the substratum is represented by lower-middle Carboniferous continental dacites, pyroxene-hornblende andesites, and the rhyolite ignimbrites that are most important in terms of volume. The felsic volcanics eruption overlapped with intrusion of a biotite leucogranite massif in depth. Remnants of small circular vents surrounded by a radial system of fractures filled by small bodies of quartz-syenite porphyries, are still recognizable. The latter, as well as a circular granite stock, are probably a product of cauldron subsidence. A variety of dikes (felsite, diabase, quartz-syenite porphyry) intrude all the earlier rocks.

⇐

argillic alteration such as andalusite, diaspore). 1=late Paleozoic granitic rocks; 2=early Paleozoic "granites"; Paleozoic felsic=3, intermediate and mixed=4 and mafic=5 volcanics. 6=sediments of post-orogenic basins; 7=Paleozoic (meta)sediments. After Nakovnik (1968).

b) Major hydrothermal deposits related to late Paleozoic granites, and their correlation with granite cupolas, cauldrons and Cb-Pe volcanic centres (stippled). Abbreviations: KA=Kairakty; BA=Bainazar; Bo=Borly; KE=Kyzyl-Espeh; SO=Sary Oba; KT=Karatas; Ko=Kounrad; EK=East Kounrad; SA=Sayak. Base map simplified after Yesenov, ed., (1972); ore deposits added.

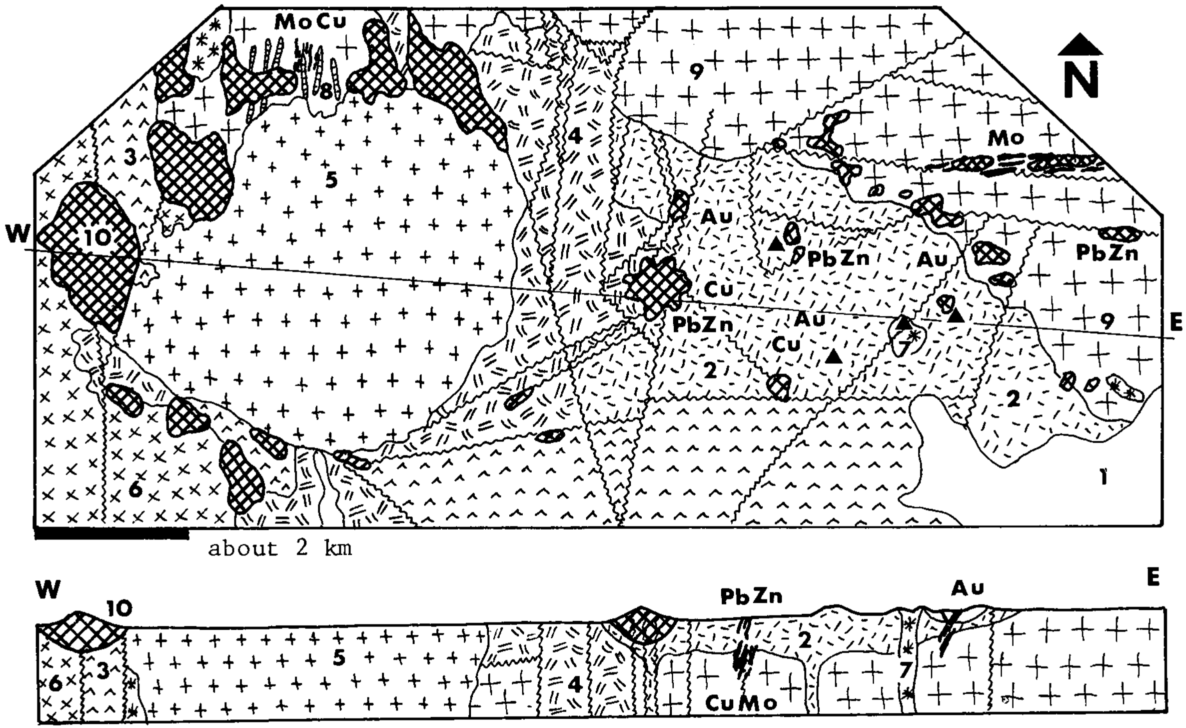


Fig. 28-8. Sary-Oba (Kazakhstan), a high-level mineralized volcanic–plutonic complex. Most ore occurrences are associated with fault-controlled silicified massifs ("secondary quartzites"). 1=Q, alluvium; 2=Cb_2 ignimbrite, rhyolite flows, tuffs; 3=$Cb_{1,2}$ andesite; 4=Cb_1 rhyolite flows and tuffs; 5=$Cb_{2,3}$ leucocratic granite; 6=granodiorite; 7=quartz syenite porphyry; 8=felsite porphyry dikes; 9=Cb_1 biotite leucocratic granite; 10=secondary quartzites; triangles= volcanic vents; Mo=molybdenite stockworks, veins; Cu=disseminated Cu sulphides assoc. with feldspar porphyry dikes. Modified after Laumulin et al. (1973).

Quartz-dominated post-magmatic hydrothermal metasomatites (secondary quartzites) are widespread, (1) fringing the leucogranite and controlled by the cauldron rim faults; (2) marking former vents and (3) situated along faults and fault intersections. The pure "secondary quartzite" is a fine-grained, granoblastic rock replacing both volcanics and intrusions, and it contains grains of ilmenite and rutile. It is gradational into quartz-sericite, quartz-kaolinite, quartz-alunite and alunite-diaspore alteration assemblages. It is quite possible that a portion of the "quartzite" formed by supergene modification of other alterations, because the largest masses do not continue to depth. A variety of ore showings has been recorded, but no information is available concerning their size and economic importance. Gold occurrences are situated along fault zones accompanied by strong pyritization. Most promising are the simple lens-like quartz-pyrite veins grading to stockworks. Persistent quartz-barite veins also carry low gold values in depth. Minor Pb,Zn,Cu-bearing veins hosted by the ignimbrites along faults, grade downward into poor "porphyry Cu-Mo" stockworks in granite. The Mo showings (e.g. the Birek showing) appear to be the most interesting. Molybdenite occurs as disseminated flakes in quartz veins and in silicified, greisenized and albitized biotite granite along a S.W.-N.E. fracture zone, up to 2 km long and 100-250 m wide.

Kounrad porphyry Cu-Mo deposit (estim. 10 Mt Cu, 70 Tt Mo; Gazizova, 1957; Samonov and Pozharisky, 1974; Fig. 28-9) is the largest Soviet "porphyry" located 17 km from Balkhash (city). It cropped-out in a low hill of heavily silicified rocks surrounded by Cainozoic alluvium. Lower Carboniferous volcanics (andesite, basalt, rhyolite lavas and tuffs and ignimbrite locally albitized to keratophyre) have been forcibly intruded by a high-level granodiorite porphyry body, fractured, invaded by felsic dikes, altered and mineralized. The dominant alteration is pervasive silicification grading to quartz-andalusite, quartz-sericite and propylitic alterations. Lesser diaspore, dickite and alunite are present and andalusite is recovered as a by-product. This phase of alteration is considered pre-ore, affecting all rocks, but only the fractured granodiorite porphyry, silicified or quartz-sericite altered, contains the ore. The hypogene mineralization consists of disseminations, veinlets and discrete veins filled by quartz, pyrite, chalcopyrite and minor molybdenite. Late-stage rich quartz, pyrite, enargite, bornite veins are rare and occur locally. The Kounrad orebody is pipe-like with dimensions of about 1.7x1.3 km. It is distinctly supergene zoned. Leached capping (about 27 m thick) is followed by an oxidation zone (22m) with an overall subeconomic grade of 0.2% Cu, but containing local rich patches. A thick (135m) zone of secondary chalcocite enrichment with grades between 0.7 and 1.2% Cu has provided most of the ore mined so far. The hypogene zone is said to average between 0.3 and 0.4% Cu.

NORTH-EASTERN QUEENSLAND

In North-Eastern Queensland (Georgetown Inlier and the adjacent Tasman Foldbelt), Carboniferous epizonal granites and comagmatic continental volcanics interact in numerous cauldron subsidence, ring and neck complexes described in detail by Branch (1966; Fig. 28-10). In contrast to the earlier treated examples affiliated with Cu, Pb-Zn and Au mineralization this is a distinct Sn(W) province.

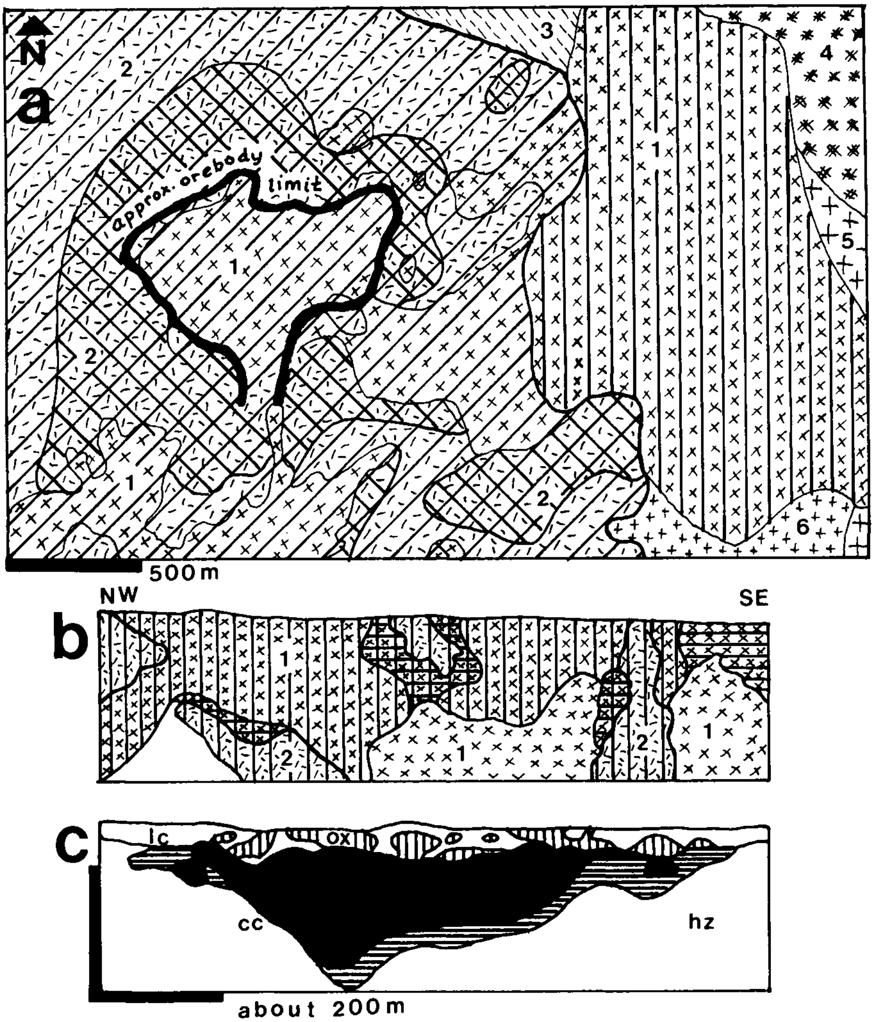


Fig. 28-9. Kounrad "porphyry" Cu-Mo deposit, North Lake Balkhash area, Kazakhstan. (a) Geological map. Rock types: 1=Cb_1 granodiorite porphyry; 2=Cb_1 rhyolite; 3=D sandstone, shale, contact hornfels; 4=Cb_1 granodiorite; 5=Cb-Pe biotite granite; 6=Pe aplite granite. Alterations: (shown by ruling superimposed on geology); N.E.-S.W ruling: quartz-sericite (secondary quartzite); N.W.-S.E. ruling: andalusite-sericite, grading in depth into diaspore-corundum; vertical ruling: supergene argillization. (b) Cross-section, showing alterations; vertical ruling: early silicification and quartz-sericite ("secondary quartzite"); horizontal ruling: late argillization. (c) Cross-section, mineralization; cc=chalcocite blanket; ox=oxidized ores; lc=leached capping; hz=hypogene zone. Modified after Nakovnik (1968).

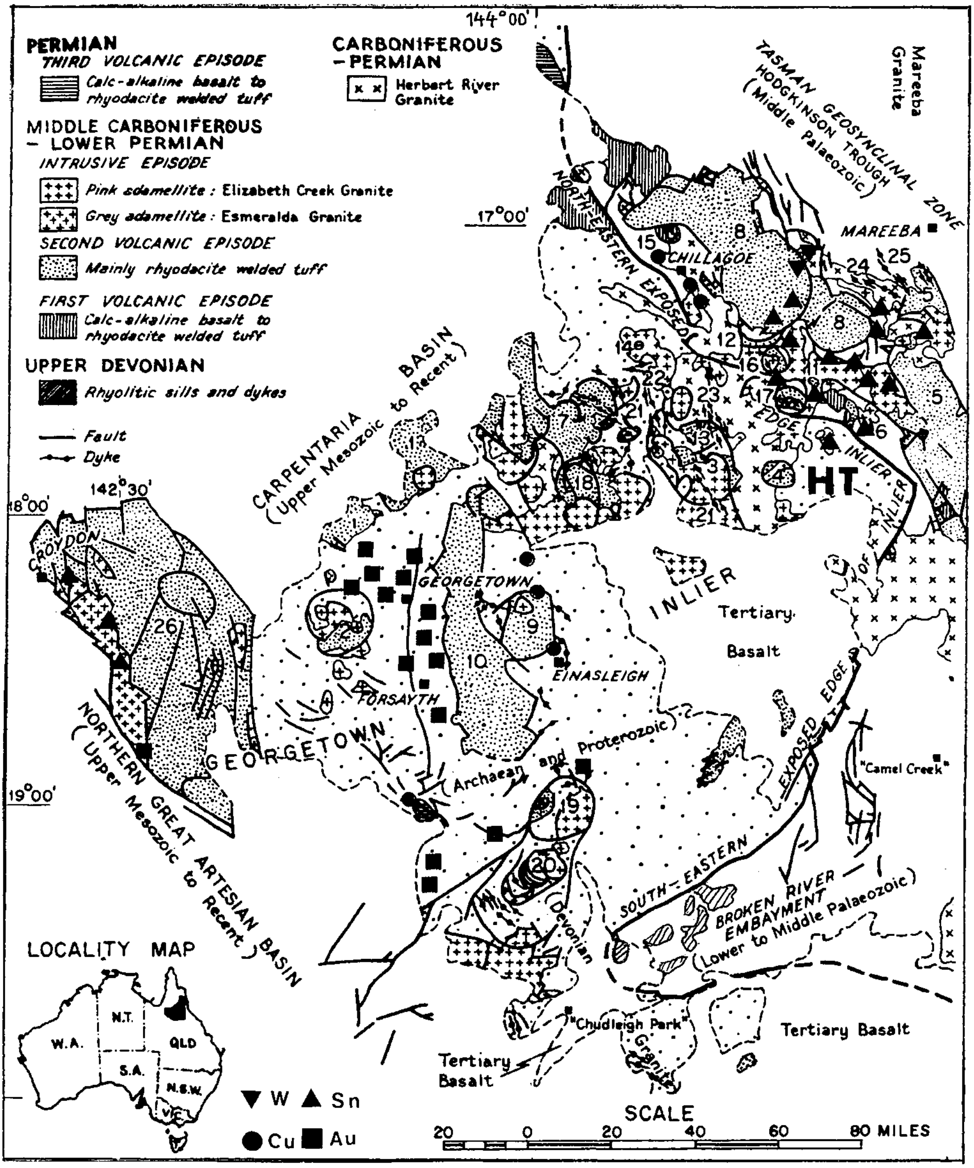


Fig. 28-10. Permo-Carboniferous high level plutonic province of N.E. Queensland and its metallic mineralization (granite-related, interaction and relict). HT=Herberton Tinfield; numbers indicate named complexes, 11=Gurrumba volcanic neck (Fig. 28-11); 17=Claret Creek ring complex (Fig. 28-12). The gold deposits in the Georgetown district are of Proterozoic age. From Branch (1966), with additions. Courtesy of the Bureau of Mineral Resources, Geology, Geophysics, Canberra.

In the Georgetown Inlier (western) portion, the basement rocks are Precambrian metamorphics and granitic rocks. In the east, the old crystalline basement is topped by a prism up to 13 km thick, of detrital and very minor carbonate sediments of a stable shelf facies, ranging in age from upper Ordovician to Carboniferous. The late Paleozoic continental magmatic activity followed a folding in the "geosyncline" and fragmentation (activation, rejuvenation) in the basement, and it proceeded in several cycles. The initial extrusion of small amounts of calc-alkaline acid, intermediate and mafic volcanics in the Carboniferous period was followed by a vast outpouring of compositionally monotonous rhyodacite ignimbrite and ash-flow tuffs. Ring complexes and cauldron subsidence centres formed at intersections of major basement fractures. After this, acid magma stoped through the upper crust and intruded the base of the felsic pyroclastic cover. This was followed by dike emplacement and terminated, in the Permian period, by another weak outburst of sequentially differentiated volcanics.

The volcanic-intrusive central complexes treated in Branch (1966) are interesting geologically, but they carry little mineralization contemporary with their formation. Small Pb-Zn veins (Greenhills), Cu veins (Mt. Jardine), Mo,Sn,W veins (Lochaber), Au and Sn veins (Croydon), Au veinlets associated with microdiorite in the Gurrumba volcanic neck (Fig. 29-11) and others, have been reported. The U-Mo veins in Carboniferous welded tuff (Ben Lomond) have been reviewed in Chapter 26. The bulk of the Northern Queensland ore metals (over 100 Tt Sn, 10 Tt W, some Bi, Pb-Zn, Cu, magnetite) is, or was, contained in over 2,500 lode deposits and several hundred placers, all genetically related to late Carboniferous granite plutons, postdating the circular centres. This is apparent from Fig. 28-12, showing the minor Sn and Cu-Fe occurrences along the fringe of the Claret Creek ring complex.

The Elizabeth Creek Granite, a high-level pink leucocratic biotite quartz monzonite, is responsible for most of the ore occurrences. It was emplaced as little as 170 m below the surface, under its comagmatic ignimbrites. The Esmeralda Granite and its hornblende-biotite granodiorite phase, accounts for the rest (e.g. magnetite and/or chalcopyrite skarns in the Chillagoe area, small porphyry Cu, Ruddygore and Zn-Pb replacements in carbonate).

Most of the Sn(W) orebodies are small greisen or quartz, chlorite, cassiterite pipes or fissure veins located in both endo- and exocontact in the granite roof. Taylor and Steveson (1972) argued convincingly that the known mineralization accumulated preferentially in a number of small, circular to elliptical, metal-zoned patches, is controlled by a series of emanative centres in the Elizabeth Creek Granite that in turn overlie the "highs" (cusps, ridges and cupolas) on the generally flat surface of the pluton. The "highs", in turn, are fault-controlled and some of the structures are cauldron subsidence rims or branching faults.

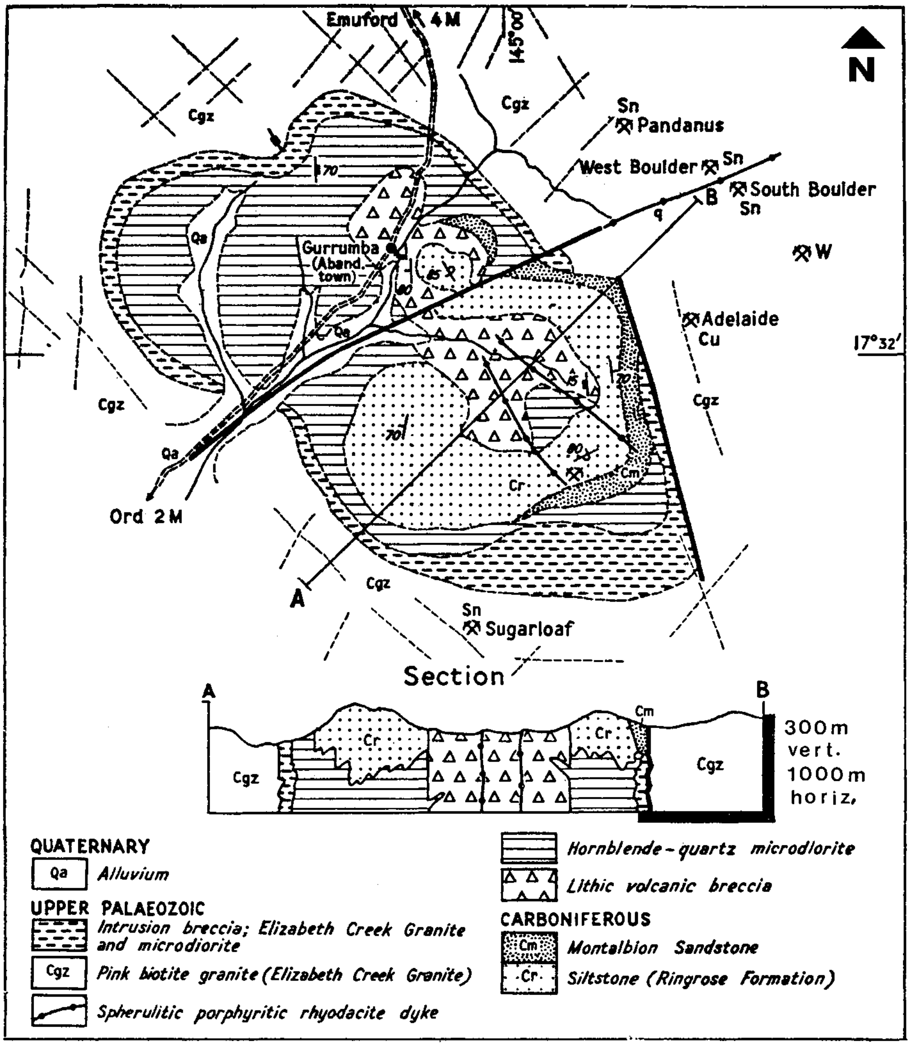


Fig. 28-11. Gurrumba (paleo)volcanic neck, 35 km W.S.W. of Herberton, N. Queensland. The Sn and Cu mineralization postdates the neck emplacement and is related to the postmagmatic phase of the Elizabeth Creek Granite. From Branch (1966), courtesy of the Bureau of Mineral Resources, Geology, Geophysics, Canberra.

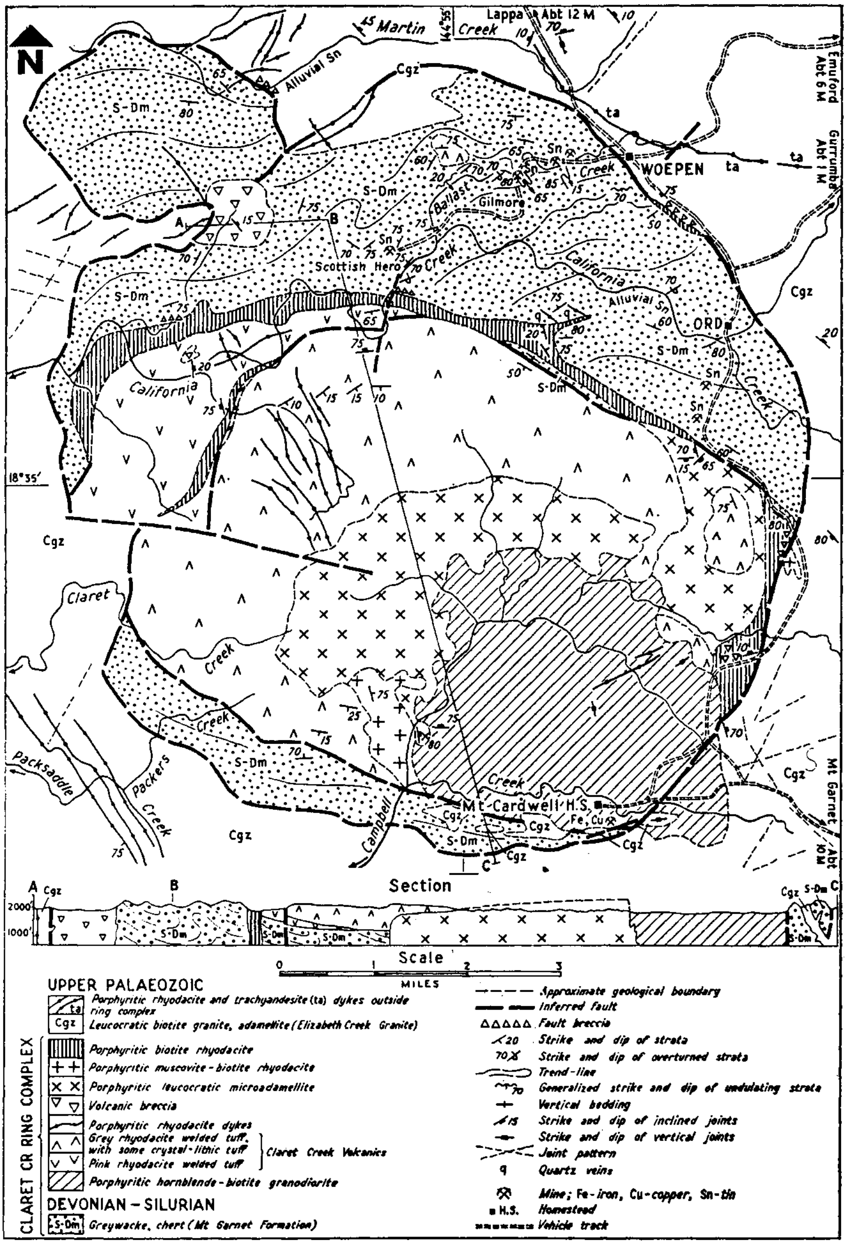


Fig. 28-12. The Claret Creek late Paleozoic ring complex 70 km W.S.W. of Herberton, N. Queensland. The minor mineralization (placer cassiterite and magnetite, chalcopyrite disseminations and replacements), are related to the young intrusion of biotite leucogranite (Cgz). From Branch (1966), courtesy of the Bureau of Mineral Resources, Geology, Geophysics, Canberra.

COLORADO ROCKY MOUNTAINS MINERAL BELT

The Colorado Rocky Mountains are a N.N.E.-trending young uplift deformed during the Laramide Orogeny (late Cretaceous-early Tertiary period), and it separates the little deformed Colorado Plateau in the west from the North American Platform in the east. The Rockies are dominated by deeply eroded lower Proterozoic metamorphics (gneisses, migmatites, schists) and kata- to mesozonal granites. There are lesser Paleozoic and Mesozoic platformic sediments preserved on flanks of the basement domes and ridges. The Laramide Orogeny was followed by magmatic activity, and two age groups of magmatic rocks are present: (1) pre-Oligocene and (2) Oligocene to Pliocene. The magmatic belt is in the N.E. extension of the San Juan Mts. volcanic field (Chapter 26).

The "Laramide" magmatites (Lovering and Goddard, 1950) are mostly porphyritic high-level intrusions of calc-alkaline diorite to alaskite forming small, often inconspicuous stocks, dike swarms and single dikes, "porphyry" laccoliths, etc. Most of these intrusions congregate in a narrow belt crossing obliquely the Front Ranges, extending in the S.W. direction from Boulder to Breckenridge. Most of the classical Pb,Zn,Ag and Au,Ag vein districts or fields occur in the aureole, forming the Colorado Mineral Belt (Fig. 28-13). Additional intrusions are scattered outside this belt and some of them (e.g. Climax, Red Mountain) are affiliated to giant Mo stockworks.

Although extrusive equivalents of the Laramide intrusions are known locally on the flanks of the Rocky Mountain belt (e.g. in the Denver basin), the intrusions themselves generally lack affiliated volcanics and were emplaced mainly in the crystalline basement along faults and crush zones. The high emplacement levels are demonstrated by intrusive textures and many wide, open, breccia or mylonite-filled faults ("breccia reefs"). It is likely that the Colorado Rockies' small intrusions are apophyses of a mesozonal batholith situated at a greater depth.

The Colorado Mineral Belt is one of the classical regions of metalliferous geology and of genetic affiliation of "granites", faults and postmagmatic hydrothermal ores. It contains several thousand showings. Several hundred small to medium-size Pb,Zn,Ag; Au; few W, U deposits; two significant Zn,Pb,Ag fields (Leadville and Gilman); two or three large Mo stockworks (Mt. Emmons, Mt. Tolman) and two Mo giants (Climax and Red Mountain). This represents some 4 Mt Mo, 1.8 Mt Pb, 1.9 Mt Zn, 15 Tt Ag and 975 t Au (portion of Au came from placers). Cu,W,Sn,U,Bi,Re and other minor metals form lesser accumulations.

Metallogenically, this is a distinct "continental" association and the deficiency in copper is conspicuous. Disregarding young placers and old relict deposits in the intruded basement (e.g. pegmatites, katazonal skarns and greisens, hydrothermal veins, minor concordant pyrite and Zn-Pb sulphide bodies or metalliferous horizons), three ore styles are the most prominent: (1) fissure veins in intrusive exocontacts; (2) replacements in exocontact carbonates and (3)

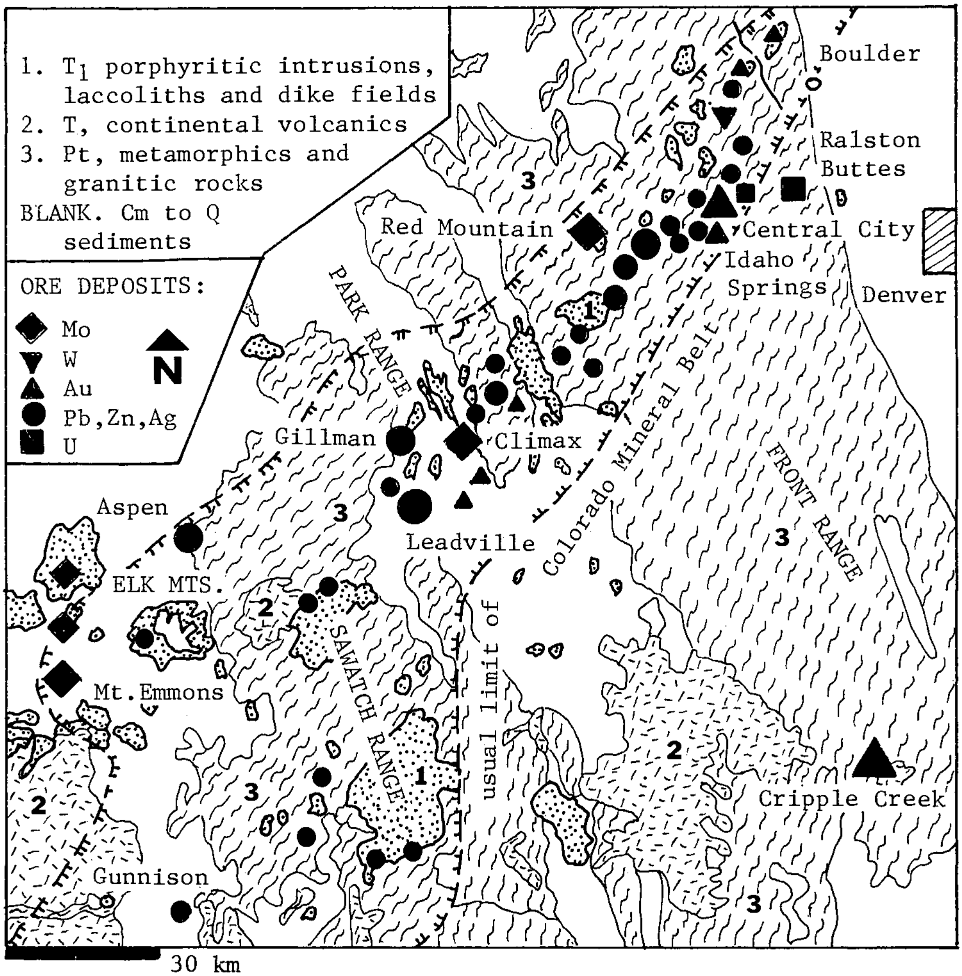


Fig. 28-13. Colorado Mineral Belt. From LITHOTHEQUE.

sulphide stockworks in altered "porphyries".

Category (1) is most common but represented only by small to medium-sized deposits. The veins either singly or in groups, are exercising a variety of structural controls for which they have been extensively treated in the literature from the first half of this century. The brittle rocks (Proterozoic granites, metaquartzites, amphibolites, etc.) are favourite hosts whereas sheared and faulted schists and shales produce tight structures and inpenetrable gouge so they rarely contain veins. Most mineralized structures are approximately parallel with the regional trend of the "porphyry" belt and many such fissures carry ore when they intersect the otherwise barren N.W.-trending "breccia reefs". The veins usually have quartz gangue and a banded-to-scattered filling of pyrite, sphalerite and galena. Lesser chalcopyrite, arsenopyrite. Ag-sulphosalts, gold, Au tellurides, occur locally. Pb-Zn only; Pb,Zn,Au; and Au-only orebodies have been identified in almost all districts. Individual ore shoots tend to be short with length several hundred metres, but the mineralized depth range may exceed 700m.

Category (2) is best developed in the Leadville field, already mentioned briefly in Section 20.10.1. (see also Fig. 20-28). There, both fissure filling and discordant replacement Zn,Pb and Fe sulphide veins grade into peneconcordant mantos in Mississippian limestones, directly at the contact or in the vicinity of quartz-feldspar porphyry sills and dikes.

Category (3) is primarily represented by the great molybdenite stockworks at Climax and Henderson (Red Mountain), described later. There, quartz, pyrite and molybdenite veinlets and fracture coatings are situated in a large mass of an altered cylindrical composite intrusive body. Recently, Mutschler et al. (1981) argued that the Colorado Mo deposits are affiliated to the petrochemically true granites and occur in cupolas on tops of epizonal batholiths coincident with, or shortly predating, a regional extensional tectonism. Metals other than Mo rarely accumulated in endocontact stockworks. The small Jessie mine in the Breckenridge field (about 2 t Au; Lovering and Goddard, 1950; Fig. 28-14) is an example of a gold-bearing stockwork in sericite-altered Tertiary tongue of quartz monzonite porphyry.

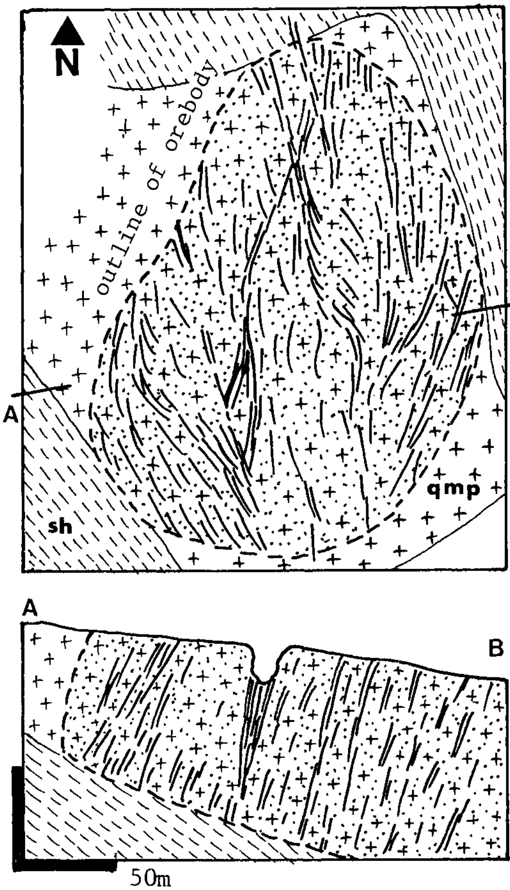
OTHER MINERALIZED EPIZONAL PLUTONS

These have a worldwide distribution and are affiliated to the bulk of porphyry Cu-Mo deposits (in the south-western United States and adjacent Mexico, in Chile and Argentina, in Yugoslavia, Rumania and Bulgaria, in Iran, the Philippines, Melanesia and elsewhere), to tin deposits (Sundaland, Cornwall, Sikhote Alin, eastern Australia), to Pb,Zn,Ag provinces (e.g. western United States and Mexico, Rhodopen Mts. in Bulgaria), to Au, W, Mo, Sb and other metals. Example deposits will be discussed below.

HIGH-LEVEL "GRANITIC" LACCOLITHS

Laccoliths are concordant injected masses that lifted their roofs by arching, so they appear not to be located immediately by major regional tectonic structures. A major factor in their emplacement has been the local lithostratigraphy, in which incompetent rocks were favourable for a laccolith generation. In the La Sal Mountains, Colorado, laccoliths rose on salt anticlines and spread mostly in the salt horizons.

Laccoliths typically developed in platformic cover sequences, and



sh Cr_1 shale to siltstone

qmp T_1 quartz monzonite porphyry, unaltered

OREBODY:

sericitized and quartz-sericite altered, fractured porphyry with disseminated and veinlet-filling auriferous pyrite, sphalerite, minor galena. Richer portions of ore follow zones of closely spaced parallel fissures and veinlets

Fig. 28-14. Jessie gold mine, Breckenridge, Colorado. From LITHOTHEQUE, after Ransome in Lovering and Goddard (1950).

classical terrains of their distribution are the Colorado Plateau (e.g. Henry, Navajo, La Sal, Carrizo, La Plata, Rico, etc. Mountains; Hunt, 1956) and the Cordilleran Foreland in Montana. Compositionally, many laccoliths consist of alkaline or highly undersaturated rocks (Chapter 33), but GDG intrusions are widespread. Given the nature of their emplacement, laccoliths are a special form of epizonal intrusions and deserve a brief treatment.

In the Colorado Plateau province, Hunt (1956) and Hunt et al. (1953) recognized two major phases of laccolithic emplacement. In the earlier phase diorite, monzonite and syenite porphyries formed by physical injection of viscous magma of low temperature and a low content of volatiles (Fig. 28-15). In the later phase, compositionally similar rocks formed in part by assimilation or

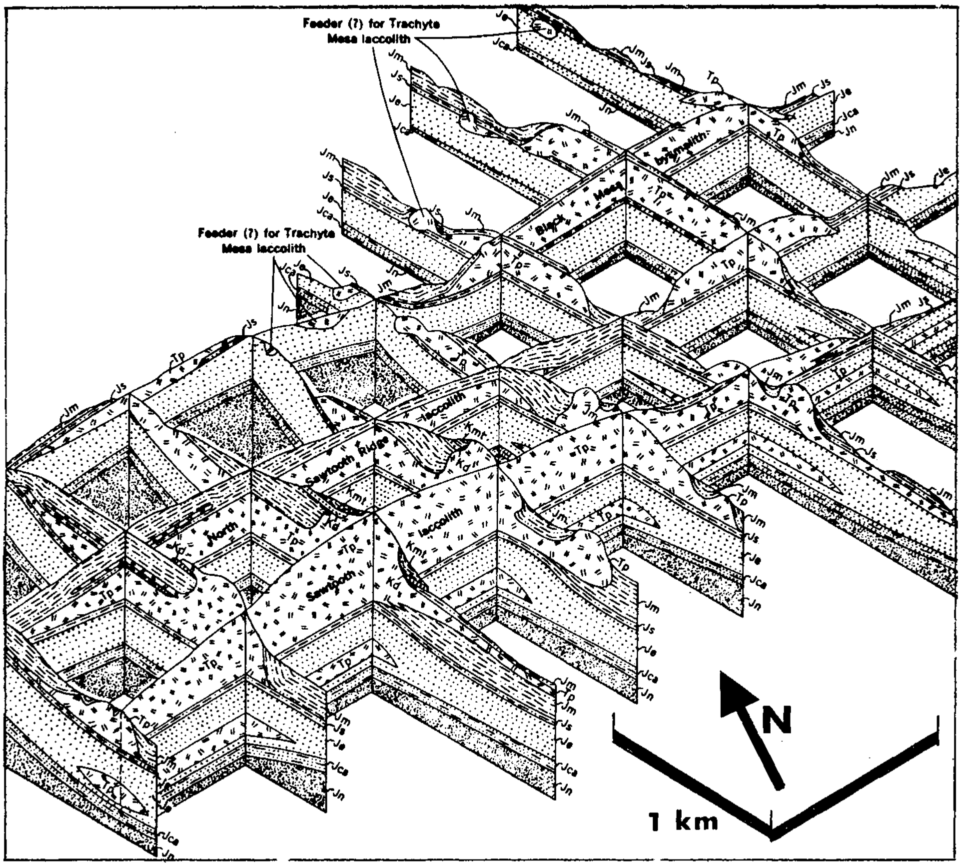
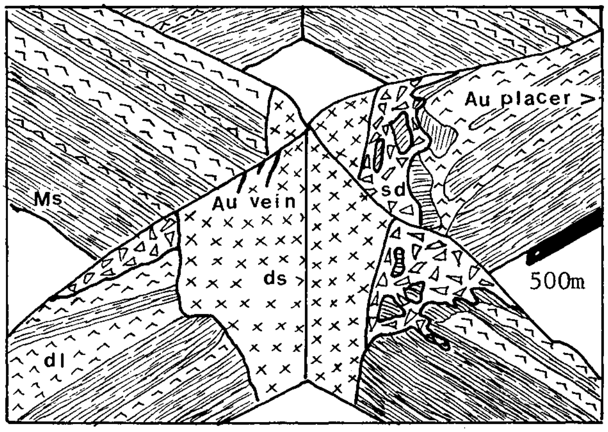


Fig. 28-15. Tertiary diorite porphyry laccoliths and bysmaliths (Tp) emplaced in Jurassic platformic sediments and shales, Sawtooth Ridge, Henry Mts., Utah. From Hunt et al. (1953).

replacement of the earlier intrusion. Their magmas, however, were more fluid, of higher temperature and with higher volatile content. The emplacement was usually forceful. The magmas solidified as holocrystalline stocks and dikes (Fig. 28-16). The small gold occurrences recorded by Hunt et al. (1953) from the Henry Mts. (Mt. Ellen, Mt. Pennell) are related to the late stage stocks, and carry auriferous pyrite in fissure veins and in shear zones along intrusive contacts. The succesful processing of the very low grade vein and stockwork gold deposits at several localities in the Cordilleran Foreland in Montana (Little Rocky Mts., Judith Mts., etc. described



Ms=J and Cr sediments (sandstone, shale)
dl=T, diorite porphyry of the laccoliths
ds=T, diorite porphyry stock
sd=shattered endocontact of diorite porphyry stocks

Fig. 28-16. Mount Ellen stock (ds) and adjacent laccoliths (dl), Henry Mountains, Utah, showing diagrammatically the minor ore occurrences. Modified after Hunt et al. (1953).

later), indicates a possible potential of the laccolith/stock systems for gold.

The majority of the Colorado Plateau laccoliths are unmineralized, but there are minor exceptions. In the La Plata district N.W. of Durango, Colorado (Eckel et al., 1949; Fig. 28-17), the Phase 1 diorite porphyries are unmineralized but Phase 2 diorite, monzonite and syenite stocks are genetically associated with exocontact fissure veins of quartz, carbonate, galena, sphalerite, gold and Au tellurides (6.2 t Au, 57 t Ag, 322 t Pb). The Copper Hill showing contains disseminated and stockwork hematite, magnetite, chalcopyrite, quartz, ankerite and garnet in the endocontact of a syenite stock.

In the Iron Springs iron field, Utah (Mackin, 1968; min. 200 Mt Fe/47.5% Fe; Fig. 28-18), replacement exocontact bodies of magnetite and hematite in Jurassic limestones and minor endocontact magnetite veins, occur at or near the contact with a 19-24 m.y. old laccolithic quartz monzonite intrusion. The most unusual feature of the Iron Springs geology is the general concordancy of the intrusion with the sedimentary bedding as well as with Laramide bedding thrusts. The intrusive emplacement has probably been controlled by a graben structure. The replacement iron orebodies are tabular and lens-like, high in fluorine and immediately adjacent to (or hosted, as in the case of low-grade ores) by hornfelsed metasedimentary or intrusive breccias. The low-intensity contact alteration rarely reached the skarn stage, but the endocontact has been altered, possibly deuterically (K- and Na-feldspathization, biotitization, silicification). Mackin (1968) believed that the endocontact metasomatism was a sufficiently powerful process to release the metals from the parent intrusion and accumulate the iron along the contact.

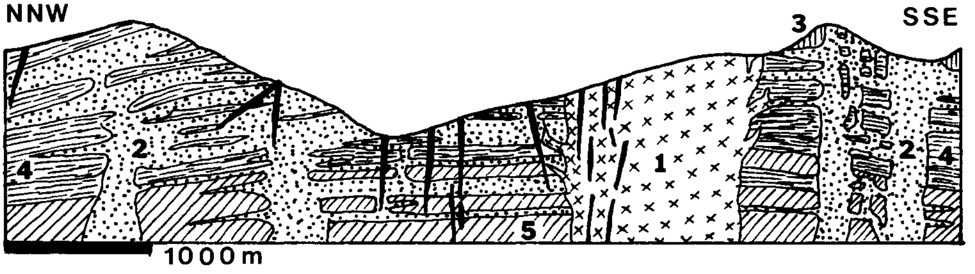
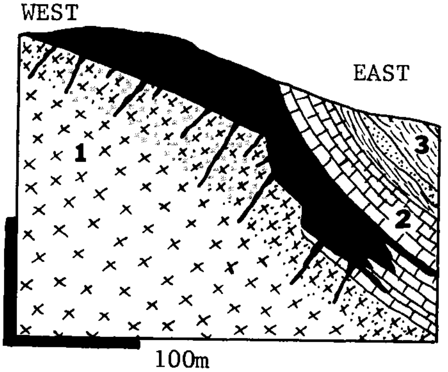


Fig. 28-17. La Plata Au,Ag,Pb,Zn district, S.W. Colorado, showing distribution of ore veins (black) in relation to Cr-T syenite stocks (1) and slightly earlier diorite-monzonite porphyry laccoliths (2). 3=J-Tr red shale, sandstone; 4=Pe red shale, sandstone; 5=Ps gray and red shale, sandstone, limestone. From LITHOTHEQUE, after Eckel et al. (1949).



1. Ol_3 quartz monzonite laccolithic intrusion
2. J siltstone,argillite,limestone, thrust faulted, brecciated and altered in the ore zone
3. J_3 maroon and gray shale, interbedded with arkosic sandstone

BLACK: replacement magnetite-hematite body

Fig. 28-18. Iron Springs, Utah, replacement iron orebody related to laccolithic intrusion of quartz monzonite. From LITHOTHEQUE, based on data in Mackin (1968).

28.2.3. Mesozonal plutons

Mesozonal plutons, the most widespread and "typical" bodies of the "granites" (Buddington, 1959; Hutchison, 1977; Hughes, 1982), formed at depths of between 6-12 (or 4-16) km by forceful diapiric emplacement. They generally display a primary igneous foliation (alignment of feldspar tablets, biotite or hornblende crystals), and have a sharp to gradational boundary against the wallrocks. In the higher levels of a pluton, the wallrocks are usually regionally greenschist metamorphosed and over this metamorphism is superimposed a thermal aureole marked by biotite, andalusite, cordierite, etc. hornfelses. In their lower levels, mesozonal batholiths may grade into katazonal zones of granitization or, when they terminate at depth, be floored or flanked by "contact" migmatites. At considerable depths there was only a minor thermal contrast between the "granite" and the wallrocks, so thermal aureoles are inconspicuous or missing completely.

Mesozonal batholiths frequently contain contact metamorphosed roof pendants, septa and rafts of the country rocks, often partly assimilated. Pegmatites and aplites are moderately common. The K-feldspars are pure or perthitic stable polymorphs, orthoclase or microcline. The rocks range from gabbro to granite, and tonalite or granodiorite compositions are the most common. The majority of rocks are equigranular and medium crystalline, but coarse porphyritic varieties are also common. Large, syn- to post-kinematic elongated composite batholiths in cores of orogens are characteristic. There is no visible presence of comagmatic volcanics, but sometimes (as in the Sierra Nevada Batholith/Great Valley Sequence couple) sedimentary petrofacies faithfully record an early pyroclastic supply attributed to continental volcanism, gradually changing into an epiclastic detritus of "granitic" provenance derived from an unroofed pluton undergoing erosion. Many (perhaps most) mesozonal batholiths, however, probably never communicated with the surface.

Late Paleozoic and early Mesozoic plutons are in their "prime time" of exposure, but mesozonal "granites" range from Archean to middle Tertiary. Granitization and assimilation effects are frequently apparent, particularly when the granitic magma came into contact with compositionally contrasting wallrocks (e.g. mafic metavolcanics, carbonates). Some writers (e.g. Lee and van Loenen, 1971) even maintain that, locally, all the equivalents of the classic differentiation sequence formed through assimilation of chemically distinct and contrasting rocks, such as quartzite, shale, limestone and amphibolite.

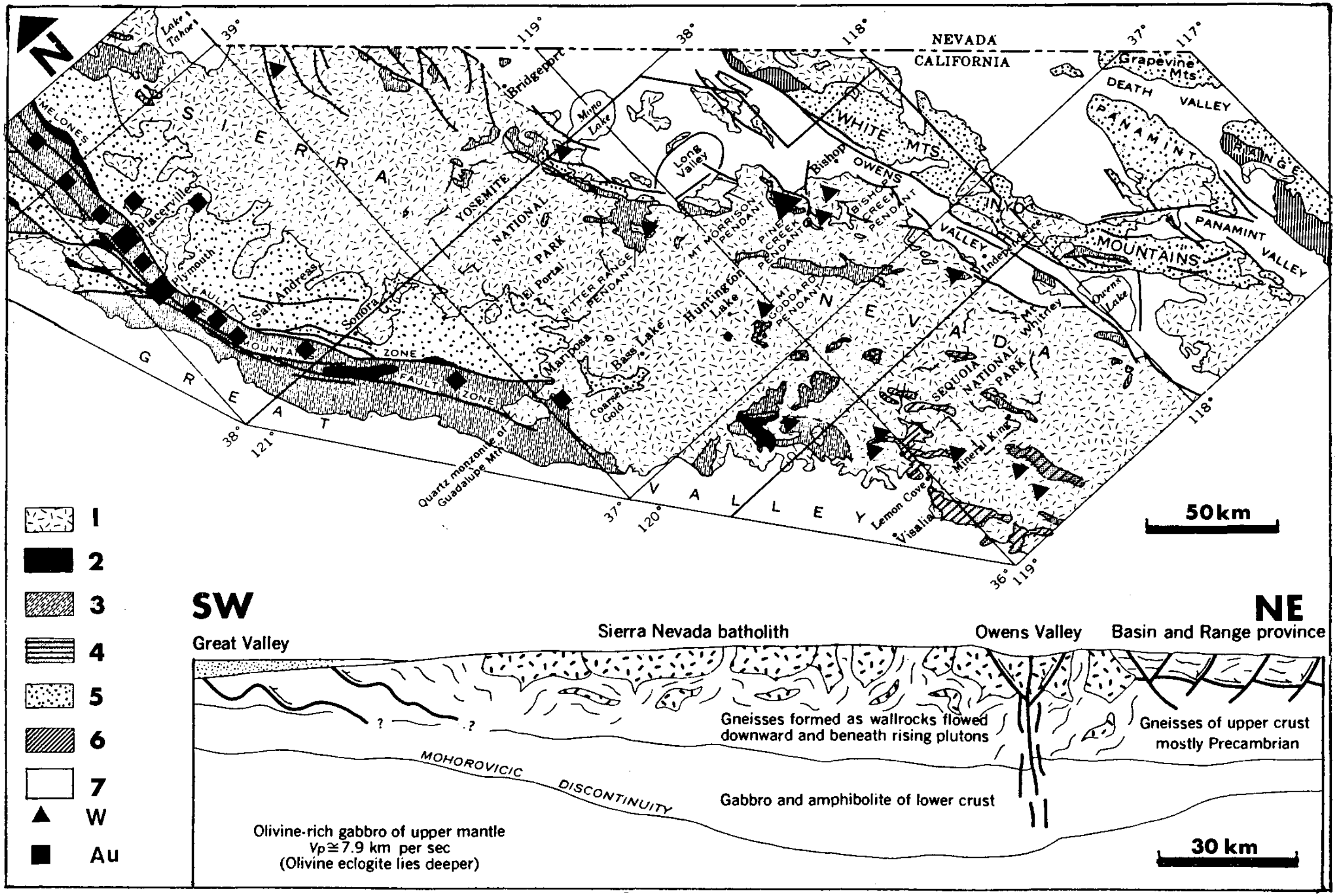
Mesozonal granites sometimes generated and drove far-reaching mafic and acid "fronts". These fronts are believed to have caused metasomatic alteration of certain metamorphics so now, megascopically, they resemble plutonic rocks such as quartz diorite or tonalite. In the gneissic (pseudo)quartz diorite and tonalite near Orofino (Idaho batholith, Hietanen, 1962), sedimentary relic textures and structures are apparent. Fe,Mg,Ca,Al and Na were the principal elements introduced into, and Si, K removed from, the altered metamorphics. Metasomatic fronts are often associated with increased proportions of accessory ilmenite, zircon, apatite and allanite.

SIERRA NEVADA BATHOLITH, CALIFORNIA

The late Triassic to Cretaceous Sierra Nevada Batholith of California is 55-110 km wide. Its exposed length is 650 km, and it has been the most frequently studied mesozonal batholith in the New World (Hamilton and Myers, 1967; Bateman et al., 1963; Peck and Wones, 1980; Fig. 28-19). The batholith straddles the "eugeoclinal" and "miogeoclinal" megafacies boundary and occupies the axial part of a complex N.N.W.-trending synclinorium. It is composed of several nested plutons which frequently become progressively younger, less mafic and more potassic towards the centre, and are interpreted as products of fusion events in the lower crust. The intrusion took place in five major epochs within a time span of about 131 m.y.

The plutons comprise quartz-bearing intrusive rocks having a compositional range from quartz diorite to alaskite, but the batholith also includes small scattered masses of diorites and gabbros ("forerunners"), remnants of metasediments and metavolcanics and local ultramafic inclusions. The discrete plutons have either sharp, steep contacts, or are separated by septa of metamorphics, mafic igneous rocks or later aplitic dikes. The plutons along the western ("eugeoclinal") side are older, more mafic, and indicate greater involvement of a more primitive, possibly partly oceanic, basement in their origin. Assimilation of wallrocks along contacts is widespread, and the flow structures in plutons indicate that they have risen past their wallrocks. The plutonic intrusion was mostly forcible, although local contact breccias indicate stoping during late stages of intrusion. Hamilton and Myers (1967) assumed, on geophysical evidence, that the batholith is relatively thin (15-20 km) and floored by more mafic and heavier rocks of the lower crust.

The mineralization and metallogeny of the Sierra Nevada Batholith (Fig. 28-20) has recently been reviewed by Dodge and Bateman (1977) and by Albers (1981). It is quite representative of many of the mesozonal batholiths of the world. If one plots all the metallic deposits of California and Nevada onto a map, the Sierra Nevada "granitic" core will appear as a distinct minimum in the density and size of ore occurrences, surrounded by a heavily mineralized fringe. Of the sparse ore occurrences within the batholith , at least 90% is scheelite, all of which is in skarns hosted by metasedimentary roof pendants and rafts, in the granite exocontact. The only two mineralization styles of proven or potential importance, hosted by the plutonic rocks themselves, are the gold-quartz veins in the Grass Valley-Nevada City field and the Lights Creek porphyry copper deposit. It is worthy of note that both the above deposits occur in small satelite plutons outside the main batholithic mass. The small fracture infiltrations of U minerals (mainly autunite) in granodiorite explored


N
Lake Tahoe
NEVADA
CALIFORNIA
Grapevine Mts
DEATH VALLEY
PANAMINT RANGE
WHITE MTS
OWENS VALLEY
PANAMINT VALLEY
PANAMINT MOUNTAINS
Owens Lake
Mono Lake
Long Valley
Bridgeport
Bishop
Independence
Mt Whitney
SIERRA NEVADA
YOSEMITE NATIONAL PARK
SEQUOIA NATIONAL PARK
El Portal
RITTER RANGE PENDANT
MT MORRISON PENDANT
PINE CREEK PENDANT
BISHOP CREEK PENDANT
MT GODDARD PENDANT
Huntington Lake
Bass Lake
Mariposa
Coarse Gold
Mineral King
Lemon Cove
Visalia
Quartz monzonite of Guadalupe Mtn
MELONES
Placerville
Plymouth
San Andreas
Sonora
FOOTHILL FAULT ZONE
GREAT VALLEY
39°
38°
37°
36°
121°
120°
119°
118°
117°
50km
1
2
3
4
5
6
7
W
Au
SW
NE
Great Valley
Sierra Nevada batholith
Owens Valley
Basin and Range province
Gneisses formed as wallrocks flowed downward and beneath rising plutons
Gneisses of upper crust mostly Precambrian
MOHOROVICIC DISCONTINUITY
Gabbro and amphibolite of lower crust
Olivine-rich gabbro of upper mantle
Vp≅7.9 km per sec
(Olivine eclogite lies deeper)
30 km

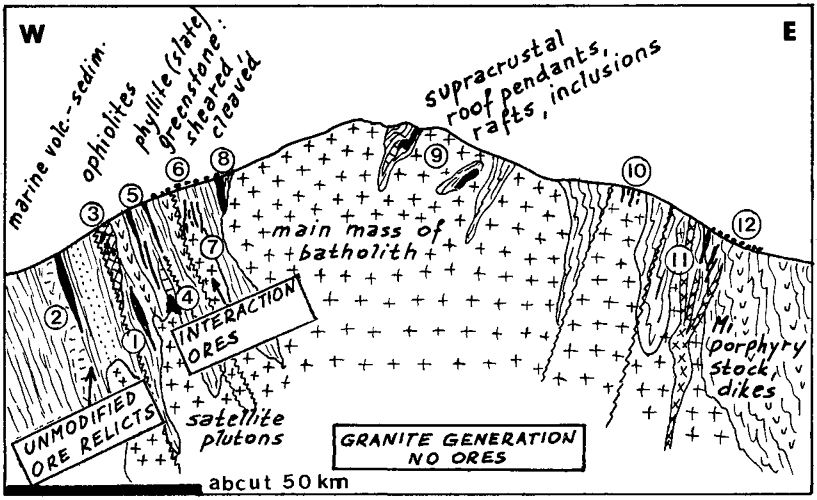


Fig. 28-20. Diagrammatic section of the Sierra Nevada Batholith, showing ore styles: 1=stratiform Mn in chert; 2=unmodified metavolcanics-hosted Cu-Zn massive sulphides; 3=podiform chromite; 4=magnetite skarns; 5=gold-quartz lodes; 6=gold placers; 7=porphyry Cu; 8=Ba silicate, barite; 9=scheelite skarns; 10=U oxide infiltrations (Kern Co.); 11=scheelite veins (Atolia); 12=scheelite placers. From LITHOTHEQUE.

in Kerr County have no practical importance.

The metallic deposits along the western fringe of the Batholith in the Sierra Nevada Foothills are located in late Paleozoic and Mesozoic greenschist-metamorphosed "eugeoclinal" metasediments (gray, green and black phyllites, metagraywackes), greenstones (metabasalts), serpentinites and mélanges. Most are gold, arsenopyrite, quartz, ankerite shear and fissure lodes and low-grade disseminations or stockworks in altered greenstones, in the Mother Lode system (already reviewed in Chapter 10). There are also several stratiform lenses of Mn silicates and oxides in jasper gangue, and occurrences of podiform chromite in serpentinite. The two latter styles even if, in places, they occur in the thermal aureole of the plutons, are clearly relics contemporary with the formation of their hostrocks.

Fig. 28-19. Sierra Nevada Batholith, California; geological map showing major scheelite (W), gold deposits, and crustal section. 1=J-Cr granitic rocks; 2=PZ-MZ serpentinite; 3-6=PZ-MZ metamorphics; 7=MZ-CZ flanking sediments. From Bateman et al. (1963) and Hamilton and Myers (1967), ore deposits added.

The gold deposits in supracrustals, on the other hand, are largely epigenetic, and show genetic or associational links with both the phyllites or greenstones and with "granites". Satellite plutons are widespread in or near the Mother Lode system so at least a portion of the gold probably accumulated as a consequence of interaction.

No recognizable metal zoning of the classical (Emmonsian) type is evident around the batholith (Albers, 1981). The only zoning is in the style and genetic interpretation of the ores, from the (sparse) (1) intra-plutonic ores outward into (2) granite-supracrustals interaction ores, to (3) granite (thermally, hydrothermally) modified relic ores, to (4) unmodified relic ores. The latter, outside the granite influence, are represented by the volcanics-hosted massive Fe,Cu,Zn sulphides in the Foothills Copper Belt (Chapter 12). Dodge and Bateman (1977) concluded that the source of most metals in the Batholith and its vicinity may have been in the country rocks adjacent to the deposits, rather than in end-stage hydrothermal solutions supplied by the plutons.

Geological and metallogenic conditions, similar to those around the Sierra Nevada Batholith, prevail in the plutons of the Klamath Mountains, except that the latter are more mafic (quartz diorite is the most common variety). The economic mineralization is almost entirely gold in exocontact lodes. Significant scheelite has not, so far, been discovered.

COAST BATHOLITH OF BRITISH COLUMBIA

This batholith (Douglas, ed., 1970) is, with its length of 1,800 km, one of the world's longest continuous intrusive bodies. It is a composite assembly of plutons ranging in age from upper Triassic to Miocene; the bulk is Jurassic to early Eocene. The batholith is surrounded by a high-grade gneiss complex from which probably at least a portion of the "granitic" magma was derived, and transitions from katazonal autochthonous migmatitic masses into mesozonal allochthonous intrusive plutons are widely apparent and have recently been described by Hutchison (1970). Unmetamorphosed and weakly metamorphosed rocks contemporary with the Coast plutonism and earlier occur on flanks of the pluton. They are most obvious in the east (the western margin of the batholith is, to a considerable degree, hidden under the Pacific ocean). Quartz diorite and granodiorite are the most common plutonic rocks, followed by diorite and quartz monzonite. Gabbro and granite are rare.

In terms of metallic mineralization, the Coast Batholith is the weakest mineralized belt in the Canadian Cordillera (with the exception of the Rocky Mountains thrust belt). This is particularly apparent in southern British Columbia north of the U.S. border, where both the adjacent facies belts (Insular Belt in the west, e.g. on Vancouver Island and Interior Belt in the east) are densely mineralized. The ore occurrences within the batholith fall into the following categories (Fig. 28-21): (1) relic concordant massive sulphide lenses: (a) in high-grade gneisses at the level of katazonal

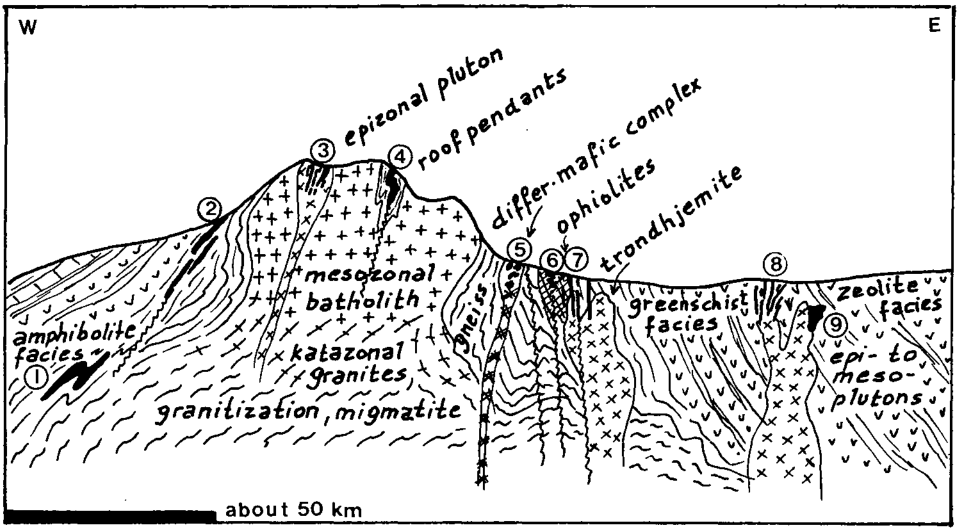


Fig. 28-21. Coastal Batholith of British Columbia, mineralization styles (diagrammatic): 1=relic massive sulphides (Ecstall); 2=Mother Lode-style Au; 3=stockwork Mo, wolframite vein; 4=massive sulphides (Britannia) in roof pendants, screens; 5=Ni-Cu sulphides; 6=disseminated cinnabar; 7=Au veins in shears and fissures (Bralorne); 8=porphyry Cu and aureole Au veins; 9=Cu skarn. From LITHOTHEQUE.

plutons, e.g. Ecstall and (b) in moderately regionally metamorphosed but contact hornfelsed metavolcanics or metasediments (Anyox, Granduc, Britannia). The Britannia deposit (Chapter 12) is particularly interesting, being hosted by a small roof pendant completely surrounded by granodiorite yet only slightly remobilized. (2) Magmatogene pyrrhotite, pentlandite, chalcopyrite in small gabbro-ultramafic stocks and dikes (Hope, Wellgreen, etc.; Chapter 9). (3) Endo- and exocontact quartz-gold lodes such as Bralorne (in soda "granite" intrusive into ophiolite and chert assemblage), Surf Inlet. (4) Endocontact wolframite, scheelite and minor Pb,Zn,Cu veins, e.g. Red Rose near Hazelton. (5) Mo-stockworks in altered hypabyssal intrusions as in the Alice Arm district, Adanac, Salal Creek. All the deposits of the latter category and probably also those in the group (4) are affiliated to epizonal granites of Miocene high-level centres, emplaced into older mesozonal plutons and surrounding metamorphics. In contrast to Sierra Nevada, scheelite skarns are virtually missing.

The above review reinforces the observation made earlier that the metallogenic balance of the deep mesozonal granite terrains is highly negative. They generate hardly any new ores while the deep erosion (of the order of 16 km) has removed much of the former wealth presumably present. As a consequence, preservation potential becomes an important indicator of exploration predictions and conformable massive sulphides that have one of the highest preservation potentials tend to survive until actually stoped away or removed by erosion. The mineralized epizonal "granites" are a random, superimposed feature. They may be suspected but are generally impossible to establish until radiometric ages become available. Once, however, one leaves the batholithic core and moves into the flanking assemblage of volcanic and sedimentary low-grade supracrustal metamorphics intruded by small meso- to epizonal satelite plutons, ore occurrences (porphyry Cu; Cu, magnetite, Zn-Pb skarns; stockwork Mo; Pb,Zn,Ag and Au veins, etc.) become plentiful.

CENTRAL BOHEMIAN PLUTON, W. CZECHOSLOVAKIA

The Central Bohemian Pluton (Svoboda, ed., 1966; Fig. 28-22), is a N.E.-elongated batholith, 150 km long and 30 km wide. It is composed of about 20 named intrusive bodies of variable composition and appearance. The Pluton occupies a former complex fault zone along the boundary between the high-grade metamorphosed block of Moldanubicum in the south and south-east, and the little metamorphosed late Proterozoic ("Algonkian") slate and spilite association in the north-west. It is interpreted as a late syn-kinematic to post-kinematic product of the late Paleozoic Variscan orogeny (middle Devonian to Permian; mostly lower Carboniferous).

Katazonal granites, interpreted by some as feldspathized metasomatites, occur along the south-eastern margin of the Pluton, represented mostly by porphyritic melanocratic biotite granite and syenodiorite (durbachite) and melanocratic biotite-pyroxene syenite. The central and north-western body of the Pluton has, mostly, truly mesozonal equigranular hornblende-biotite tonalites and granodiorites, lesser biotite quartz monzonites and small bodies of biotite granite. Minor bodies of gabbro and gabbrodiorite are known. There are abundant dikes of porphyries, aplites and lamprophyres and pegmatites are rare (except in the south-eastern katazonal domain). The intrusive rocks range from cataclastic to undisturbed (massive) and the large number of stone quarries provides excellent outcrops of fresh rocks. The area is easily accessible and has been studied in considerable detail. Virtually every outcrop has been recorded and documented which makes the Pluton and its aureole very suitable for metallogenic study. In particular, a wealth of data is available for a comparative study contrasting the "mineralogical" (minor) and "depositional" (economically significant) metallic occurrences.

The Pluton and its surroundings contain over a thousand individual metallic occurrences (Fig. 28-22), amongst which is one large Pb,Zn,Ag and U district (Příbram; compare also Chapter 17 and Fig. 17-8); one medium-size Au ore field (Jílové) and close to one hundred small mines, formerly producing Au, Au-Sb, Pb,Zn,Ag and U. There are virtually no Cu,Sn,and W accumulations. The total economic metal content is estimated to be of the order of 1.2 Mt Pb, 1 Mt Zn, 6 Tt

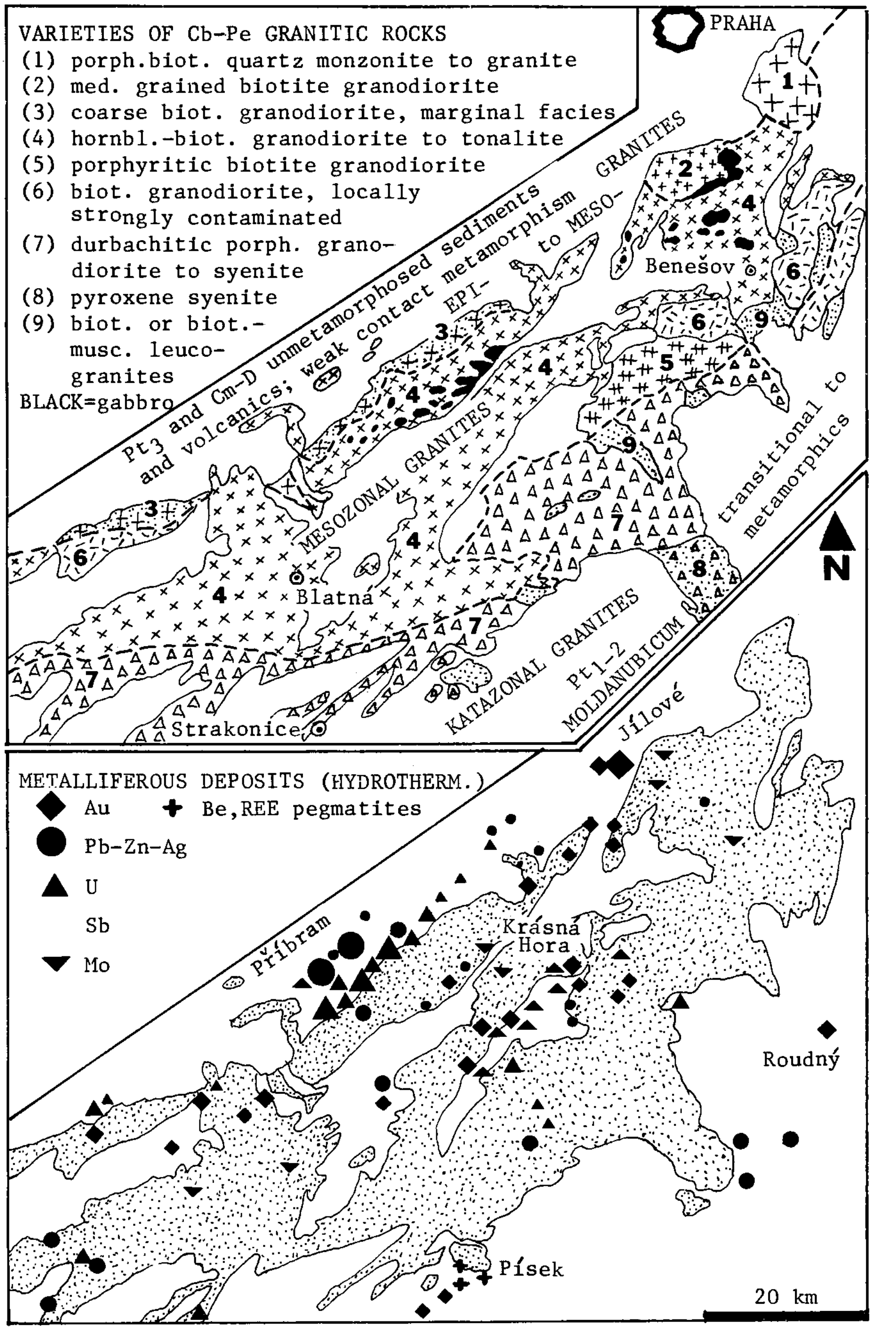


Fig. 28-22. Central Bohemian Pluton, Czechoslovakia, intrusive varieties and postmagmatic mineralizations. From LITHOTHEQUE.

Ag, 100 t Au (most in ancient placers), 40 Tt Sb and 90 Tt U. The metallogeny of the Central Bohemian Pluton has been discussed in numerous publications (Koutek, 1963; Sattran et al., 1966; Bernard and Klomínský, 1974) and much of the field observations assembled below is based on this writer's fieldwork in the period from 1957 to 1967.

Relic mineralization in the exocontact of the intrusive massifs (this includes several inliers, "islands" of supracrustals preserved within the Pluton) is extremely rare and represented by stratiform pyritic horizons in hornfelsed slates (Plíškovice) and probably Lahn-Dill "type" occurrences near Vranov. Small pegmatite masses formed at two separate depth levels. Those associated with katazonal granites near Písek and Sušice carry mineralogical occurrences of ilmenorutile, strüverite and monazite with minor volumes of REE,Th,Nb, etc. or Li-minerals and beryl. A single pegmatite dike near Skalsko is adjacent to a mesozonal granite and it contained a small orebody of scattered molybdenite.

Hydrothermal veins are the dominant style associated with the Pluton and they have been placed into the following major paragenetic associations: (1) quartz, albite, carbonate, pyrite, arsenopyrite, gold; e.g. Jílové, Libčice, Kasejovice, N. Knín; (2) quartz, siderite, galena, sphalerite, Pb,Zn sulphides, Pb,Cu,Ag sulphosalts; Příbram, Bohutín, Vrančice, Velhartice, etc.; (3) quartz, stibnite, gold or frequently stibnite-only forming stringers in fault gouge and mylonite; Krásná Hora and Milešov and (4) dolomite, calcite, pitchblende, lesser Co-Ni arsenides, native silver; Kamenná-Bytíz zone in the Příbram district, Újezdec.

Two age maxima for the veins formation have been distinguished: upper Devonian for the gold veins, and Permian for the polymetallic veins (and possibly also the uranium veins). All the vein deposits are within several hundred meters of igneous/supracrustal contacts, in both exo- and endocontacts. All display a strong structural control by open faults, and most veins are interchangeable with (or occur within) dikes of intrusive porphyries (diabases in Příbram, aplites near Bytíz, kersantites near Krásná Hora) filling fairly open, mylonite-filled or slickensided faults. This would indicate a relatively high level of mineralization. The main intrusive host masses are mesozonal, but the veins may have formed in the epizone. Bernard and Klomínský (1974) pointed out that there was a time gap of up to 100 m.y. between the vein and intrusive emplacements.

There is a characteristic correlation between the accumulated metals and the lithologic associations in the exocontact hosts. The Jílové gold-quartz veins are situated in cleaved slates and greenstones as well as in tonalite and they resemble the Mother Lode-Grass Valley (California) styles. The Pb,Zn,Ag and U veins show close spatial association with black slates, members of the slate-spilite association.

Major disseminated, stockwork, breccia, etc. deposits are absent, a fact which is easy to attribute to the depth of erosion. There are, however, widespread "mini-showings" (mineralogical occurrences that mimic, on small scale, the aspects of industrially important styles) corresponding to the porphyry (stockwork) Cu and Mo, apparent on joints in granites and tonalites exposed in stone quarries. There, in particular, the Q joints (open joints parallel with the stress vector) contain thin veinlets of quartz, K-feldspar, chalcopyrite, lesser molybdenite or quartz-molybdenite, fringed by a narrow pink feldspathized stripe. The presence of Cu minerals in the Permian "molasse" arkoses and mudrocks preserved in a small remnant near Český Brod (adjacent to the N.E. termination of the Pluton) indicates such a possibility.

The Pluton and its environs are transected by a system of relatively open faults, broad open zones of brecciation and mylonite or breccia-filled "reefs", some of which frame narrow grabens. The structures are believed to be ancient (pre-Variscan), repeatedly rejuvenated. Some contain fracture coatings of torbernite and autunite, grading downward into simple dolomite, calcite, pyrite, pitchblende, sometimes fluorite lens and stringer-like veins in the mylonite (e.g. Heřmaničky, Kovářov, Kvasejovice). There is a distinct wallrock "reddening" (bleaching and hematite pigmentation) and the origin is uncertain, but there is an almost exact correspondence with some of the U occurrences in the Massif Central, France, interpreted by Barbier (1974) as descendent infiltration veins.

THE MAIN RANGE BATHOLITH, MALAYSIA

The great Sundaland tin belt (Burma, Thailand, Malaya, Indonesia) can be subdivided into several parallel facies zones as well as several transversal segments. By far the most important is the western belt in the Malaya Segment, corresponding to the Main Range Batholith (MRB). This granite belt is interpreted by Hutchison (1977) as mesozonal in contrast to the Eastern Granite Belt which is epizonal. MRB is emplaced into penetratively deformed lower Paleozoic metasediments (phyllite, some marbles), and less deformed and metamorphosed upper Paleozoic slates. In the east, this belt is in fault contact with sediments of the Central Triassic-Jurassic Graben, and there are some ophiolite slices along the boundary lineament.

The majority of the MRB granites are Permian to Triassic, but Hosking (1973) also reported occurrences of upper Carboniferous and late Cretaceous to Tertiary granites. The bulk of the granites are coarse porphyritic biotite quartz monzonites to muscovite-biotite granites containing perthitic microcline. Contact metamorphic aureoles against the phyllites and slates are generally narrow to indistinct. It should be noted that fresh outcrops are extremely rare in the humid tropics and this could affect some geological conclusions.

As already noted, the plutonic mineralization is overwhelmingly dominated by tin, and the bulk of Sn comes from a variety of placers (eluvial, colluvial, alluvial, beach) although the primary cassiterite source is in granites and their aureole. The Kinta Valley tinfield (near Ipoh) and Kuala Lumpur tinfield, are among the richest in the world. Disregarding the secondary mineralization, the MRB and its aureole-hosted metallic ores can be subdivided into the following styles: (1) relic orebodies in the wallrocks. These are rare, represented by the small occurrences of disseminated and podiform chromite in ultramafics along the eastern tectonic contact of MRB. (2) "Magmatic" disseminated cassiterite in granites has been mentioned several times in the literature, but the occurrences examined by Hosking (1973) were all epigenetic, postmagmatic. (3) Pegmatites. These contributed cassiterite and columbite-tantalite to placers,and small regolithic occurrences (Gunong Kedah, Bakri) were mined in the deepest eroded Carboniferous granites. (4) Magnetite, magnetite-cassiterite, cassiterite (Ampang) and scheelite (Kramat Pulai) skarns and replacements at granite/carbonate contacts. (5) Hydrothermal veins and pipes of quartz-cassiterite and minor quartz-wolframite in granite endo- and exocontacts, mostly formed during the postmagmatic phase of the Triassic mesozonal granites, and associated with their apical cusps. Hosking (1973) believed that several "xenothermal" deposits in the Kinta Valley and elsewhere are near-surface mineralizations that would require a younger (possibly Tertiary) high-level intrusion.

28.2.4. Katazonal plutons

Generation of katazonal plutons is usually placed in the depth interval exceeding 12 or 16 km. Because most katazonal granites are autochthonous (in situ), this is also the zone of granite generation. There, the granites cannot easily be separated from the high-grade metamorphics so both rocks will be discussed in Chapter 29.

28.2.5. Petrogenesis and setting of GDG association

In the voluminous literature from the past 15 years (summarized in Hughes, 1982) the sites of magma generation that ultimately produce the GDG association, have been sought (1) above Benioff (subduction) zones, (2) under collisional fronts and (3) under intercontinental and occasionally under interoceanic taphrogenic (extensional) systems ("anorogenic continental terrains") e.g., in the initial stages of rifting, which, in turn, were attributed to the heat supplied by mantle plumes (hot spots). A site of type (1) is now favoured asa craddle of the bulk of the calc-alkaline "granitic" magmas (e.g. Hughes, 1982, treats the batholiths in orogenic belts under the heading "Igneous rocks above Benioff seismic zones"). The site of type (2) is generally ignored by the petrologists although frequently mentioned or reviewed in geotectonic and metallogenic compilations (Burke et al., 1976; Mitchell and Garson, 1976; Sawkins, 1984). Rocks developed along sites of type (3) are jointly reviewed in Chapters 30 and 33. As a metalliferous geologist sensitive to transitions and anomalies, I find the above division too simplistic. In particular, it accomodates poorly the transitional situations among the supra-Benioff belts and the intracontinental melting events as well as magmas generated as a consequence of a small-scale taphrogenesis along consuming plate margins.

Wyllie (1981) prepared a recent review on magma generation concurrent with subduction but, significantly, did not impose a numerical limit on the proximity of the magma-generating site to the Benioff zone. Such an explanation thus allows the magma melting to take place fairly high in the continental crust in the ultrametamorphic environment, which makes it possible to bypass the former awkward dogma that magma had to form directly along the subduction plane and then progress, somehow, to the near-surface region through a slab of mantle and crust 150-700 km thick. Wyllie (1981) listed three "end-member" variations of magma generation by partial fusion above subduction zones roofed by continental margins or mature island arcs: (1) fusion of mantle peridotite modified by siliceous melts or hydrothermal fluids produces a magma ranging in composition from quartz-normative basalt to andesite; (2) fusion of oceanic crust produces intermediate magmas (andesites) and (3) fusion of a deep-seated continental crust approximately composed of granite and amphibolite equivalents, produces tonalitic magmas (or a granitic/rhyolitic magma when the crust is entirely "granitic"). It should, however, be realized that the magma generated by partial melting undergoes further differentiation and modification within the continental crust, so one can finally obtain petrographically identical differentiates (e.g. a granodiorite) out of the three parental magma series (and their mixes).

It seems logical that provenance has some bearing on the trace metal distribution in the parental magma and this, in turn, influences the metallogeny. It follows from the earlier review of mineralization styles associated with mesozonal and epizonal granites that petrographically comparable rock types (e.g. a quartz monzonite) could be associated with a very different suite of ore minerals (e.g. Cu,Mo as in Butte; Mo in Smithers; Au in the Colorado Mineral Belt; Sn-W as in N.E. Queensland). Disregarding, for the time being, the possibility of a proximal metal extraction from the country rocks, it appears natural that the site of magma derivation (and by implication the geographic location and geotectonic setting of the magmatic system) influenced the metal selection and metallogeny. This possibility was not considered in the classical (1930s to 1950s) models of postmagmatic metallogeny associated with granites and it resulted in several over-generalizations e.g. in interpretation of the metal zoning patterns. The latter subject is reviewed more fully in Laznicka (1985c).

PETROMETALLOGENETIC SERIES; I AND S GRANITES; ILMENITE AND MAGNETITE GRANITES

Abdullaev (1964), Sattran et al. (1970) and others applied the concept of petrometallogenic series of intrusive rocks to explain and predict the affiliated mineralization. The concept relied on the combination of magma series (calc-alkaline, K-alkaline, Na-alkaline) and basicity of the differentiate. For example, within the GDG association the strongest contrast was found between the "intermediate" (dioritic) series affiliated with Au deposits, and "granitic" series associated with tin deposits. Out of the regional examples discussed earlier, the Sierra Nevada and Central Bohemian plutons are members of the "intermediate series" with mostly Au deposits. The N.E. Queensland and western Malaya massifs belong into the "granite" series with tin deposits.

Later on, Chappell and White (1974) working on a different premise, distinguished two contrasting "types" of granitic rocks (I and S) which, in terms of affiliated mineralizations, broadly correlate with the two petrometallogenic series distinguished above (I granites carry mainly Au, S granites Sn). The above writers assumed that a granitoid magma is derived by partial melting and consists of a mixture of granitic liquid and a residuum (restite). The restite are inclusions as well as much of the crystal content of plutonic rocks, while the former granitic liquid is now represented by the interstitial phases.

The I granites are believed to be derived from igneous, the S granites from (meta)sedimentary precursors (essentially shales). Both granite varieties have distinct linear geochemical variation trends when plotted on the Harker diagram. Despite the elegance and present popularity of the model, there are many areas where it does not work (e.g. along continental margins where volcanogenic graywackes were partially melted as in the Coast Batholith of British Columbia or in the Precambrian shields). Such sediment-derived granites usually have an I signature. Most recently, several authors added "A" (for "anorogenic") and "M" (sodic granites of immature island arcs) granites.

The latest contribution to the classification of the granitoid series from metallogenic viewpoint came from Ishihara (1981). This author distinguished "magnetite series" and "ilmenite series" of granitic rocks, based on the accessory content of either mineral. The magnetite series has a positive $\delta^{34}S$ value and a low $\delta^{18}O$ value, is depleted in lithophile elements and is commonly associated with sulphide mineralization. It more or less correlates with the I granite. The ilmenite series contains less than 0.1% magnetite, has a low magnetic susceptibility, negative $\delta^{34}S$ values, high $\delta^{18}O$ value, and enrichment in lithophile elements. It is commonly associated with Sn,W,Be and fluorite, and includes equivalents of both I and S granites. Ishihara (1981) believes that the two series of granitoids resulted from the prevalence of different oxygen fugacities during evolution of the granitic magmas. The dissociation of water in hydrous magmas was the main oxidizing agent in the magnetite series, and incorporation of crustal carbon was the most essential reducing medium for the ilmenite series magmas.

So now we have at least three methods for the interpretation of the granite metallogeny using rock geochemistry. None is perfect. There are numerous exceptions, but at least a rough correlation between rock geochemistry and prevalent metallic mineralization is now available to justify the earlier empirical observations. When both I and S granites form facies belts along a continental margin, I tends to be more internal (closer to the paleo-ocean), S more external (closer to the paleo-craton). The former have relatively low Rb, Rb/Sr, Sr 87/86 and high K/Rb and Sr signatures. The latter have higher Rb, Rb/Sr, Sr 87/86 and low K/Rb and Sr values and tend to be strongly peraluminous.

A down-to-earth exploration geologist is cautioned against placing excessive faith in the above generalizations, because a small metasedimentary microcontinent accreted along with dominant metavolcanics to a continental margin, may produce a "S" enclave capable of, for example, accumulating tin "where it should not have been". Faults, thrusts, "suspect terrains", multiphase terrains, etc. can do the same and have been found to do so.

28.2.6. The magmatic/metasomatic controversy and hydrothermal-metasomatic "granites"

The high point of the classical controversy of the 1940s-1950s regarding the derivation of granitic magmas, has now been more or less settled with the realization that the magma first formed by partial melting of a solid (that is, anatexis when in the continental crust), after which the melt travelled into the higher levels of the crust in the form of a "granitic magma". The neo-controversy partially outlined earlier is concerned with the site of the melting. Marmo (1971) gave a good review but old problems still remain although often under different names. One problem of fundamental importance to metalliferous geologists is the possibility of hydrothermal origin of "granites" by means of metasomatic fronts. The concept of granitization or de-granitization as summarized by Marmo (1971, p.72,73) is as follows: in the upper levels of the SIAL, extraction of potassium from sediments undergoing metamorphism takes place in loaded areas (granodioritization); K and Si move to areas of low energy in anticlinoria, causing granitization. When the granitized segments are exposed to further load due to the advancing orogeny, potassium removal will take place and potassium will move to areas with a still lower free energy. The formation of igneous-looking metasomatites interpreted by Hietanen (1962) was reviewed earlier.

Approached from a different angle, the formation of igneous-looking rocks virtually identical compositionally and texturally with orthomagmatites, by a high-level hydrothermal metasomatism and mineral crystallization in open spaces, is now a well-documented reality. Potash feldspar and biotite neoformation in porphyry copper systems tend to produce hard, fresh-looking rocks, visually often unrecognizable from magmatic "granites", and often containing disseminated sulphides. They are a far cry from the popular image of an altered wallrock as being a spotty, dirty, disintegrating tortured rock. In the North American literature the rocks produced by alteration (alterites) do not have a status of "independent rocks". In the Russian literature they are called "metasomatites" (e.g. K-feldspathite, biotitite, secondary quartzite). Some old descriptions of disseminated chalcopyrite in "unaltered granodiorites" were later identified as K-alterites.

An equivalent situation, though more obscure, is a part of the "magmatic cassiterite" controversy. Is the cassiterite sometimes found in a hard, fresh-looking, feldspathic rock (granite, aplite, pegmatite) really a product of magmatic crystallization, or has it been introduced in a highly mobile fluid from outside, deposited by replacement, and the associated alteration feldspars erroneously interpreted as melt crystallizates ? The second interpretation is now prevalent. Apogranites (Smirnov, ed., 1968; hydrothermal metasomatites in apexes of granite cupolas) include albitites, quartz-albitites, microclinites, and other rocks. These hard, fresh-looking feldspathic rocks often carry disseminated columbite-tantalite, cassiterite, Be-minerals and grade into greisens. Feldspathization (particularly albitization) may obscure petrochemical groups of intrusive rocks , in particular place an altered calc-alkaline rock into the alkaline family.

Many albite "syenites": pink, often miarolitic syenite-looking rocks within granite batholiths as well as outside them, are hydrothermal metasomatites. Laznicka and Edwards (1979) interpreted "syenites" associated with gabbro and diorite dikes at Dolores Creek, Yukon, as albitites formed in dilations and in porous breccias by metasomatic albitization and open space filling. They contained minor disseminated chalcopyrite, and resembled "porphyry coppers". Many pegmatite-looking veins are in fact hydrothermal feldspathites.

28.3. INTRODUCTION TO GDG METALLOGENY

28.3.1. General

Average trace metal contents in granitic rocks are available from the literature. Given the wide basicity range and the various magmatic series involved, such contents are inaccurate in detail. They are usually used for approximating the average composition of the upper continental crust and, contrasted with the trace metals in basalts, give some appreciation of the evolutionary trends. Average trace metal data for narrower rock categories are in Table 5-3.

There is an enormous number of factors governing "granite" metallogeny, most of them poorly understood. Some are related to the "granite" petrogenesis and petrochemistry as discussed earlier and others are to be sought primarily in the exocontact lithologic association, in structure, thermal and hydrological regimes during cooling, etc. The classical, all-embracing model of "granite"-affiliated postmagmatic hydrothermal metallogeny as presented in text and reference books from the 1930-1950 period (Lindgren, 1933; Bateman, 1951; Schneiderhöhn, 1955) is now largely outdated, although several restricted subjects still remain valid.

A substitute overall granite metallogeny model is not yet available because, to a considerable degree, it depends on the conclusion of the problem of GDG derivation and petrogenesis which, despite the considerable progress made in the past fifteen years, is still not yet here. In the meantime, modern models have been developed for several styles and categories of ore deposits (e.g. porphyry coppers, stockwork molybdenums, skarns, granite cupola tin, etc.) and these are briefly reviewed later. There is, however, little cross-pollenation among these models and large gaps abound. "Fringe" ore styles lack modern coverage altogether.

Modern interpretation of hydrothermal systems, the core of the "granite" metallogeny, is now a highly sophisticated and specialized field of research. The reader is referred to the summaries and reviews available in Stanton, 1972; Holland, 1972; Barnes, ed., 1967 and 1979; Cathles, 1981 and others. In the following paragraphs, several problems directly influencing the field occurrence of the GDG-affiliated ores, will be touched upon briefly.

28.3.2. Hydrothermal systems

CONVECTIVE SYSTEMS

At present, the best documented hydrothermal system is a convective system utilizing meteoric water, seawater or connate water (that is, non-magmatic, exo-granitic fluids), driven by a cooling intrusion (Cathles, 1981). The active periods of such systems are considered short in geological terms, ten thousand to hundred thousands years. Much depends on permeability. Longer active times can be expected if the top of a geothermal system is impermeable. Hydrothermal convection usually takes place in the above-intrusion zone largely in supracrustal exocontact rocks, and the area affected gradually shrinks and drops to involve, subsequently, the top of the cooling magmatic body itself. Recognition of paleo-convective systems facilitates the interpretation of metal sources to ore-bearing fluids and ultimately to metallic deposits. Such sources tend to be relatively proximal and often in the same unit that hosts the orebodies.

Certain convective systems could have been driven by the heat from radioactive decay. Such heat sources could have been unusually persistent, and convection initiated within and in the vicinity of an U-enriched pluton every time fracturing took place (Fehn et al., 1978). This model seems to be supported by empirical evidence of the frequent pitchblende deposits formed in relatively open mylonite or breccia-filled fractures and faults, the filling of which considerably postdated the host granite emplacement and cooling (e.g. in the Hesperian and Central Massifs, Spain and France; Bohemian Massif). Alternative genetic explanations , however, are available for the same deposits.

MAGMATIC VOLATILES

The mass of magmatic volatiles vented by an intrusion is much less than the mass of the outside water likely to circulate convectively in response to such intrusion (Cathles, 1981). The volatiles stream upward and tend to accumulate in granite cupolas or in small elevated stocks, under the confinement of impervious strata. This is facilitated by a permissive intrusive emplacement in which the roof is not shattered. In settings having a shattered or permeable roof, venting and volatile escape may take place. Explosive outbursts of volatiles, however, may produce mineralized breccia pipes. Particularly complex but effective mineralization systems may develop when magmatic volatiles interact with convecting groundwaters, as interpreted for several porphyry copper systems.

Once a hydrothermal system is in operation, ore precipitation is governed by the physical and chemical principles many of which had already been satisfactorily interpreted in the classical period (e.g. the "second boiling"), while the rest benefited from the recent advances in fluid inclusion and stable isotope studies. To form an orebody, however, an actively convecting system requires a metal source. Many recent theoretical studies assumed "normal" (=close to clarke values) metal sources as the basis for calculation. This may, under favourable conditions, suffice for ore deposition, but the system has to operate at top efficiency, something that is fairly rare in nature. Empirical observations and probabilistic deductions based on field data, however, indicate that in most cases ore formation probably took place in systems interacting with "better than normal" metal sources, so interpretation of and search for such sources are an important ingredient of exploration strategy.

28.3.3. Metal sources to ore-bearing fluids

In the classical model of the 1930-1950s the "granitic magma" (usually interpreted as being a differentiate of basaltic magma) was automatically believed to carry along the entire complement of ore metals, sequentially released and deposited in the course of cooling of the intrusion. A classical (Emmonsian) metal zoning pattern around and above the intrusion (from centre outward: Sn-W-Au-Cu-Pb,Zn-Ag-Sb-Hg) resulted (Bateman, 1951; Fig. 28-23A). Concurrently and also later, alternative models have been introduced, mostly in response to the changing interpretation of granite origins. The "granitization model" in which the granitic magma obtained its components including metals from crustal sources during anatexis

(Fig. 28-23B) became the chief alternative of the 1950s. By now, many more alternatives have been proposed (Fig. 28-23C). The subject of metal sources to ore deposits and zoning has recently been reviewed by Laznicka (1985c,e).

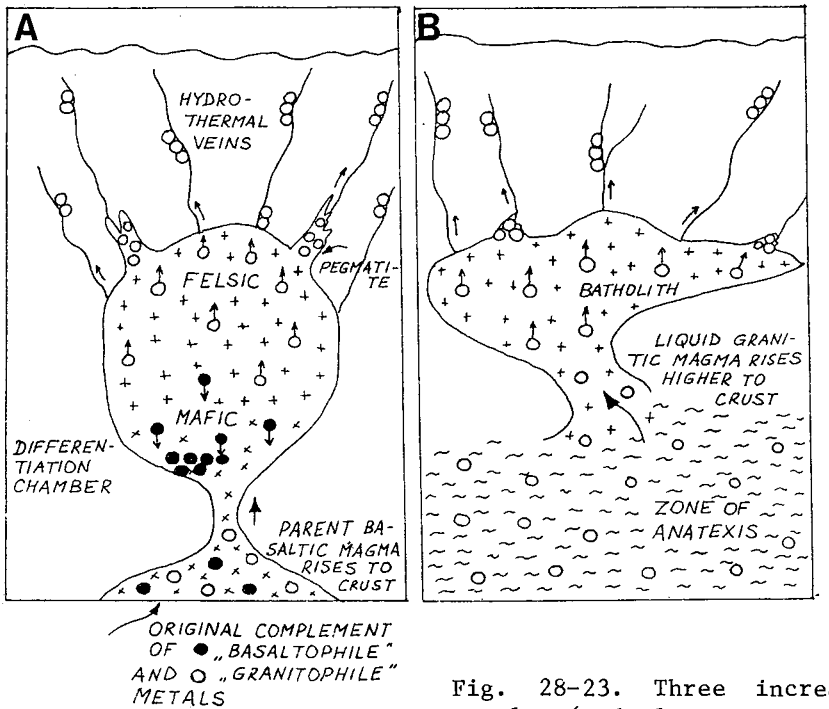
Very briefly, the ore metals may enter the "granitic" magma (become dissolved in it or carried as solid phase): (a) at the site of the dominant magma generation (within the mantle, along and above Benioff zone; within the continental crust); (b) above the magma passage that is chiefly in the lower and upper continental crust or (c) in magma reservoirs within the upper continental crust and at sites of emplacement. These metals are considered to be relatively mobile within the developing magma, and capable of accumulation during the cooling history at sites located both inside (endocontact) and outside (exocontact) of the intrusion. With respect to the intrusion, these are active metal sources.

Ore metals, however, need not actually enter the magma and pass through the stage of dissolution (dispersion) in the magma first, followed by release, migration and accumulation in orebodies. The metals could be present in the rocks surrounding the generator intrusion, leached, transported and accumulated by convecting hydrotherms at sites asociated with a rapid drop in solubility. This has been discussed earlier. Alternatively, solidified and fractured "granite" itself may be the site of hydrothermal convection and metal leaching. Both the above alternatives have been termed "passive metal sources" in Laznicka (1985e).

Recognition of the difference between active and passive metal sources is a useful ingredient in speculations on mineralization potential of a "granitic" intrusion and ore prediction. The distant metal sources (in the mantle, in the oceanic crust and other rocks melted along subduction zone, etc.) are impossible to observe or to deduce from field observation, so they are highly hypothetical and changing with fashion and the progress of science. Their interpretation is made within the limits of geochemical and petrochemical constraints (e.g. stable isotopes, trace metals such as the REE), and the degree of controversy is high. Academic debates about the metal sources at depths of hundreds of kilometres are of dubious merit to a prospector.

Numerous down-to-earth speculations involving milieus much closer to the present sites of ore deposits and supported, as much as possible by actual field data can, on the other hand, aid considerably in exploration. Several examples of such speculations appear later in this chapter, in sections dealing with specific metals. The problem of trace metal and rock-forming mineral compatibility is reviewed briefly here as an example of reasoning that is of practical help.

During magmatic differentiation trace base, rare and precious metals can behave as compatible or incompatible in regard to the major rock-forming minerals (Stanton, 1972). The compatible elements are removed from the melt by crystallizing major minerals, while the incompatible elements remain in the rest liquid and ultimately accumulate in the intergranular spaces, or they migrate with



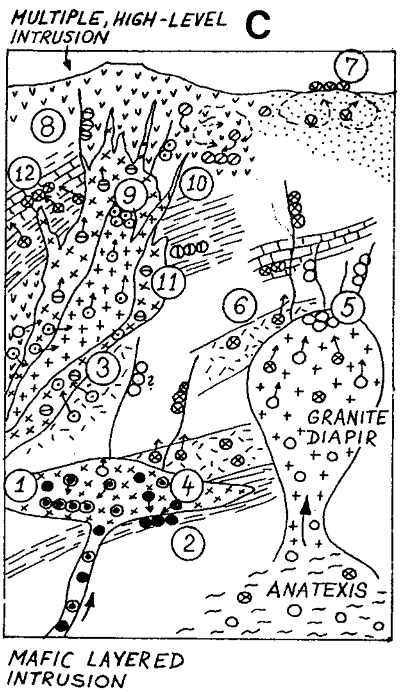


Fig. 28-23. Three increasingly more complex (and also more recent) models of "granite" affiliated mineralizations. A: Classical, closed system model of differentiation and crystallization of a "juvenile" mafic parent magma. B: Crustal granitization or anatexis, ascent of granitic magma, followed by its fractionation and crystallization. C: Selected contemporary alternatives in which a wide range of interactions of magmatic rocks with their surroundings is stressed.
EXPLANATIONS: Scattered small circles indicate dispersed trace metals. Small circles with arrows indicate directions of trace metals movements. Groups of small circles indicate orebodies; not to scale.
(continued on right)

postmagmatic fluids. It is known that various rock-forming minerals preferentially accumulate certain trace metals. Olivine and Mg-pyroxenes accumulate Ni,Cr,Hg; pyroxenes and amphiboles accumulate Cu,Zn; biotite accumulates Sn,U,Th; magnetite accumulates Cu,Zn; K-feldspars accumulate Pb. The variable proportions of these minerals in rocks and their preservation or destruction, can thus have a substantial influence on the ore-generating potential of an intrusion. The general rule is that in a progressive magmatic differentiation process reaching completion, the metals that remain most incompatible throughout the entire process have the greatest chance of accumulating in magmatic or post-magmatic deposits so they constitute an important active metal source.

Eilenberg and Carr (1981) studied the anomalously copper-rich andesitic and basaltic volcanics of the recently active San Miguel Volcano (El Salvador), and explained the high Cu content in the volcanics as being due to the lack of early augite and magnetite in the rocks. They reasoned that, since these minerals tend to

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Fig. 28-23 explanation (continued)

INDEXES USED IN SECTION C: 1=cumulus settling (e.g. chromite); 2=immiscible liquid, settling of droplets, squeeze-up, down or laterally beyond the limit of intrusion; also possible contact sulphurization and precipitation of non-sulphide trace Ni content; 3=gaseous or hydrothermal transfer of fractionated metals (Sn) to veins; 4=magmatic heating expels high trace metals (with their carriers) in surrounding rocks to veins (e.g. Cobalt Ag,Co; Ontario); 5=mobile metals and volatiles gather in apical portions of a granitic diapir; 6=granite heat and hydrothermal activity triggers metal remobilization from metalliferous contact rocks; 7=hydrotherms (heated groundwater) circulate in a metal-enriched aquifer dissolving, concentrating, reprecipitating metals; 8=trace metals which arrived as a component of the original magma, ascend and fill veins; 9=trace metals picked-up from intruded (or replaced) crustal rocks, enriched in an older intrusive phase; from there they are overtaken by a younger intrusive phase, further concentrated and deposited as ores; 10=trace metal enriched in porous overlying sediments was picked-up by circulating heated groundwaters, carried downward, and redeposited stratigraphically below the source; 11=an existing orebody in intruded wallrocks was modified by an intrusion; 12=geochemically enriched metal in argillite was remobilized by magmatic heat or solutions and redeposited in adjacent, reactive carbonate (e.g. as scheelite skarns).
Black symbols: "basaltophile" metals; white symbols: "granitophile" metals.

In the complex diagram (C) several internal patterns have been added to both categories of metal symbols, and these serve no purpose other than to help the reader to trace the hypothetical metal movement from the source to the site of deposition. From Laznicka (1985e).

accumulate copper, their lack prevented the early depletion of the magma in trace Cu and allowed Cu to reach its maximum trace content in the relatively dispersed form easily leacheable, not only by high pressure/temperature hydrotherms, but even by rainwater (compare Chapter 5). Eilenberg and Carr (1981) concluded that porphyry copper deposits can form preferentially in the roots of a volcano whose mafic to intermediate lavas are relatively poor in magnetite and augite, so that the abundance of these two minerals could be used as one of the exploration leads for porphyry Cu source areas.

The above reasoning, although probably correct in regard to the surficially leached copper, can be reversed (Fig. 28-24). If magnetite and augite do exist in abundance and consequently the content of incompatible (dispersed) copper is low, the rocks may still be high in their trace metal content but it would be a compatible Cu stored in magnetite and augite. Indeed, the Cu-anomalous (around 200 ppm Cu) andesitic and basaltic associations hosting some porphyry coppers (e.g. the Nicola, Nikolai and Karmutsen Groups, North American Cordillera; the Farellones Formation of Chile) are conspicuous for having abundant porphyritic augite andesites with high magnetite contents. These rocks could have provided Cu to the porphyry coppers, but they would have been passive sources, requiring a thermodynamically intensive pyroxene and magnetite-destructive process to release the Cu and set it in motion. Intensive hydrothermal metasomatism around and under porphyry copper systems attests to a possible existence of such a process. Similar reasoning can be applied to tin deposits associated with young, altered muscovite-biotite granites usually superimposed on older biotite quartz monzonites possibly storing Sn in biotite. In nature, most metalliferous magmatic systems do not become productive and parental to a distinct suite of associated metals suddenly, but as a result of a lenghty, multistage development history progressing in the direction of "increased favourability".

28.3.4. The rocks above and outside of the "granitic" intrusion

The rocks outside any "granitic" intrusion under consideration can be (1) older than the "granite" and have intrusive contacts with it. In high-level plutonic systems such rocks show a distinct thermal metamorphism, which can be indistinct in the more abyssal emplacement levels. Alternatively, they may be (2) older or younger than the "granite", having a mutual tectonic contact or (3) younger than the "granite", having a non-conformable contact and deposited transgressively over the eroded granite, and composed either of the granite-derived detritus, or independent of it.

In terrains undeformed and unmetamorphosed after the "granite" emplacement, the "granite"/outside rock relationship is usually easy to recognize. In repeatedly deformed and metamorphosed terrains this could cause some problems. In this short section, we will be concerned with the type (1) relationship. Virtually all the known

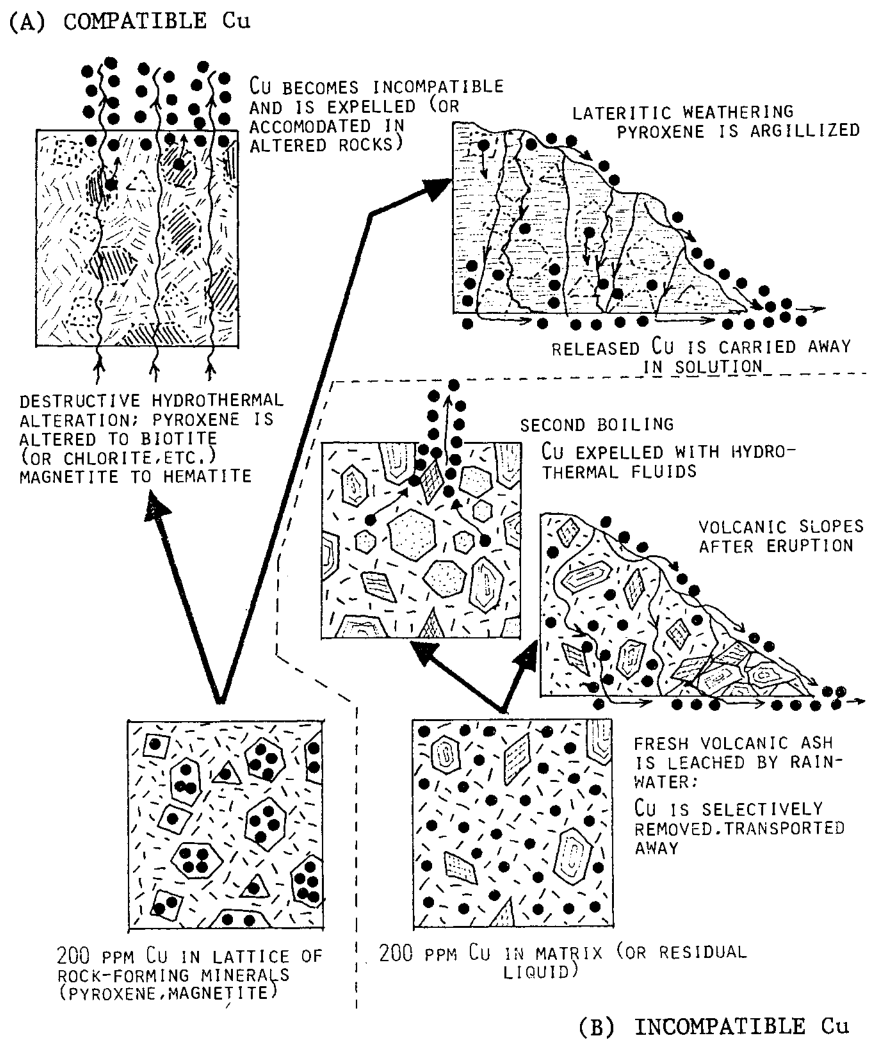


Fig. 28-24. The contrasting behaviour of compatible (in regard to the common rock-forming minerals during the magmatic crystallization) and incompatible copper in the post-magmatic history of a basalt or andesite. Black dots denote schematic representation of the trace copper, arrows indicate copper movement and the direction of concentration. From Laznicka (1985e).

pre-Quaternary lithologic associations can be intruded by "granites", including older generations of "granites" themselves. The contacts range from knife-sharp ones to gradational fronts of hybrid rocks on both sides of the contact (but more in the exocontact).

In regard to orebodies, the exocontact rocks have several functions that have to be evaluated carefully when interpreting granite aureoles. (a) The exocontact rocks host orebodies and some 40% of Cu orebodies, 30% Sn orebodies, 20-40% Mo orebodies, 90% Pb-Zn orebodies and over 95% of scheelite orebodies, are in the exocontact. There, they fill open spaces or replace solid rocks. The orebodies have a significant structural as well as lithological control, and the variety of mineralized structures has been adequately described in the classical literature (e.g. Bateman, 1950; Newhouse, ed., 1942). When orebodies (e.g. veins) fill open spaces, brittle rocks tend to be preferentially mineralized whereas the more ductile ones remain barren.

(b) Exocontact rocks exert an important physical influence on ore deposition, in particular by providing impervious screens. When a flat-lying or gentle dipping unit of a ductile shale tops a brittle fractured quartzite, replaceable marble, etc., ascending mineralizing solutions are trapped under the impervious horizon and often forced to precipitate their load and form orebodies. Such orebodies often take the form of peneconcordant lenses, frequently confused with stratiform orebodies.

(c) Chemical and physicochemical influences that cause metals to precipitate are often exerted by a variety of rocks placed in the way of ascending mineralizing solutions. The most widely quoted examples are horizons of graphitic and pyritic rocks.

(d) Exocontact rocks often constitute the metal sources for ores. Conforming to the "principle of minimum effort" (it states that metallic deposits will preferentially form on sites where the requirement of energy for their generation will be the lowest, and anomalous metal content the nearest; Laznicka, 1985e), lithologic associations anomalously enriched in certain elements or even containing earlier orebodies, have the greatest potential for influencing the selection of metals in hydrothermal orebodies to form in the vicinity. Some lithologic associations or rock types are predictably (systematically) enriched in certain trace metals. Fig. 28-25 shows the clarke values of selected lithologic associations contrasted with average ore grades. Empirical experience indicates that many metallic deposits are preferentially affiliated to units (rocks) having the highest clarke values, and "granite"-related metallic deposits are similarly associated with interaction complexes involving such rocks. In the latter case, sufficient metal mobility in hydrothermal fluids is a necessary prerequisite and immobile (e.g. Ti) or insufficiently mobile (Cr) metals rarely form depositional accumulations precipitated from hydrothermal fluids, even if their environment is anomalously rich in such metals.

Zn,Pb,Sb,Cu,W,Bi, Mo,U,Ag and Au have the systematically highest clarkes in a variety of mostly black mudrocks and indeed a large

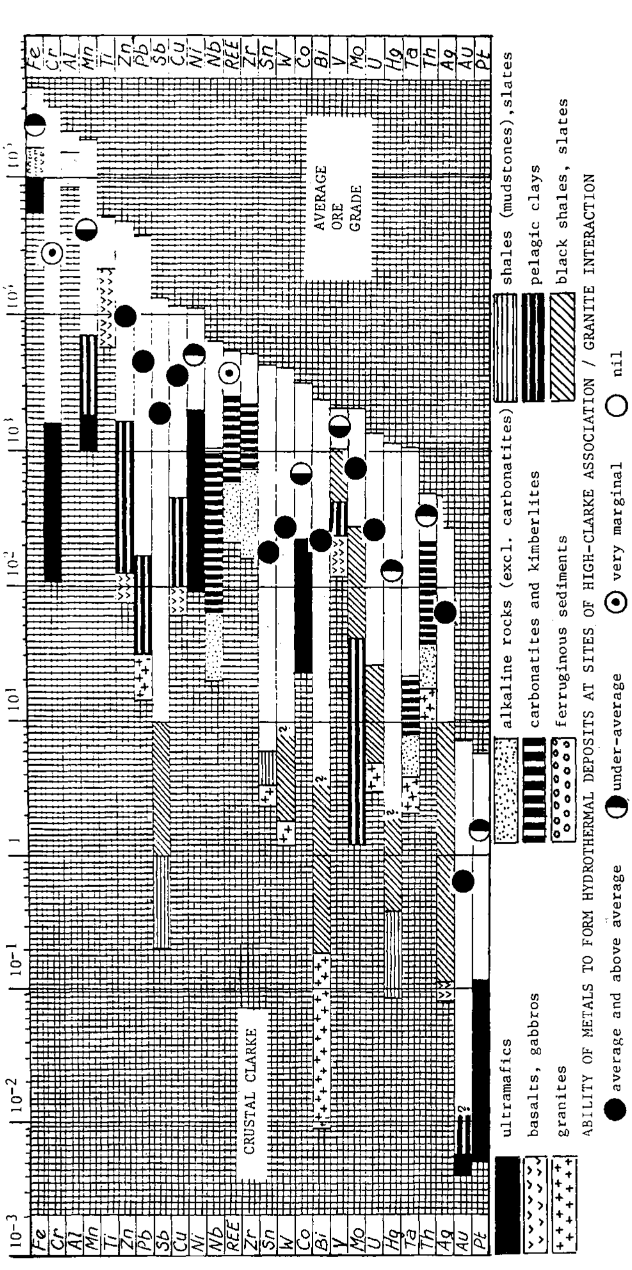


Fig. 28-25. Ability of metals to form hydrothermal deposits at sites of high clarke lithologic association and granite interaction. Rock groups with the highest average trace metal contents are contrasted with the ore grades of respective metals. Log scale. The grid pattern represents the crustal clarke (left) and the average ore grade (right). The gap between the highest trace metal content in a rock category and average ore grade corresponds to the factor of concentration (when it can be demonstrated that the ore and the rock category have a source relationship). Expanded, after Laznicka (1985e).

number of postmagmatic hydrothermal deposits of these metals does occur within or near these rocks (compare Chapters 7,15,17 and 19). Jensen (1971) postulated that most of the hydrothermal polymetallic deposits in the western United States (mostly in the Great Basin) had their metal sources in the organic-rich (black) "shale" horizons penetrated and flushed by "granite"-heated convective systems.

Cu and Zn have also high clarkes in (meta)basalts, andesites and gabbros, and these rocks are repeatedly associated with postmagmatic plutonic deposits of these metals (e.g. porphyry coppers). Pb,Sn,W,Bi and U are significantly enriched in felsic granites, and indeed many or even most of their hydrothermal deposits are proximal to older generation of granites or are part of multiphase granite intrusive systems. Non-systematic metal enrichment in a variety of rocks is more difficult to predict. Often it is regional, crossing lithologic boundaries and suggesting a heredity.

Availability of metals for ore generation in passive source rocks is not only a function of abundance, but also a function of setting (bonding) of the metal. Such settings can be arranged by the ease of release of the metal from the host mineral or rock as follows (from easiest to most difficult to release): (1) metals forming their own sulphide (or other) phase, located in fracture veinlets or in pores; (2) the same minerals, located on surface of rock-forming minerals and interstitially; (3) the same minerals present as inclusions in rock-forming minerals; (4) trace metals carried by common sulphides (e.g. pyrite); (5) native metals and metallic oxides forming their own phases; (6) trace metals present in easily soluble and degradeable rock-forming minerals (carbonates, organic compounds, volcanic glass); (7) trace metals forming own accessory silicates or (8) trace metals substituting in the lattice of rock-forming silicates and oxides.

28.3.5. Mineralized versus barren "granites"

The problem of why some "granites" (plutons, batholiths, massifs) are mineralized and others barren, is from time to time, discussed in the literature, but at present there is not a single, universally valid answer. All the aspects of "granite" origin and emplacement reviewed earlier, seem to be of importance. Probably of greatest importance is the depth of erosion. Epizonal and upper mesozonal plutons are often mineralized, while the deeper plutons are uniformly barren except for pegmatites or modified relic deposits.

The second most important feature appears to be the pluton morphology. In the tin-bearing regions in particular, elevated cupolas, cusps and ridges "sitting on the back" of a more or less flat batholith, are foci of mineralization while the rest is barren. Porphyry Cu and stockwork Mo also favour central, upward-evolving intrusive systems.

Third in importance is the state and composition of the over-intrusion lithologic association, in which convection took place. In regions where extensive "granitic" batholiths are roofed by a variety of rocks, segments composed of the more variegated and "fertile" assemblages (black metasediments, marbles, amphibolites, a variety of metavolcanics), tend to be more commonly mineralized than monotonous gneiss, schist, sandstone or common shale terrains.

A significant number of geologists (Noble, 1970; Routhier, 1980;

the Soviet school) interpret richly mineralized segments of the crust (including those intruded by granites) as being predetermined by local metal anomalies in the mantle, or simply by the relative proximity to the mantle. When a mantle inhomogeneity and a "granitic" intrusion overlap, the granites are believed to have acted as "revelateurs", "developing" the anomaly and lifting a portion of its metals into the near-surface region.

28.4. MINERALIZATION STYLES ASSOCIATED WITH PHANEROZOIC (HIGHER-LEVEL) GRANITE, DIORITE, (GABBRO) ASSOCIATION (Fig. 28-26; Table 28-1)

28.4.1. Ore minerals disseminated or scattered in "normal" (unaltered) "granites"

The ordinary rock-forming and accessory metallic minerals in "granites" (magnetite, ilmenite, zircon, rutile, monazite) are of little importance as sources of metals, unless additional conditioning, sorting and accumulation of the valuable substance takes place. This happens by the action of tropical weathering and by a hydrodynamic transportation and sorting of the detritus. Weathering slightly enriched accessory magnetite in "granites" used to be recovered in the past in Japan as an iron ore (Chapter 23). A portion of the detrital zircon, monazite, ilmenite and rutile in alluvial and beach placers described earlier came from granitic rocks.

Gabbros are particularly high in ilmenite, occasionally enriched anomalously in schlieren and inhomogeneities. Such ilmenite after weathering release could be added to placers, but no "primary" ilmenite or Ti-magnetite accumulations in "granite"-affiliated gabbros are known.

Rare and "special" accessory minerals in "granites" include orthite (allanite), xenotime, euxenite, columbite-tantalite, beryl, uranothorite, uraninite, fergusonite, betafite, molybdenite and cassiterite. Most of these accessories are fine crystalline and megascopically unrecognizable. They may accumulate in proximal placers. Granites unusually rich in some of the accessory minerals listed above may develop into "metalliferous granites", that might be economic to mine in bulk in the future. Most examples of such granites are members of the alkaline or peralkaline association (Chapter 33), katazonal granites (Chapter 29), Precambrian granites (Volume 2), or both.

Of the reminder one can mention: uranothorite-rich "granite" in the Khantau massif, southern Kazakhstan, and several orthite-rich granites in the Susamyr Batholith, Tian Shan (both in the U.S.S.R.; Lyakhovich, 1973), both containing up to 3% Th. Elberton Granite in Georgia, rich in orthite, contains, as a whole, about 45 ppm Th, and feasibility tests have been made to extract this thorium directly by chemical leaching in situ. In the You Yangs Granite in Victoria, Australia (Baker, 1937), allanite there is a rare accessory in the granite, but it accumulates in mafic schlieren in which it constitutes

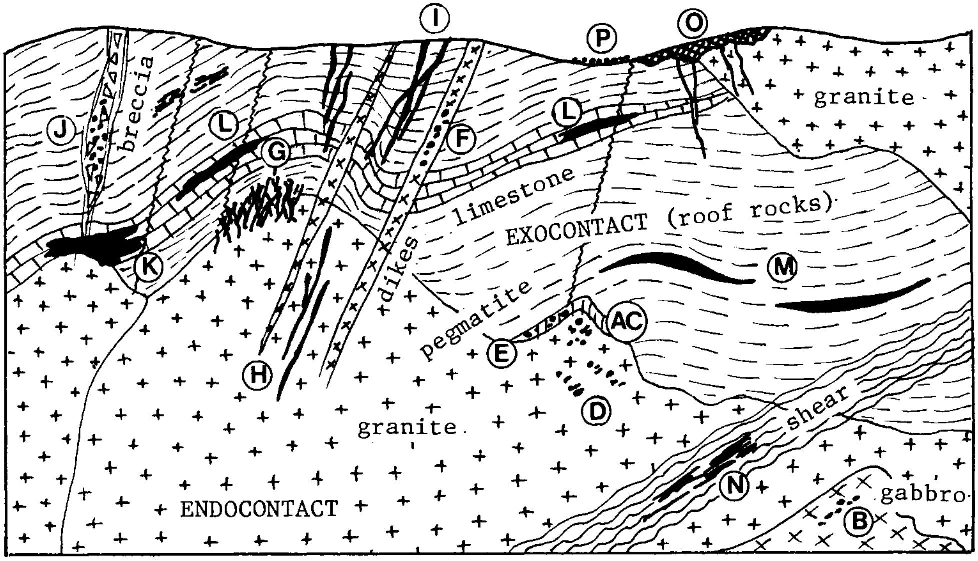


Fig. 28-26. Principal mineralization styles associated with Phanerozoic GDG ("granitic") intrusions. See Table 28-1 for explanation of letter codes. From Laznicka (1984)

Table 28-1. Principal mineralization styles associated with Phanerozoic "granitic" intrusions

(A)	physically separable ore minerals disseminated (scattered) in unaltered "granites" (zircon, monazite, U,Th,REE minerals, magnetite, beryl, rutile
(B)	higher than accessory disseminations, schlieren, etc. of ilmenite, magnetite or chalcopyrite in gabbros
(C)	dispersed metals in granites in supra-clarke concentrations (U,Th)
(D)	mineralized inhomogenities in "granites"
(E)	mineralized high-level pegmatites (Sn,W,Mo,Be)
(F)	mineralized intrusive dikes
(G)	stockworks and pervasive ore disseminations along altered contacts in non-carbonate hosts (Au,W)
(H)	veins in intrusive endocontacts
(I)	veins in intrusive exocontacts
(J)	mineralized breccias, breccia pipes, replacement pipes
(K)	skarns
(L)	non-skarn carbonate replacements
(M)	relic and remobilized ores in granite aureoles
(N)	mineralized meta-granite and metamorphic ores in granites
(O)	ore accumulations resulting from weathering of "granites" and their mineralized aureoles
(P)	ores formed by sedimentogenic reworking of "granite" - associated mineralizations

3.5% of the rock. Pink perthitic post-kinematic granites forming small stocks in the Sawtooth Massif S.W. of Stanley, Idaho (Killsgaard et al., 1970) and in the Bugaboo and adjacent creeks near Spillimacheen, S.E. British Columbia, contain disseminated accessory euxenite-polycrase. In both areas, placer accumulations have formed. Fergusonite is said to be abundant in the marginal zone of a granodiorite in the Nanling Range, S. China.

Accessory uraninite has been found in almost all granites known to host vein or "unconformity-type" uranium deposits, or interpreted as uranium sources to groundwater-epigenetic deposits in the vicinity. Many such localities (N. Australia, Wyoming) are Precambrian, but the French uraniferous granites (particularly those in Vendée, N.W. France; Barbier, 1972) are late Paleozoic. There, the discovery of one U mineralization style (e.g. U veins) can serve as a starting point for a search for other styles, including uraniferous granites.

Beryl-bearing granites have been discussed by Burke et al. (1964). Several occurrences of scattered, fine-grained beryl mostly in high-level granites of ring complexes in Ireland, Scotland and elsewhere, have been documented. Such beryl is very inconspicuous, but detectable by portable berylometers. At most localities, disseminated beryl in granite is a minor variety located on fringe of Be greisens or pegmatites. It is economically unimportant

Cassiterite-, molybdenite-, wolframite-, scheelite-, etc.-bearing granites are genetically enigmatic, and discussions as to whether such occurrences are "orthomagmatic" or "postmagmatic" appear periodically in the literature (see Hosking, 1973 and Taylor, 1979, for discussion). In most cases this is a matter of misunderstanding or carelessness in writing, in which authors equated "granite-hosted" ores with orthomagmatic ones. It appears that emplacement of the economically interesting quantities of cassiterite and some other minerals postdated the main crystallization of granites and accumulated in late stage pegmatites (in deep-seated granitic terrains) or in hydrothermal replacements, stockworks and veins accompanied by alteration. As mentioned earlier, the high-temperature hydrothermal feldspathization or biotitization often produces minerals virtually indistinguishable from their magmatic counterparts and gives the rocks a fresh, "primary" look. The largest accumulations of cassiterite in "unaltered granite" as in the Čistá deposit, Czechoslovakia (Ďurišová et al., 1969) are always situated along fringes of greisenized or otherwise altered zones so their orthomagmatic emplacement has a low credibility.

Molybdenite is a much more common (and conspicuous) "accessory" in "granites". Close examination, however, almost always indicates that the mineral is, in fact, in fracture veinlets, coats joints, or replaces biotite flakes within an alteration band. The same applies to wolframite and scheelite (e.g. in the Atolia field, California).

28.4.2. Granites with low-grade dispersed metallic component ("metalliferous granites")

Earlier we discussed metals accumulated in discrete ore minerals, but some granites could have an anomalous trace content of various metals perhaps recoverable in the near future by cheap, bulk leaching methods. The biotite phase of the Jurassic Conway Granite, New Hampshire (Finch et al., 1973) has been studied with this in mind. The granite averages 12 ppm U and 56 ppm Th (this corresponds to clarke of concentration of 4 and about 10, respectively), but this represents about 675 Tt U and 3 Mt Th available within an area of 768 km^2 to a depth of 330m.

The increased trace metal contents in granites are either evenly distributed throughout the rock, or restricted to certain major or accessory minerals. There is a possibility that accumulation of such "metalliferous rock-forming minerals" may evolve into future ore deposits. Most examples involve tin. Hosking (1973, 1974) reported up to 2% Sn in some zircons, up to 10% in sphene, up to 2% Sn in andradite and up to 1.6% Sn in axinite. High Sn contents are in högbömite, an inconspicuous mineral resembling biotite. Furthermore, a high content of Sn (X00 ppm) is found in some amphiboles, biotites, and staurolites. Lead, on the other hand, accumulates in feldspars (up to 3% Pb), particularly in the green microcline (amazonite).

28.4.3. Mineralized inhomogeneities in granites

Inclusions (xenoliths) and schlieren may contain ore minerals that their host granites lack. The common mafic (gabbroic) xenoliths in tonalites and granodiorites almost always contain scattered grains of chalcopyrite (together with pyrrhotite), probably released during conversion of pyroxene into amphibole and amphibole into biotite. Didier (1973) described "mineral nodules" from leucogranites in Britanny (N.W. France) containing minor beryl.

Tsypukov and Vladykin (1976) described occurrences of native gold (up to 2.1 ppm) associated with gabbro rafts in some "granites" in Mongolia. The gold was located in strongly hybrid sections accompanied by pegmatite and fluorite. Relics of former metalliferous deposits in supracrustals invaded by "granites" often survived, remarkably little modified, in xenoliths and rafts. One example of a "granite"-dismembered conformable massive sulphide lens has already been reviewed and illustrated (Chapter 12, Fig. 12-11).

Xenoliths and rafts of reactive rocks (e.g. carbonates) may carry contact metasomatic metalliferous replacements such as magnetite or scheelite skarns. Many scheelite skarns in the Sierra Nevada, California, are in such rafts. The rafts grade down in size into centimetres-sized xenoliths and into even smaller particles. It is possible that several occurrences of disseminated scheelite occurrences in "granites", in fact, contain small metacarbonate inclusions completely replaced by scheelite.

The Minto copper deposit, Yukon (Pearson and Clark, 1979; 160 Tt Cu/1.86%, 55 t Ag, 3.6 t Au) is one of the recently described enigmatic deposits associated with inhomogeneities in "granite". The main orebody is a flat-lying lens of foliated biotite granodiorite and gneiss with dimensions of 335x247 m and 30 m average thickness, enclosed in a generally unfoliated late Triassic mesozonal granodiorite. The ore confined to the foliated matrix consists of disseminations and veinlets of chalcopyrite, bornite, lesser magnetite and pyrite, often accompanied by clusters of biotite. After deposition, the ore and its surroundings suffered deformation, light metamorphism and dismemberment by faults and intrusive dikes. Although Pearson and Clark (1979) considered the mineralization to be pre-granite, the original protolith and ore style remain uncertain.

28.4.4. Mineralized high-level pegmatites

Granitic pegmatites are most widely associated with katazonal granites (and sillimanite-grade metamorphics), so their main review is in Chapter 29 (also in Volume 2, because the majority of economic pegmatites are Precambrian). Here, the small and relatively uncommon pegmatites affiliated with mesozonal, and even epizonal, granites are reviewed briefly. In the classification of pegmatite associations by depth prepared by Ginzburg et al. (1979), two classes fall into the present field of coverage. They are (1) miarolitic pegmatites forming pods in the upper parts of granitic intrusions and containing miaroles filled by quartz, fluorite, topaz and beryl and (2) intermediate-depth rare-element (Li,Rb,Be,Ta,Sn,Nb) pegmatites. The type locality of the miarolitic pegmatites is in the Precambrian Korosten Massif, hence they are considered in Volume 2. The rare element pegmatites are all associated with apical portions of "S granites" in Sn,W,Mo,Be,etc. mineralized provinces where they represent a minor mineralization style of limited economic importance. They could be lithian, but Li is mostly in zinnwaldite or lithionite. These pegmatites should not be confused with the "typical" Li-pegmatites (with lepidolite, spodumene, etc.) treated in the next chapter.

The rare-element pegmatites as outlined above occur (1) as "syngenetic" schlieren, nests and small lenses in acid granites, or as "linings" of granite stocks along contacts with the outside rocks ("Stockscheiders") or (2) as independent pegmatite bodies such as dikes, sills, lenses, filling dilations in both endo- and exo-contacts in granites. Both varieties may carry irregularly scattered crystals of wolframite and scheelite (Soktui and Adun-Chalon Massif, Transbaikalia; several massifs in the Kolyma belt in Siberia; Shcheglov and Butkevich, 1974; Modoto and Tsagan-Daba deposits, Mongolia; Marinov et al., 1977); cassiterite (Kalba district, Kazakhstan; Baga-Gazryn Sn deposit, Mongolia); stannite (Vernéřov near Aš, W. Czechoslovakia, in amblygonite pegmatite); molybdenite (Condor Huta deposit near Milipaya, Bolivia, where an apophysis of a coarse granodiorite changes into a pegmatitic granite and ultimately pegmatite with scattered flakes of molybdenite; Ahlfeld and Schneider-Scherbina, 1964. Similar deposits have also been found near Skalsko, Czechoslovakia); columbite-tantalite, beryl and other minerals (Zhanchublin and Khukh-Del-Ula occurrences, Mongolia; Umana, Bolivia). Although of little value considered searately, the occurrences listed above could be gradational into quartz, feldspar, muscovite, tourmaline, cassiteite veins (e.g. Zigei-Khundei showing, Mongolia); to quartz, wolframite or cassiterite veins and to molybdenite veins. Sn-W greisens could be superimposed on pegmatites and their surrounding. The pegmatite presence can serve as an exploration lead for the more productive styles of Sn,W(Mo,Ta-Nb) deposits, and widespread occurrences of stanniferous pegmatites may contribute detrital tin to placers.

Probably the best known representative of a small mesozonal Sn pegmatite deposit is the Mina Fabulosa in the Sorata Batholith, Cordillera Real, Bolivia (Ahlfeld and Schneider-Scherbina, 1964). There, numerous dikes of microcline-quartz pegmatite are found at both sides of contact of a coarse Mesozoic muscovite granite and Paleozoic spotted andalusite phyllites and biotite contact hornfelses. Coarse cassiterite in zoned crystals, up to 15 cm in diameter, is haphazardly scattered in the dikes, and there is also minor lazulite, triplite, trifyline-lithiophyllite, molybdenite, pyrrhotite, arsenopyrite and stannite. The average grade is 1% Sn and the pegmatite grades to quartz-muscovite veins and is sometimes partly converted into greisen along sahlbands.

Several additional varieties of "pegmatites" are actually hydrothermal metasomatites or open space fillings. This is probably where the "amazonite" (microcline) pegmatites belong, that are associated with albitized "apogranites"; pegmatitic nests and portions of K-feldspar and biotite metasomatites in porphyry copper systems; etc. Many metallic ores hosted by pegmatites are epigenetic, of hydrothermal origin, and introduced after completion of the pegmatite stage. When the hydrothermal gangue minerals are feldspar, quartz and mica, the superimposed origin of the ore is commonly missed. In this category, for example, belong several localities of the "auriferous pegmatites" listed by Boyle (1979, p. 248,249).

28.4.5. Mineralized porphyry, lamprophyre, diabase, etc. dikes

Intrusive dikes are a typical feature of most hydrothermal vein and stockwork fields, where they often occupy the same fissures filled by veins. They are often hydrothermally mineralized in preference to the other, more voluminous hostrocks. In the Březové Hory field, Příbram district, Czechoslovakia, the majority of Pb,Zn,Ag veins are located in narrow diabase dikes. In the Berezovsk goldfield in the Urals (Magak'yan, 1968) granite, plagiogranite and syenite porphyry dikes believed to be derived from a late Paleozoic granitic pluton, intersect Devonian mafic metavolcanics, metasediments and serpentinites. The dikes are 2-40 m thick and up to 8 km long. Within the 64 km^2 of the field, the dikes are intersected by more than 70,000 thin quartz, pyrite, tourmaline, gold veins. About 40% of the total length of dikes is productive and on average, each 3 m of a dike contains one ore vein. In the Kochkar goldfield (the Urals, U.S.S.R.) over 1,500 mafic to felsic dikes are biotite, amphibole, feldspar-altered and carbonatized in the aureole of a small microcline granite stock. The altered dikes were then preferentially mineralized by quartz, arsenopyrite, pyrite, tetrahedrite, tellurides, gold, etc. veins.

Elsewhere, dikes often overlap with the ore vein deposition and pre-, syn- and post-ore dikes have been reported. Dikes are considered to be a favourable indication of the possible presence of ore veins, mainly because dike swarms are one of the indicators of an over-intrusive setting. Abdullaev (1957) devoted a whole book to the ore and dike association. The many varieties of vein arrangement in dikes have been thoroughly treated in the classical literature on structural control of ore deposits. In addition to the predictable varieties of mineralization hosted by dikes, there are several unique examples of metalliferous dikes. Boyle (1979, p.248) listed several examples of auriferous dikes. In the Central City district, Colorado, a set of quartz-bostonite porphyry dikes is highly radioactive (max. 0.013% equivalent U) and intimately associated with pitchblende-bearing hydrothermal veins in the district (Wells, 1960).

28.4.6. Stockworks and pervasive disseminations in altered endo- and exocontacts

The bulk of the large volume, low grade, hydrothermal-plutonic deposits of Cu(Mo), Mo and Sn occur in distinct stockworks and disseminations-dominated alteration-mineralization systems (porphyry coppers, stockwork molybdenums, cupola tin deposits), that are reviewed as units later. The remaining metals may occasionally accumulate in stockwork or dissemination-style orebodies, but these deposits are of substantially lesser importance than alternative ore styles, particularly veins and replacements (Fig. 28-27). There is an intermediate style of orebodies distribution between stockworks and fissure veins, taking the form of swarms of closely-spaced, parallel veins (e.g. Endako, British Columbia, Bainazar, Kazakhstan and Mt. Carbine, Queensland, Mo and/or W deposits).

GOLD DEPOSITS

The small gold stockwork at Jessie mine, Colorado, has already been mentioned. Boyle (1979) reviewed additional localities of auriferous stockworks, many of which are in volcanics and subvolcanics typically associated with explosive volcanic centres (Chapter 26) or with Precambrian intrusions (Volume 2). Further examples of plutonic Au

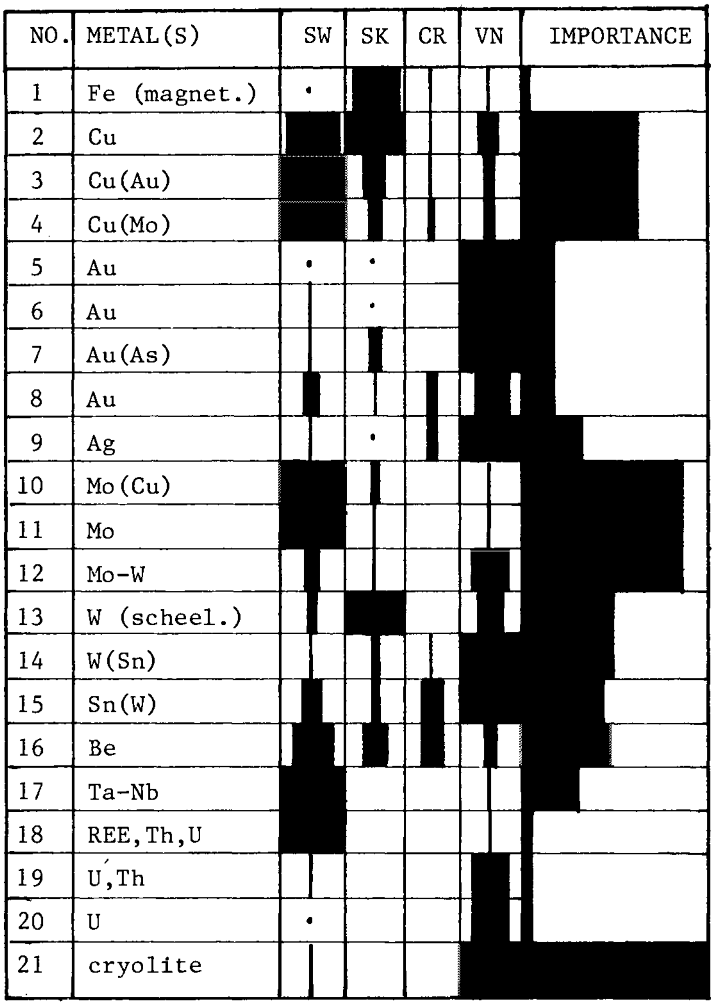


Fig. 28-27. Relative importance of stockwork or disseminated, skarn, carbonate replacement, and vein deposits of metals. Abbreviations: SW=stockworks; SK=skarns; CR=carbonate replacements; VN=veins. Column IMPORTANCE denotes the importance of granite-associated deposits of the respective metal among all deposits of such a metal.

Table below lists examples of associated intrusives and endocontact stockwork, disseminated and exocontact skarn ore deposits:

NO.	METAL(S)	AFFILIATED INTRUSIVE ROCKS	STOCKWORKS/ DISSEMINATIONS	SKARNS
1	Fe (magnet.)	quartz diorite, quartz monzonite	Iron Springs, Utah	Iron Springs, Utah

2	Cu	soda granite (trondhjemite) "primitive" assoc.	Tsessovka, Voznessenskoe	Tur'ya (partly)
3	Cu(Au)	quartz-free (diorite, syenite) association	British Columbia, Boshchekul	Princeton, Brit. Columbia
4	Cu(Mo)	high-quartz qtz.monzonite, granodiorite	widespread worldwide	Ely, Bingham, Tucson South
5	Au	soda granite (trondhjemite) "primitive" assoc.	Bralorne,B.C.	
6	Au	quartz-free (diorite, syenite) association	Vunda, Fiji	
7	Au(As)	quartz monzonite, granodiorite, qtz. diorite	Jessie,The Patch, Colo.	Hedley, B.C.
8	Au	syenite, granosyenite to qtz.monzonite, granite	Zartman-Landuski, Zarmitan	Judith Mts.
9	Ag	quartz monzonite, granodiorite porphyries	Nenzel Hill, Hahn's Peak	
10	Mo(Cu)	quartz monzonite, granodiorite, porphyries	Boss Mountain, Shakhtama	Cannivan Gulch, Rossland, B.C.
11	Mo	high K calc-alkali and alkali-calcic granite	Climax, Henderson, Colorado	
12	Mo-W	high-K leucogranite and related porphyries	Akchatau, Koktenkol'	
13	W (high lv.sclt.)	granodiorite, quartz monzonite, granite	Gabbs, Boguty, Haut Auxelles	Tyrny Auz Xi Zhoyouang
14	W(Sn)	biotite and musc.-biot. granite, leucogranite	Hemerdon, S. England	
15	Sn(W)	as above	Altenberg,Cínovec, Krásno	Doradilla,Moina, Lost River
16	Be	as above	minor in Ireland,Scotland	Xi Zhoyouang Iron Mountain
17	Ta-Nb	peralkaline to alkaline granite	E.Transbaikalia Kaffo Valley,	
18	REE,Th,U	as above	Khantau, Susamyr, Bugaboo	
19	U,Th	peralkaline granite	Bokan Mt., Sawtooth Massif	
20	U	syenite, bostonite	Central City, Colorado	
21	cryolite (Al)	peralkaline granite	Ivigtut, Greenland (PCm)	

stockworks include the Zarmitan Complex of Permian granosyenites in Uzbekistan (Garkovets et al., 1979). There, gold-bearing stockworks and discrete quartz veins with auriferous pyrite and arsenopyrite are enveloped in microcline and albite alteration metasomatites.

In the Klyuchi gold field (E. Transbaikalia; Borodaevskaya and Rozhkov, 1974), networks of quartz, tourmaline, pyrite, chalcopyrite, arsenopyrite and gold are hosted by strongly tourmalinized Paleozoic and Mesozoic granitoids. In the Zartman-Landusky field in the Little Rocky Mts., Montana, numerous, very low-grade auriferous veinlet stockworks and veins in Tertiary quartz monzonite and syenite are mined on large scale, and locally heap leached.

SCHEELITE DEPOSITS

Disseminated and stockwork ("porphyry") scheelite deposits are known, both in the form of local sections of composite ore zones, and as independent orebodies. Examples include the Victory Mine near Gabbs, Nevada (scheelite disseminated in granodiorite); Boguty stockwork, S. Kazakhstan (quartz-scheelite veinlets enveloped in greisenized and quartz, sericite, chlorite-altered Carboniferous granite and Ordovician sandstone); Haut Auxelles, Vosges, France (quartz-scheelite veinlet stockwork in a silicified dike of microgranite) and other localities. In the Yellow Pine ore zone, Idaho (Cooper, 1951), disseminations and fracture coatings of scheelite, stibnite, pyrite and gold are found in altered quartz monzonite along an important shear.

28.4.7. Veins in intrusive endocontacts

A great variety of hydrothermal veins formed in the brittle rocks of granite endocontacts, is discussed in the classical literature on structural control and in textbooks. The more typical veins emplaced contemporaneously with, or shortly after, the cooling of a post-tectonic granite body in a stress field, fill the regularly developed perpendicular joints in granites. Of the three regular joint directions, the open Q joints (parallel to stress) and the "flat" (low angle, L) joints tend to be preferentially filled by veins. In granite cupolas such veins often occur in parallel systems and may grade into stockworks. In Cínovec, Czechoslovakia, a system of parallel flat quartz, cassiterite, wolframite, etc. veins is arranged in an onion-skin fashion parallel with the outer perimeter of a granite cupola.

In forcefully emplaced plutons, in late tectonic plutons, in plutons deformed by post-solidification faulting, etc., regular and predictable vein patterns are rare. The veins fill fissures and faults often healed earlier by dikes, striking in all directions and mostly dipping steeply. Conjugate vein systems may form, as for example in the Grass Valley field, California. Several vein examples have been recorded located in thrusts. Lodes filling shears in "granite" plutons are also known. Open-space filling veins are slightly more abundant than replacement veins.

28.4.8. Veins in granite exocontacts

Exocontact veins show even greater variety than the veins hosted by granites (Fig. 28-28), because of the wide range of rock competency (e.g. in alternating slates and quartzites), reactivity with hydrothermal fluids (carbonates versus silicate rocks) and a variety of "topomineralic" influences and proximal metal source relationships.

In aureoles of high mesozonal to epizonal "granites" emplaced in a slate unit (as is common in many tinfields), the contact-proximal hard and brittle quartz, biotite, plagioclase hornfels "welded" to the granite is mechanically comparable with the "granite" and often hosts stockworks of numerous short fracture veins or veinlets. Outside the hornfelsed rim, discrete, more persistent and usually richer veins form along faults. In terrains of alternating slates and quartzites (as in the Paleozoic sediments of Bolivia), through-going fissures are tight and virtually unfilled in the slates, but widen to form "bolsons" (ore shoots) in the brittle quartzites. The latter often take the form of mineralized breccias or stockworks.

This general relationship extended to include the endocontact veins, has been supported statistically by evaluation of the average hydrothermal vein dimension, prepared by Smirnov, ed. (1968; Fig. 28-29). There, the veins of metals preferentially situated at the greatest distance from granite contacts (Pb-Zn, Au, Cu) are long and deep. Those present close to the contact (W, Sn, Mo, fluorite) are short and shallow.

Probably the greatest regularity and predictability of vein occurrence exists above granite cupolas, in compositionally homogeneous metasediments. There, veins, in most cases, are subvertical and subparallel with cleavage (e.g. Burnt Hill, New Brunswick), but there are important exceptions. At Panasqueira, Portugal (Kelly and Rye, 1979), a subhorizontal swarm of quartz-ferberite veins cuts sharply across the steep bedding and foliation of pelitic schists, above and in the exocontact (and partly endocontact) of a granite.

In regions of alternating silicate rocks and carbonates, veins in the former and bedded replacements in the latter often coexist. Under special conditions, ore veins are repetitively associated with a "favourable" lithologic and stratigraphic unit (horizon) and may occur within it (// with bedding and schistosity; e.g. wolframite veins in Bolsa Negra, Bolivia). Alternatively barren fissures or veins may become mineralized in the intervals cutting such horizons (e.g. Kti Teberda W deposit, the Caucasus). This strongly suggests (re)mobilization of metal from an earlier metalliferous horizon.

There are numerous variations of fissure veins, rated by the regularity and persistence of filling. Some are continuously

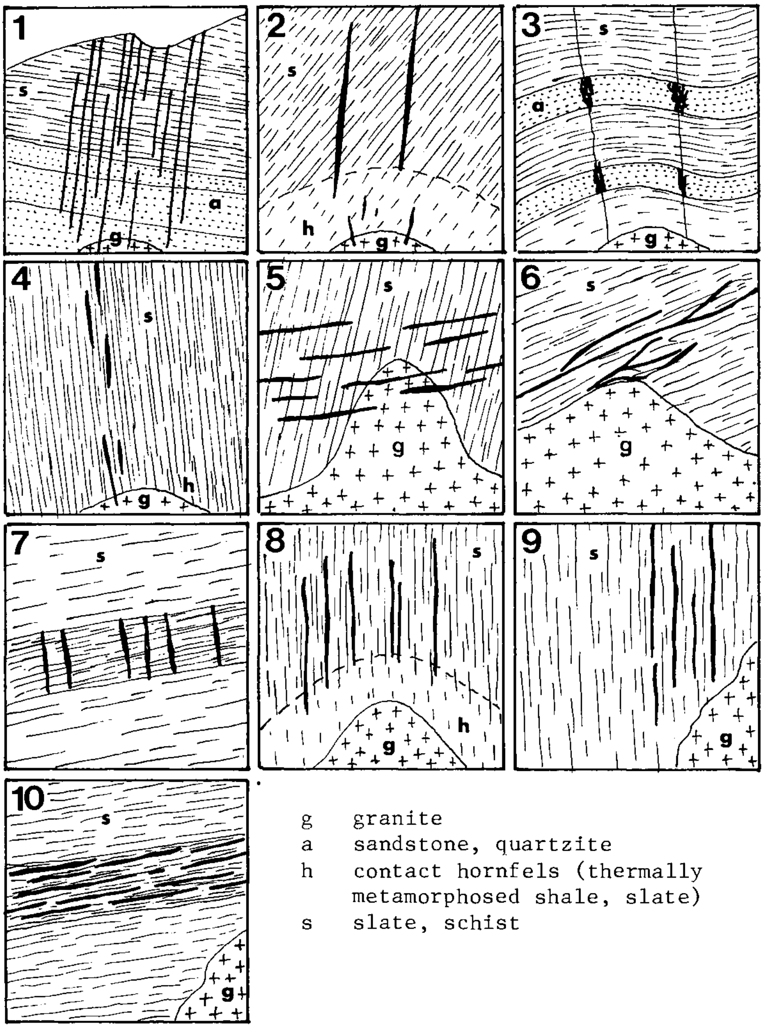


Fig. 28-28. Diagrammatic representation of the variety of hydrothermal Sn and W veins in non-carbonate exocontact rocks: 1=closely spaced veins almost normal to bedding (e.g. Tachishan); 2=persistent veins along faults in slates (Bolivia); 3=thin veins or barren fissures (leaders) in slates widen and become economic in quartzite (Bolivia); 4=veins parallel with slate cleavage above granite cupola (e.g. Burnt Hill); 5=subhorizontal fissure veins crossing bedding above, and partly within, granite cupolas (e.g. Panasqueira); 6=an inclined vein swarm in hornfelsed slates, above granite (Storeys Creek); 7=productive ore shoots confined to a "favourable" sedimentary unit (Kti-Teberda); 8,9=veins parallel with foliation (e.g. Boriana); 10=veins and veinlets confined to and conformable with, bedding of a "favourable unit" (e.g. black slates; Bolsa Negra). From Laznicka (1984).

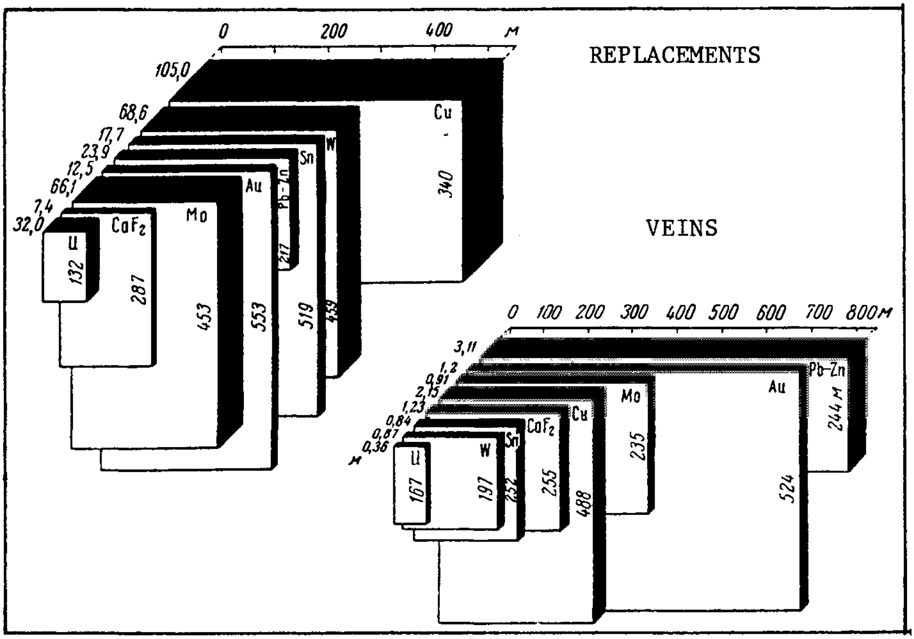


Fig. 28-29. Mean dimensions of postmagmatic hydrothermal veins and replacements. From Smirnov, ed.,(1968).

mineralized, for example by ore bands interlayered with gangue minerals; gangue filling containing scattered ore minerals; or rarely massive ore fill. Other veins change zonally with depth (the proportion of ore substance usually decreases), so in the deeper portions the vein often becomes barren although still continuing. Other "veins" are essentially tectonic structures mineralized at intervals, or filled by gangue material in which ore-bearing shoots appear from time to time.

28.4.9. Zoning in veins and hydrothermal mineralized structures

Metal (e.g. Sn-W-Mo), mineralogical (e.g. cassiterite →wolframite →molybdenite), ore style (e.g. greisen → endocontact stockwork → exocontact vein), alteration (e.g. greisenization→tourmalinization→ sericitization) and other zonings are common features of a "granite"-affiliated mineralization system. These have been well known for over 80 years. Understanding and application of local zoning patterns contributed to ore discoveries but, on the other hand, orebodies have been missed and ore discoveries delayed for decades by insensitive application of the few popular zoning patterns highlighted in the literature. The extensive subject of zoning has recently been reviewed by Laznicka (1985c) and local zoning patterns as well as the repetitive zonings pertinent to specific mineralization styles are reviewed later in this chapter.

Given the variety of the petrochemical types of "granites" and their settings, surrounding rocks, variety of mineralization processes, etc., it is not surprising that there is not a single, master zoning pattern applicable to all granitic intrusions and their aureoles. The classical Emmonsian metal zoning pattern and its variations and modifications that adorn classical textbooks had already been termed "a wonderful oversimplification" by several authors at the time of its introduction in the 1920s, so it is not treated here. Instead, a diagram (Fig. 28-30) showing the frequency of occurrence of the various hydrothermal epigenetic ores at various distances from a "granite", is provided. The diagram is entirely empirical, based on a population of several hundred orebodies, and free of undocumented speculation. It shows how far from a genetically related igneous intrusion various hydrothermal orebodies most frequently occur worldwide, but it in no way suggests that all such orebodies (or their majority) are to be expected in the same area and that the pattern of the graph might appear as an actual vein, field, district or even mineralized belt zonality. There seems to be little doubt that mineralizations that have a narrow interval of occurrence and are constantly proximal to the "granite" contact (such as Sn greisens, skarns), are also genetically closely related to it. Ores showing a wide spread (e.g. quartz-hematite veins) or those that are systematically located in areas showing few signs of "granite" presence (e.g siderite veins), need not be genetically related to "granites" at all, at least not directly.

28.4.10. Breccias, breccia pipes and replacement pipes

Mineralized and unmineralized breccias are fairly common in the plutonic association, being particularly widespread in and near epizonal plutons. The ore-bearing breccias were favourable loci for ore deposition by virtue of their porosity and also because they were often the products of the dynamic interplay that generated ores regionally. Finally, breccias may contain ore fragments derived from older mineralizations present below, above or laterally, so that they often constitute an excellent exploration guide for hidden orebodies.

There is a bewildering variety of breccias and brecciated rocks in general, matched by an extensive list of genetic explanations proposed to account for their origin. These will be reviewed in a separate chapter in Volume 2. Here, only those breccias located in calc-alkaline intrusive terrains are considered. A characteristic feature of such terrains is a variety of breccia bodies having a circular or elliptical outline, and vertical to steep attitude. Some may be eroded volcanic vents (e.g. the Braden "Formation" at El Teniente, Chile; Camus, 1975), while the remainder are genetically uncertain. Gilmour (1977) termed breccias believed to be associated

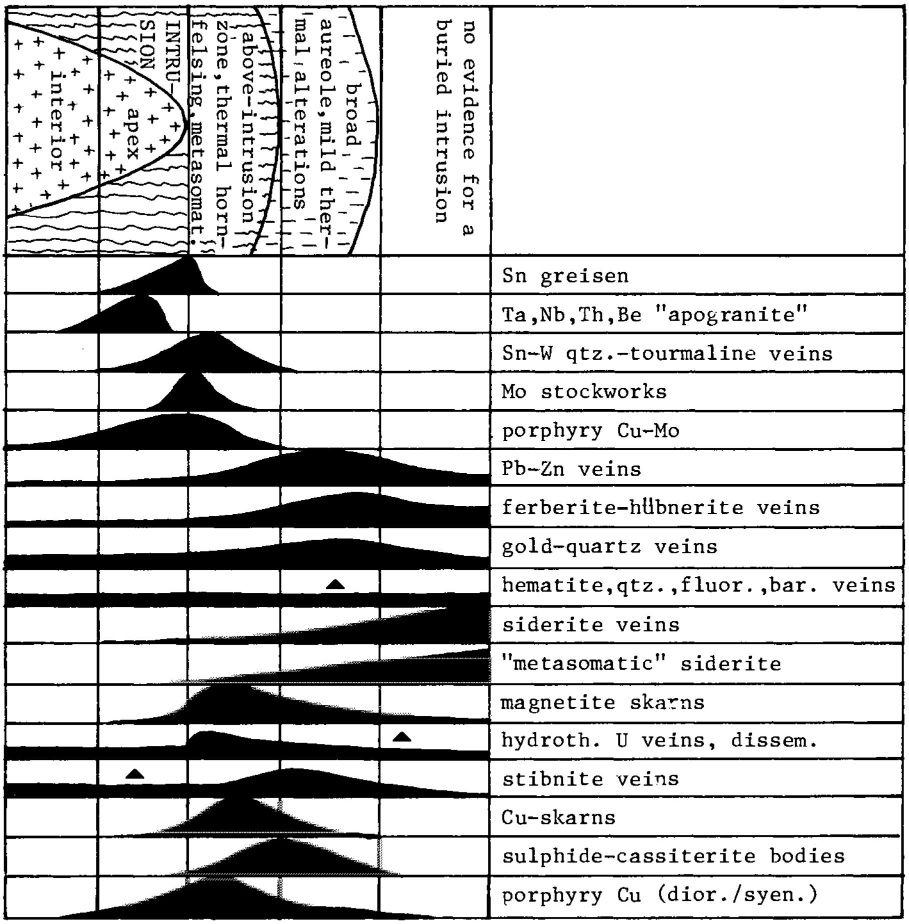


Fig. 28-30. Empirical frequency of occurrences of metallic mineralizations with respect to granitic intrusions (the ores need not be contemporary with, or shortly postdating, the granite emplacement). Triangles: major mineralizations postdating granite emplacement. From Laznicka (1984)

in some way with intrusive activity "intrusive breccias". Bryant (1968) who contributed a classical study of breccias present in the Bisbee porphyry copper field, Arizona, on the other hand, used a different terminology. His "intrusive breccias" were intruded (that is, forcefully emplaced) into their present position, not necessarily as a consequence of an igneous intrusion. At Bisbee, such breccias take the form of heterolitic irregular sheets and masses controlled by bedding planes of metasediments and by faults. Intrusion breccias, on the other hand, developed within an igneous intrusion. Many geologists find these terms too confusing.

The breccias vary in appearance and composition. Some are porous, almost loose and uncemented. The rest are hydrothermally altered or cemented and/or replaced by alteration minerals and sometimes ores. Where there is strong evidence for emplacement as a suspension in a hydrothermal fluid, the term "hydrothermal breccia" is sometimes used.

Most breccia pipes are downward-tapering, shallow to deep bodies, the depth ranging from several metres to over 800 m. Their diameter range from about one metre to about 2 km and most occur in clusters, usually controlled by fault zones. Their fragments range from angular to rounded (rounded fragments are most characteristic in "pebble dikes") and there is a variable degree of fragment rotation. Almost unrotated fragments are generally considered local. The fragment and matrix composition is also variable although volcanic and intrusive fragments are dominant. The genetic interpretations offered include: (1) fluidization, mostly by upward-streaming volatiles released from a late stage intrusive stock; (2) hydrothermal dissolution that created void subsequently filled by collapse; (3) hydrothermal or late magmatic deposits filling void created by magmatic water trapped in the apical region of an intrusion (Norton and Cathles, 1973); (4) meteoritic impact and (5) other mechanisms.

Because of the considerable heterogeneity and interpretational uncertainity, breccia pipes cannot be classified satisfactorily at present either on the morphological and compositional basis, or by their origin. The safest way is to treat them individually (by region) or by associated mineralization. Proportionally, most breccia pipes are associated with porphyry copper systems (e.g. Cananea), including copper-bearing tourmaline breccia pipes (Rio Blanco-Disputada); with stockwork Mo; with apical portions of Sn,W,Mo,Bi mineralized granites; with gold disseminations and stockworks; etc. Fig. 28-31 shows several examples diagrammatically. Additional pipes at subvolcanic level are treated in Chapter 26. More detailed description of several pipes appears under the heading of metals they contain.

In terms of exploration, the most important species are the breccia pipes suggesting the presence of concealed mineralized plutonic systems, especially porphyry coppers. They are of two possibly end-member styles: (1) conical, deep-reaching subvertical pipes and (2) thin to wide, lens to cap-like breccia hoods topping intrusive cupolas. Examples and case histories from Arizona have been reviewed by Gilmour (1977).

Certain pipes in granite endocontacts are dominated by hydrothermal replacements to such an extent that the original breccia fragments may have been obliterated entirely. Alternatively, the hydrothermal minerals (usually quartz)-filled pipe need not originally have been a breccia, but merely a densely fractured zone. Short pipes taking the form of downward (into the granite) tapering cones are most common in some Sn,W,Mo,Bi regions. The pipes in the Wolfram Camp, N. Queensland (Plimer, 1975; about 3.1 Tt W, 900 t Mo, 190 t Bi) are hosted by sericitized Carboniferous quartz monzonite. They are elliptical in cross-section and often bulbous or branching. They range from several centimetres to 6m wide and reach a depth of about 200 m.

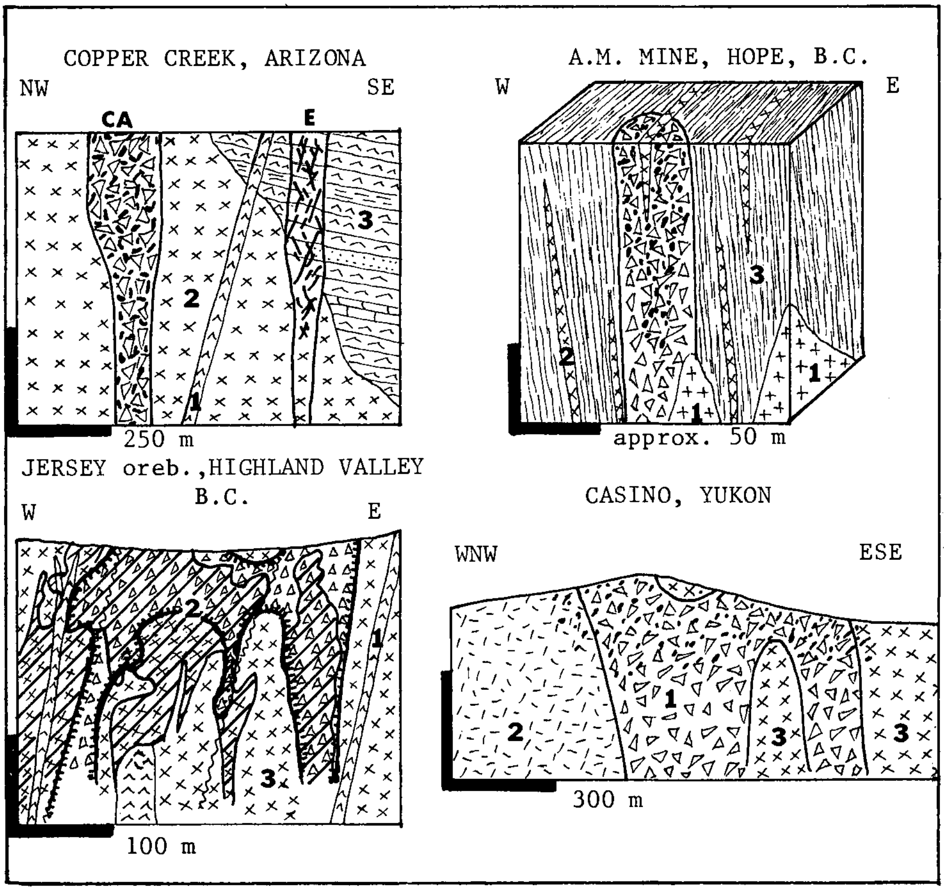


Fig. 28-31. Mineralized breccias in granitic intrusions and non-carbonate exocontacts.

Copper Creek Cu,Mo, Arizona; CA=Childs Aldwinkle altered and mineralized breccia pipe; E=Eagle deposit, fracture Cu stockwork in andesite; 1=T_1 latite and andesite dike; 2=Cr_3 granodiorite; 3=Cr andesite, tuff, minor sediments.

A.M. Mine, cp,po,py disseminations in the matrix of a breccia pipe. 1=Cr_3 ? granodiorite, quartz diorite; 2=Cr ? diorite to gabbro sills; 3=J_{1-2} hornfelsed distal turbidites.

Jersey mine, mo,cp disseminations and stockworks in granodiorite and breccia; 1=Tr dacite, latite, porphyry dikes; 2=breccia; 3=Tr granodiorite; ruled: orebody.

Casino, stockwork cp,mo in breccia, porphyry, quartz monzonite; 1=Cr_3 breccia; 2=Cr_3 quartz-feldspar porphyry; 3=Cr_2 quartz monzonite.

From LITHOTHEQUE, generalized after Kuhn (1941), Gilmour (1977), Briskey and Bellamy (1976) and Godwin (1976).

Compositionally they consist of quartz in a greisen envelope, and carry patches of wolframite, molybdenite, Bi,As,Cu,Zn and Pb sulphides.

An extensive but relatively unproductive cluster of Mo-Bi-bearing replacement pipes is found near Kingsgate (New England, Australia), hosted by a Permian leucogranite. The pipes are 1 to 20 m in diameter and up to 170 m long. They have been traced down to a depth of about 80 m. The core is composed of vuggy quartz grading into brecciated and silicified granite. Flakes of molybdenite and grains of bismuth and bismuthinite are irregularly scattered in all the zones.

28.4.11. Skarns

The term skarn originated in the Precambrian mineralized terrain of central Sweden (Bergslagen, Volume 2), and it referred to a mineralogical association of Ca,Fe,Mg silicates (Ca-Fe garnet, Fe-rich pyroxene) associated with iron ores. Elsewhere, similar silicates may be associated with ores of other metals (Cu,W,Sn,Au, etc.) and in such association the garnets and pyroxenes need not be highly ferruginous (e.g. grossularite, diopside). Some authors coined the term "tactite" for the iron-low assemblage.

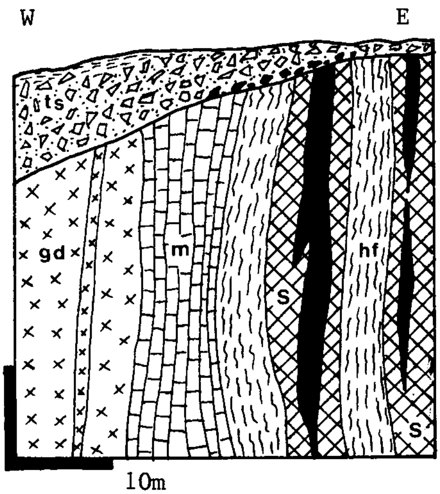
The skarn association may have a variety of origins: (1) localized metasomatic replacement of limestone or dolomite in "granite" exocontacts (Fe and Si have to be supplied from outside, Ca and Mg are local); (2) isochemical metamorphism of a supracrustal rock of suitable composition (e.g. pelosiderite, ferruginous marl); (3) local exchange of components between adjacent rocks of contrasting composition during a high-grade metamorphism ("reaction" or "bimetasomatic" skarn); (4) replacement or exchange of components between broad mobile fluid "fronts" triggered by metamorphism or plutonism, and solid rocks or (5) multistage origin (e.g. initial formation of volcanic-hydrothermal or hydrothermal-replacement siderite or ankerite, followed by an essentially isochemical metamorphism; e.g. Rushiţa, Rumania).

Possibility (1) is most characteristic of the meso- and epizonal granite aureoles to such an extent that most authors writing about skarns consider only the most "typical" variety of them, that is the "granite"/carbonate contact metasomatic variety. After a period of conceptual uncertainty, skarns, s.s., have now been organized satisfactorily and modelled (Einaudi et al., 1981; Economic Geology Special Issue on Skarns, v.77, No. 4, 1982). Consequently, only a short summary is provided here and the reader is referred to the sources quoted above.

Skarn profiles are considered most typical when the garnet, pyroxene, etc. assemblage has formed on the (meta)sedimentary side of the "granite"/sediments contact, that is in the exocontact. The Milford Cu and magnetite skarn, Utah (Fig. 28-32) is a typical example. In exceptional cases the mineralogical skarn association formed on the intrusive side of the contact (endocontact). An example of this is found at Christmas, Arizona. In these cases, however, a less intensive alteration is always present. Many skarns formed along minor dike contacts or along conduits entirely within the sedimentary host, in which case an efficient structural control was important to provide plumbing to the mineralizing solutions. The composition of the skarn silicate assemblage depends, to a considerable degree, on the composition of the replaced precursors, and calcic (limestone-replacing) and magnesian (dolomite-replacing) skarns are the two most common varieties. Most skarns are evolutionarily complex and were formed over the course of at least three successive stages (Einaudi et al., 1981; Fig. 28-33):

(1) Contact metamorphic stage: formation of a zoned contact metamorphic aureole of generally iron-poor silicates (diopside-plagioclase, wollastonite, grossularite, etc. hornfelses in impure carbonates; biotite-plagioclase, lesser quartz hornfelses in pelites) and carbonate marbles. This stage is usually devoid of ore minerals, unless they are relic ores (including siderite and ankerite precursors).

(2) Metasomatic skarn growth. The Stage (1) was usually followed by brittle fracturing, and late-stage magmatic fluids rose along the outer contact of the pluton, along dikes, fissures, sedimentary contacts, etc., and infiltrated the wallrocks. As a consequence a second generation of zoned anhydrous skarns formed and these skarns, as a rule, possess a greater mineralogical variety and coarser grain.



ts Q talus

EXOCONTACT

m PZ, white to beige marble

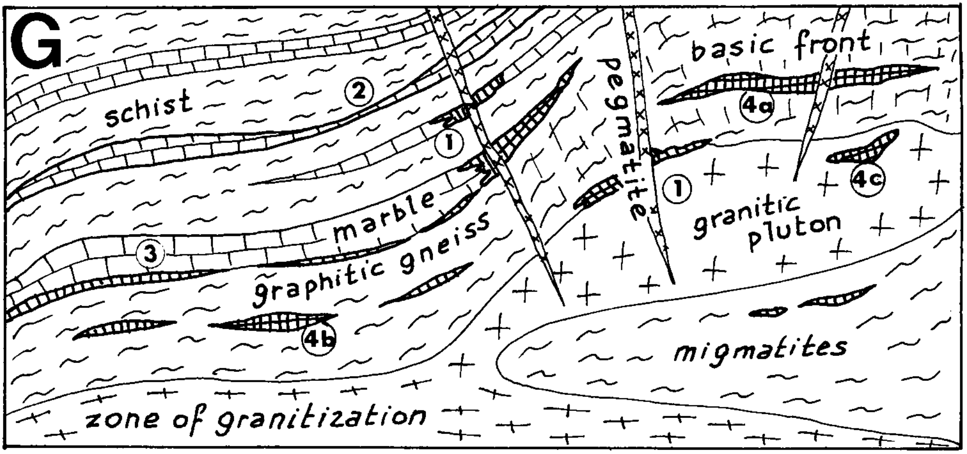
hf thin-bedded plagioclase-diopside-quartz hornfels

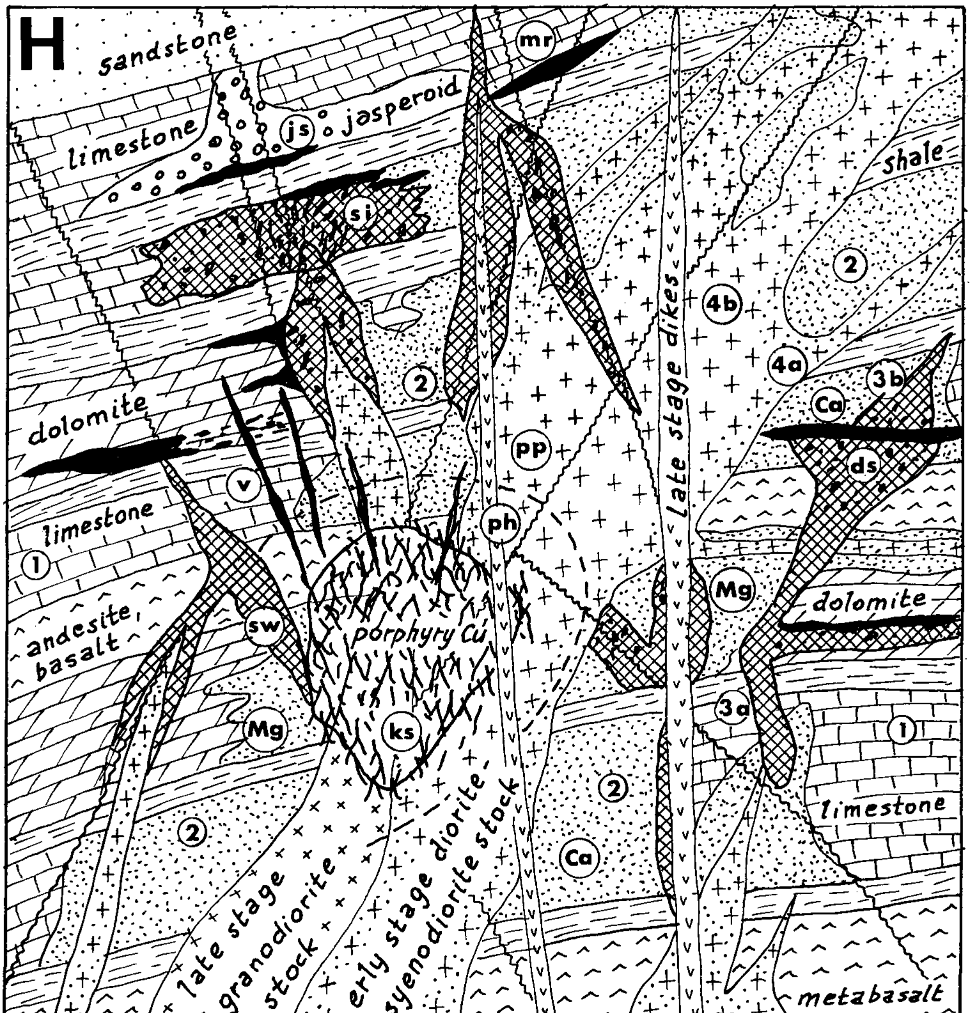
S grossularite, minor epidote skarn with lenses of magnetite (black) and scattered blebs of chalcopyrite

ENDOCONTACT

gd T_1 granodiorite to quartz monzonite with aplite dikes

Fig. 28-32. Simple magnetite chalcopyrite skarn, Milford, S.W. Utah. From LITHOTHEQUE.


G
schist
2
1
marble
graphitic gneiss
3
4b
pegmatite
basic front
4a
1
4c
granitic pluton
migmatites
zone of granitization


H
sandstone
limestone
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2
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3b
Ca
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v
limestone
1
andesite, basalt
sw
porphyry Cu
Mg
ks
Mg
dolomite
3a
1
limestone
2
2
Ca
late stage dikes
late stage granodiorite stock
erly stage diorite-syenodiorite stock
metabasalt

Fig. 28-33. General skarn model.

(G) General concept and deep level skarns (katazone to lower mesozone). 1="Normal" (contact magmatic or hydrothermal metasomatic) skarn; 2=skarnoid (pseudoskarn); skarn association resulting from regional isochemical metamorphism of a rock of suitable composition (e.g pelosiderite, pelitic ankerite); 3=bimetasomatic (reaction) skarn, generated by a local exchange between unlike lithologies in thermal or metamorphic aureoles; 4=multistage, genetically uncertain or relic skarns: a=skarn produced in a "basic front" of magmatism or metamorphism; b=relic skarn in metamorphic terrains; c=relic skarn in rafts and xenoliths in plutonic rocks.

(H) Skarns (and affiliated mineralizations) associated with high level "wet" plutonic systems emplaced in carbonate containing supracrustal rocks. All the skarns here correspond to the "normal" (magmatic and hydrothermal metasomatic) skarn (1) in (G) above. Based on Cu skarn-porphyry copper system.

1=Isochemical contact hornfelses and recrystallized carbonates in place of all sediments present in the thermal aureole (the rock names used are the original compositions); 2=early ("primary") metasomatic skarn resulting from local exchange at high temperatures between magmatic and wallrock components. Garnet, pyroxene, forsterite, etc. + magnetite. No sulphides formed; Ca=calcic skarn (in place of limestone); Mg=magnesian skarn (in place of dolomite). 3=Late ("postmagmatic hydrothermal", infiltrated) skarn, formed by a large scale transfer and exchange of components between hydrothermal fluids and carbonates. Sulphides may replace skarn (2) or any other rocks (including the intrusive rocks) along faults and fractures. 3a=Prograde skarn, invades rocks not previously converted to (2) skarn; 3b=retrograde, retrogressively altered (e.g. by hydration) skarn (2), along fractures.

Common mineralizations associated with (3): ds=disseminations of sulphides in (3a) or (3b) skarns; sw=stockworks superimposed on skarn (actinolite, chlorite, quartz, calcite, etc. gangue); si=stockworks, impregnations superimposed on non-skarn hornfelses; v=fracture veins; mr=massive replacement, typically at "marble line" (contact of skarn and unreplaced marble); js=massive or disseminated sulphide replacements in silicified carbonate (jasperoid).

4=Endoskarn (within the intrusion); 4a=proximal (garnet, pyroxene, epidote); 4b=distal (biotite and hornblende converted to diopside, epidotized or argillized plagioclase, etc.). The same mineralizations as in (3) may be present. 5=Late stage intrusive stock (more siliceous) associated with porphyry Cu stockwork in a K-silicate alteration envelope (ks); ph=phyllic alteration; pp=propylitic alteration. From Laznicka (1984).

Simultaneously deposited ore minerals include magnetite, borates (e.g. ludwigite) and scheelite.
(3) Hydrothermal stage (retrograde alteration and mineralization). The cessation of the skarn growth (2) was followed by an influx of hydrothermal fluids of magmatic derivation as well as of groundwater, connate and similar water origin. The fluids caused retrogressive alteration of the earlier skarn minerals, as well as alteration of any other silicate rocks present, and dissolution of the rock carbonate remains. The skarn alteration products include hornblende, biotite, epidote, chlorite, albite, plagioclase, tremolite, actinolite, serpentinite, talc, etc. The ore minerals, mostly sulphides (pyrrhotite, pyrite, sphalerite, galena, etc.) as well as a late-stage scheelite, cassiterite, etc., accumulated as open space fillings (in breccias, stockworks, fractures) or as replacements of carbonates. The replacement of small carbonate relics in the skarn zone produced a scattered mineralization. Replacement of the marble along the skarn/marble contact ("marble line") produced the largest and richest hydrothermal-metasomatic orebodies, particularly of Zn-Pb. This was caused by the sudden neutralization effect of carbonate on the mineralizing fluids.

Realisation that the economic mineralization of most base, rare and precious metals in skarns is a late-stage hydrothermal one is of a considerable practical importance to the prospector. It places several constraints on the ore search in the skarn association. Since the hydrothermal stage was, to some extent, independent of formation of the earlier skarn zones, hydrothermal deposits other then skarn could have formed simultaneously in the area, in both the fractured and altered intrusive (e.g. porphyry Cu) as well as in the supracrustals (e.g. Pb-Zn replacements in carbonates; compare the next section; metalliferous fissure veins and stockworks).

Skarns are widespread and have a range in age from Proterozoic to Pliocene, although Mesozoic and early Tertiary skarns have now reached their "prime time" of exposure and are most numerous and productive. Skarns are common members of complex local mineralization systems (e.g. porphyry Cu stockwork + skarn + veins; scheelite skarn + Mo stockwork). Examples of metalliferous skarns are reviewed later in the framework of economically accumulated metals.

28.4.12. Replacements other than skarns

Replacements of carbonates in granite aureoles are the most common. These are frequently present without the associated skarn silicates at some distance from major intrusive contacts, or adjacent to intrusive dikes and sills. The most common affiliated alteration is silicification by which the carbonate was converted into a gray alteration chert (jasperoid of Lovering, 1972). Lovering described the petrography and field occurrence of jasperoid in considerable detail and concluded that, in mineralized regions, jasperoid silicification is usually of an early stage and was followed by a later sulphide emplacement. In galena-sphalerite, jasperoid-hosted deposits (e.g. East Tintic, Pioche, Leadville, Gilman, Eureka) the sulphides typically fill open spaces (fractured, brecciated portions) in jasperoid and also replace carbonate relics.

Silicification in carbonates is common and not every jasperoid indicates the presence of ores. Lovering (1972) pointed out that phaneritic texture, abundant vugs, brown colour, highly variable grain size, reticulated microtexture, the presence of goethite, jarosite, pyrite and high trace metal contents, are characteristic features of the ore-associated jasperoids. In some cases discussed in greater detail in Chapter 23 (under karst), jasperoid and hydrothermal sulphides were superimposed on paleokarst, and some Pb-Zn (and other) mantos could be modified relic Mississippi Valley-"type" ores.

Replacements or jasperoid-associated open space fillings in carbonates usually take the form of mantos (peneconcordant sheets and lenses), chimneys (subvertical tubular bodies) or irregular masses. Fault control is important. Faults are often hard to interpret due to the "healing effect" of carbonate recrystallization and redeposition.

Metals other than Pb-Zn and Sb are relatively rare in jasperoids, unless one includes the copper ores in silicified carbonates in porphyry copper systems such as Clifton-Morenci, Bisbee, Ely and others. Gold associated with pyrite has been reported in jasperoid replacing Cambrian carbonates in the Drum Mountains, Utah.

Despite the jasperoid abundance, it is not necessarily a dominant gangue in all non-skarn replacements. The pyrrhotite-cassiterite mantos in dolomite in north-western Tasmania (Renison Bell, Mt.Bischoff, Mt. Cleveland) are contained in recrystallized and lightly talc-altered dolomites with little quartz. Many Pb-Zn replacements are also located here.

Ore replacements in non-carbonate rocks are substantially rarer and usually enigmatic. Often they formed originally as open space fillings (e.g. stockworks or breccias) and later healed to such a degree that the former avenues of passage of the ore-bearing hydrothermal fluids were obliterated. Examples are numerous. In the Midnite uranium mine near Spokane, Washington (Nash et al., 1981), pitchblende and coffinite form replacements as well as disseminations parallel with foliation and fracturing in Proterozoic schists and metacarbonates, about one metre from the margin of a late Cretaceous porphyritic granite. A special case in which a carbonate (dolomite) was first generated by hydrothermal alteration of ultramafics and was later replaced by Pb-Zn and Sn ores (in the Dundas field, Tasmania), was reviewed in Chapter 7.

28.4.13. Relic and remobilized orebodies in "granite" aureoles

Every metallic mineralization present in a "granite" aureole and older than the postmagmatic suite of ores is a relic from the past, genetically unrelated to the "granite". Some such relics, mostly veins, may have formed shortly before the granite emplacement at the present (higher) crustal level, where they were later approached by the rising and stoping intrusion. Other orebodies formed during older periods of magmatic activity, during deposition of the supracrustal rocks e.g. from hydrothermal fluids discharged on the seafloor or during continental sedimentation (paleoplacers), etc. Concordant and peneconcordant deposits and metal-enriched horizons are most characteristic.

A relic orebody may suffer a contact metamorphism, but remain otherwise unmodified and generally recognizable. Examples of this include the metavolcanics-hosted massive Cu-Zn sulphide orebodies in the Akenobe field, Japan, mentioned in Chapter 26. In remobilized orebodies, earlier metallic accumulations were thoroughly reconstituted (texturally as well as, usually, mineralogically) and redeposited within the newly generated pattern of plutonic deposits, from which they are often difficult to distinguish. Ore remobilizations (reconstitutions involving no substantial increase in grade or tonnage) and mobilizations (accumulation of ore substance from a previously more dispersed precursor that required concentration) have recently been reviewed by Laznicka (1985b).

28.4.14. Mineralized metamorphosed "granites" and metamorphogenic ores in meta-granites

Regionally metamorphosed granitic rocks often act as passive, genetically unrelated hosts to younger intrusions and affiliated orebodies (e.g. the Precambrian "granites" in the Tertiaty Colorado Mineral Belt), but metamorphosed old relic hydrothermal-plutonic ores, particularly veins, are quite rare. This is because the deep portions of "granite" batholiths that form the bulk of the meta-granites originally lacked associated ores, and because thin ore veins involved in penetrative deformation and metamorphism most probably underwent dispersion. The recorded examples of metamorphosed deposits of plutonic affiliation are all controversial.

The Gibraltar (Granite Mountain) copper deposit, British Columbia (Sutherland Brown, 1974b; 1.33 Mt Cu/0.371%, 37 Tt Mo; Fig.28-34), is interpreted as an example of a dynamometamorphosed porphyry copper, with a gneissic fabric. This deposit is hosted by a foliated Triassic tonalite and granodiorite pluton, intruded into a Permian "oceanic" volcanic-sedimentary assemblage. The plutonic rocks are marked by a primary foliation over which is superimposed a largely parallel secondary foliation. The most intensively foliated "granite" is now a phyllonitic schist entirely lacking feldspar. The Cu-Mo mineralization is in four elliptical, W.N.W.-elongated orebodies, that have well developed leached capping and oxidation, cementation zones. The hypogene ores are in stockworks of quartz, pyrite and chalcopyrite veinlets and veins, with sericite and chlorite selvedges parallel with foliation. Superimposed on these are irregular and lensoid, thicker veins, reminescent of the "secretion veins" in metamorphic terrains. They contain large nests of pyrite, chalcopyrite and molybdenite and

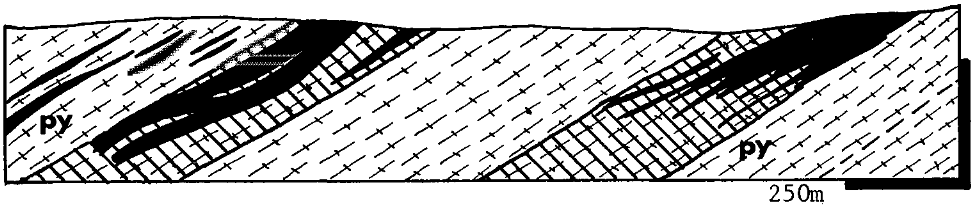


Fig. 28-34. Gibraltar field, British Columbia, disseminated Cu mineralization in Mesozoic foliated and metamorphosed quartz diorite. Diagonally ruled section denotes the ore zone; black=orebodies; py=pyrite halo. From LITHOTHEQUE, after Drummond et al. (1976).

may be drusy. Visually, the ore specimens are reminescent of ores in deformed and altered marine metavolcanics, such as those described in Chapter 11 (e.g. Mt. Lyell).

Another example, the Tungsten Queen hübnerite deposit in the Hamme District, North Carolina, was in a vein, 3.5 km long and up to 10 m thick, traceable through a slate belt and a granitic pluton. Eight en-echelon ore shoots are in the vein. Foose et al. (1980) demonstrated recently that the vein and its surroundings have been deformed, lightly metamorphosed and remobilized during at least two episodes of folding and shearing. This produced a pronounced alignment of ore and gangue minerals and may have caused the en-echelon arrangement of the ore shoots.

28.4.15. Ore accumulations resulting from weathering of "granites" and their mineralized aureoles

Tropically weathered "granites" are of little importance economically, although the accessory magnetite used to be recovered from regoliths in Japan (Chapter 23). Gibbsite nodules may form in lateritic profiles over "granites", but bauxite deposits formed only on sorted clays winnowed from such profiles. Weathering of hydrothermally mineralized regions results in a variety of leached cappings (Blanchard, 1968), gossans and secondary enriched zones, too complex to be satisfactorily reviewed here but treated in textbooks and several reference books (e.g. Smirnov, 1951).

Weathering and residual enrichment superimposed on zones that are only lightly metal enriched (for example in Mn) and are uneconomic in the fresh state, may produce economically valuable orebodies. Sizeable Mn-oxide bodies formed over altered carbonates containing replacement and vein Zn-Pb ores, as in Philipsburg, Montana or Novo Brdo, Yugoslavia.

28.4.16. Ores formed by sedimentogenic reworking of "granites"

Ordinary "granites" contribute too little of a valuable heavy mineral fraction to form significant placer deposits. Gabbros are more fertile and may supply significant quantities of ilmenite. Low-grade and widely dispersed occurrences of resistate minerals in mineralized granites and their aureoles (e.g. cassiterite, columbite-tantalite, wolframite, scheelite) can result in valuable placer accumulations (as in the Sundaland, S.E. Asia). Trace metals from granites released in solution (particularly U), often find their way into proximal sediments in which they can precipitate (e.g. the SUV deposits). To a lesser extent, U accumulation can take place already within the granite by infiltration and precipitation from descending solutions along fractures.

28.5. "PORPHYRY" (STOCKWORK, DISSEMINATED) Cu-Mo DEPOSITS

28.5.1. Introduction

"Porphyry" Cu(Mo) deposits constitute a broad and complex category the members of which have only two common characteristics: (1) they represent relatively low-grade but large-tonnage ore accumulations almost always outlined by assay boundaries and (2) they are genetically related to calc-alkaline (exceptionally other) intrusive activity and tend to have a simple hypogene mineralogy (pyrite, chalcopyrite, lesser molybdenite). Their economic importance is extraordinary. The deposits around the "Pacific Basin" alone (Titley and Beane, 1981) represent 365 Mt Cu in 56.7 Bt ore, and 7.02 Mt Mo in 24.2 Bt ore. The "porphyry" deposits outside this probably represent a further 53 Mt Cu and 1 Mt Mo, yielding a grand total of about 420 Mt Cu and 8 Mt Mo.

The reservoir and generator rocks to "porphyry Cu" need not be porphyritic (although in the typical localities they are), so the term is not completely representative. Considered from the viewpoint of lithologic associations, "porphyry Cu" in this book have been broken down into deposits in volcanic association (Chapters 10, 13, 14, and 26), deposits in plutonic association (this chapter) and Precambrian deposits (Volume 2). The plutonic "porphyry" association is the largest, most important and most "typical".

Mesozoic and early Cainozoic "porphyry" Cu(Mo) deposits are currently enjoying their prime time of exposure, but the age range of this class is from Archean to about 1.2 m.y. "Porphyry" Cu(Mo) are the most intensively studied category of hydrothermal deposits and the one on which the most detailed and numerous experimental and physicochemical data (many of which provide genetic constraints) have accumulated. Their treatment, however, is far beyond the scope of this book and the reader is referred to the recent review of Titley and Beane (1981). There are few monographies dedicated to porphyry coppers in general (e.g. Pavlova, 1978), but excellent summaries can be found in several regional reviews and special volumes (e.g. Sutherland Brown, ed., 1976; Hollister, 1978).

28.5.2. Porphyry Cu terrains: the hypabyssal and plutonic levels

Porphyry coppers occur in former (some in still existing) island arcs and Andean-type continental margins (Chapter 5), and much has been written about their position above former Benioff zones. They are characteristically associated with calc-alkaline, I-type, multi-stage plutonic systems and the bulk of orebodies formed within the depth range between about 500m and 5 km (most between 2-3 km; compare Fig. 27-3). As a consequence, porphyry Cu are most abundant in continental margin plutonic belts eroded to depths of around 2-3 km. In less eroded regions marked by andesite to rhyolite volcanics, the "porphyries" are still largely hidden in depth. In deeper-eroded regions they have disappeared irreversibly. The depth variations of porphyry coppers have been integrated in the often quoted model by Sillitoe (1973), and two (transitional) depth levels: hypabyssal and plutonic, are repeatedly emphasized in the literature.

In the higher level of exposure, hypabyssal, "phallic", or "stock" porphyry copper systems are developed (Nielsen, 1976; Sutherland Brown, 1976; Hollister, 1978; Fig. 28-35). There, the orebodies are associated with high-level (epizonal) composite intrusions dominated by porphyritic textures. These are usually emplaced in a comagmatic volcanic suite typically deposited within a former subaerial volcanic centre and composed of andesite and rhyolite lavas and pyroclastics. In many cases, the volcanics are completely missing and a great variety of basement rocks genetically unrelated to the magmatic complex surround the intrusions and interact with them. The intrusive stocks usually consist of a variety of small plugs, intrusive breccias and dikes having a substantial vertical extent but a small area. Petrographically, quartz-feldspar porphyry, latite and quartz monzonite porphyry, granodiorite porphyry, are the most common in the "continental" setting. Quartz diorite and diorite are dominant in island arc settings, where the surrounding rocks range from basalts to pyroxene andesites.

The copper (molybdenum) mineralization is usually associated with a specific intrusive phase that tends to be among the youngest, but often not the youngest because, almost always, the mineralized phases are intersected by minor post-ore dikes. The economic orebodies are most commonly situated at the periphery of the generator intrusion in both endo- and exocontact, and the alteration-mineralization pattern is broadly concentric and centered on the intrusion. When reactive rocks (carbonates, calcareous tuff) form the wallrocks, the stockwork or disseminated Cu-Mo ore in the intrusive endocontact usually grades into a copper skarn in the exocontact.

At the lower level of exposure corresponding to the "plutonic" or "batholithic" porphyry copper systems (Fig. 28-36), a fairly deeply eroded mesozonal pluton is the dominant unit in the ore zone, and the

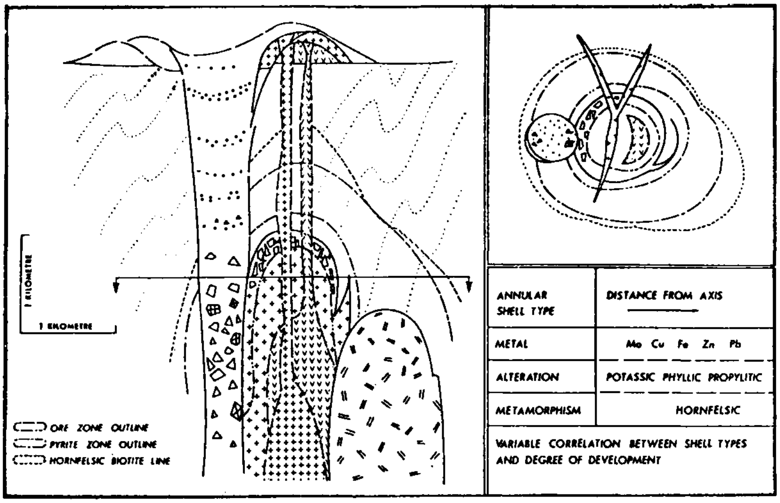


Fig. 28-35. Hypabyssal ("phallic") porphyry copper model, plan and section. From Sutherland Brown (1976), courtesy of the Canadian Institute of Mining and Metallurgy and the author.

former roof rocks occur mainly as relics outside the ore field. The mineralized plutons are usually multiphase, and porphyry Cu tends to be associated with the youngest phases and occur in the interior or at margins of plutons. Structural control is of paramount importance and mineralization is often contemporaneous with active deformation, commonly associated with more felsic minor higher-level intrusions (stock, dike swarm) emplaced into a more mafic reservoir rock. The reservoir rocks are entirely intrusive when ore zones are situated in plutonic interiors, and differentiation between generator and reservoir rocks may prove to be problematic. Marginal orebodies can be partly hosted by the basement rocks in plutonic exocontacts (including carbonates), but in general the variation of mineralization styles in plutonic deposits is less than in the hypabyssal systems. This statement is, however, invalid when multistage mineralizations involving leaching and redeposition of an earlier ore took place, as in Butte, Montana. The ore zones are more commonly tabular rather than equidimensional. They have a linear surficial expression and are controlled by the intensity of fracturing. The alteration-mineralization zones consist most commonly of broad areas showing weak alteration and low-grade ore mineral distribution, over which are superimposed more localized, higher-grade ore-bearing fracture zones or discrete veins.

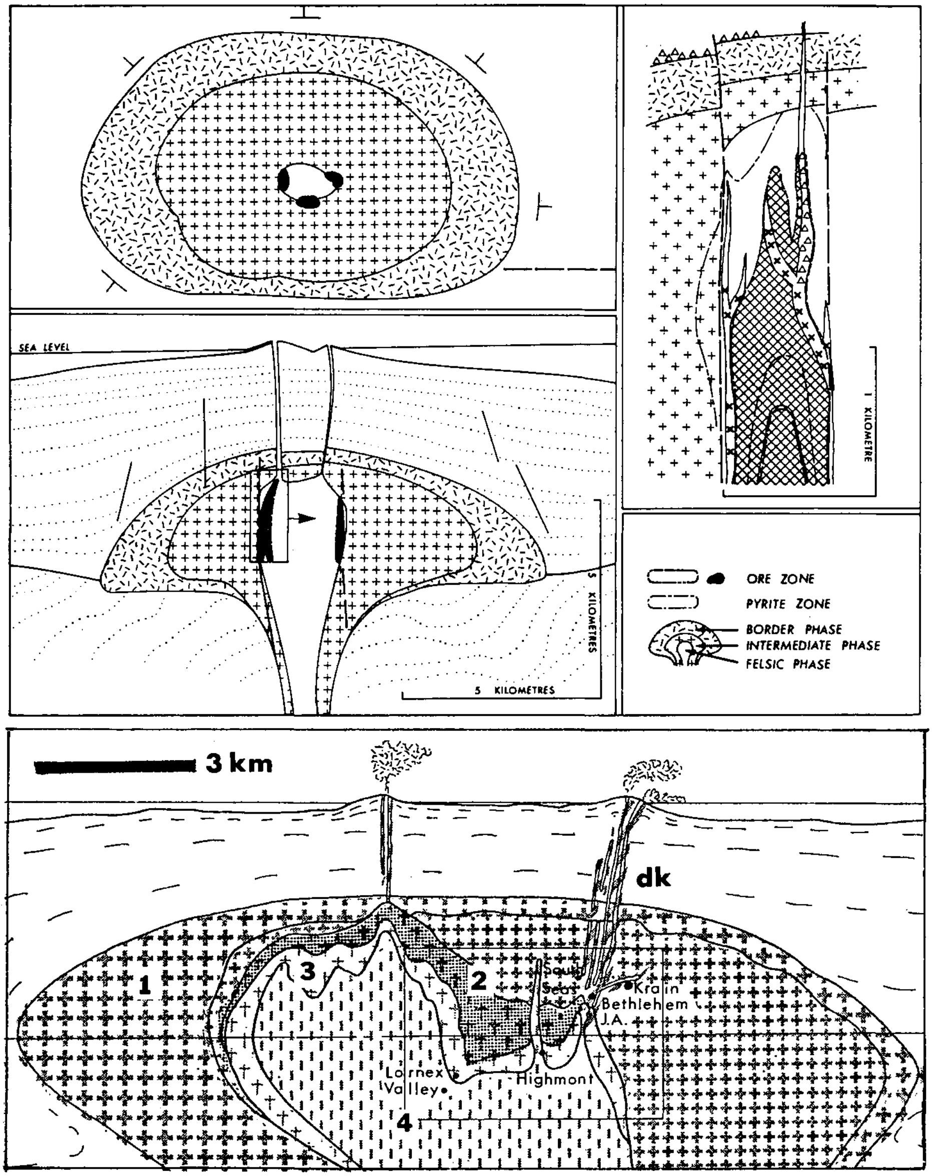


Fig. 28-36. Plutonic porphyry copper model: general (top) from Sutherland Brown (1976), and representing the Highland Valley plutonic porphyry copper field (bottom), from McMillan (1976). Highland Valley is hosted by the late Triassic Guichon Creek Batholith. 1=Border phase, diorite to quartz diorite; 2=quartz diorite to granodiorite; 3=leucocratic granodiorite; 4=quartz monzonite to granodiorite; pd=porphyry dikes. Courtesy of the Canadian Institute of Mining and Metallurgy and the authors.

28.5.3. Intrusive associations

Regardless of the level of emplacement, there are two or three distinct intrusive associations affiliated with porphyry coppers. These have been contrasted in the literature (e.g. Hollister, 1978). They comprise (1) high-quartz, granodiorite or quartz monzonite plutons, marked by low Na_2O:K_2O ratios (calc-alkaline, "normal", etc. association); (2) quartz-free plutons (diorite, syenite, alkalic suite, etc. association) and (3) low-quartz quartz diorite and soda granitoid plutons of former island arcs have a high Na_2O:K_2O ratios and are transitional in many respects between (1) and (2). In the literature, the latter are most commonly considered with an association of type (1).

The intrusive association has a considerable influence on the alteration pattern: (1) usually has a "full" (model) range of alteration zones, from potassic through phyllic to propylitic and (2) generally lacks the phyllic zone and potassic alterites grade directly into the propylitized rocks. The metallogeny differs substantially too. Copper in chalcopyrite is the dominant metal in both associations, but in (1) Mo in molybdenite is the principal by-product in the disseminated or stockwork ores (the Cu:Mo ratios have a range between 20:1 and 100:1) and Pb,Zn,Ag veins or replacements commonly occur along the fringe of a porphyry stock. In (2), Mo is virtually absent and so are Pb-Zn occurrences, but the ores are usually high in Au and small gold showings are sometimes associated zonally. The type (1) and (3) associations carry at least 90% of porphyry copper occurrences. The (2) affiliated "porphyries" have been documented in only a few places in the world, being best developed in the mafic volcanic facies belts in British Columbia.

In a recent paper dealing with petrochemical affiliation of the stockwork molybdenite deposits, Mutschler et al. (1981) recognized "granodiorite" and "granite" molybdenite systems. The former have affiliation identical to the "normal" porphyry coppers into which they are gradational (e.g. Brenda or Boss Mountain, British Columbia). The latter Mo stockworks ("Climax-type") are spatially separated from porphyry and other copper deposits (as in the Colorado Mineral Belt). The affiliation of several Mo-Cu deposits in eastern Mongolia and East Transbaikalia (e.g. Zhireken) said to be in "granites", is uncertain.

28.5.4. Hypogene alteration and mineralization patterns

Although it had long been known that porphyry Cu deposits were associated with intensive alteration, it was not until the 1970s that the prevalent alteration / mineralization pattern had been incorporated into several all-embracing models. The model of Lowell and Guilbert (1970) based on the San Manuel-Kalamazoo deposit in Arizona and believed to be close to an average situation in the western United States, is essentially representative of the hypabyssal porphyry system emplaced into silicate rocks. In a later paper

(Guilbert and Lowell, 1974), additional alteration pattern variation due to the presence of carbonate wallrocks or deeper levels of exposure (plutonic porphyry Cu) have been incorporated. Gustafson and Hunt (1975) in their meticulous paper on the El Salvador deposit, Chile, stressed the dynamism of the porphyry Cu systems complete with numerous progressive and retrogressive events creating new alterations and mineralizations as well as destroying or modifying the existing ones. Hollister (1978) reviewed the "diorite" model of lithologic association and alteration. At present, alterations in porphyry deposits almost possess the status of a separate science and there is a broad range of variation (Figures 28-37 and 28-38).

Briefly, as in the skarn systems, the first consequence of igneous intrusion into the wallrock is contact metamorphism. This is most apparent in pelites or in marine volcanic associations, that change into brownish biotite-plagioclase or greenish amphibole-plagioclase hornfelses. There is virtually no obvious thermal metamorphism, when intrusions were emplaced into older "granites", gneisses or migmatites. Brittle fracturing in contact hornfelses as well as in the intrusive rocks provided openings for the movement of hydrothermal fluids.

In silicate hostrocks, the earliest K-silicate progressive alteration resulted either in the growth of neoformed minerals (K-feldspar and biotite), or in reconstitution of existing potassic constituents. Quartz and minor albite, sericite, anhydrite and apatite may be associated. The K-silicate alteration assemblage forms within or close to the generator intrusion and because it involves minerals that are also common constituents of unaltered granitic rocks, it may be difficult to recognise. Fresh-looking fracture veinlets filled by K-feldspar and scattered fresh biotite flakes cutting across fractured and generally altered (decomposed plagioclase, amphibole, biotite) "granite" or other rocks, are most diagnostic. The K-silicate zone is of greatest importance economically and it usually carries the bulk of chalcopyrite and molybdenite in the form of scattered grains on the walls of dense fractures, in quartz or silicates-filled veinlets or pervasively disseminated in an alteration partially healed hostrock. Hand specimens of low-grade hypogene ores are very inconspicuous. Many are virtually unrecognizable from a "rock" granite.

Phyllic (sericite, quartz-sericite) alteration is substantially more conspicuous than the anhydrous K-silicate alteration. The altered rocks have a mottled or monotonous beige to yellowish-green appearance when fresh, contain abundant scattered pyrite and are often laced by fractures covered by slickensided coatings of greasy-looking sericite. Chalcopyrite may be present and several porphyry coppers have their ore in the phyllic zone. In weathered outcrops, sericite zones create a mottled beige, yellow and brown scenery, a consequence of pyritic weathering. It has been suggested that K-silicate alteration results largely from the magmatically-derived fluids, while the phyllic (and argillic, propylitic) alterations are the result of convecting meteoric waters.

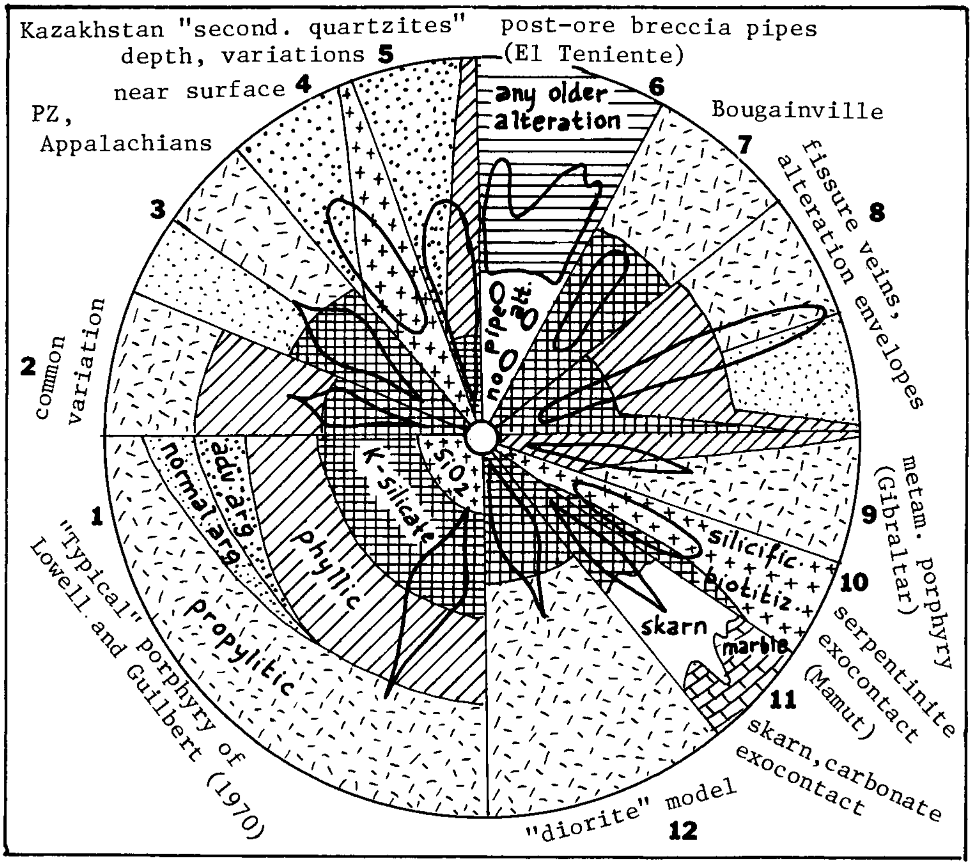


Fig. 28-37. Examples of the variations of porphyry copper alteration patterns. The position of economic Cu mineralizations is outlined by a thick black line. From Laznicka (1984).

Argillic alteration ("normal": mostly kaolinite or advanced: dickite, diaspore, andalusite, corundum, alunite, dumortierite) resulted from acid leaching. A portion of it is attributed to supergene processes caused by descending meteoric waters containing high concentrations of sulphuric acid released by sulphide breakdown. This alteration is sulphide-destructive and it causes impoverishment. Cu mineralization in this zone largely takes the form of relics of chalcopyrite in fracture quartz veinlets or veins, or chalcocite-coated pyrite. Hypogene, late-stage sericitization and argillization are often associated with the process of hypogene leaching, short-distance metal transfer and generation of localized, high-level fissure veins filled by enargite, chalcocite, bornite and other minerals which are gradational into epithermal veins (e.g. in

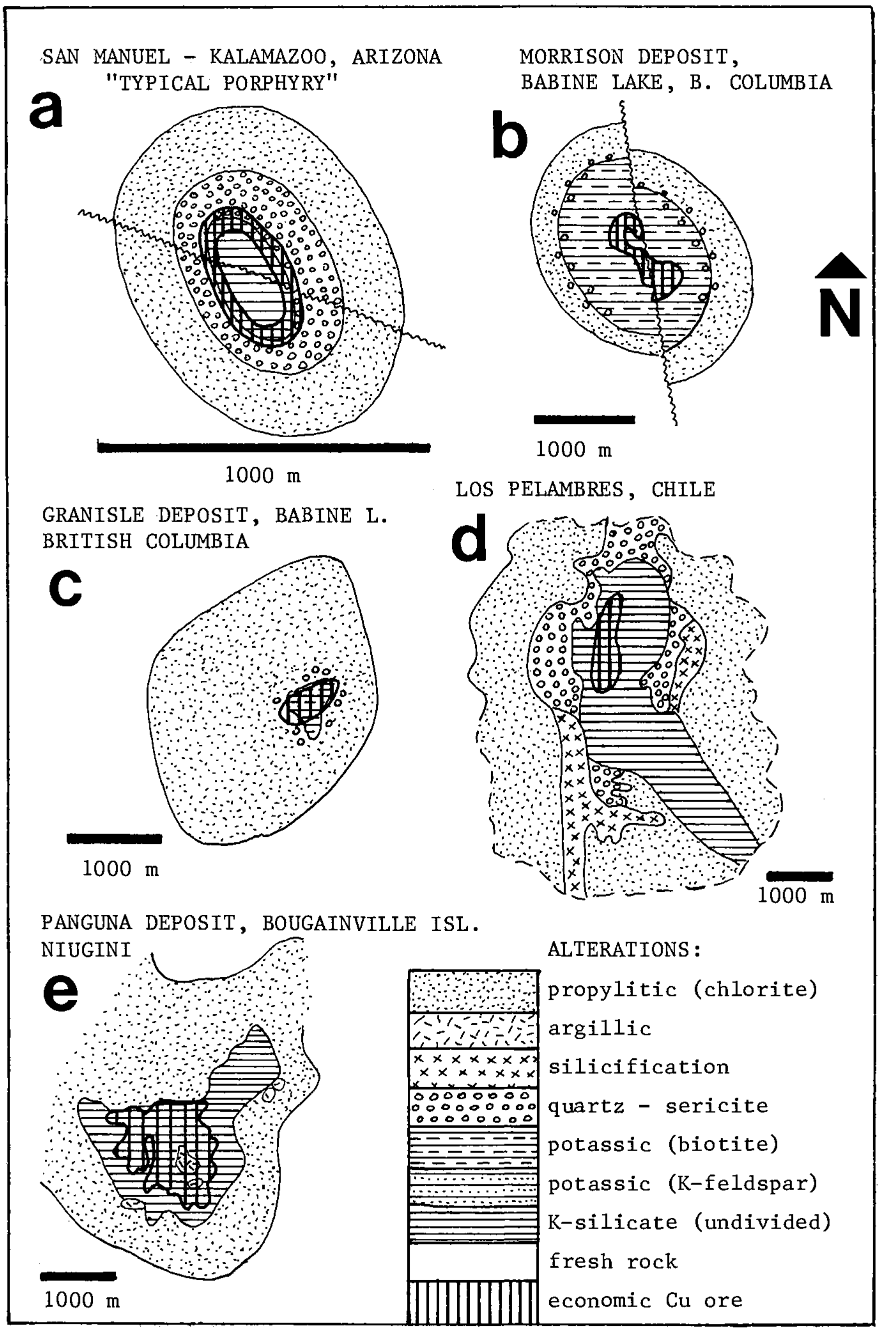
Butte, Morococha, Récsk).

Propylitic alteration is closely equivalent mineralogically to the greenschist metamorphic facies (chlorite, epidote, calcite, albite). In completely zoned alteration profiles propylites are generally devoid of ore minerals, but they may contain orebodies in several "volcanic" porphyry coppers hosted by metabasalts or mafic metaandesites; by quartz-free intrusions of the "diorite" model; by pre-ore diabase dikes; by retrograded skarn profiles, etc. (e.g. Afton, B.C., El Arco, Sierrita, Esperanza, Bozschekul', etc.).

A variety of additional alterations involve tourmalinization and rare greisenization. Thorough silicification often results in the generation of monomineralic quartz metasomatites ("secondary quartzites"). Silicification is the most widespread and genetically the most controversial. Following a literature review of several hundred porphyry coper occurrences and a brief examination of at least one hundred of them in the field, one gains the impression that there are at least three major genetic categories of silicification which are often transitional. These are as follows: (1) a high-temperature, early "magmatic" silicification, localised in the core of zoned hypabyssal porphyry systems, flanked by, and often transitional into, the zone of K-silicate alteration. It may carry scattered flakes of molybdenite. (2) "Convective" ascending silicification, associated with phyllic and advanced argillic envelopes. Its position is variable. It reaches into moderate depths where it wedges out. Underneath are often K-silicate altered intrusive rocks. (3) Supergene silicification in some respects reminescent of silcretes, associated with leached cappings and zones of descendent argillization.

28.5.5. Weathering modification and supergene ore zoning

Dense fracturing and widespread sulphides (Cu and Mo sulphides as well as the more widespread pyrite) combined with humid climates, cause a rapid and deep weathering of exposed porphyry copper deposits. In mountainous, rapidly eroded and well-drained humid tropics (e.g. in the Caribbean, Panama and western Colombia, Indonesia and the Philippines) a porphyry copper deposit may be exposed, weathered and completely removed within several hundred thousand years. From the discussion above it may appear that weathering of porphyry coppers is a completely destructive process. This is not always the case. In fact, the early generation of "porphyries" in the western United States developed in the early 1900s, were all producing ores from the secondary supergene enriched zones that had the form of a locally almost solid chalcocite blanket. At that time primary (hypogene) "porphyries" were uneconomic. El Teniente, Chile, was one of the first primary porphyry Cu-Mo deposits to start production in the 1930s, but there the ore was unusually rich (1.5-2% Cu). A wave of post-World War II discoveries and development of "porphyries" in the 1960s consisted of a majority of deposits not substantially enriched, having a grade as low as 0.284% Cu.


SAN MANUEL - KALAMAZOO, ARIZONA
"TYPICAL PORPHYRY"
a
1000 m
MORRISON DEPOSIT,
BABINE LAKE, B. COLUMBIA
b
1000 m
N
GRANISLE DEPOSIT, BABINE L.
BRITISH COLUMBIA
c
1000 m
LOS PELAMBRES, CHILE
d
1000 m
PANGUNA DEPOSIT, BOUGAINVILLE ISL.
NIUGINI
e
1000 m
ALTERATIONS:
propylitic (chlorite)
argillic
silicification
quartz - sericite
potassic (biotite)
potassic (K-feldspar)
K-silicate (undivided)
fresh rock
economic Cu ore

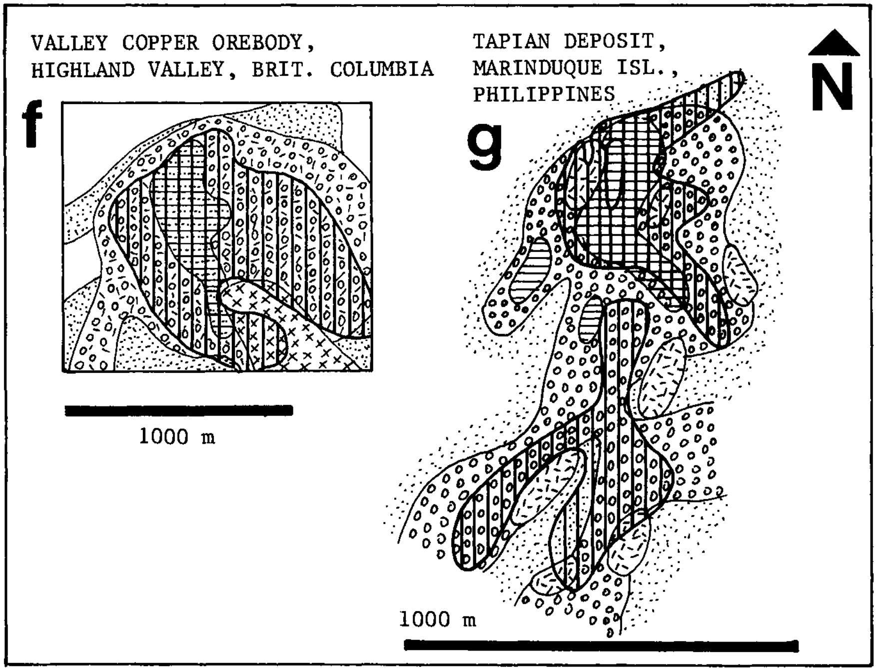


Fig. 28-38. Alteration patterns (in plan) of selected porphyry copper deposits; a-e=hypabyssal deposits, f,g=plutonic deposits. From Laznicka (1984), based on data in Lowell (1968), Carson and Jambor (1974), Sillitoe (1973b), Baumer and Fraser (1975), Osatenko and Jones (1976) and Loudon (1976).

At present, a few deposits still produce exclusively from secondary enriched zones (e.g. Clifton-Morenci, Arizona). A large number of deposits started in the enriched zone and now produce both primary and secondary ore (e.g. most Arizona "porphyries"). The majority of mines produce from the hypogene zone (e.g. the Canadian "porphyries") or from non-enriched ores in the various stages of weathering modification (most of those in the humid tropical belt).

From the economic point of view, it is important to make a distinction between weathering modification and secondary enrichment. All porphyry deposits are weathering modified at the outcrop, the style and intensity of which is influenced by the local climatic zone. In the recently glaciated terrain of Alaska and Canada, the primary (hypogene) zone often crops out as a hard rock on the surface often in glacially scoured hummocks, and is virtually fresh except for thin superficial coatings of malachite or limonite on sulphide grains (e.g. the discovery outcrop of the Brenda mine). Elsewhere, yellowish-brown "limonite" coating marks the mineralized rock (e.g. the Orange Hill near Nabesna, Alaska), but this coloration tends to be better

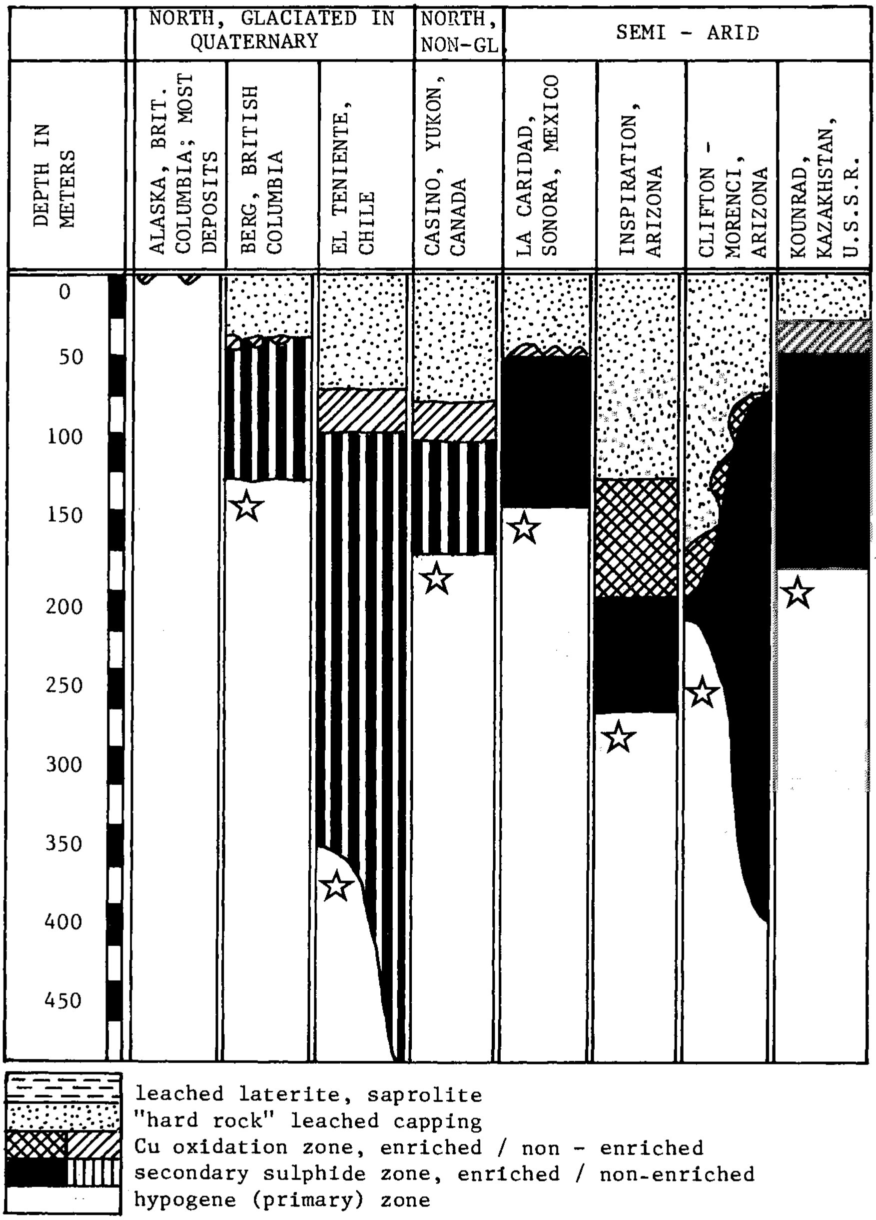
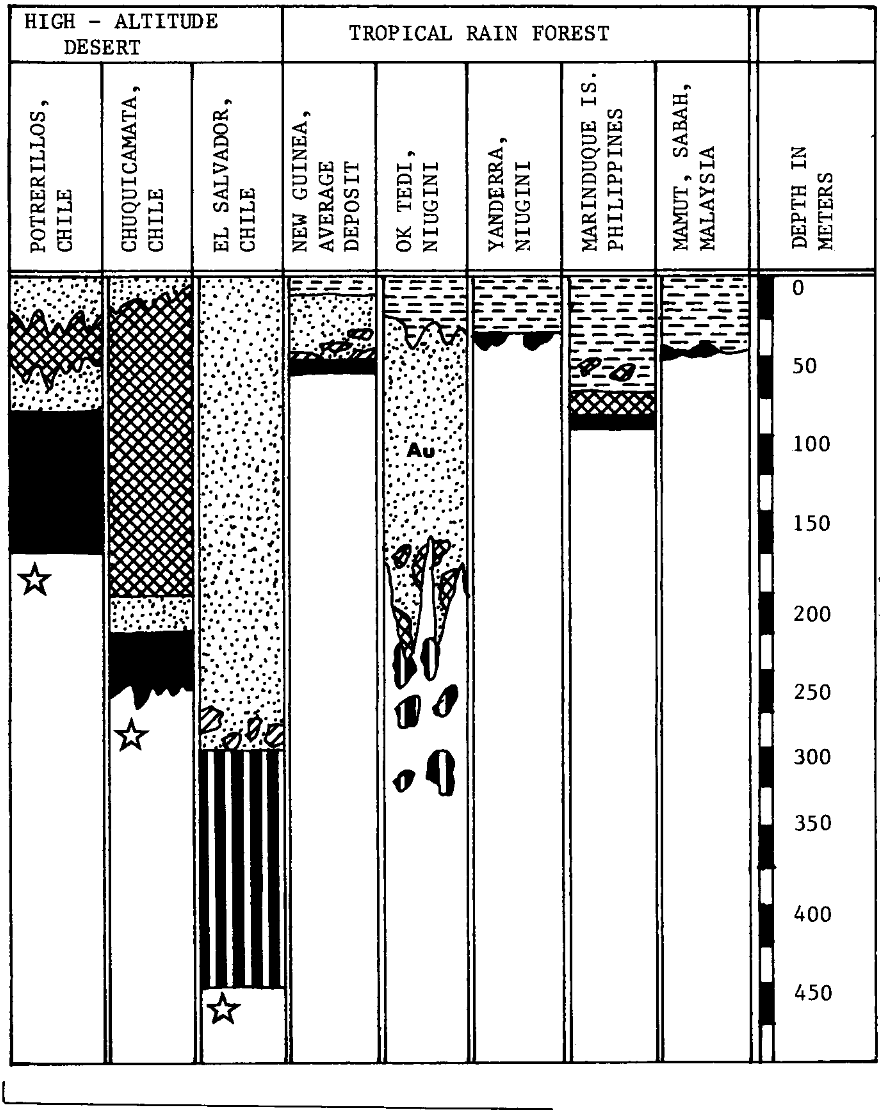


Fig. 28-39. Supergene zoning at selected porphyry copper deposits in different climatic zones. Stars indicate full or partial relic (pre-Quaternary) zoning. From Laznicka (1984).



developed over the sericite-pyrite altered fringe than over the Cu-Mo bearing core (when this is in the K-silicate alteration zone). There are, however, exceptions and some recently glaciated deposits are weathering modified (e.g. Casino, Yukon, to a depth of 170 m; El Teniente, Chile, to a depth of up to 600 m; Fig. 28-39).

In the rugged humid tropics (as in New Guinea, Melanesia, Philippines), considerable differences in the thickness and nature of the weathered zones exist among deposits situated on high ridges (up to 330 m thick weathered zone, Ok Tedi, Niugini), steep flanks (thin weathered zone) and floors of mountain streams (fresh rock). In the ridge setting as well as over "porphyry" deposits located in a rolling hills countryside, the top several tens of metres above a porphyry orebody are represented by a soft lateritic soil devoid of visual traces of mineralization as well as being significantly impoverished in the trace Cu content. Trace Mo, however, may occur in higher concentration and gold is often preserved in the residuum. There, ore discoveries have been made chiefly by stream geochemistry. Sometimes, oxidized but not lateritized alteration and ore zones were sighted in stream valleys and on landslide and erosional scars on mountainsides.

In high-pyrite ore systems the next zone under the laterite is a silica-rich leached capping, coated and impregnated by goethite, jarosite and hematite. Again, visible copper minerals are virtually absent and sporadic chrysocolla, cuprite, etc. may appear towards the bottom of this zone. Gold, however, remains and at Ok Tedi a deposit of 30 Mt of 3 ppm Au material (=90 t Au) remains in the leached capping. Zones of secondary sulphides (chalcocite, covellite) are usually patchy and poorly developed in the tropics as well as in the immature recently glaciated profiles. In most cases the Cu sulphides coat or pseudomorph relic hypogene pyrite or chalcopyrite. This is underlain by the primary zone.

In low-pyrite systems or where the acidity is neutralized by wallrock carbonates, serpentinites, etc., brown "limonitic" gossans tend to develope on the surface (e.g. at Mamut, N. Borneo), and malachite, azurite or chrysocolla stains and pseudomorphs after sulphide grains are common in the underlying oxidation zone. In the climatic zone of northern and mountain forests, malachite-stained cliffs were sometimes the discovery sites (e.g. Catface, Lorraine, deposits, British Columbia). At some localities (e.g. Viví Arriba, Puerto Rico) the mineralized intrusion has the form of a tropical saprolite with a well preserved relic texture and feldspars pigmented green by infiltrated Cu oxides.

In the arid to semi-arid zone as found at the Chuquicamata deposit located in the Atacama Desert, Chile (Ruíz, 1965), a thin, siliceous, leached capping is underlain by a rich and conspicuously green oxidation zone composed of a variety of minerals (antlerite with lesser atacamite, brochantite, krohnkite and other). Underneath is a barren (leached) gap floored by an enriched blanket of secondary sulphides (chalcocite, covellite, bornite), followed by the hypogene zone. This local departure from an orderly zoning pattern is interpreted as being a consequence of a fluctuating water table. The rich oxidation zone at Chuquicamata formed by destructive replacement of an ancient zone of secondary sulphides. The present chalcocite zone is the product of more recent supergene activity. A similar situation exists at Potrerillos.

At the El Salvador deposit (Gustafson and Hunt, 1975) located in the same arid setting, no secondary enrichment took place. The uppermost leached zone has a jarosite and goethite coating gradational downward into a zone of hematite-goethite coating. This, in turn, changes into a zone where chalcocite coats relics of the primary sulphides. Little enrichment took place in the latter zone and the grade is only slightly higher than in the primary ore. The effects of supergene processes, however, are traceable to a depth of 450 m.

In the classical area of secondary enriched ores in the western United States (Butte, Bingham, Globe-Miami, Santa Rita, Bisbee, etc.), a beige to rusty, siliceous leached capping with little clay, is underlain by a zone of supergene argillization containing small areas and pockets of jarosite and goethite-limonite in its upper part; sporadic Cu oxides (chrysocolla, malachite, azurite, cuprite) in the centre, and chalcocite with lesser covellite at the bottom. The chalcocite is black, sooty, fracture-coating or pseudomorphing pyrite or chalcopyrite, but locally it can accumulate into almost pure, homogeneous masses of steely gray ores. The chalcocite blankets were up to 200 m thick and were significantly enriched (1-2% Cu with local 30% Cu plus "bonanzas"), compared with the lean hypogene ore (0.1-0.6% Cu). The enrichment is a relic, formed in places as early as the Mesozoic and, at most localities, in the lower Tertiary age. Enriched supergene profiles over the Arizona porphyry coppers were already buried under a thick pile of middle Tertiary volcanics, thus preserved from removal, and only recently exhumed. Livingston et al. (1968) pointed out that all the western U.S. enriched porphyry coppers crop out within few kilometres of the edge of the cover volcanics.

In the Globe-Miami field, Arizona (Peterson, 1962; Fig. 28-40), the different effects of two periods of supergene modifications of porphyry coppers are well apparent. The Tertiary period produced chalcocite enrichment blankets, while the Quaternary period caused oxidation of a portion of the Tertiary chalcocite and also of the erosion-exposed hypogene ore. Substantial amounts of copper are present in "in situ" as well as exotic (transported) chrysocolla and malachite ores, recovered by heap as well as in-situ leaching at the Inspiration mine.

Supergene alterations of porphyry coppers are a fascinating, as well as a practically important, subject. Surprisingly, little new

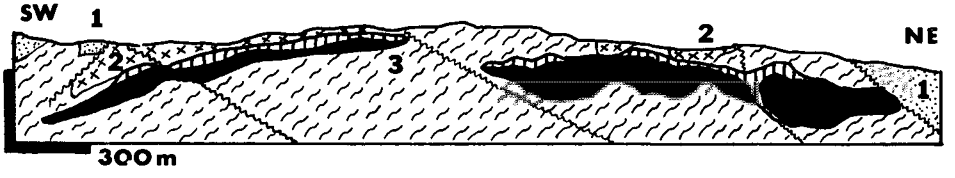


Fig. 28-40. Miami-Inspiration mine area, Arizona, showing an oxide and sulphide enriched porphyry copper. 1=Q-T continental gravels (fanglomerate), volcanics; 2=Cr_3-T_1 quartz monzonite porphyry; 3=Pt $_{1-2}$ schist. BLACK: sulphide enriched (chalcocite) orebodies; VERTICALLY RULED AREA: oxide (chrysocolla, malachite) and mixed oxide-sulphide ores. From LITHOTHEQUE, after Peterson (1962).

research has been carried out in the past 15 years, in contrast to the progress in the interpretation of the hypogene "porphyry" systems. The recent comprehensive reviews of porphyry coppers barely mention the subject at all. The success or failure of a prospecting venture for porphyry deposits in terrains other than the recently glaciated ones really depends on the correct interpretation of their surficial expressions, particularly of leached cappings. There are few other mineralization styles known in which their outcrop area is as completely devoid of any conspicuous traces of copper minerals as the high-pyrite "porphyries" of the tropics and the temperate zones. Blanchard (1968) reviewed the art of the interpretation of leached outcrops in considerable depth.

28.5.6. Porphyry copper regions of the world (Fig. 28-41, Tables 28-2, 28-3)

N.W. PACIFIC PROVINCE: THE ALEUTIANS AND THE CORDILLERA IN CANADA AND IN THE UNITED STATES

This extensive province has recently been reviewed by Hollister (1978) and by a number of authors in Sutherland Brown, ed. (1976). Its most consistent unifying characteristic is the general lack of deep supergene modification which is the consequence of glacial scouring of ancient weathering profiles (exceptions: Casino, Krain, Berg, Afton, Cariboo Bell, Taurus, Butte, deposits) and a generally cold climate that accounts for the low rate of present weathering. For that reason, "fresh" porphyry Cu complexes generally crop out at the very surface.

The Aleutian Islands

The western portion of the Aleutian Islands is a Cainozoic active island arc, developed on the oceanic crust. Ore occurrences are rare and porphyry coppers are represented by a showing at the Attu Island affiliated with a 5.9 m.y. old stock of a sodic quartz diorite porphyry, emplaced into Cretaceous mafic volcanics (Hollister, 1978). The eastern Aleutians as well as the Pacific continental margin of Alaska are dominated by Mesozoic and Cainozoic low-grade metasediments and metavolcanics, believed to have been formed in an arc-trench gap setting. Scattered porphyry copper showings are affiliated with Tertiary quartz diorite to quartz-monzonite porphyries and no important deposits have, so far, been discovered.

Pacific coastal belt

This belt follows approximately and discontinuously the Pacific coast west of the great Coast Ranges Batholith from eastern Alaska to Oregon and it includes the islands in the Alaska Panhandle, Queen Charlotte Islands and Vancouver Island. It is marked by a great variety (and also antiquity) of basement rocks (Paleozoic metamorphics, Carboniferous and Permian marine volcanics and sediments

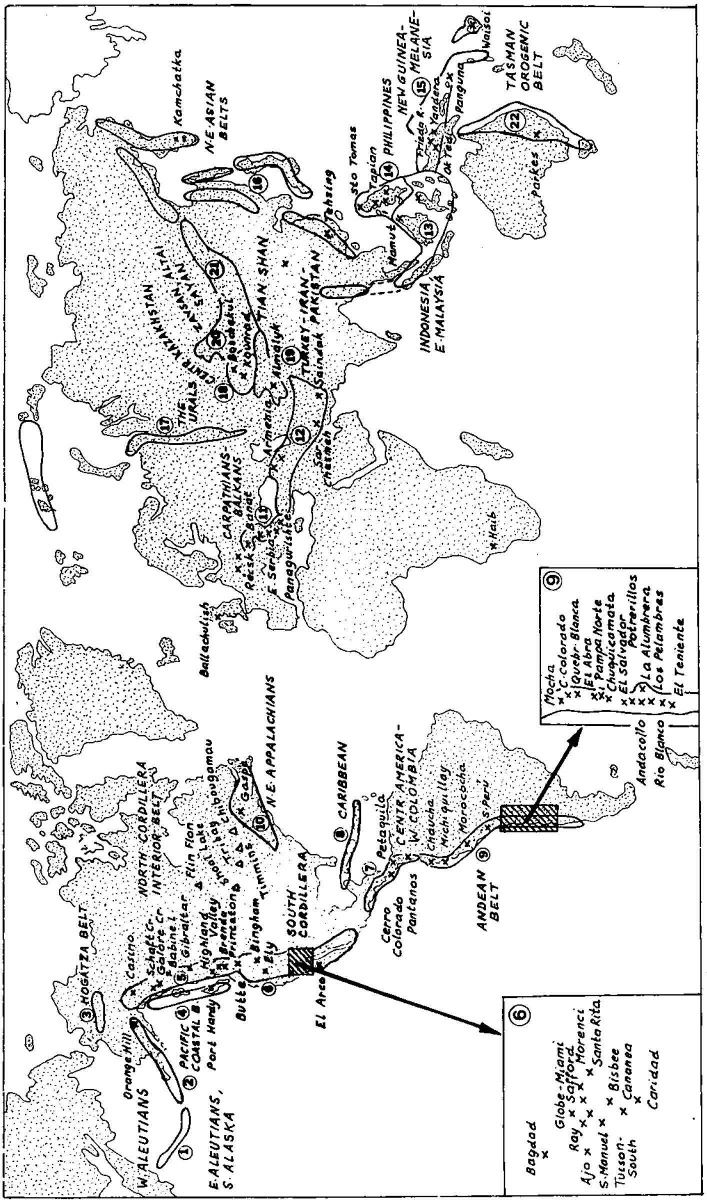


Fig. 28-41. Major porphyry copper provinces of the world (compare also Table 28-2).

including ophiolites, Triassic to Cretaceous island arc and continental margin volcanics and sediments). It is intruded by Permian to late Tertiary granitic rocks.

Of the cluster of ore occurrences in eastern Alaska (south of the Denali Fault), the most important is Orange Hill near Nabesna (Table 28-3).

On the Queen Charlotte Islands, Vancouver Island and on the

Table 28-2. Major porphyry copper provinces and sub-provinces of the world

PROVINCE, SUBPROVINCE	BASEMENT GEOLOGY	MINERALIZ.INTRUSIONS	PORPHYRY COPPERS	REFERENCES
Western Aleutian Isl. (Attu showing),U.S.A. **1**	Cr_3-Q immature isl. arc developed on oceanic crust	T,sodic quartz diorite intrusion	stockwork,most ore in phyllic zone	Hollister (1978)
E.Aleutians and Alaska continental margin U.S.A. **2**	J-T low-grade metagrayw.,slate,mafic to bimodal volc.	T(3.3-59 m.y.) quartz dior. and qtz.monzon. porphyry	stockw.,brecc.,ph, less KF alter.,hypog. ore only; 11 show.	Hollister (1978)
Hogatza Plutonic Belt, W.C. Alaska U.S.A. **3**	D,Pe metased.,metavolc.,Cr marine andes.,sedim.	Cr_3 qtz.monzonite porph. and D? granodiorite	4 stockw.,1 breccia, 1 skarn;ph, some ppl alter.,6 showings	Hollister (1978)
N.E.Pacific coastal belt (E.Alaska,Brit. Columbia,Washington, Oregon) **4**	$PZ_{1,2}$ metavolc.,metased.;Cb-Pe ophiolites,marine seds., volc. Tr-Cr island arc,cont.mg.andes.	Pe qtz.monzon.pluton Cr granod.(5 dep.) T granod.,qtz.monz.,qu.-feldsp.porph.(the bulk)	stockworks,less brec. ph,KF alter.,36 prsp. 2 dep.,about 1.5 Mt Cu	Hollister (1978)
N.Cordillera Interior Belt; Alaska,Yukon, Br.Columb.,Washingt. Idaho,Montana **5**	Pt_1,PZ metam.;Cb,Pe marine sd.,ophiol. Tr_3-Cr marine and. and seds.	Tr_3-J dior.,qtz.dior., granod.,syenite J_2-T_1 qtz.diorite to qtz.monzonite	300 occurr.,2 giants (Butte,Highland Val.) most calc-alk.stockw. in KF,ph alter.; lesser "diorite" md. 66% lack superg.alt. 36 Mt Cu,1.3 Mt Mo	Sutherland Brown,ed. (1976) Hollister (1978)
S.Cordillera,U.S.A. and Mexico (W.of Rocky Mts.,E.of Sierra Nevada) **6**	Pt_1 schist,grenst., granite; $Pt_{2,3}$ diabase,quartzite; PZ, carb.,shale; MZ marine sedim., andesitic volc.	J-Mi qtz.diori.to qtz. monzon.intrusions; most "Laramide" (Cr_3-T_1)	mostly endocont.stwks import.exoct.skarns Signif.superg.enrich. Local breccias. X00 occur.,103 Mt Cu, 3 Mt Mo	Lowell and Guilbert (1970)

Central America (Panama, Costa Rica) **7**	Cr_3-Q tholeitic to andes.volc.,pyrocl. early qtz.diorite	34-4 m.y. potass.granodior. and qtz.-feldspar porphyries	veinl.and dissem. stockw.in endo and exocont. Cerro Colorado mostly in volc. 25.2 Mt Cu,510 Tt Mo	Kesler et al. (1977)
Caribbean (Cuba,Hispaniola,Pto Rico, Virg.Islands,Jamaica) **8**	J-Eo arc basalts, andes.,graywacke, shale,minor carb.	63-31 m.y.qtz.diorite, less granodior.porph.	stockworks in KB or ph.alter.,low Mo, high Au; about 30 occur.,1 Mt Cu	Hollister (1978)
Andean belt, 4,800 km long, South America **9**	PZ sedim.,MZ-T marine to cont.basalt andes.,rhyol.volc. local PCm metam.	Cb to 4.3 m.y.(most Cr_3-T_2) quartz diorite to quartz monzonite intr.	mostly Cu-Mo stockw. assoc.with hypabys. intrusions; some important tourm. brecc.pipes (Rio Blanco); X00 occur., 182 Mt Cu,3.25 Mt Mo	Oyarzún and Frutos (1980) Hollister (1978)
N.E. Appalachian belt, Canada and U.S.A. **10**	PCm to D basement metam.,overl.by Cm to D marine volc.-sedim. and sedim.	Cm to D qtz.monzon.equigranul.to porph.; D most common	mostly stockw.,py and cp.,minor moly.KF and KB alter.,ph.mostly absent. Grade to skarns. 20 occur.,1 deposit; 1.9 Mt Cu	Hollister (1978)
Carpathians,Balkans, Hellenides in Hungary,Rumania,Yugoslavia, Bulgaria,Greece **11**	PCm metam.basem. topped by PZ,MZ ophiol.,volc.-sed., sedim. association	Cr_3-Pl qtz.dior. to qtz. monzon., contemp. with subaerial andesite-dacite volcanism	largest dep.in Timok Mass.are in andes., rest in endo-,exo-cont.stockw.grading to skarns; about 20 occur.,12.5 Mt Cu	Ianovici and Borcoş (1982) Janković (1982)

Table 28-2 (continued). Major porphyry copper provinces and sub-provinces of the world

PROVINCE, SUBPROVINCE	BASEMENT GEOLOGY	MINERALIZ. INTRUSIONS	PORPHYRY COPPERS	REFERENCES
Turkey, Caucasus, Iran, Pakistan belt **12**	MZ marine volc.-sedim. mobile belt encl. Pt-PZ metam. blocks; Cr_1-Q cont. volcanism	Eo-Pl qtz. dior. to qtz. monzon. stocks and plutons	zoned stockworks in endo and exocont., KB, KF, minor ph. alt. 12.5 Mt Cu	Pidzhyan (1975)
Burma, Indonesia, E. Malaysia (Sumatra, Sulawesi, E. Borneo) **13**	mostly MZ-CZ island arc volc. and sedim.	T hypabyssal stocks and plutons, quartz dior. to qtz. monzon.	stokworks, about 30 showings, 1 mine; 1 Mt Cu	Hamilton (1979)
Philippines (Luzon, Marinduque, Negros, Cebu Islands) **14**	Cr-T_1 marine sedim. and mafic metavolc. (basalt, spilite, andesite)	60-2 m.y. dior. and qtz. dior., rarely granodior. and qtz. feldsp. porph. plutons and stocks	dissem., fault controlled prism. to elong. oreb., irreg. zoning, silicif., KB, KF alter. X00 occur., 80 depos. 25-30 Mt Cu, low Mo	Bryner (1969) Wolff (1978)
New Guinea-Melanesia belt (the Solomons, Vanuatu, Fiji) **15**	NG: J-Q sedim. cover PCm sialic block in S. Tr-Q seds, volc., in N. and islands	Ol-Pl dior. to quartz dior., granod. and qtz. monz. rare and latest	stockw. high in Au, low in Mo, in KB, KF alter.; miner. 01 to 1.2 m.y. 35 occurr., 15 Mt Cu, 900 t Au 4 Tt Ag	Davies (1978) Titley (1975)
N.E. Asian discontin. porphyry Cu occurrences (S.E. China, Okhotsk-Chaun belt, Japan, Kamchatka) **16**	MAINLAND: MZ-T_1 cont. marg. andes. to rhyol. volc. belt ISLANDS: T-Q isl. arc volc., sedim.	MZ-T_1 qtz. dior. to qtz. monzonite T diorite to granodior.	mostly endocont. stockw. in KB, KF alt. granodior., qtz. dior. about 20 occurrences	Laznicka (1976a)
The Urals, U.S.S.R. **17**	PCm to Cb deform. metam. maf. volc. sd.	D-Cb dior. to qtz. monz. plutons	"granod." and "dior." stockw., skarn; 500Tt Cu	Laznicka (1976a)

North Lake Balkhash distr.,Kazakhstan, U.S.S.R. **18**	Pt metam.,Cm-D marine volc.-sed. D_2-Pe marine to cont.and.-rhyol.	Cb-Pe high level granodior. to qtz.monzon. qtz.-feldsp.porphyry	calc.-alk.porph. Cu-Mo stockw. in KF, KB,ph,silicific. alt. superg. enrichment; about 100 occur., 15 Mt Cu, 500 Tt Mo	Laznicka (1976a)
Tian Shan orogen, Soviet Centr.Asia, Kurama Range distr. **19**	Pt-Pe metam.,sed., andes.-rhyol.volc.	Cb-Pe syenodior.,granodior.,qtz.monzonite	stockw. in KB,KF,ph and silicif.zones, superg. enr.,about 20 occur.,6 Mt Cu	Laznicka (1976a)
Zaysan,Altai, Sayan orogens,S.Siberia, Mongolia, China **20**	Pt to Pe metam., volc., sedim. on S. fringe of Siberian Platform	Cm dior.,syen.complexes Or-Pe granod.,qtz.monz. granosyenite	"diorite" model calc-alk.Cu stockw. grad.to subvolc.Cu-Mo and Mo-Cu; about 50 occur., estim. 4 Mt Cu	Laznicka (1976a)
E.Mongolia, East Transbaikal, Amur Belt, U.S.S.R. **21**	PCm basement, PZ_3 deeply eroded dior.,gran.plut.	J-Cr epizonal plutons, qtz. monzon.,granite	Sn,W,Mo stockw. in KF alter.grade to Mo-Cu stockworks; about 5 Cu occur.	Marinov et al. (1977) Laznicka (1976a)
Tasman Orogenic Belt Eastern Australia **22**	Cm-Cb fold.sedim., andesitic volc.	Cm to Cr_1 dior. to qtz. monzon. plutons	fract.controlled plutonic porph.Cu, KF,KB alter. 120 occur.,2.5 Mt Cu	Horton (1978)

ABBREVIATIONS: KF=K-feldspar; KB=biotite; ph=phyllic; ppl=propylitic alteration
BOLD NUMBERS=provinces as shown of Fig. 28-45

Table 28-3. Hypabyssal and plutonic porphyry Cu-Mo deposits, selected example localities

1. LOCALITY	2,NO	3,4. SETTING (3=BEDROCK, 4=INTRUSION)
Orange Hill, Nabesna, central Alaska	4	3) Pe mafic metavolc., metasediments 4) 105m.y. quartz dior.porph.intruding quartz-diorite pluton
Casino, Yukon, Canada	4	3) PZ or PCm? schists intr.by Cr_2 bathol. 4) Cr_3 (70 m.y.) subvolc.compl., qtz-feldspar porphyry, tuff breccia
Babine Lake (Granisle, Bell, Morrison) C. Brit. Columbia	5	3) J_1-Cr siltst., limest., andes.and volcanocl., hornfelsed 4) Eo, small stocks, plugs, dikes; quartz dior., qtz.monz., biot.-feldsp.porphyry
Highland Valley, S. Brit.Columbia Canada	5	3) Cb-Pe argill., chert, congl.; Tr_3 m-bas., andes., argill., volcaniclastics 4) Tr_3 semiconc., domal compos.bathol., dior. to qtz.monzon., abundant dikes
Butte, Montana U.S.A.	5	3) PCm-PZ metam., Cr_3 qtz.latite cont.volc. 4) Cr_3-T_1 (70-72 m.y.) qtz.monzon.pluton followed by aplite, qtz.porph., biotite breccia; miner. 57-63 m.y.
Bingham, Utah, U.S.A.	6	3) Ps calcar.quartzite, sandst., limestone 4) 39-32 m.y. qtz.monzon.stock, porphyry, porphyry dikes; miner. 35.8 m.y.
Ely (Robinson), Nevada, U.S.A.	6	3) D-Pe hornfelsed platf.shale, limestone 4) Cr_1 qtz.monzon.porphyry (115-103 m.y.) Eo-Ol (41-37 m.y.)post-ore dikes
Globe-Miami field, Arizona, U.S.A.	6	3) Pt_1 schist, $Pt_{2,3}$ granite, diabase; PZ limest., shale 4) Cr_3-T_1 qtz.monzonite, qtz.monzon.porph.
Ray, Arizona, U.S.A.	6	3) Pt_{2-3} quartzite, diabase; D-Cb limest. 4) Cr_3 (70-60 m.y.) qtz.dior., granod.porp.
Bagdad, Arizona, U.S.A.	6	3) Pt_1 greenst., schist, granite 4) Cr_3 (71 m.y.) granod., qtz.dior.porph.
Ajo (New Cornelia), Arizona, U.S.A.	6	3) PCm gneiss; Cr andes.to rhyol.flows, brecc., tuff, continental; 4) Cr_3 (63 m.y.) qtz.dior., qtz.monzon.
San Manuel, Arizona U.S.A.	6	3) Pt_1 quartz monzonite pluton 4) Cr_3 (67 m.y.) qtz.monzon.porph.dikes and stocks

5.STYLE	6.ALTER.	7.ORES	8.ENR.	9.TONN./GRADE	REFERENCES
H/S I,W	CA; KF,ph *KB	distant AuV	0	800Tt Cu/0.4%	Hollister (1978)
S,H,B I,W	CA; KF,ore in KB	AuV Pb-ZnV	?70%	570Tt Cu/0.37% 30Tt Mo/0.002%	Godwin (1976)
S,H I,W	CA; KB *ppl	none	?10%	940Tt Cu/0.42-0.51%	Carson and Jambor (1974)
P/D,Fr I	CA; KF,KB *ph, ppl	CuV,CuSk AuV	2%	9 Mt Cu/0.4% 150Tt Mo	McMillan (1976)
P,*S D,Fr I	CA; KF,KB ph	++CuAsV ++ZnMnV	30-60%	8.3Mt Cu 2.2Mt Zn 19.3Tt Ag 84 t Au	Miller,ed. (1973)
H I,*W	CA; KF,KB *ph	++PbZnR ++PbZnV Au plac.	?50%	21.5Mt Cu 820Tt Mo	Lanier et al. (1978)
H skarn	CA; KF, *ph,Si	++CuSk CuZnPbAg veins	?30%	4.3Mt Cu/0.8%	James (1976)
P,H,Fr I,*W	CA; KF ph,arg,at second.ore	++CuV ZnPbV AuV	60-70%	5 Mt Cu	Peterson (1962)
H/Fr W,*I	CA; KB,KF ph,ppl	exotic Cu	? 25%	1.5Mt Cu 1.2t Au, 120tAg	Phillips et al. (1974)
H I,*W	CA; KF,ph	PCm mass. sulphides CuZn;WV	?50%	+760Tt Cu/0.76%	Lowell and Guilbert (1970)
H I,*W	CA; KF,ph *Si		?10%	3.8Mt Cu	Wadsworth (1968)
H I,W	CA; KF.*ph	PbZnMoV	?10%	4.33Mt Cu/0.75%	Lowell (1968)

Table 28-3 (continued). Hypabyssal and plutonic porphyry Cu-Mo deposits, selected example localities

1. LOCALITY	2.NO	3,4. SETTING (3=BEDROCK, 4=INTRUSION)
Clifton-Morenci, Arizona, U.S.A.	6	3) Pt_1 schist, granite, granod.; PZ,MZ shale, limestone 4) Cr qtz.dior.laccol.,dikes,intr.by Cr_3-T_1 qtz.monzonite porphyry stock
Santa Rita (Chino) New Mexico, U.S.A.	6	3) Cm-Pe carb.,shale; Cr shale 4) Cr (63 m.y.) granod. and qtz.monzonite
Bisbee (Warren) Arizona, U.S.A.	6	3) Pt_1 schist, PZ limest.,shale; Cr shale 4) 163 m.y. gran.and qtz.felisp.porph. stock and dikes
Tucson-south (Pima, Mission,Twin Buttes) Arizona, U.S.A.	6	3) PZ siltst.,sandst.; Tr-Cr contin.andesite, rhyol., ignimbrite, conglom. 4) Cr_3-T_1 qtz.monzon.,granodior.,andes. rhyolite
Cananea, Sonora, Mexico	6	3) Pt_2 (1.44 b.y.) qtz.monzonite; Cm-Ps limest.,dolom.,shale,quartzite; MZ, continental volcanics 4) 69-64 m.y. quartz monzonite porphyry
La Caridad,Sonora, N.Mexico	6	3) T_1 contin.volc.,dior.to granod.pluton 4) T_1 younger phase qtz.monzon.porphyry, intrusive breccia
Pegadorcito and Pantanos, N.Colombia	7	3) T volcanics, Ol tonalite bathol. 4) T_2 qtz.dior.porph.,intrus.breccia, qtz.monzon.,dacite porphyry
Chaucha, Ecuador	9	3) T andesite, granodiorite 4) Mi (9-12 m.y.) qtz.monzon.and granodiorite porphyry
Michiquillay, N.Peru	9	3) Cr quartzite, limestone 4) 20.6 m.y. qtz. monzonite porphyry
Morococha (Toromocho) central Peru	9	3) Pe contin.andes.and dac.volcanics Tr_3-J_1 limest.,shale,dolom.,basalt,anh. 4) 7 m.y. quartz monzonite porphyry
Cerro Verde and Santa Rosa, southern Peru	9	3) MZ granodiorite 4) 58.8 m.y. granodior.,qtz.monzon.porph.
Cuajone, southern Peru	9	3) Cr_3-T_1 volcanics,basalt,rhyol.,andes.

5.STYLE	6.ALTER.	7.ORES	8.ENR.	9.TONN./GRADE	REFERENCES
H I,*W	CA; KF,ph	CuV	100%	13Mt Cu/0.8%	Moolick and Durek (1966)
H W,*I	CA; KF,ph Si,skarn	+CuSk +FeCuSk ZnPbR	?66%	6.28Mt Cu/0.78%	Hernon and Jones (1968)
H,D,Fe,Br W,*I	CA; ph,*Si skarn	CuSk,CuR PbZnR	?50%	4.4Mt Cu	Bryant (1968)
H W,*I	CA; KF,KB ph,skarn		?30%	5.92Mt Cu	Lowell and Guilbert (1970)
P,Br I,W	CA; KF,KB ph,skarn	CuSk CuZnPbSk, replac.	?50%	15.255Mt Cu 135Tt Mo 360Tt Zn	Meinert (1982)
P,H I,W	CA; ph,*KF		100%	5.3Mt Cu/0.8% 66Tt Mo/0.01%	Saegart et al.(1974)
H,Br I,W	CA; ph			9.7Mt Cu/0.5%	Hollister (1978)
H I,W	CA; ph			1.6Mt Cu/0.7%	Hollister (1978)
H I,W	CA; ph,arg.		?20%	4.14Mt Cu/0.72%	Hollister and Sirvas (1974)
H,S I	CA; KB,ph	CuAsAgV CuAsR PbZnR;AgV	?75%	2.7Mt Cu/0.76%	Velazquez, oral comm. (1977)
Br I,W	CA; KF,KB, ph,tourm.	AgPbZnV		8.04Mt Cu/0.67%	Bellido and de Montreuil (1972)
H,S,Br I,*W	CA;KF,ph tourmaline	PbZnV	16%	13Mt Cu/1%	Manrique and Plazal-les (1975)

Table 28-3 (continued). Hypabyssal and plutonic porphyry Cu-Mo deposits, selected example localities

1. LOCALITY	2.NO	3,4. SETTING (3=BEDROCK, 4=INTRUSION)
Toquepala, southern Perú	9	3) Cr volcanics, T_1 diorite intrusion 4) 58.7 m.y. dacite porphyry
Quelleveco, southern Perú	9	3) Cr volcanics 4) T_1 quartz monzonite porphyry
Mocha, Tarapacá, northern Chile	9	3) T volcanics; 4) 56.4 m.y. quartz diorite porphyry
Cerro Colorado, Tarapacá, N.Chile	9	3) J marine sedim.,Cr volcanics 4) T quartz diorite porphyry
Quebrada Blanca, northern Chile	9	3) MZ volcanics 4) T granodiorite, dacite porphyry
El Abra, northern Chile	9	3) J_3 shale,sandst.,limest.,granodiorite 4) 33.2 m.y. dior.to syen.complex,dacite
Pampa Norte, northern Chile	9	3) T granodiorite 4) 29 m.y. quartz monzonite porphyry
Chuquicamata, northern Chile	9	3) D-Cb schist,gneiss,amphib.,gabbro Cb-granite; J_3 shale,siltst.,limest., andes.,granodiorite 4) 29.2 m.y. qtz.monzonite porph.stock
El Salvador, Chile	9	3) Cr_3 andesite flows,volcaniclastics T_1 rhyolite,ignimbr.,granod.porphyry 4) 39.1 m.y. granodiorite porphyry
Potrerillos, Chile	9	3) J limest.,shale,sandstone 4) 34.1 m.y. quartz diorite porph.stock
Andacollo, Chile	9	3) J-Cr andesite volcanics, diorite 4) 90 m.y. granodiorite porphyry
La Alumbrera, N.W. Argentina	9	3) T continental andesite-rhyolite volc. 4) 7.5 m.y. qtz.monzonite porphyry
El Pachón (Argentina) and Los Pelambres, Chile	9	3) J_3-Cr contin.andesite volc.and volcaniclastics 4) 9.8 m.y. tonalite, diorite porphyry
Rio Blanco-Disputada central Chile	9	3) Eo contin.basaltic andes.flows and pyroclastics; T_2 qtz.monzonite, granodiorite plutons 4) 4.3 m.y. dacite porphyry dike

5.STYLE	6.ALTER.	7.ORES	8.ENR.	9.TONN./GRADE	REFERENCES
H,Br I,*W	CA; ph, tourmal.		?20%	4Mt Cu/1%	Hollister (1978)
H I,W	CA; ph.	PbZnV		1.9Mt Cu/0.95%	Bellido and de Montreu-il (1972)
H I,W	CA; ph, arg.			1.07Mt Cu/1%	Hollister (1978)
H I,W				1.2Mt Cu/1.3%	Hollister (1978)
H I,W	CA; KF,ph.	PbZnCuV		2Mt Cu/1%	Hollister (1978)
H to P Br I,*W	CA to D KB,ph	CuV	20% oxid.	16.35Mt Cu/1.09%	Ambrus (1977)
H I,W				1.82Mt Cu/0.7%	Hollister (1978)
H to P I,*W	CA; ph, *KF,KB	exotic Cu,Mn	70%	43Mt Cu/1.3% 1.1 Mt Mo/0.04%	H.Soto P., pers.comm. (1977)
H I,*W	CA; KF *ph		?60%	5.5Mt Cu/1.34% 200Tt Mo	Gustafson and Hunt (1975)
H,Br I,W	CA;ph,KF	CuSk	?80%	3Mt Cu/1.43%	Ruiz (1965)
H I,W	CA; KF *KB,ph	AuV PbZnV		2.45Mt Cu/0.7%	Hollister (1978)
H I,W	CA; KF			2.5Mt Cu	Hollister (1978)
H,D I,W	CA; KF,KB		under 5%	8 Mt Cu 127 Tt Mo	Sillitoe (1973b)
H to S,Br I,W	CA;Si,ph, tourmal.		none	17Mt Cu	Ruiz (1965)

Table 28-3 (continued). Hypabyssal and plutonic porphyry Cu-Mo deposits, selected example localities

1. LOCALITY	2.NO	3,4. SETTING (3=BEDROCK, 4=INTRUSION)
El Teniente (formerly Braden) near Rancagua central Chile	9	3) Eo contin.andesite flows, Ol-Mi quartz diorite 4) 4.3 m.y. dacite porphyry stock,breccia
Gaspé Copper, Murdochville,Québec, Canada	10	3) D_1 calcar.siltst.to limestone 4) D_3-Ms rhyodac.porph.sills, plugs
Moldova Nouă, Banat, S.W. Rumania	11	3) MZ limest.,hornfels, skarn 4) Cr_3-T_1 qtz. diorite porph.stock
Radovište (Bučim, Borova Glava), S.E. Yugoslavia	11	3) Pt gneiss, schist, amphibolite 4) andesite porphyry stock
Panagurishte field (Medet),Bulgaria	11	3) PZ granodiorite,diorite 4) Cr_3 granod.,qtz.monzon.porphyry
Ankavan,Armenia, U.S.S.R.	12	3) PCm-PZ_1 schist, marble interbeds 4) Ol granodiorite,qtz.monzonite
Kadzharan, Armenia, U.S.S.R.	12	3) Eo hornfelsed ands.,dac.,rhyol. 4) Ol or Mi quartz-feldspar porphyry
Agarak, Armenia, U.S.S.R.	12	3) Eo hornfelsed andes.,dacite,rhyolite volcanics and volcaniclastics 4) Ol qtz.monzonite and granosyenite
Sar Chesmeh, Kerman, southern Iran	12	3) T_1 andes.lavas and pyrocl., granodior.porphyry 4) T_3 granod.,qtz.monzon.porph.;breccia laced by late-stage dikes
Saindak, Baluchistan, N.W.Pakistan	12	3) Cr_3-Ol andes.volc.-sedim. association 4) 19-20.3 m.y. tonalite porph.,granodior. porph.,andesite,diorite dikes
Kalmakkyr dep.,Almalyk distr.,Uzbekistan, U.S.S.R.	19	3) Or-S sandst.,shale; D-Cb limest.,sand., shale,basalt,andes.,dac.,rhyol.,horfld. Cb_{1-2} syenodiorite, diorite 4) Cb_{2-3} granodiorite porphyry
Kounrad, N.Lake Balkhash distr.,Kazakhstan, U.S.S.R.	18	3) Cb_1 contin.andes.,basalt lavas,tuffs 4) Cb_{2-3} granod.porph.,qtz.-feldsp.porph.
Boshchekul', N.E. Kazakhstan, U.S.S.R.	18	3) Pt_3-Cb_1 m-chert, spilite, m-basalt 4) Cb_2 diorite, monz.porph. dikes
Erdentuin field, N.E. Mongolia	20	3) Cm metavolc.,Pe contin.basalt, andes., rhyol.; Pe granosyen.,monz.,diorite 4) Pe gran.,granosyen.,granod.porphyry

5. STYLE	6.ALTER.	7.ORES	8.ENR.	9.TONN./GRADE	REFERENCES
H to S I,W	CA; KF,KB *ph; post-ore breccia	CuV	?10%	62Mt Cu/1.05% 1.6Mt Mo	Camus (1975)
H I,W	CA; KF,KB, ph,arg., anhydrite	CuR	?10%	1,848Mt Cu	Allcock (1982)
H I,W	CA; KB, skarn	CuFeSk	?20%	230Tt Cu/0.23 43Tt Mo	Ianovici and Borcoş (1982)
S,H W,*I	CA; KF	AuAgTeV		459Tt Cu	Janković (1982)
H I,W	CA; KB *ph		?10%	525Tt Cu/0.43 13Tt Mo	Iovchev (1961)
H I,*W	CA; KB	CuSk		min. 150Tt Cu	Pidzhyan (1975)
H I	CA; KB			min.500Tt Cu 30Tt Mo	Pidzhyan (1975)
H I	CA; KB			min.700Tt Cu 17Tt Mo	Pidzhyan (1975)
H I,*W	CA; KB,KF ph		20%	9.04Mt Cu/ 1.13% 240Tt Mo	Hakim (1980)
I,W	CA; KF,KB			1.47Mt Cu/0.4	Sillitoe and Khan (1977)
P to S I,W	CA; KF,KB ph	CuFeSk,R AuV PbZnR;Be	?80%	2.1Mt Cu	Musin (1970)
P to H Br,Fr I	CA; Si, adv.arg. ph	CuAsV	90%	10Mt Cu/0.95%	Gazizova (1957)
H,D I,W	D; ppl, *KF,KB		?80%	2.16Mt Cu/0.4 to 0.81%; Au	Trofimof (1973)
P to S I,*W	CA to D ph,Si	AuV Au plac.	100%	3Mt Cu/1%	Marinov et al.(1977)

Table 28-3 (continued). Hypabyssal and plutonic porphyry Cu-Mo deposits, selected example localities

1. LOCALITY	2.NO	3,4. SETTING (3=BEDROCK, 4=INTRUSION)
Mamut, Mt.Kinabalu, Sabah, N.E. Borneo, Malaysia	13	3) Cr_3-T_1 flysch,ultramaf.tectonite,tuff, black shale, sandst.,deformed 4) 9 m.y. qtz.monzon.porphyry,granod.porph.
Sto Tomas II, Tuba, Luzon, Philippines	14	3) Eo-Ol slate,phyllite,chert,limest., volcanics 4) T diorite to andesite
Tapian, Marinduque Isl.,Philippines	14	3) Eo-Ol slate,phyllite,chert,limest.volc. 4) Mi_2 qtz.dior.,granodior.stock
Sipalay, W. Negros Island, Philippines	14	3) Cr_3-T_1 mafic metavolcanics 4) T, quartz diorite stock
Basay (Muhong Creek) S.W. Negros Isl., Philippines	14	3) Cr_3-T_1 mafic tuff, metasedim. 4) T, diorite stock
Lutopan group, Cebu Isl.,Philippines	14	3) Cr_3-T_1 metavolc.(spilite,basalt) 4) 59.7 m.y. biot.diorite porphyry
Ok Tedi (Mt.Fubilan) Niugini	15	3) MZ-T fine clastics; Ol-Mi limestone 4) 4-1.2 m.y. monzonite stock,dior.pluton
Frieda Prospect, Sepik R. area, Niugini	15	3) Cr-Eo shale,phyll.,seric.sch.,marble mafic metavolc.,ultramafics; Mi clast. 4) Mi_2 porph. microdior.plut.incl. hornblende, hornbl.-pyrox.porphyries
Yandera, N.W.of Goroka, Niugini	15	3) 12-14 m.y. synorog, granod.batholith 4) 6.5 m.y. qtz.monz.porph.,qtz.diorite, dacite
Panguna, Bougainville Isl.,Niugini	15	3) Ol, andesite volc.,4-5 m.y. qtz.diorite pluton 4) 3.4 m.y. biot.dior.,granod.,qtz.dior.

NOTES AND EXPLANATIONS:

Column 2: number of porphyry Cu province from Table 28-2.

Column 5: style of ore-bearing intrusion and mineralization; H=hypabyssal; P=plutonic; S=subvolcanic; D=dikes; Fr=fault control (elongated); Br=breccia I=ore in intrusion (could be of older phase); W=ore in wallrocks

5.STYLE	6.SLTER.	7.ORES	8.ENR.	9.TONN./GRADE	REFERENCES
H I,W	CA; Si,KB tremolite actinolite	CuV	?5%	852Tt Cu/0.48% 90t Au/0.5ppm	Kosaka and Wakita (1978)
H,S I,W	CA-D; ph,Si anhydrite		?20%	645Tt Cu/0.43% 133t Au/0.89ppm 150t Ag	Bryner (1969)
H,P I,W	CA; KF,Si		?20%	1.6Mt Cu/0.57%	Loudon (1976)
H,Br I,W	D-CA; KF,KB			8.71Mt Cu 65.1Tt Mo 1.6Tt Ag; 48t Au	Wolff (1978)
H I,W	D, KF,KB			960Tt Cu/0.48%	Wolff (1978)
H,F	D,KB,*Si			6 Mt Cu/0.46% 121t Au/0.124 ppm; 600t Ag	Bryner (1969)
H I,W	D-CA; KF skarn	FeCuAuSk CuR	Au in leach cap.	2.33Mt Cu/0.88 262t Au 29Tt Mo	Bamford (1972)
H I,W	D-CA; ppl arg.			2.5Mt Cu/0.5% 100t Au/0.2ppm	Whalen and Britten (1982)
P,H,Br I,W	CA; KF,KB			1.43Mt Cu/0.42	Grant and Nielsen (1975)
H,Br I,W	CA; KB	AuV,CuV Au plac.		4.32Mt Cu/0.48 450t Au/0.5ppm 2.7Tt Ag/3 ppm	Baumer and Fraser (1975)

Column 6: alterations; CA=calc-alkaline parentage; D="diorite" model; KF=K feldspar; KB=biotite; ph=phyllic; ppl=propylitic; Si=silicification; arg=argillic

Column 7: other ore styles present in the ore field; Sk=skarn; R=replacements and V=veins

Column 8: approximate percentage of secondary enriched ore.

adjacent British Columbia coast, magnetite-chalcopyrite skarns are the most widespread plutonic copper mineralization style (Chapter 10). The largest "porphyry" (Island Copper near Port Hardy) is largely volcanics-hosted, and has been described in Chapter 14. The plutonic "porphyry" prospects (O.K., Catface) are of limited importance (Carson, 1969).

In the Cascade Range in Washington and Oregon, Hollister (1978) recorded fourteen "porphyry" occurrences, associated with Pliocene (6.2 m.y.) to Oligocene quartz diorite, granodiorite and quartz-monzonite porphyries (also dacite porphyries), intruded into Paleozoic metamorphics, Cretaceous and Tertiary sediments and Tertiary volcanics. Most are stockworks in potassic alteration zones. No economic deposit has been found, so far.

The Northern Cordilleran Interior porphyry Cu-Mo Belt which is over 3,000 km long and including the western Yukon, British Columbia, eastern Washington, Idaho and Montana (Sutherland Brown, ed., 1976; Hollister, 1978) contains almost 300 "porphyry" occurrences. This includes two giant fields (Butte, Montana and Highland Valley, British Columbia) and almost 50 major deposits, some of them in production (Table 28-3). The eastern and southern portion of this belt is underlain by Proterozoic and lower Paleozoic metamorphics along the western continental margin of North America. Also included are some of the "exotic" terrains added to this continent by collisions and displaced along strike-slip faults. Late Paleozoic "oceanic" association (ophiolites, deep marine sediments; Chapters 7, 10) crops out intermittently in the central part of this belt. The two sequences mentioned above form a "passive basement" to the porphyry copper complexes (Ney and Hollister, 1976), all of which are affiliated with Triassic to lower Jurassic (215 to 180 m.y.) and upper Jurassic to lower Tertiary (150 m.y. to 42 m.y.) plutonic rocks.

In the earlier lithogenetic and metallogenetic epoch, widespread mafic andesitic volcanics and associated sediments (e.g. Nicola Group, Chapter 13) formed in an island arc setting. "Volcanic" porphyry deposits corresponding to the "diorite" association-alteration model of Hollister (1978; e.g. Cariboo Bell, Galore Creek, described in Chapter 13) as well as "normal" plutonic porphyry coppers (Highland Valley, Lorraine, etc.) are the main examples of affiliated ores.

In the later epoch, marine to continental sedimentation and basalt, andesite, rhyolite volcanism were active in a series of intercontinental and marginal basins, situated to the east of the rising magmatic arc. The deeply eroded Coastal Batholith (Section 28.2.3.) is virtually devoid of ores, except for a few relicts. Porphyry copper deposits, however, are associated with smaller epizonal and upper mesozonal plutons located east of this batholith. Most of them are in terrains underlain by upper Paleozoic or Triassic volcanics.

The Casino deposit in western Yukon, described by Godwin (1976), is in an upper Cretaceous (70 m.y.) subvolcanic complex of quartz-feldspar porphyry plugs and breccia pipes, emplaced in a mid-Cretaceous granitic batholith. This batholith, in turn, intruded a Paleozoic or earlier metamorphic complex. Chalcopyrite and molybdenite are concentrated in a phyllic alteration zone surrounding a K-silicate altered breccia pipe. This deposit situated in the present zone of permafrost (average yearly temperature -5° C) is notable for the presence of up to 170 m deep supergene alteration zones (Fig. 28-39), interpreted as a relict of Paleogene subtropical weathering and a recent sporadic activity of groundwater heated by pyrite oxidation.

In the Babine Lake area, central British Columbia (Carson and Jambor, 1974), a north-west trending string of medium-size porphyry Cu deposits is associated with Eocene hypabyssal intrusions (stocks, dikes, dike swarms) of quartz diorite, quartz monzonite and in particular biotite-feldspar porphyry (Fig. 28-38). These intrude Jurassic to Cretaceous marine to continental andesite, litharenite, shale association as well as Jurassic mesozonal plutons. Chalcopyrite is the dominant mineral, whereas molybdenite occurs in mineralogical quantities and is not recovered. In the largest Granisle orebody, chalcopyrite and minor bornite fills fractures, 1-5 cm thick, in a stockwork hosted by biotite-altered porphyry and hornfelsed metavolcanics, and there is a gradation into irregular veins up to 30 cm wide, filled by coarse ("pegmatitic") chalcopyrite, bornite, quartz, biotite and apatite. The Granisle orebody is fresh to the very top, whereas at the nearby Bell deposit a supergene chalcocite zone extends to a depth of as much as 100 m.

The Highland Valley porphyry Cu(Mo) field (McMillan, 1976; Fig. 28-38) is located between Ashcroft and Merritt, southern British Columbia, and is the largest Canadian porphyry copper complex (over 9 Mt Cu; Table 28-3). Five major and several minor orebodies are located in the central part of a composite upper Triassic Guichon Creek Batholith that has an area of about 1,000 km^2. All orebodies are of the "plutonic" style. The batholith intruded broadly comagmatic basalt and andesite volcanics, pyroclastics and volcaniclastics of the Nicola Group (Chapter 13), and probably also Permo-Carboniferous marine sediments in the basement. The early plutonic phases are hybrid and largely of diorite-quartz diorite composition, but the younger phases are granodiorite and quartz monzonite. The low-grade stockwork chalcopyrite-lesser molybdenite mineralization is in broadly equidimensional to elongated orebodies largely controlled by N.-S., E.-W., and N.W.-S.E.-trending fault zones and grabens. The orebodies are affiliated to one of the youngest granodiorite to quartz monzonite phases (Bethsaida Phase), with swarms of porphyry dikes or with intrusive breccias. The model alteration and mineralization zoning is developed, but its regularity is considerably modified by the intensity of fracturing and faulting.

The Lorraine deposit (Duckling Creek; N.C. British Columbia; Wilkinson et al., 1976; Fig. 28-42) is insignificant by modern porphyry copper standards (67 Tt Cu/0.6-0.75% Cu, 2.03 t Au), but it has been included as an example of a "diorite" (syenite)-model mineralization set deeper than the "volcanic" equivalents reviewed in Chapter 13. The ore zone is associated with an upper Triassic-Lower

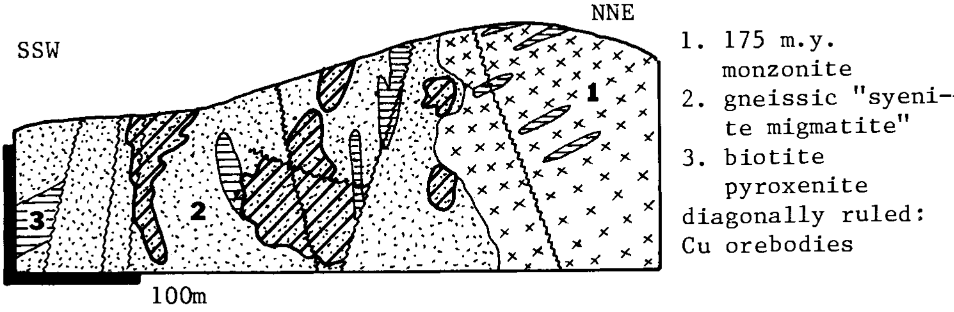


Fig. 28-42. Lorraine (Duckling Creek) porphyry Cu orebody, British Columbia. After Wilkinson et al. (1976).

Jurassic syenite-monzonite complex, a N.W. elongated, intrusive body emplaced into amphibolitic basement metamorphics and upper Triassic island arc basalts, andesites and their volcaniclastics. This measures 32x5 km. Erratically disseminated and veinlet chalcopyrite and bornite with local pyrite and magnetite are associated with high biotite and chlorite contents, potash feldspathization, pervasive sericitization, and the presence of accessory epidote along faults. The immediate host rock is an enigmatic "syenite migmatite", a hybrid rock, and rare bodies (possibly rafts or resisters) of biotite pyroxenite. The ore was emplaced at about 175 m.y. and it gives an impression of a K-silicate metasomatized mafic metavolcanics along a fault or shear zone.

Of the porphyry deposits on the American side of the border, the largest and most famous is Butte, briefly described earlier.

SOUTHERN CORDILLERA, U.S.A. AND MEXICO

Scattered porphyry copper occurrences are distributed over a broad region 3,300 km long and up to 800 km wide, reaching from southern Idaho through Utah, Nevada, Arizona and New Mexico to the latitude of Mexico City. The western United States' segment of this belt is the craddle of porphyry coppers, where this type of deposit was first utilized and interpreted. It is also the most thoroughly investigated porphyry copper region and the second richest (after the Andean belt) of the world. It represents some 103 Mt Cu contained in at least 500 occurrences that include 3 giant fields with more than 10 Mt Cu (Bingham, Clifton-Morenci, Cananea), 12 large fields with more than 1 Mt Cu and at least 50 deposits with more than 100 Tt Cu.

The region is bordered in the west by the Sierra Nevada Batholith in the United States and the Pacific Ocean in Mexico. In the east, no porphyry coppers are known at present, either within or to the east of the Laramide thrust belt and the Precambrian uplift of the Rocky

Mountains (but there are important stockwork Mo deposits). The geology as might be expected is very heterogeneous. The greater portion of the area is underlain by Precambrian metamorphics, topped in the east by Paleozoic and Mesozoic platformic and "miogeoclinal" sediments. These change facies westward into an "eugeoclinal" facies represented by deeper marine, siliceous sediments, mafic volcanics and minor ophiolites. As in the northern Cordillera, the porphyry deposits started to form only in the Mesozoic time (the oldest are Triassic) and the formation terminated at the onset of the Basin-and Range block faulting and continental rifting in the Miocene age. The bulk of the deposits, as in Canada, are "Laramide" (Cretaceous to Oligocene), associated with calc-alkaline plutons sometimes accompanied by subaerial volcanic equivalents. Most porphyry coppers are associated with small hypabyssal stocks and "plutonic" occurrences are rare.

The lonely Bingham, Utah (Lanier et al., 1978; 21.5 Mt Cu, min. 820 Tt Mo; Fig. 28-43) is the largest porphyry copper deposit in North America mined from what may be the world's largest (certainly the most pictoresque) open pit. The deposit is associated with an Oligocene (39-32 m.y.) multiphase (six equigranular to porphyritic phases) quartz monzonite stock emplaced into Pennsylvanian calcareous siltstones and sandstones, against which it is bordered by a zone of hybridization and recrystallization. The stock is cut by porphyry dikes. The porphyry Cu orebody is in the centre of a very regularly concentrically zoned metal distribution pattern, underlain in depth by a dominantly stockwork molybdenite body and flanked laterally by a ring of galena-sphalerite hydrothermal veins and limestone replacements. Over 80% of the Cu-Mo ore is in the K-silicate and phyllic-altered intrusive stock, the rest is in the metasediments. The pear-shaped copper orebody has dimensions of 1.7 x 2.2 km, and is composed of bornite, chalcopyrite and minor primary chalcocite veinlets and disseminations. A rich chalcocite zone topped the hypogene ore.

Ely, Nevada (James, 1976) is a west-trending zone of alteration and mineralization, 13 km long and 460 m wide, associated with six bodies of lower Cretaceous quartz monzonite porphyry. It is localised by a thrust fault separating Pennsylvanian limestone and Mississippian black shale. Chalcopyrite and pyrite are the main hypogene minerals and they occur as disseminations and fracture fillings in K-silicate altered porphyry, hornfelsed shale, and skarn. A quartz-sericite alteration zone in silicate rocks has silicification as its counterpart in limestones. There is widespread pyrite and numerous small Cu, Au and Pb-Zn bearing fissure veins were mined in the past.

Globe-Miami field in Arizona (Peterson, 1962) is notable for the variety in its rock units (Lower Paleozoic schist and amphibolite, middle Proterozoic granite, late Proterozoic diabase, Paleozoic sediments, "Laramide" granodiorite and quartz monzonite and Tertiary volcanics and sediments. The porphyry mineralization is associated with the upper Cretaceous-lower Tertiary quartz monzonite phase of a composite pluton, and it has chalcopyrite, pyrite, minor molybdenite

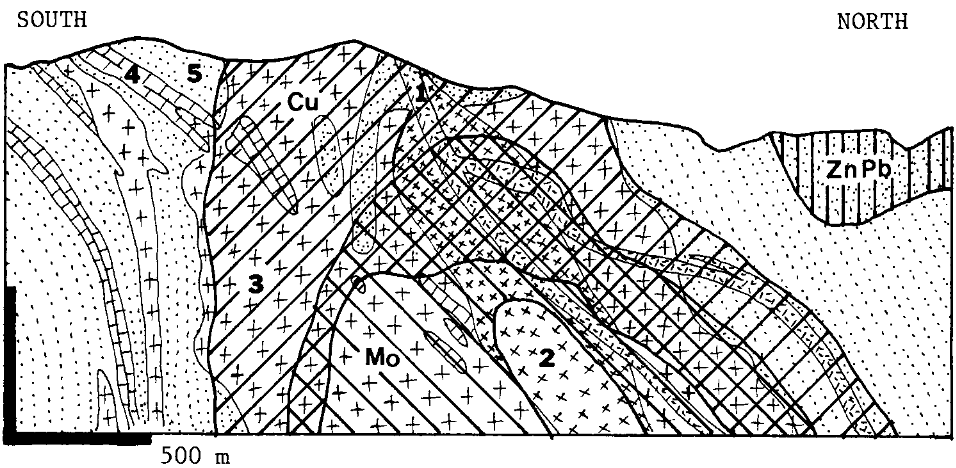
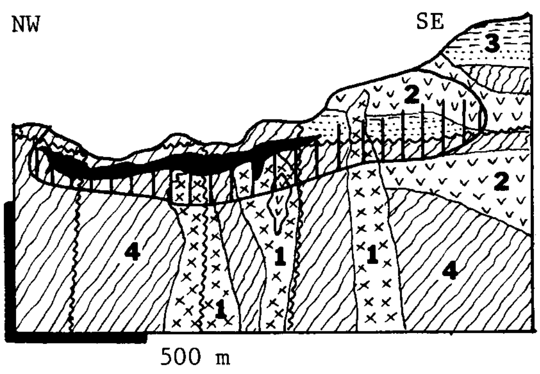


Fig. 28-43. Bingham porphyry Cu-Mo deposit, Utah, showing overlapping Cu and Mo stockwork zones; 1=Eo latite porphyry; 2=Eo quartz monzonite porphyry; 3=Eo monzonite and quartz monzonite; 4=Ps limestone; 5=Ps quartzite. From LITHOTHEQUE, after John (1978).

disseminations and veinlets in both endocontact and exocontact. There is a strong fault control. The porphyry orebodies are fringed by a system of fissure and breccia veins filled by quartz, pyrite, chalcopyrite and specularite, that contributed about 450 Tt Cu to the production. The "porphyry" mineralization is both hypogene and supergene. In addition to chalcocite blankets formed chiefly during the Tertiary period and recently exhumed, Cu oxides (chrysocolla, malachite, azurite) pseudomorphically replacing sulphide grains or infiltrated along fractures, have been recovered by leaching. The Inspiration Company has pioneered the leaching methods since 1926. Some of the secondary enriched orebodies are outside the original K-silicate altered hypogene mineralized zone, in the phyllic zone or in argillized schist.

The Ray deposit, Arizona (Phillips et al., 1974; Fig. 28-44) has a similar setting as Globe-Miami. Most of the disseminated and veinlet high chalcopyrite and bornite, low pyrite ore, is in biotite and chlorite-epidote altered Proterozoic diabase and quartzite near "Laramide" quartz diorite and granodiorite porphyry stocks. The alteration type and zoning is strongly lithologically controlled. Potash feldspar missing in the diabase is developed in the porphyry and quartzite.

Bagdad ore field, Arizona (Anderson et al., 1955), is interesting because of the coexistence of a stockwork and disseminated pyrite, chalcopyrite and molybdenite orebodies mostly in the endocontact of a late Cretaceous quartz monzonite porphyry stock, and several small



1. Cr_3 quartz monzonite porphyry
2. Pt_3 diabase and amygdaloidal basalt
3. Pt_3 quartzite, shale, conglomerate
4. Pt_2 Pinal Schist

OREBODY:
black=enriched zone
vertically ruled: hypogene zone

Fig. 28-44. Ray porphyry copper deposit, Arizona. From LITHOTHEQUE, after Metz and Rose (1966).

pyrite, sphalerite and chalcopyrite massive sulphide bodies. The latter are relics, hosted by the lower Proterozoic greenstone basement. Minor quartz-wolframite fissure veins are further associated with a Proterozoic granite.

San Manuel and Kalamazoo deposits, Arizona (Lowell, 1968) are two segments of a tilted and fault-displaced porphyry copper orebody. The locality has been made famous as an "average" western U.S. deposit and a model locality of the hypogene alteration-mineralization zoning of Lowell and Guilbert (1970). The orebodies are hosted by a coarse-grained Precambrian deep mesozonal quartz monzonite, intruded by late Cretaceous swarms of quartz monzonite porphyry dikes and irregular stocks. Two broken ring-shaped orebodies (Fig. 28-38) hosted by both the Precambrian and Cretaceous quartz monzonites, have very gradational assay boundaries, and consist of hypogene pyrite, chalcopyrite, minor molybdenite and bornite disseminations and veinlets. The ore shell has an average thickness of 200 m and is situated close to the overlapping border of the K-silicate and quartz-sericite alteration zones. The relative uniformity of the alteration zones and the mineral distribution is attributed to the compositional and physical near-uniformity of the host "granites", regardless of their significant age difference.

Clifton-Morenci field, Arizona (Moolick and Durek, 1966; 13 Mt Cu) has been in operation since 1872, and is most notable for the fact that 100% of its ore is secondary enriched. The hypogene material with its 0.1-0.15% Cu remains a protore even today. The hypogene mineralization which is virtually invisible, is hosted by and genetically associated with a stock of Laramide quartz monzonite porphyry, intruded into a variety of wallrocks ranging from Proterozoic schist, granite, granodiorite to Paleozoic and Mesozoic shale and limestone and an earlier Cretaceous diorite porphyry laccolith and sills. Three small breccia pipes are known. The principal orebody has been a chalcocite blanket up to 330 m thick, averaging 0.8% Cu, formed in the Tertiary time under 70-200 m of leached capping and recently exhumed.

Santa Rita (or Central Mining District), New Mexico (Hernon and Jones, 1968; Fig. 28-45), is one of the "complete" concentrically zoned districts. There, an apex of a "Laramide" quartz monzonite and granodiorite stock (Chino mine) has a porphyry copper deposit, a stockwork pyrite-chalcopyrite topped by a supergene chalcocite blanket. The basement is a thick sequence of Cambrian to Permian shallow marine carbonates interbedded with shale, topped by Cretaceous shale. These rocks host skarn and replacement chalcopyrite bodies in the exocontact of the Chino stock. Magnetite and chalcopyrite skarns at Fierro, and sphalerite skarn and sphalerite-galena replacement bodies in silicified limestone near Hanover and Bayard, are in the exocontact of the Chino and Hanover-Fiero stocks.

Bisbee (Warren) field, Arizona (Bryant and Metz, 1966), has a wide variety of ore styles, most of which depart considerably from the image of a "typical" porphyry copper. In fact, Bisbee ores are closer in appearance to those in Cerro de Pasco, Peru or Burra,

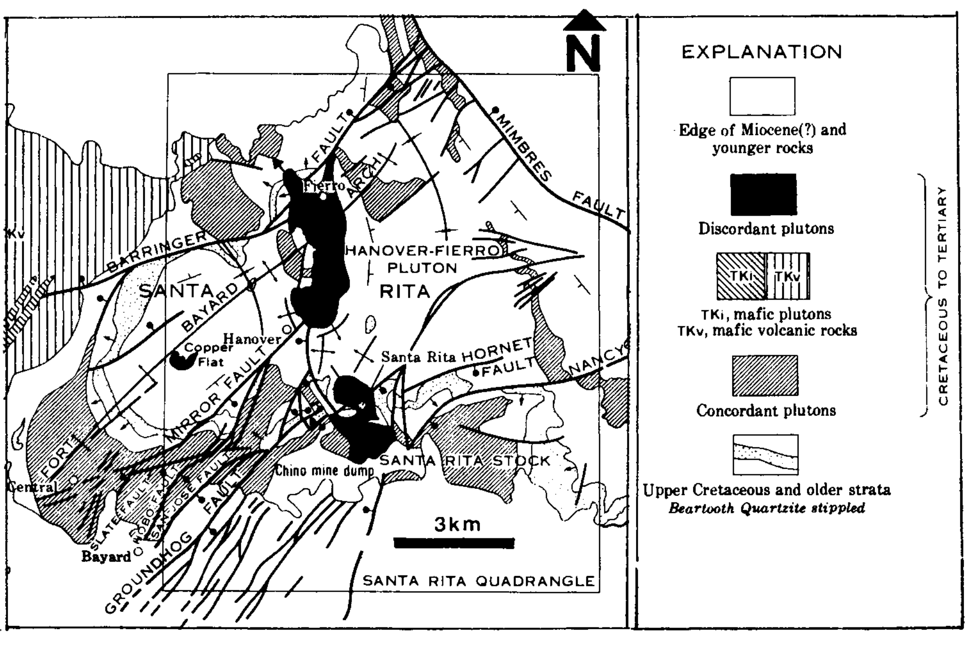


Fig. 28-45. Santa Rita (Central) district, New Mexico. The Chino porphyry Cu deposit is in the Santa Rita stock. From Jones et al. (1967).

South Australia, than to other Arizona porphyry coppers such as San Manuel. The basement at Bisbee is composed of a lower Proterozoic schist, overlain by Paleozoic limestone and shale, and intruded by a Jurassic quartz-feldspar porphyry stock. The area is intensively faulted, and ores occur in three ways: (1) as bedded (mantos) and discordant (pipes, sheets) massive pyrite, chalcopyrite, lesser galena, sphalerite replacements in silicified limestone (rarely skarns) in porphyry exocontacts, along faults and along bodies of intrusive breccia; (2) as low-grade disseminations of chalcopyrite and pyrite in the matrix of intrusion breccia or (3) as disseminations and veinlets in sheared and altered quartz-feldspar porphyry and its brecciated segments. Supergene alteration is extremely intensive and thick in the ore field, and it masks much of the primary alteration and mineralization. Silicification and argillization are the most conspicuous alterations, probably superimposed on hypogene sericitization. Many of the orebodies in carbonates were converted to rich and colourful Cu-oxides (cuprite, malachite, azurite, chrysocolla), whereas a blanket of sooty chalcocite has been the major ore style in the breccia and in porphyries, produced from the Lavender Pit. The intrusive breccias described by Bryant (1968) are heterolithic unsorted masses controlled by faults, and emplaced largely as sills peneconcordant with sedimentary bedding, dikes, pipes and irregular bodies, rather than as vertical columns as elsewhere. Bryant assumed that they had been transported in fluidized state by hydrotherms.

The Cananea ore field in Sonora, northern Mexico (Velasco, 1966; Meinert, 1982) is a giant copper accumulation (15.255 Mt Cu; Fig. 28-46). It has many points of similarity with Bisbee in that a substantial portion of the ore is in skarns, replacement mantos in carbonates and in breccia pipes. The rest is in "Laramide" quartz monzonite and quartz porphyries. The basement in Cananea is represented by Cambrian to Carboniferous limestones and basal quartzite, unconformably resting on middle Proterozoic porphyritic quartz monzonite. The most important primary orebodies at Cananea are associated with three major breccia pipes. The Cananea-Duluth pipe is a steep, oval-shaped vertical structure, 80 m wide and 400 m long. It cuts through gently dipping Tertiary felsic volcanics. It is composed of altered and brecciated weakly mineralized volcanic interior with a strongly mineralized peripheral ring. In the ring chalcopyrite, sphalerite, quartz and minor adularia cement the rock fragments. The La Colorada pipe is related to an intrusive plug of quartz porphyry and it carries a massive and brecciated body of chalcopyrite, bornite and molybdenite in its core. This grades into a pyrite-rich outer ring.

Meinert (1982) established a time framework for the alteration-mineralization, particularly in the exocontact carbonates where it follows the general model of skarn origin discussed earlier. After hornfelsing and subsequent metasomatic skarnization, emplacement of a series of quartz monzonite porphyry stocks, followed by

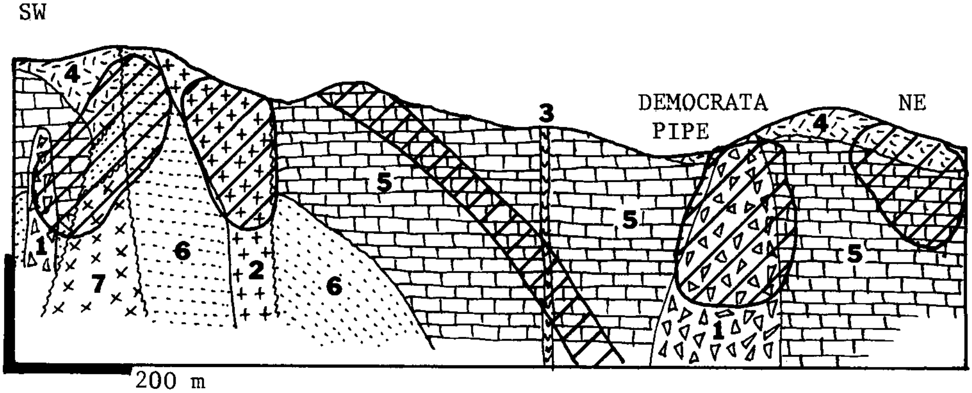


Fig. 28-46. A portion of the Cananea (Sonora, Mexico) Cu field (generalized). 1=T breccia pipes; 2=Cr_3-T_1 quartz porphyry and quartz monzonite porphyry stocks; 3=Cr_3-T_1 diabase dikes; 4=Cr_3 continental rhyolite, andesite, dacite, and tuffs; 5=Cm,D,Ms-Ps limestone, dolomite, minor shale, siltstone; contact metamorphosed; 6=Cm quartzite; 7=1.44 b.y. porphyritic quartz monzonite. Diagonally ruled are disseminated, skarn, fracture filling, breccia replacing Cu-Mo orebodies. From LITHOTHEQUE, based on data in Velasco (1966).

sericitization, produced stockwork porphyry Cu mineralization in the endocontact and disrupted the skarn and hornfels. This was followed by formation of Fe,Cu and Zn sulphide mantos in the carbonates.

La Caridad, Sonora, Mexico (Saegart et al., 1974) is another major porphyry deposit, discovered in the 1960s. Stockwork and disseminated pyrite, chalcopyrite and molybdenite are mostly in quartz, sericite, pyrite-altered Tertiary quartz monzonite porphyry stock and intrusive breccia, emplaced in an older diorite and granodiorite. Most of the economic ore comprising fossil supergene blanket, up to 250 m thick, mineralized by sooty chalcocite, buried under a thick leached capping.

Scattered small to medium-sized porphyry Cu deposits (Santo Tómas, Sinaloa; 750 Tt Cu/0.5%; La Verde, Michoacan; 770 Tt Cu/0.7%; Inguarán, Michoacan) have been discovered in the past 15 years. Disseminated copper deposits hosted largely by volcanics and subvolcanic bodies (Safford, Arizona; El Arco, Baja California, 3.9 Mt Cu/0.6%, were reviewed in Chapter 26).

CENTRAL AMERICA

A new porphyry copper province in Panama continuing westward into Costa Rica and eastward into Colombia, has been discovered in the past 15 years. The mineralization (Kesler et al., 1977) is affiliated with high-level potassic granodiorite intrusions 33-4 m.y. old. These represent the latest stage of igneous activity that took place originally in an island arc setting 60-70 m.y. ago. The largest deposit Cerro Colorado with a potential of 18 Mt Cu is largely hosted by volcanics and by subvolcanic bodies and was reviewed in Chapter 26. The deposits in N.W. Colombia (Pantanos, Pegadorcito) are located in the extension of the mineralized belt in eastern Panama.

THE CARIBBEAN

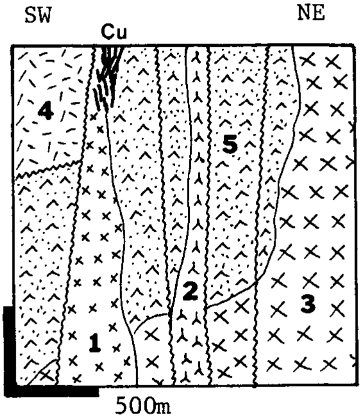
In the Caribbean (Hollister, 1978), porphyry copper occurrences have been reported on all the major islands of the Greater Antilles and Jamaica. The largest and most extenisively studied occurrences that include two small to medium-size deposits are in Puerto Rico (Fig. 28-47). The oldest dated rocks in the Greater Antilles are Jurassic, and they are marine "eugeoclinal" sediments and volcanics. Between the Jurassic and Eocene periods the region was an active island arc and a considerable thickness of largely andesitic volcanics, derived sediments and comagmatic quartz diorite-granodiorite intrusions, accumulated. The porphyry Cu occurrences are stockworks, almost invariably associated with "Laramide" quartz diorite porphyries. The ore zones are most commonly situated in biotite-altered endo- and exocontacts. They are low in Mo, but relatively high in Au.

ANDEAN BELT, SOUTH AMERICA

If the Colombian porphyry Cu occurrences are not considered here, the Andean porphyry Cu occur in a N.N.W.-S.S.E. trending belt 4,500 km long between Chaucha, Ecuador, and Campana Mahuida, Argentina (Hollister, 1978; Putzer, 1976). Several hundred occurrences are known and these include 5 giant deposits (10 Mt Cu plus; see Table 28-3); 16 large deposits (between 1 Mt and 10 Mt Cu) and several tens of medium to small-sized deposits. As in the Cordillera, the porphyry Cu belt is situated between the chain of Mesozoic coastal batholiths in the west, and the eastern limit of the Precambrian craton and the "miogeoclinal" thrust and molasse belt of the Eastern Cordillera of the Andes. The intrusions with which the "porphyries" are associated range in age from 4.32 m.y. (El Teniente) to lower Carboniferous (Oyarzún and Frutos, 1980) and they have been emplaced in a continental to transitional crust environment along faults. Further generalization on the setting of the deposits is impossible, and each has to be considered individually.

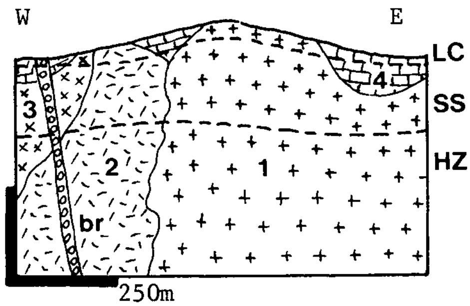
The isolated northern Peruvian deposit Michiquillay (Hollister and Sirvas, 1974) is a stockwork of chalcopyrite, pyrite, minor bornite, chalcocite, molybdenite and sphalerite veinlets in a phyllic and argillic alteration zone of a Miocene hornblende-biotite quartz monzonite stock. The stock intruded Cretaceous quartzite and limestone without causing much contact metamorphism.

Morococha, 110 km E. of Lima, Peru (Petersen, 1965; M. Velasquez R., guided tour, 1977; Fig. 28-48) is a zoned Cu-Mo, Cu-As, Pb-Zn,



1. Eo, qtz. diorite stocks
2. Eo, hornblende quartz diorite and diorite
3. Cr_3-T_1 quartz diorite and granodiorite pluton
4. Eo, marine to contin. andesite, dacite, tuff, volc. sediments
5. Cr, mafic andesite, volc. arenite, shale, limestone

Fig. 28-47. Diagrammatic representation of the setting of the Puerto Rican porphyry coppers (Viví Arriba, Piedra Hueca) S.S.E. of Utuado. From LITHOTHEQUE, based on data in Cox et al. (1973).



supergene zones:
LC=leached capping
SS=secondary sulphides
HZ=hypogene zone

geology:
1=Mi_{2-3} granodiorite stock
2=Mi quartz porphyry
3=8 m.y. porphyritic diorite
4=Tr_3-J_1 cont.metasom.carbonate
br=Mi breccia pipe

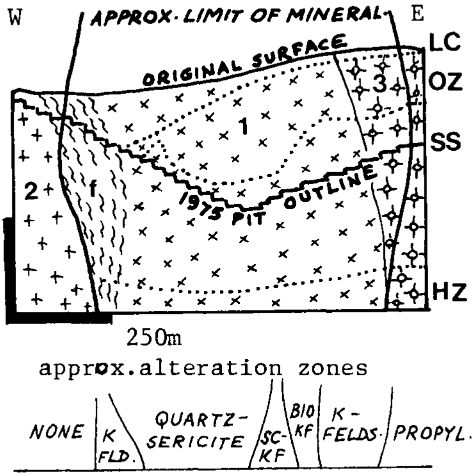
Fig. 28-48. Toromocho porphyry Cu-Mo deposit, Morococha, Peru. From LITHOTHEQUE, diagrammatic, after M. Velazquez R., guided tour, 1977.

Ag, ore field. The mineralization is associated with Pliocene quartz monzonite porphyry stocks intruded into a petrographically variable sequence of Triassic-Jurassic limestone, black shale, anhydrite, gypsum and metabasalt suite. This rests unconformably on Permian continental andesite and dacite lavas, tuffs and breccia within a symmetrical, N30°W-trending anticline. As in Santa Rita, the most central mineralization is a porphyry Cu-Mo stockwork (Toromocho deposit). The hypogene ore consists of pervasively disseminated and fracture coating pyrite, chalcopyrite, molybdenite with quartz, in an intensely altered quartz monzonite. In places, biotite forms an almost monomineralic matrix to sulphide grains. The largest tonnage of economic ore is in the zone of secondary sulphide enrichment where quartz, pyrite, chalcocite coatings are in quartz-sericite altered and in places argillized hostrocks.

Above and laterally with respect to the porphyry copper, rich pyrite, chalcopyrite and enargite "contact pipes" formed along the intrusion-carbonate contact, in diopside, tremolite or serpentinite, chlorite or talc-altered carbonate. Mantos and irregular replacement bodies in lightly altered carbonates further from the contact carry rhodochrosite, ankerite, pyrite, enargite and bornite, or galena and sphalerite. Several tens of E.-W.-trending epithermal fissure veins filled by quartz, pyrite and enargite are hosted by another quartz monzonite stock. Silver-rich quartz, pyrite, ankerite, tennantite veins are situated mostly in the Permian basement volcanics.

The important string of porphyry copper deposits in the Arequipa area, S.W. Peru (Cerro Verde, Cuajone, Quelleveco and Toquepala), together represent some 27 Mt Cu. The largest deposit, Cuajone (Manrique and Plazalles, 1975) has a stockwork ore hosted by a K-silicate and sericite-altered Tertiary quartz monzonite porphyry, emplaced into a late Cretaceous-early Tertiary continental basalt, andesite and rhyolite suite. Chalcopyrite-tourmaline mineralized breccia pipes also occur, but they are best developed at Toquepala (Hollister, 1978). There, a breccia pipe affiliated with and emplaced into a dacite, has a diameter of about 600 m and is concentrically zoned. Its central zone is a "pebble breccia". It postdates alteration and ore emplacement and it changes into a mixed fragment breccia and a monolithic (dacite) breccia. The outer breccia zones are quartz-sericite altered and cemented by tourmaline containing scattered pyrite, chalcopyrite and molybdenite. A stockwork of quartz, tourmaline and chalcopyrite veinlets encircles the pipe.

The large and interesting Chilean porphyry coppers start, in the north, with Chuquicamata (Ruíz, 1965; Sillitoe, 1973; 43 Mt Cu, 1.1 Mt Mo; Fig. 28-49). This deposit has dimensions of about 4x2 km and has been explored to a depth of 600 m. Hypogene pyrite, chalcopyrite, lesser bornite, enargite and molybdenite occurs as stockwork, pervasive disseminations and discrete veins in a zone of quartz-sericite, lesser K-feldspar and biotite alteration, within and around a composite Oligocene granodiorite to quartz-monzonite stock. The Chuquicamata orebody is one of several bodies located in a N.-S. trending, fault-controlled belt. The ore mined at present and in the past has come from a zone of secondary enrichment, in which chalcocite and minor covellite are in supergene argillized wallrocks. Formerly, the oxidation zone with antlerite, atacamite, brochantite, chrysocolla, and other rare minerals contributed to copper production (and excitement of the visiting mineralogists). The Exotica chrysocolla and atacamite, broachantite deposit, still actively forming by precipitation in the alluvial fan below Chuquicamata, has been described in Chapter 23.



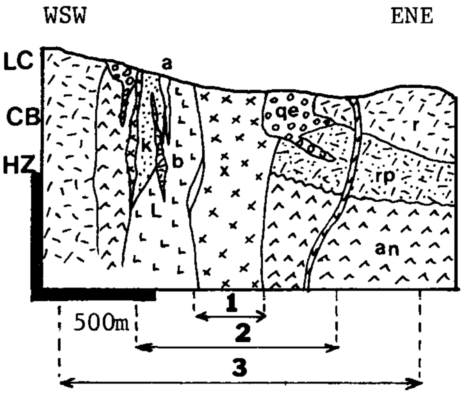
supergene zones:
LC=leached capping
OZ=oxidation zone
SS=secondary sulphides
HZ=hypogene zone
geology:
f=Falla Oeste fault zone
1=46-32 m.y. altered quartz monzonite to granodiorite stock
2=35 m.y. granodiorite
3=J granodiorite

Fig. 28-49. Chuquicamata porphyry Cu-Mo deposit, Chile. From LITHOTHEQUE, after H. Soto, guided tour, 1977 and CODELCO materials for visitors.

El Abra porphyry copper deposit (Ambrus, 1977; 16.35 Mt Cu), is 42 km north of Chuquicamata and controlled by the same tectonic structure (Falla Oeste). There, a multiple alteration-mineralization related to a diorite-syenite complex was later intruded and remobilized by several dacite necks, capped by biotite breccia. The low pyrite, chalcopyrite-molybdenite ore lies in structurally controlled bodies. The hypogene ore is capped by a chrysocolla-mineralized oxidation zone.

El Salvador, a "minor" deposit by Chilean standards (5.5 Mt Cu; Fig. 28-50), is best known for its excellent modern description and interpretation by Gustafson and Hunt (1975). The ore is associated with a system of high-level granodiorite porphyry intrusions (39.1 m.y.), emplaced into comagmatic and slightly earlier andesite-rhyolite volcanic pile. Economically, the most important earlier mineralization phase lies in endo- and exocontact quartz veins, fracture coatings and pervasive disseminations, and has chalcopyrite, bornite and pyrite in K-feldspar and biotite—altered rocks. In the later stage pyrite-rich quartz, anhydrite, bornite, chalcopyrite, enargite, tennantite, sphalerite and galena veins and veinlets formed, surrounded by feldspar-destructive sericite and sericite-chlorite alteration haloes. The economic mineralization originally outlined coincides with a supergene enriched blanket containing chalcocite, pyrite and bornite. This is confined under a leached capping.

Los Pelambres, Chile and the adjacent El Pachón, Argentina (Sillitoe, 1973; about 8 Mt Cu), are related to a late Miocene



41 m.y. old rocks
b=igneous breccia
k,L,a,x=varieties of granodiorite porphyry
qe=45 m.y. quartz-eye porphyry
r=50 m.y. rhyolite dome
rp=T_1 ignimbrite, rhyolite pyroclastics
an=Cr_3 andesite flows, pyroclastics
supergene zones:
LC=leached capping
CB=chalcocite blanket
HZ=hypogene zone
alteration-mineralization zones
1=low sulphide zone
2=K-silicate alteration, chalcopyrite-bornite
3=qtz,pyrite,sericite alter., chalcopyrite-pyrite miner.

Fig. 28-50. El Salvador Cu-Mo deposit, Chile. From LITHOTHEQUE, simplified after Gustafson and Hunt (1975).

tonalite and diorite porphyry stock and dike. The intrusive rocks are emplaced in Mesozoic continental andesites and volcaniclastics. Chalcopyrite, bornite, pyrite and minor molybdenite stockwork is hosted by biotite and K-feldspar altered rocks in the centre of a concentrically zoned alteration complex.

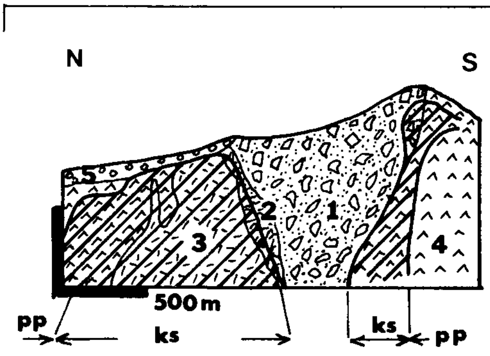
Rio Blanco-Disputada. This giant field is located in glaciated alpine country 50 km N.E. of Santiago, within sight of Aconcagua (Ruíz, 1965; 17.6 Mt Cu). The area is underlain by early Tertiary andesitic lavas of the Farellones Formation (the same unit that hosts El Teniente), intruded by a granodiorite-quartz monzonite pluton. These "basement" units are intruded by subvolcanic bodies of dacite porphyry and capped by several erosional remnants of rhyolite. Cu and minor Mo,Au,Ag, Pb-Zn mineralization occurs within an area of about 11 x 5 km, and is subject to significant control by N.-S. fault zones.

The Disputada (Los Bronces) orebody is hosted by granodiorite and it consists of a breccia composed of angular intrusive clasts in a matrix of tourmaline, pyrite and chalcopyrite. The larger Rio Blanco (Andina) group of orebodies is mostly in andesite at contact with dacite porphyry, and also in a subvertical subvolcanic porphyry plugs. The andesite-hosted orebodies are mostly tabular breccias and brecciated metavolcanics, silica, biotite, sericite, tourmaline and chlorite – altered. Pyrite, chalcopyrite, specularite, lesser molybdenite, bornite and enargite are disseminated or form veinlets in the breccia matrix. Secondary enrichment is insignificant.

The El Teniente (formerly Braden) deposit east of Rancagua, central Chile (Camus, 1975; 62 Mt Cu/above 1%, 1.6 Mt Mo; Fig. 28-51), is a giant metal accumulation and the world's largest porphyry copper. The orebody having more then 0.5% Cu is a N.W. elongated zone measuring 6x3 km of fractured and altered volcanic and intrusive rocks, surrounding the almost barren Braden breccia pipe. The mineralization correlates with the emplacement of a 4.3 m.y. dacite porphyry into the bedrock composed of Paleocene to Eocene subaerial, massive homogeneous andesite and minor conglomerate (Farellones Formation), and an Oligocene-Miocene quartz diorite. The Farellones andesites are load metamorphosed and thermally contact hornfelsed in the ore field, and they have a high trace Cu content. They host about 20% of the stockwork ore, the rest of which is in the quartz diorite and dacite porphyry. Hypogene chalcopyrite, pyrite, bornite, molybdenite, tennantite-tetrahedrite, lesser magnetite, specularite, enargite, etc., occur without gangue (or with quartz and anhydrite) in a K-silicate and less quartz-sericite and propylitic alteration envelope. The K-silicate zone has a biotite, K-feldspar, lesser anhydrite and quartz assemblage. Tourmaline is locally widespread. Argillic alteration is supergene and it contained patchy chalcocite and small amounts of oxidation zone minerals such as chrysocolla, malachite, brochantite and antlerite, reaching along faults to a depth of 600 m.

NORTH-EASTERN APPALACHIANS, CANADA AND THE UNITED STATES

About 20 occurrences of "porphyry Cu-style" deposits ranging in age from Cambrian to Devonian, have been recorded in the Appalachian Orogen between Newfoundland and Maine (Hollister, 1978). With the



1. Pl, breccia pipe (fragments of andesite, dacite porphyry, quartz diorite)
2. brecciated rocks
3. Pl, dacite porphyry
4. Pc-Eo, subaerial metaandesite flows, agglomerates; contact hornfelsed
5. Q, talus, glacial sediments

ruled: orebodies above 0.5% Cu cutoff

Fig. 28-51. El Teniente porphyry Cu-Mo, Chile. From LITHOTHEQUE, after Camus (1975).

sole exception of the Gaspé (Murdochville) deposit, none is of economic importance. As expected, the occurrences are deeply eroded so that most appear to represent only the "roots of the porphyry system". Among the peculiarities of these occurrences as a set, Hollister (1978) noted the general lack of a well developed phyllic zone (most mineralizations are in the potassic zone); most intrusions having a fresh, unaltered core; many intrusions being equigranular instead of porphyritic, and some containing a sparse, possibly magmatic chalcopyrite. There is no clear connection between intrusions and extrusive volcanics; missing argillic zones; and pyrite is rarer than in the Meso-Cainozoic systems. The "porphyry" deposits are members of an ensialic orogen, formed during periods of distension immediately following a compressive event.

The Gaspé Cu field (near Murdochville, Gaspé Peninsula, E. Quebec; Allcock, 1982; Fig. 28-52), contains several disseminated copper orebodies genetically associated with a late Devonian to Mississippian intrusion of rhyodacite porphyry sills, dikes and plugs into lower Devonian calcareous sediments. The orebodies are of two styles: (1) replacement bodies in metasediments at Needle Mountain (736 Tt Cu/0.7-1.35%). These consist of disseminated to massive chalcopyrite and pyrrhotite, lesser bornite, and they are peneconcordant, lithologically controlled or discordant, controlled by faults and (2) disseminations and veins in and around fractured Copper Mountain porphyry plug (1.112 Mt Cu/0.4%). There, the ore is composed of pyrite, chalcopyrite and minor molybdenite and is of five generations. The Stage 2 quartz, anhydrite, K-feldspar veinlets with traces of chalcopyrite and magnetite are coeval with K-feldspar and biotite alteration. Stage 3 which is economically the most important contains quartz, lesser anhydrite, chalcopyrite, pyrite and molybdenite veins associated with kaolinization, sericitization and minor anhydrite alteration in the endocontact, and with the formation of tremolite, epidote and chlorite in the exocontact.

CALEDONIAN AND HERCYNIAN OROGENS OF EUROPE

Scattered occurrences of "porphyry copper-style" mineralization are known in several places in Caledonian and Hercynian Europe (e.g. Ballachulish, Scotland; Miedzianka, Polish Silesia), but are presently of little economic significance. The only exceptions are the chalcopyrite stockworks in the subvolcanic felsic intrusions underlying some massive sulphide systems, as in the Rio Tinto belt (e.g. Cerro Colorado; compare Chapter 12).

CARPATHIANS, BALKANS, THE HELLENIDES OROGENS

An economically significant porphyry Cu province has been outlined only recently in the Cainozoic ("Alpine") orogen of the Carpathians and in its continuation into the Balkans and Hellenides systems. The

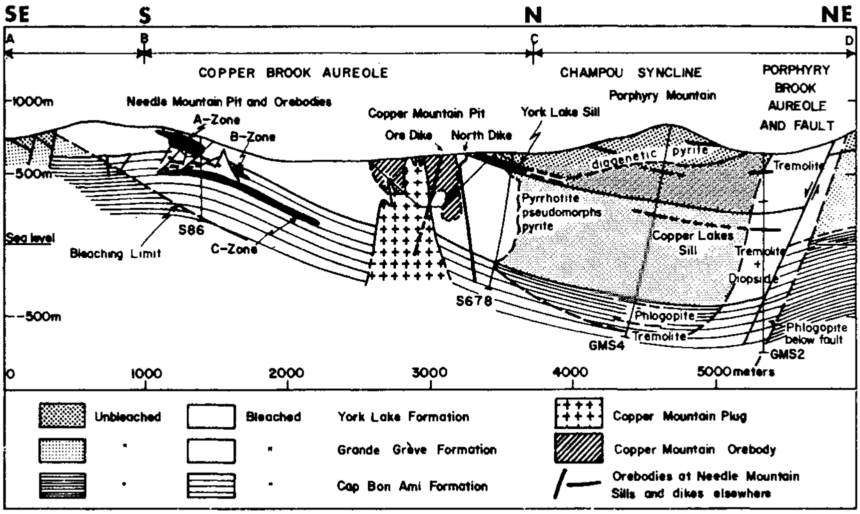


Fig. 28-52. Gaspé Cu field, Quebec, Canada, showing Needle Mountain skarn and Copper Mountain porphyry deposits. From Allcock (1982), courtesy of Economic Geology.

known deposits in Hungary (Récsk); Rumania (Moldova Nouă, Ciclova, Deva, etc.); Yugoslavia (Bor, Majdanpek, Veliki Krivelj, Bučim); Bulgaria (Panagurishte) and Greece (Skouries) are associated with later Cretaceous and Tertiary intrusive activity, and represent some 12.5 Mt Cu.

The Récsk deposit is mostly volcanics-hosted, so it has been reviewed in Chapter 26 as was the Musariu Nou occurrence in the Rumanian Apuseni Mts., and the Yugoslav deposits Bor and Majdanpek. In the Banat district of S.W. Rumania (S.E. of Timişoara; Ianovici and Borcoş, 1982), three parallel N.-S. lineaments are marked by late Cretaceous quartz diorite to quartz monzonite plutons, emplaced in the geologically complex basement of Devonian bimodal volcanic-sedimentary association, Jurassic ophiolites and Cretaceous sediments including limestones, and andesitic volcanics. Several tens of Fe, Cu, Pb-Zn, Ag, Au deposits mostly of vein, skarn and limestone-replacement styles occur in the hydrothermal aureole of the plutons, but endocontact porphyry Cu mineralization has been outlined only recently in about 10 localities.

In the largest exploited deposit, Suvorov in the Moldova Nouă field (230 Tt Cu/0.23%, 43 Tt Mo/0.0043%) disseminated pyrite, chalcopyrite, minor molybdenite in a biotite-altered quartz diorite porphyry grade into magnetite, pyrite, chalcopyrite skarn. The skarn is in the immediate exocontact as well as rafts and inclusions in the intrusive body. Additional porphyry copper localities in the Banat are Ciclova, Sasca Montană, Oraviţa, Lapusnic, and others.

In Bulgaria, the producing porphyry copper deposit Medet is situated in the Panagurishte district in the Sredna Gora Range (Iovchev, 1961). There, late Cretaceous continental explosive andesite, dacite, rhyolite association and comagmatic intrusions were emplaced in a Proterozoic crystalline basement intruded by late Paleozoic tonalite-granodiorite plutons, along a system of W.N.W.-trending fault zones. Medet is a low-grade stockwork of pyrite, chalcopyrite and molybdenite veinlets in a biotite-altered granodiorite and quartz monzonite porphyry endocontact, and in the Paleozoic tonalite exocontact. Several small massive pyrite-chalcopyrite deposits hosted by quartz-sericite altered dacites (e.g. Elshitsa), are probably the subvolcanic equivalents of the "porphyry" ores.

The Serbian-Macedonian Massif, a large block of Paleozoic crystalline basement extending from S.E. Yugoslavia to Greece and Bulgaria, contains several porphyry copper occurrences associated with Tertiary volcanics and intrusive stocks. The ore zone near Radovište, Yugoslavia (Janković, 1982; 459 Tt Cu) is mostly situated in K-silicate altered Proterozoic metamorphics in the exocontact of subvolcanic andesite and hypabyssal quartz diorite intrusions. The occurrences in the Eastern Chalkidiki Peninsula in Greece are associated with granodiorite and quartz diorite porphyries, and they contain one possibly economic orebody (Skouries).

TURKEY, CAUCASUS, IRAN, PAKISTAN

This 3,000 km long portion of the Alps-Himalayas orogenic system is in the eastern continuation of the Balkan-Hellenides belt, and terminates on the Himalayan collisional structures. Throughout almost its entire course, it is marked by numerous rigid blocks of older (probably Precambrian) continental crust, most of them in the position of median massifs. These are surrounded by Mesozoic-Cainozoic foldbelts composed of "eugeoclinal" (marine volcanic-sedimentary) megafacies rocks. Porphyry copper deposits (about 9) and occurrences (about 100) represent some 12.5 Mt Cu and they occur either isolated or in groups. Most are associated with Tertiary hypabyssal intrusions emplaced in the transitional crust along margins of the old continental blocks.

In Turkey, the important copper deposits Lahanos and Murgul (Chapter 26) represent a transition between deposits that are probably volcanogenic or subvolcanic and porphyry coppers, and are sometimes treated as members of the latter category. The Bakircay porphyry Cu showing in northern Turkey is associated with a 42 m.y. old granodiorite porphyry.

The economically important porphyry copper province in the Lesser Caucasus Range of the Soviet Armenia (Pidzhyan, 1975), forms three mineralized clusters within a N.W.-trending Pambak-Zangezur belt. This belt is parallel with the Iranian border and ultimately crosses into Iran. It represents at least 2 Mt Cu and 80 Tt Mo. The most important deposits Dastakert, Kadzharan and Agarak are within the 50 km long southern extremity of the belt, west of the town of Kafan (Zangezur). The porphyry Cu belt formed along the margin of and within an old median massif in the south, south of an ophiolite belt. There, a Precambrian and lower Paleozoic crystalline basement is covered by Devonian to Cretaceous carbonates and detrital sediments. This is topped by an Eocene to Miocene andesite, dacite, rhyolite volcanic pile, and intruded by late Eocene to Miocene high-level granodiorite, quartz monzonite, granite and quartz-feldspar porphyry stocks. The porphyry Cu-Mo deposits are endo- and exocontact (in hornfelsed lower Eocene andesite-rhyolite volcanics) zoned stockworks in K-silicate alteration zones, and of all the Soviet "porphyries" they are most reminescent of the "typical porphyries" of the American Southwest.

The Tertiary volcanic-intrusive belt continues south-eastward across Iran to Baluchistan, and contains the important porphyry Cu deposit Sar Chesmeh (Hakim, 1980; 9.04 Mt Cu). There, disseminated and veinlet chalcopyrite, pyrite and lesser molybdenite lie in a K-silicate altered late Tertiary granodiorite to quartz monzonite stock emplaced in andesites, and laced by several generations of porphyry dikes.

<u>In Saindak,</u> Pakistan (Sillitoe and Khan, 1977), stockwork porphyry copper is in Miocene K-silicate altered tonalite and granodiorite stock intruded into a late Cretaceous to Oligocene volcanic-sedimentary sequence.

BURMA, INDONESIA, EASTERN MALAYSIA REGION

Porphyry copper occurrences have been discovered in the Indo-Burman Ranges, in Sumatra (Lake Singkarak, Tangse), northern Sulawesi (Tapadaa, Tombuililato) and in Borneo, associated with Tertiary high-level intrusives generally emplaced into andesitic volcanics.

<u>The Mamut Mine</u> on the slopes of Mount Kinabalu in Sabah (N.E. Borneo; Kósaka and Wakita, 1978) is, at present, the only deposit being exploited. This deposit has an unusual setting which corresponds to the somewhat unusual alteration style and mineralogy. The basement is part of a broad Cretaceous to possibly Miocene mélange zone (Hamilton, 1979) composed of imbricated flysch sandstone and mudstone intruded by slices of tectonite ultramafics. This has been further intruded by several phases of the late Miocene Kinabalu Batholith, out of which small hypabyssal quartz monzonite porphyry and granodiorite porphyry bodies are responsible for the mineralization. Most of the ore is in pyrrhotite, pyrite and chalcopyrite endocontact disseminations, accompanied by silicification and biotite alteration. The orebody is situated in an outer shell of a quartz monzonite stock, and in a hornfelsed siltstone and serpentinite exocontact. Inward (into the stock), the biotitization changes into tremolite-actinolite alteration and in the core, hornblende alteration is a most likely consequence of hybridization by the ultramafics.

THE PHILIPPINES

The Philippines are a prominent porphyry copper province. Several hundred occurrences are known, and Wolff (1978) listed 75 medium to small deposits and 6 large deposits (over 1 Mt Cu) for which tonnage figures were reported. The overall copper content in the Philippine "porphyries" is of the order of 25-30 Mt Cu. The geology of the Philippines (an active as well as a relic island arc system since the Cretaceous period) and also the ore distribution, were reviewed by Bryner (1969). Wolfe (1973) commented on the special characteristics of the Philippine porphyry coppers that set them apart from the rest of the world, in particular from the "typical porphyries" of Lowell and Guilbert (1970).

The porphyry copper occurrences range in age from late Cretaceous to almost Pleistocene (2 m.y. at Lepanto). They are typically low in Mo and high in Au, associated with quartz-deficient rocks (diorite to quartz diorite) often emplaced in or intermingled with andesite, so that sharp separation of both rocks is impossible ("intimate" andesite-diorite association; compare Chapter 13). The most acidic common rock associated with mineralization is trondhjemite, although quartz porphyries may form dikes or small stocks. In the "Visayan Type" of porphyry Cu deposits introduced by Wolfe (1973) no hypabyssal rocks are associated and the ore is in basic andesites (Chapter 13).

The majority of the Philippine porphyry Cu deposits are related to intrusions emplaced in the vicinity of Tertiary geanticlines into late Cretaceous or early Tertiary metavolcanics. The orebodies are stockworks controlled by faults, so the orebodies tend to be prismatic or tabular and are rarely concentric. Secondary enrichment is minor and usually erratic. Occurrences are known on Luzon, Marinduque, Negros, Cebu and Mindanao Islands.

The Tapian (Marcopper) ore field situated on the small Marinduque Island (Loudon, 1976; 600 Tt Cu/0.58%; Fig. 28-53) has been in production since 1969. There, middle Miocene elongated quartz diorite pluton intrudes folded and low-grade metamorphosed Eocene-Oligocene marine mafic metavolcanics and metasediments that include also reef limestones. Granodiorite, granodiorite porphyry and quartz diorite porphyry in the vicinity of orebodies probably represent a locus of a multiple intrusion. The intrusives and the hornfelsed rocks in their aureole are highly fractured and disrupted by a N.W.-S.E.-trending swarm of faults. Hypogene chalcopyrite, pyrite and magnetite fill fractures in a K-altered and silicified endocontact and to a lesser extent exocontact rocks. There is an irregular secondary enriched zone extending to a depth of 90 m.

NEW GUINEA-MELANESIA BELT

This belt extends from the western tip of New Guinea to Fiji, a distance of almost 6,000 km. About 35 porphyry copper occurrences are known, four of which have reserves over 1 Mt Cu. Geology and

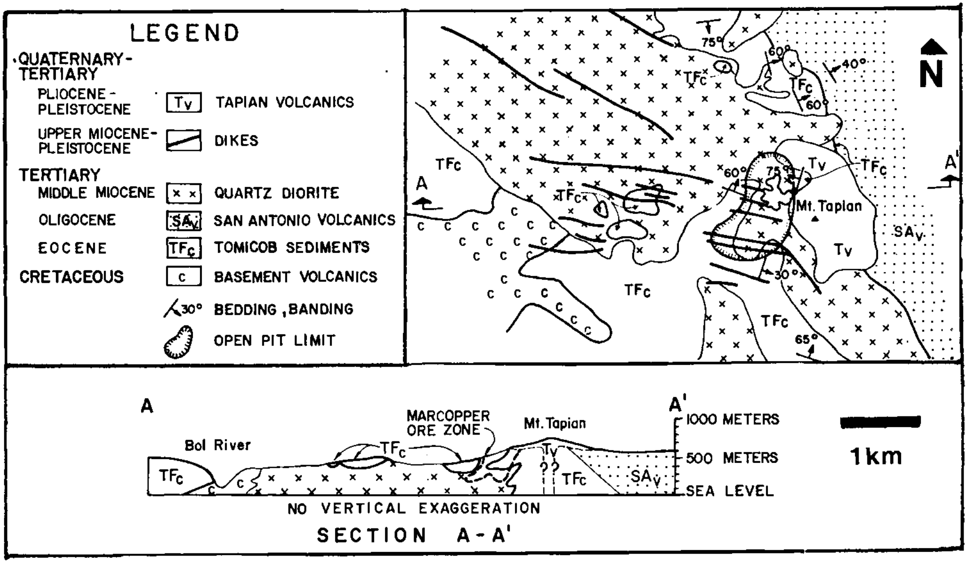


Fig. 28-53. Marcopper porphyry copper, Marinduque Island, Philippines. From Loudon (1976), courtesy of Economic Geology.

"porphyry" characteristics in this belt have been summarized recently by Titley (1975).

The island of New Guinea is underlain in the south by the stable continental crust of the Australian block, covered by Jurassic to Quaternary sediments. These change northward into an increasingly more structurally complex and metamorphosed sequence of an orogenic belt. This belt consists of Triassic to Eocene (meta)sediments and (meta)volcanics including, in the south-east, an ophiolite belt. The deformed rocks are intruded by an Oligocene to Pleistocene suite of diorite, granodiorite, syenite and granite. The large, low-grade porphyry copper deposits (Ok Tedi, Frieda River, Yandera) are associated with diorite or quartz diorite plutons and their late-stage hypabyssal differentiates, and the mineralization is in geological terms very young (middle Miocene to 1.2 m.y. old). Despite the difficult access, the large "porphyries" have recently been described in detail in a series of papers in Economic Geology.

The Ok Tedi (Mount Fubilan) deposit located near the Indonesian border (Bamford, 1972; 2.33 Mt Cu, 262 t Au) has the distinction of being the world's youngest porphyry copper deposit (1.2 m.y.). It is a part of a W.N.W.-trending tectonic belt of unmetamorphosed Tertiary and older detrital and carbonate sediments, intruded by a number of small Plio-Pleistocene diorite plutons. The ore deposit consists of a central, distinctive orthoclase-rich cylindrical intrusion of quartz latite porphyry, mineralized by disseminated chalcopyrite, bornite and marcasite in a potassic alteration zone. The intrusion is surrounded by a number of magnetite and chalcopyrite skarn bodies and a pyrite-pyrrhotite massive replacement body in the exocontact limestones. Supergene alteration is intense and chalcocite replaces the hypogene minerals to a depth of 330 m. This is topped by an oxidized and partly leached capping that includes a residual gold orebody. Data on the Frieda River and Yanderra deposits, two remaining large porphyry coppers on the New Guinea (Niugini) mainland, appear in Table 28-3.

The Melanesian island arc chain includes the territory of Niugini (New Britain, New Ireland, Bougainville, and other islands), Solomon Islands, New Hebrides (Vanuatu) and Fiji. These islands, already mentioned in Chapter 5 (Davies, 1978; Arthurs, 1979; Colley and Greenbaum, 1980), consist of Tertiary or latest Cretaceous marine to continental volcanics with volcanogenic and biogenic (coral limestone) sediments, intruded by contemporary plutonic rocks. These rocks formed on or within an oceanic or a "quasi-oceanic" crust. Major porphyry prospects are on New Britain (Uasilau, Kulu, Pleysumi, Pelapuna), New Ireland (Legusulum), Manus Island (Mt. Kren), Guadalcanal (Koloula), Viti Levu (Namosi area) and other islands. The Panguna deposit on the Bougainville Island is the largest deposit, in production since 1972. The large Waisoi Prospect (2.29 Mt Cu) in Fiji is volcanics-dominated and was reviewed in Chapter 26.

Panguna deposit (Baumer and Fraser, 1975; 4.32 Mt Cu, 450 t Au, 2.7 Tt Ag; Fig. 28-54) is a young (3.4 m.y.) system of chalcopyrite, bornite, pyrite, lesser magnetite, molybdenite veins, stockworks and disseminations. It is situated on the edge of a Pliocene high-level intrusive complex of granodiorite and quartz diorite porphyries, emplaced in a slightly older quartz-diorite pluton and Oligocene

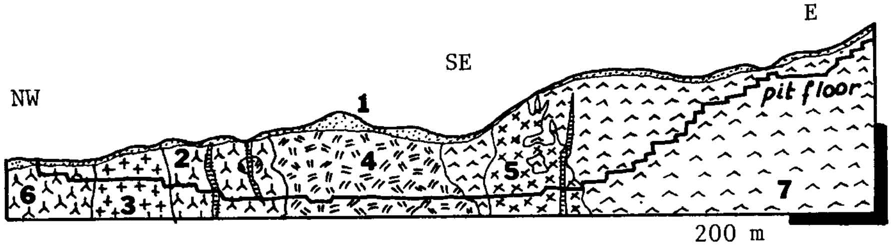


Fig. 28-54. Panguna porphyry copper deposit, Bougainville Island, Niugini. 1=Q volcanic ash, landslide, alluvium; 2=Pl pebble dikes; 3=Pl, granodiorite; 4=Pl, biotite granodiorite (concentrator intrusion); 5=Pl leucocratic quartz diorite; 6=biotite diorite; 7=Ol_1Mi_1 andesite and volcanic breccia. The orebody is approximately indicated by the pit outline. From LITHOTHEQUE, simplified after Baldwin et al. (1978).

hornfelsed andesite. The ore is in both endo- and exocontact, best developed in the zone of biotite alteration. Supergene alteration caused argillization and leaching, but no regular enrichment zone formed.

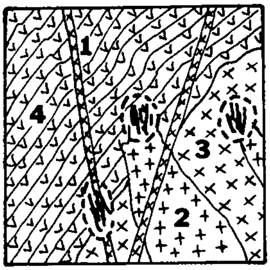
NORTH-EASTERN ASIAN BELT

This is an enormous region extending from Indochina to the Koryak Range of Siberia, unified by our ignorance rather than by geology. Included in this region are segments of a great Mesozoic to lower Tertiary andesite, dacite, rhyolite continental margin volcanic belt (in S.E. China and in the Okhotsk-Chaun volcanic belt), as well as segments of the presently active island arc (Taiwan, Japan, Kuriles, Kamchatka). It is puzzling that, given the many points of similarity with the "porphyry belts" reviewed so far and the general geological favourability, there are so few porphyry copper showings known; the best described ones being on the Kamachatka Peninsula (Tumannoye, Krasnogorskoe) and economically, the most important ones in China (e.g. the Tehsing district in Kiangsi, estimated size 8 Mt Cu). Basic information about the "porphyry" occurrences in the north-eastern U.S.S.R. can be found in Laznicka (1976a).

THE URALS BELT, U.S.S.R.

The Urals form a N.-S.-trending Paleozoic orogenic belt 2,000 km long, separating the Russian and Siberian platforms. Their complex geology is dominated by a Cambrian to Carboniferous, mostly mafic marine volcanic-sedimentary association, that hosts several hundred volcanogenic massive sulphide deposits (compare Chapters 10-14). Plutonic rocks were emplaced in several periods, but only Devonian to Carboniferous "granites" have a significant aureole mineralization, mostly of gold. The thirteen "porphyry Cu" occurrences usually listed (Laznicka, 1976a) are in the massive sulphides-mineralized terrains. Some "porphyry coppers" are closely associated with massive sulphides mostly as deeply eroded equivalents of felsic domes underlying and feeding seafloor-deposited conformable sulphide lenses. One deposit (Tsessovka) has been reviewed in Chapter 14. Others are similar in style to the "diorite-model" porphyry coppers of Hollister (1978).

The Voznessenskoe deposit (Fig. 28-55), the only one for which a pre-war reserve figure is available (250 Tt Cu), has a low-sulphur chalcopyrite, bornite, pyrite and magnetite stockwork and veins controlled by faults in Devonian gabbros and syenites, and exocontact greenstones. The orebodies are linear to irregular and are accompanied by diffuse albitization, epidotization and chloritization. In the Turya (Tur'inskoe) and other magnetite and chalcopyrite skarn fields of the Urals, minor Cu veins and stockworks have occasionally developed in the granodiorite or quartz diorite endocontacts. The Ural-Tobol anticlinorium east of the central "eugeoclinal" belt



1. porphyry dikes
2. D_{1-2} quartz monzonite, granosyenite
3. quartz diorite, gabbro
4. D_2 metabasalt, spilite-keratophyre, metasediments

Fig. 28-55. Voznessenskoe stockwork Cu deposit, the Urals; diagrammatic representation. After Laznicka (1976a).

intruded by Carboniferous "granites", is a setting where one would expect to find porphyry deposits of the S.W. United States style. Unfortunately, this zone is deeply eroded and the only better known "porphyry" occurrence is the Yelenovo quartz, tourmaline, chalcopyrite stockwork in Silurian and Devonian volcanics intruded by a granosyenite.

CENTRAL KAZAKHSTAN, U.S.S.R.

This strongly block-faulted region centered on Lake Balkhash is located near the junction of four major cratonic blocks. It includes orogenic units ranging from lower Paleozoic to Permian in age of which metallogenically the most fertile had been the Devonian to Permian period of widespread marine to continental basalt, andesite, rhyolite volcanism and intrusive activity. The North Balkhash (Cisbalkhash) porphyry copper region represents some 15 Mt Cu, most of it in the giant Kounrad deposit. The porphyry coppers are associated with silicification and sericitization of Carboniferous granodiorites, and mineralization in the K-silicate alteration assemblage is less common (Kaskyrkazgan and Ken'kuduk occurrences). This region has already been discussed (Section 28.2.2.).

The relatively small Boshchekul' orogenic belt located in the N.E. part of Central Kazakhstan has a late Paleozoic metamorphosed chert-spilite association at its base, overlain by Cambrian and Ordovician "arc" flysch and volcanic assemblage. The large Boshchekul' porphyry copper deposit (2.16 Mt Cu, 0.4-0.81% Cu) is a member of the "diorite-model", affiliated to diorite and monzonite porphyry dikes that are probably of middle Carboniferous age, intruding lower Cambrian propylitic and amygdaloidal metabasalt flows, tuffs and volcanic arenite. The veinlet and disseminated chalcopyrite lies in both the endocontact and exocontact of the hypabyssal intrusions, in a zone of propylitic alteration (Trofimov, 1973).

It appears that patchy K-feldspar metasomatism is also present. The bulk of the economic ore at Boshchekul' comes from the secondary chalcocite zone and to a lesser extent from the oxidation zone with malachite.

TIAN-SHAN OROGEN, SOVIET CENTRAL ASIA

Tian-Shan is a complex Hercynian (late Paleozoic) orogen located south of the Central Kazakh block and continuing into the Sinkiang Province of China. This is essentially a Pb-Zn, W and Au province and copper is rare, yet the important Almalyk porphyry Cu district with several producing mines is located in the Kurama Range, S.E. of Tashkent. The Almalyk district (Musin, 1970) contains 338 copper occurrences distributed over an area of approximaletly 300 km^2. Two large deposits (Kalmakkyr, Fig. 28-56, and Sary-Cheku) are in production. Veinlet and disseminated chalcopyrite-molybdenite ore occurs in K-feldspar, biotite and quartz-sericite alteration envelopes (1) in middle-upper Carboniferous granodiorite porphyry stocks and (2) in large rafts and blocks of lower-middle Carboniferous syenodiorites and quartz porphyries of the Karamazar Batholith. Most of the ore comes from chalcocite blankets and the overlying oxidation zone. The adjacent and basement Devonian and lower Carboniferous carbonates frequently contain skarn and replacement magnetite and chalcopyrite occurrences, replacement Zn-Pb, vein Au, helvite (Be) metasomatites and Pt-Pd-bearing massive replacement pyrite pipes. The Kalmakkyr deposit has dimensions of 3x1.3x0.5 km, the ore grade was 0.8% Cu for the oxide ore and 0.72% for the sulphide ore, and the pre-war reserves were 2.1 Mt Cu.

ZAYSAN, ALTAI, SAYAN OROGENS (S. SIBERIA, N. CHINA, MONGOLIA)

This is a complicated assemblage of N.W. and E.-W.-trending Paleozoic orogenic belts wrapping around the southern tip of the Siberian Platform between Tian-Shan and Lake Baikal (Laznicka, 1976a). The geology is too complex to summarize briefly. Several clusters of porphyry copper showings are known to occur in the Zaysan (Rudnyi Altai) belt (Bukhtarma, Novonikolaevskoe), in the Kuznetsk Alatau Range and its eastern extremities (Batenevski Range; e.g. Kiyalykh-Uzen and Sora fields) and in the northern Mongolia (Erdentuin, Tsagan Suburga districts). The "porphyries" are associated with Cambrian diorites and syenites and grade into skarns (Kuznetsk Alatau); with Devonian granite porphyries, granosyenites and alaskites (Batenevski Range); with Carboniferous subvolcanic quartz-feldspar porphyries (Rudnyi Altai) and with Permian granite, granodiorite and granosyenite porphyry (Erdentuin). The last locality is a major industrial deposit (about 3 Mt Cu/1%).

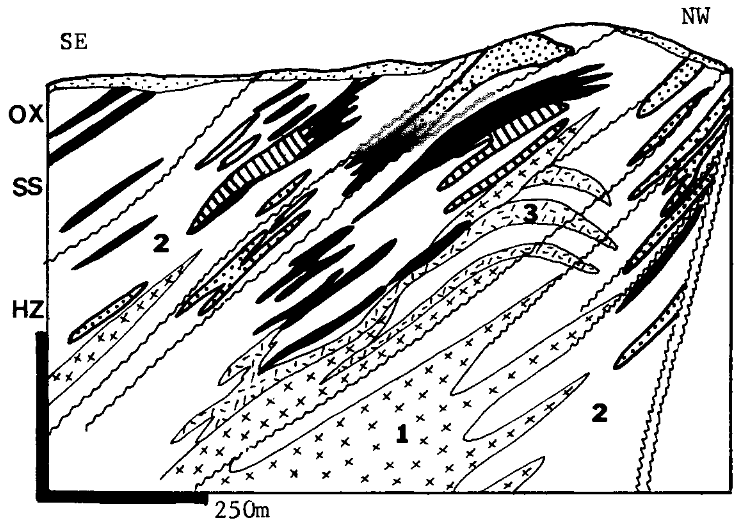


Fig. 28-56. Kalmakkyr porphyry Cu-Mo deposit, Almalyk district, Uzbekistan. Cb_{1-2} intrusive rocks: 1=granodiorite porphyry; 2=syenodiorite, diorite; 3=quartz porphyry. Zones of complete alteration (metasomatites): black: silicification; diagonally ruled: K-silicates; dots: sericitization. Supergene zones: OX=oxidation; SS=chalcocite; HZ=hypogene zone. After Musin (1970), scale and orientation added.

EASTERN MONGOLIA, EAST TRANSBAIKALIA, AMUR BELT

This belt, located in the eastern extension of the territory described earlier, is marked by a largely continental faulted old basement intruded by several generations of granitic plutons during the late Paleozoic orogeny and Jurassic-Cretaceous "activation". This is largely a Sn-W-Mo province affiliated with the Mesozoic epizonal plutons, and copper is recovered as a by-product of several vein and stockwork molybdenite deposits (e.g. Shakhtama). The Aryn-Nur showing in Mongolia (Marinov et al., 1977) has a transitional porphyry Cu-Mo mineralization associated with Jurassic granites emplaced in a Permian batholithic environment. The K-feldspar alteration is gradational into greisenization.

TASMAN OROGENIC BELT, EASTERN AUSTRALIA

The Tasman Belt traceable from Cape York to Tasmania is a composite Paleozoic orogen marginal to the Australian craton in the west. It is usually described in terms of three segments separated by post-orogenic basins. Almost 120 porphyry Cu occurrences are known. Of these, 85 are in the northern Queensland segment (Horton, 1978). In the entire orogen, there is, so far, only one large deposit (Goonumbla, N.S.W.; 2.28 Mt Cu) which has been described under the heading "volcanic porphyries" in Chapter 26, and 3 to 5 small deposits, not exceeding 100 Tt Cu (Moonmera and Coalstoun, Queensland; Copper Hill, N.S.W.). The Queensland "porphyries" (Horton, 1978) are associated with Silurian to early Cretaceous granodiorites and quartz monzonites, emplaced in a variety of basements out of which andesitic volcanics are the most common. Fracture-controlled mineralization, usually patchy, is controlled by a weak potassic alteration, but phyllic and propylitic assemblages are present in most cases. Porphyry coppers in the southern (Lachlan) segment resemble most closely the Uralian deposits and occur in settings that also contain volcanogenic massive sulphide deposits.

28.6. COPPER SKARNS AND CARBONATE REPLACEMENTS

About 20 Mt Cu are contained in skarns areally associated with porphyry copper systems, and possibly another 6 Mt are to be found in skarns or replacements hosted by carbonates in the contact region of "barren" intrusions. This represents less than 3% of the world's economic copper. Despite this, at least 1,000 individual copper skarn localities have been recorded, ranging in size from several tons of Cu to 4.73 Mt Cu (at Twin Buttes, Arizona). Accessory amounts of copper are present in and locally recovered from, skarns and replacements mined for other dominant metals (Fe,Pb-Zn,W,Sn).

Copper as well as other skarns have been reviewed recently by Einaudi et al. (1981), who summarized their characteristics as follows: (1) Cu skarns are associated with syn- to late-orogenic continental margin calc-alkaline granodiorite to monzonite stocks. The stocks are porphyry-textured, hypabyssal, locally converted to pyroxene-garnet endoskarn in a narrow zone along the contact, and frequently pervasively altered (K-silicate and phyllic alteration). (2) Compositionally, they have high garnet to pyroxene ratios, relatively oxidized assemblages (andraditic garnet, diopsidic pyroxene, magnetite and hematite) and moderate to high sulphide contents. (3) Sulphides occur as disseminations, as massive streaks, as veins and stockworks in fractured and brecciated skarns, and as massive marble replacements at the skarn front metacarbonates. In calcic skarns the pyrite, chalcopyrite, magnetite assemblage is characteristic of the more proximal contact garnet zones, bornite and chalcopyrite association is most common in the outer wollastonite zone. (4) Most Cu orebodies are in calcic, rather than magnesian, skarns and they have the form of mantos, pipes, stockworks, or irregular bodies. (5) Some pyrite, chalcopyrite, bornite replacements and open space fillings occur within or outside the skarn zone, associated with retrograde hydrous silicates, most characteristically actinolite and chlorite. Retrogression often "spreads" the mineralization outside the skarn assemblage, into fractured marbles.

Skarns are typical interaction deposits and in searching for them the characteristics of both the supracrustal association that hosts them, and of the plutonic association that generates them, are important. The most "natural" associations hosting Cu skarns are the "eugeoclinal" suites dominated by trace copper-rich marine or continental mafic volcanics (basalts and andesites), interbedded with or topped by carbonates. Examples of such associations including short descriptions of several Cu-Fe skarns have been given in Chapters 10, 12 and 13. Cu skarns are common in belts mineralized by volcanogenic massive sulphides (e.g. in the Urals), where they are related to either an early, evolutionarily immature phase of plutonism (sodic plagiogranite), or to later calc-alkaline intrusions. In this setting it seems probable that, at least a portion of the Cu and Fe, was derived from the mafic volcanics.

Important skarns, however, are also hosted by platformic or "miogeoclinal" carbonates as in the western United States (Bingham, Santa Rita, Ely), completely lacking any volcanics. There, Cu and Fe were clearly brought in from some depth with the intrusive system and the sedimentary association itself gives no clues as to the possible Cu skarn presence, except for the universally valid indicators such as the intensity of fracturing and signs of contact and hydrothermal metamorphism.

As for the intrusion favourability, a general rule is that whichever intrusion hosts (or is considered suitable to host) porphyry coppers, it could also generate skarns when carbonates (or calcic tuffs, shales, etc.) are locally available. The range of intrusive favourability for Cu skarns is, however, broader than for the porphyry Cu. In the Urals where porphyry Cu are rare and of little industrial importance, skarns are widespread and economically important.

Brief data on Cu skarns are summarized in Tables 28-4 and 5. The Christmas deposit, Arizona, is described in greater detail below as a typical example. The reader is also referred to the description of several British Columbia Cu skarns in Chapter 10, and the Tur'ya field, the Urals, in Chapter 12.

Christmas mine (Eastlick, 1968;, 700 Tt Cu/0.7%; Fig. 28-57) is 12 km N.E. of Hayden, Arizona. The orebodies are located in three Devonian to Pennsylvanian limestone, dolomite and shale units, overlying Cambrian quartzite. These are topped by late Cretaceous continental andesite flows and pyroclastics. The mine area is

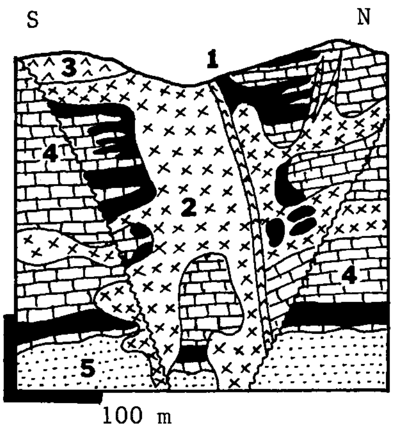
Table 28-4. Chalcopyrite (bornite)-bearing skarns, 1: associated with porphyry Cu mineralizations in the endocontact

LOCALITY	HOST ASSOCIATION, INTRUSION	MINERALIZATION	REFERENCES
Craigmont mine, Merritt, British Columbia, Canada	Tr_3 m-graywacke, limest., mylonite; Tr_3-J_1 andesite, diorite, quartz diorite. Minor access. dissem. cp. in qtz. dior., Highland Valley porph. Cu field adjacent	1) dissem. magn., cp., specularite in exoskarn; 2) late stage fract. veins of coarse pink feldspar with cp., mag., specularite. 515 Tt Cu/1.77%	Chrismas et al. (1969)
Bingham, Utah, U.S.A.	Ps calcar. sandst., quartzite, limestone; 39-32 m.y. qtz. monzon. porph., qtz. feldsp. porph., contain major porph. Cu-Mo orebody	widespread garn., pyrox., pyr., cp., born. contact rim skarn; 3.8 Mt Cu/1.2-2%	Lanier et al. (1978)
Ely, Nevada, U.S.A.	D-Pe hornfelsed shale, limestone; Cr_1 qtz. monzonite porphyry; major porphyry Cu-Mo orebodies	quartz, calcite, magn., pyr., cp., veins, veinlets, replacements superimp. on earlier garn.-pyrox skarn and in marble; 1 Mt Cu/1%	James (1976)
Christmas, Arizona, U.S.A.	Cm, sandst.; D-Ps limest., dolom., hornfelsed shale; 62 m.y. biotite diorite to qtz. diorite; minor endocont. dissem. cp.	calcic and magnes. exoskarn mineraliz. by magn., cp., born.; mantos, contact masses, fract. lodes; 700Tt Cu/0.7%	Eastlick (1968)
Twin Buttes, Arizona, U.S.A.	PZ limest., hornf. shale; Tr-Cr contin. volcanics; Cr_3-T_1 quartz monzon., andes., rhyol. dikes; major porph. Cu (1.18 Mt Cu)	widespread masses of garnet, pyrox., quartz, magn., pyr., cp., skarn; 4.73Mt Cu/0.78%	Einaudi et al. (1981)
Mission, Arizona U.S.A.	PZ limestone, hornfelsed shale; 60 m.y. qtz. monzon. porphyry with major porph. Cu miner. (268 Tt Cu)	garnet, pyrox., cp., pyr. skarn; high-grade bornite replacements in marble; 1.072Mt Cu/0.8%	Einaudi et al. (1981)

Santa Rita, New Mexico, U.S.A.	Cm-Pe hornf. shale, carbonate 63 m.y. granodior.,qtz.monzonite stock with major porph.Cu-Mo	garnet, epid.,magm.,cp. and late stage pyr.,qtz.,actinolite, skarn; 900Tt Cu/0.9%	Hernon and Jones (1968)
Yerrington, Nevada, U.S.A.	Tr_2-J metaandes.,rhyol.,hornf. sandst.,shale,black shale,limest. J, granod.,qtz.monzon.,porph. Cu	many small endo- and exoskarn deposits: magn.,ludwigite, cp., consid.second.enr. and oxide minerals (chrysoc.,malach.); 2.5 Mt Cu/0.54% (with porph.Cu)	Harris and Einaudi (1982)
Cananea (Capote Basin,Puertecitos), Sonora, Mexico	Cm-Cb limest., dolom., minor quartzite; MZ volcanics; T_1 qtz. monzon.porph.,major porph.Cu-Mo	Capote Basin:cp.,sphaler.,calc., hemat. manto superimp. on brecc. older skarn; 350Tt Cu, 400Tt Zn.	Meinert (1982)
Gaspé field, Murdochville, Québec	D_1 hornfelsed calcar.siltstone to limest. D_3-Ms rhyodac.porph. sill, plugs; porph.Cu miner.	dissem. cp. in calc-silic.hornfels, less in fine grained skarn in exocont.,often parall. with bedding; 1.2Mt Cu	Allcock (1982)
Banat (e.g.Moldova Nouă), S.W. Rumania	J-Cr limest., hornfelsed shale Cr_3-T_1 granod.,dior.,qtz.diorite; low-grade porph. Cu-Mo	garn.-magnet.skarn,rims and rafts in intrusion, contains inclus.,dissem.,masses of cp., pyr. Estim. 100Tt Cu	Ianovici and Borcoş (1982)
Ok Tedi (Mt.Fubilan), Niugini	MZ-T fine clastics, Ol-Mi limest. 4-1.2 m.y. dior.,monzon.stock wit major porphyry Cu orebody	massive garnet,pyrox. skarn and massive pyr.,pyrrhot.,cp., replacements in limest. 750Tt Cu	Bamford (1972)

Table 28-5. Chalcopyrite or bornite-bearing skarns,2: associated with "barren" intrusive stocks

LOCALITY	HOST ASSOCIATION,INTRUSION	MINERALIZATION	REFERENCES
Méme, Haiti	Cr_3 limestone,andesite flows and tuffs; Cr_3 (66 m.y.) syenodiorite, granod.,dikes and stocks	5-70 m wide zone of skarn surrounds marble pendant; garnet-epid.,diops.skarn,mass.+dissem. magn.,cp,pyr.,moly. 30Tt Cu/2.5%	Kesler (1968)
Cobriza, Cordillera Oriental, ea-tern Peru	PZ slate,sandst.,limest.,congl. T_1 quartz monzonite stock	magn.,lesser cp.,ars.,pyr.,in banded hornbl.,diops.,quartz skarn; 600Tt Cu/1.3%, 650 t Ag	Petersen (1965)
Tintaya, Cordillera Occidental, southern Peru	Cr, limestone, shale T, granodiorite, qtz.monzonite	s-shaped, narrow skarn zone (magn.,cp,born.,chalcoc.) topped by 80m deep oxid.zone; 996Tt Cu/2.12% (hypog.z.)	Eng.Min.Journ. Nov. 1984
Sayak, central Kazakhstan, U.S.S.R.	Cb_{1-2} marine andesite flows,volcanicl.,arenite,shale,limestone; Cb_{2-3} granod.,qtz.monz.,stocks, dikes	N.-S.zone of faults miner.by magnetite skarn; cp,born.,moly., pyrrh.superimp.,assoc.with epid.,actinolite along fract. Estim. 600Tt Cu	Samonov and Pozharisky (1974)
Tongling distr., central China	PZ_1-J shelf sedim.(shale,sandst., limest.) incl.thick Tr limestone. J qtz.diorite, granodiorite	several hundred magn.,cp.,born., oreb. in garnet-pyrox. exocont. skarns; est.400Tt Cu/1.18%	Min.Magazine Aug. 1980
Kamaishi mine, N.Honshu,C.Japan	Cb andes.m-pyrocl.,slate,limest. Cr_1 diorite, diorite porphyry	linear,N.-S.line of magn.,cp., pyrrhot.,cubanite in garn.-pyroxene exoskarn; min.80Tt Cu	Uchida and Iiyama (1982)
Ertsberg, W.Irian, Indonesia	PZ sandst.,phyll.,limest.,volc., coal; T,limestone; 3.1 m.y. granodiorite intrusion	plug-like magn.,cp.,born. oreb. in garn.,diops.,actin.,chlorite, epid.skarn in a m-carb. block engulfed by granod. 825Tt Cu/2.5	Adams (1973)



1. T, andesite dikes
2. Cr_3-T_1 quartz-mica diorite
3. Cr_3 subaerial andesite flows and pyroclastics
4. D-Ps limestone and dolomite
5. Cm sediments, mainly quartzite

BLACK: exo- and lesser endoskarn with disseminated chalcopyrite

Fig. 28-57. Christmas mine, Arizona, a Cu-skarn deposit. From LITHOTHEQUE, based on data in Eastlick (1968).

intensively block faulted and intruded by a "Laramide" quartz-mica diorite porphyry stock and by a swarm of lower Tertiary dikes. In the central part of the intrusive stock, magmatic stoping caused fragmentation of the gently dipping sediments and their engulfement in the diorite to form "floating" blocks, rafts, vertical sheets and xenoliths. The sediments are hornfelsed and recrystallized in the intrusive aureole and the carbonates in proximity of the intrusion are converted to skarn.

Calcic skarn (andradite, diopside) formed in the stratigraphically higher limestones. Magnesian skarn (forsterite-magnetite) is contained in the lower dolomites. Christmas mine is well known for the strong postmagmatic hydrothermal endoskarn alteration in the diorite. At some distance from the orebody, hornblende and biotite are replaced by clinopyroxene, and plagioclase is epidotized or argillized. Brown crystals of sphene appear as a common accessory. Close to the contact, diorite is non-selectively replaced by garnet which, in turn, may be selectively substituted by diopside. The endoskarn is not substantially mineralized, but small disseminated pyrite-chalcopyrite porphyry copper orebodies occur at several places in the ore field, accompanied by potassic alteration.

The principal orebodies occur in both the calcic and magnesian endoskarns and they are tabular bodies that selectively replaced carbonate beds interstratified with the silicate beds, irregular masses along the subvertical intrusive-sedimentary contact, subvertical mineralized skarn sheets along faults and irregular replaced carbonate rafts in the diorite. The largest and most continuous orebody in the lowermost (Devonian) limestone has, overall, the shape of a ring, surrounding the diorite stock. Disseminated chalcopyrite and bornite are interstitial to the silicates in skarn, or form veinlets or swirly layers interbanded with magnetite and silicates.

The enigmatic Ruby Creek Cu orebody in the Brooks Range, Alaska (Runnels, 1969; 1 Mt Cu/1%) has epigenetic replacements of chalcopyrite, pyrite, bornite, tennantite and chalcopyrite in Devonian limestone. Cymrite, a barium silicate, and some jasper are the principal alteration minerals and there are no skarn silicates. The Cu orebodies are peneconcordant lenses (mantos), and there is widespread diagenetic pyrite in the associated black phyllites. Cretaceous albitic gneissic granite and soda-aplite are present in the vicinity. The general context of this mineralization suggests a proximal hydrothermal remobilization of a copper probably geochemically enriched in the sedimentary sequence or in a gabbro sill complex.

Large replacement mantos of copper sulphides in silicified (jasperoid) carbonates far outside skarn zones are rare. This contrasts with the abundant Pb-Zn sulphides in equivalent settings.

28.7. COPPER VEINS

Copper sulphides-dominated fissure veins can best be thought of as an end-member of complex and gradational copper mineralized systems. They occur in the company of porphyry copper stockwork complexes (the late stage veins in Butte), as minor remobilization or feeder veins in and around volcanics-hosted massive sulphide deposits, as remobilized veins in mineralized sediments such as the Kupferschiefer and in association with skarns. Where fissure veins occur independently of disseminated, massive or stratabound copper sulphide accumulations, only a few are dominantly copper-bearing. Copper is common in most polymetallic (Pb-Zn), "silver" (e.g. tetrahedrite veins), cassiterite, uranium, siderite, and other veins in lesser quantities, and may be recovered as a by-product. Most veins have probably been filled by metals precipitated from convecting hydrotherms. Although most such hydrotherms were probably driven by the heat from "granitic" intrusions, other alternatives have also been recognized. Of these, gabbro and diabase intrusions related to crustal extension have also affiliated Cu veins (e.g. Churchill River field, British Columbia). These are treated in Chapters 31 and 32.

The number of examples of hydrothermal-plutonic dominantly Cu veins listed in classical textbooks shrunk considerably as a consequence of genetic reinterpretation. It is interesting to note how many localities have been excluded from the category of "Mesothermal Cu veins" listed in Schneiderhöhn (1955). Kitzbühel, Britannia mine, Hidden Creek and others are now considered to be deformed volcanics-hosted massive sulphides and Copper Mountain is now an example of the "diorite-model" porphyry copper. The remainder of "true" granite-affiliated Cu veins, however, still represent some 3 Mt Cu and although this is less than 0.5% of the world's copper contained in ores, it could be of significance locally. The largest Austrian copper deposit Mitterberg, for example, is a vein.

Table 28-6 lists selected examples of dominantly Cu veins, and it is apparent that each locality has a high degree of individuality and modern typification is virtually impossible. The common features of these veins include: (1) pronounced structural control and (2) occurrence in a "granite" exo- or endocontact, in regions that are distinct "copper provinces", that is containing other styles of Cu accumulations as well, most of them economically more important than the veins. Cu veins are thus often useful exploration leads. (3) Proximity to a unit rich in trace Cu, a postulated Cu source (e.g. greenstone, gabbro, diabase, red beds sediments, some black "shales").

Naturally, there are numerous exceptions. The copper-bearing lodes near Redruth, Cornwall, very productive in the past, constitute a link between Sn and Cu provinces. Copper is abundant when "greenstones" are present in the wallrock suite. The chalcopyrite-bearing siderite or quartz, siderite, barite veins that have a wide distribution in the Paleozoic phyllite and schist cores of the Alps and Carpathians (e.g. Mitterberg, Slovinky) do not show clear association with "granites", but buried plutons are now postulated under the Spiš-Gemer region of Slovakia.

Most copper veins contain chalcopyrite, sometimes with bornite, as the main ore minerals. The common gangue associations are quartz (e.g. Tocopilla); siderite, lesser quartz, specularite, barite, ankerite (Mitterberg, Slovinky); quartz-tourmaline; quartz-chlorite; amphibole, chlorite, tourmaline and other silicates (Carrizal Alto); axinite, etc. Some veins are dominated by tetrahedrite and these are mined mostly for silver (e.g. Sunshine, Idaho). Fissure veins may grade into stockworks and replacements in carbonates (e.g. Schwaz, Austria). The wallrock alterations include either or all alterations known from porphyry coppers (K-feldspathization, biotitization, quartz-sericite alteration, propylitization) and in addition to this silicification, tourmalinization, carbonatization and light bleaching. Alteration usually forms narrow selvedges in the vein wallrocks. Where systems of closely spaced veins formed, the alteration can affect large blocks of rocks.

The Magma mine in Superior, Arizona (Hammer and Peterson, 1968; 657 Tt Cu) is a frequently quoted example of a hydrothermal Cu vein. It is hosted by a Proterozoic and Paleozoic sequence of folded and faulted schist, diabase, quartzite, shale and limestone, intruded by Cretaceous to Tertiary stocks and dikes of quartz diorite, diorite porphyry and quartz monzonite porphyry. The Magma vein follows an east-west fault and has been traced to a depth of 1,500 m. It is a branching and splitting sheet composed of high-grade quartz, pyrite, chalcopyrite, bornite, enargite, tennantite, chalcocite and other minerals that have replaced fault gouge and the sheared wallrocks. Up to a depth of 300 m, supergene leaching and sulphide enrichment took place. At an intersection with Devonian limestone, a replacement manto formed.

The Rosen ore field (Burgas district, E. Bulgaria; Iovchev, 1961; 77 Tt Cu; Fig. 28-58) is an example of Cu veins that have a setting almost equivalent to the "diorite model" porphyry coppers. There, 230

Table 28-6. Hydrothermal Cu sulphide veins, selected examples

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Magma mine, Superior, Arizona, U.S.A.	Pt_1 schist, Pt_{2-3} quartz., diabase; Cm-Ps limest., dolom., shale; Cr_3-T_1 qtz.dior., qtz. monzon.stocks, dikes	Cr_3-T_1 E.-W./65°N composite replac. vein in shear; qtz., pyr., cp., born., chalcoc., sphal., etc. filling. Manto formed at inters.of vein with lim. Ox.and sulph.enrichment; 675Tt Cu/5.69%; 716t Ag; 12.4t Au	Hammer and Peterson (1968)
Tocopilla, northern Chile	J, mesozon. tonalite pluton intr.into contin.to marine J metabasalts, metaandes., diab.	6 en echelon N.E. fract. veins; qtz., specul., magnet., pyr., cp., minor moly, U, Co, Ni. Oxid.and sulph. enr.zone; 110Tt Cu/3.1%	Ruíz (1965)
Carrizal Alto, Atacama, Chile	MZ diorite, empl.into PZ_1 ? quartzite, phyll., micaschist; diabase dikes	N.E. fiss. veins, hornbl., tourm., chlor., qtz., calc., apatite, pyr., cp., tetr. Chlorite alter., 150 Tt Cu/5%	Ruíz (1965)
Cornwall and Devon Cu veins, S.W. England, U.K.	D_1-Cb_3 slate, shale, sandst., limest., greenst., intr.by Cb_3-Pe high-level granites	fissure or bedding quartz, chlorite, tourm., cp., born., veins with or without cassiterite (e.g.Devon Great Consols, Dolcoath); 2 Mt Cu	Dunham et al. (1978)
Mitterberg mine, Austria	S, black and green phyllite Cb_3 quartzite, congl., chlor. schist (metam.red-beds)	E.-W./40-90°S, 4.5 km long fissure vein; qtz., siderite, pyr., cp., specularite; 180Tt Cu/1.4%	Bernhard (1966)
Rosen, Burgas district, E.Bulgaria	Cr_{2-3} andes.and latite lavas and tuffs, intr.by T_1 gabbro, monzon., syen.pluton, stocks	230 N.E. fiss.veins; qtz., pyr., specul., chlor., epid., cp.; wallrock silicif., chloritiz.; ox. and enrich. zones; 77Tt Cu/1.44%; 161t Mo	Iovchev (1961)
Vrli Bryag, Burgas distr., E. Bulgaria	same setting as Rosen	53 N.E. striking fiss.veins over 1 km long in volc. along intrusive cont. Fill as above, 48Tt Cu/1.42%	Iovchev (1961)

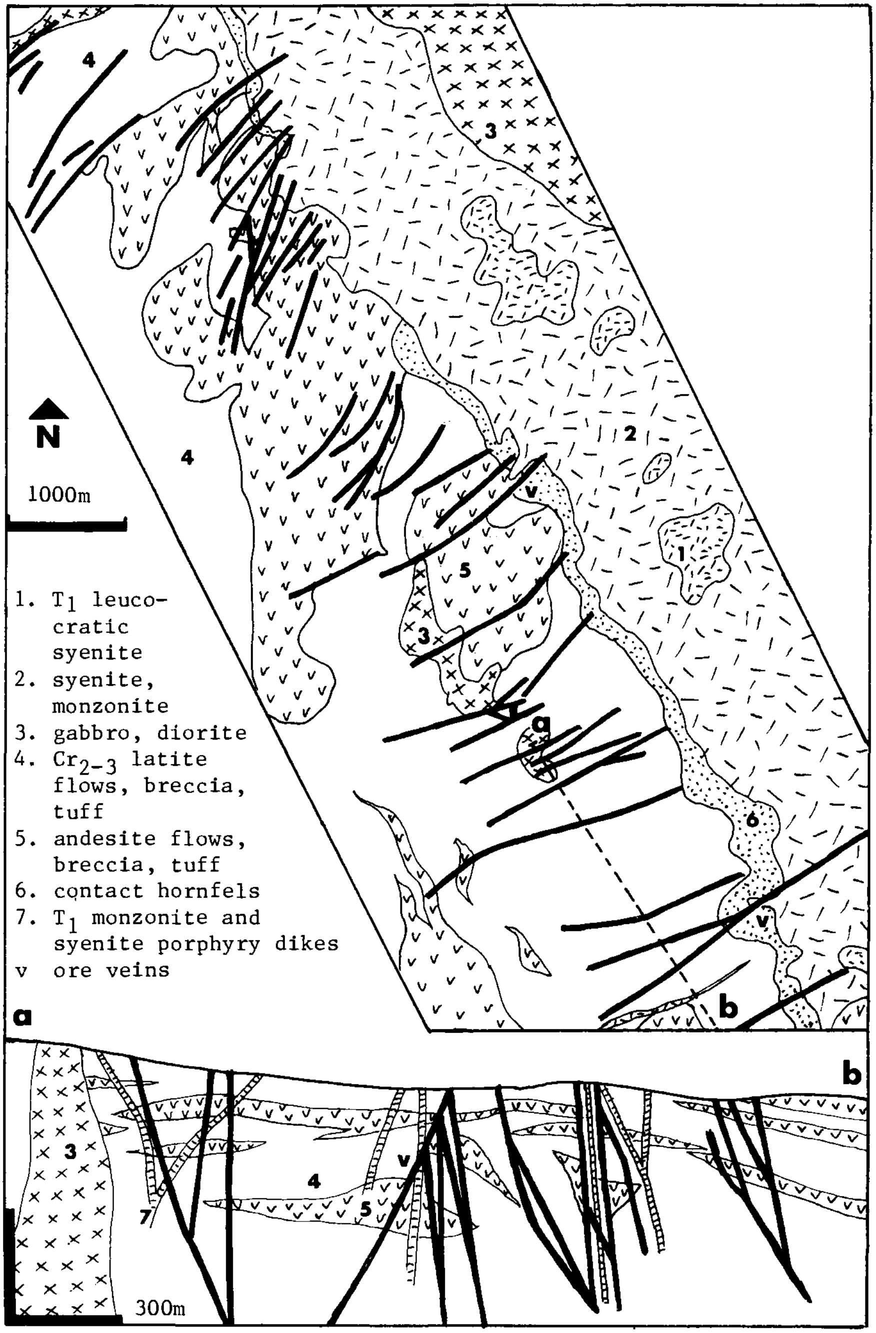


Fig. 28-58. Rosen, Burgas district, E. Bulgaria, an example of a postmagmatic hydrothermal copper vein field. Simplified after Iovchev (1961).

N.E.-striking subparallel fissure veins with an average length of 500 m and 0.1-10 m thick, are hosted by middle Cretaceous andesite and latite flows and tuffs within a 5x1 km block. The vein field is adjacent to a Paleogene gabbro, gabbrosyenite, monzonite, and syenite pluton, the small apophyses of which also include the volcanics in the ore field and host about 20% of the veins. The vein filling is quartz, pyrite, specularite, chlorite, epidote, chalcopyrite and other minerals deposited during four successive periods. The wallrock alteration is silicification, chloritization and pyritization.

28.8. Sn (W,Bi,Mo,Be,Ta-Nb) MINERALIZATIONS ASSOCIATED WITH GRANITE PLUTONS

28.8.1. Introduction

Most intermediate level (i.e. those associated with epizonal or upper mesozonal plutons) hydrothermal and possibly pneumatolytic deposits of lithophile metals are genetically and spatially associated with distinct elevations (cupolas, cusps, protuberances, ridges) that "sit on the back" of a larger buried "S-granite" pluton. A variety of actual mineralization styles (disseminations, stockworks, veins,replacements), alterations, host rocks, mineral associations, etc. can be recognized (Fig. 28-59). The most popular generalization, "tin cupolas" are similar in many respects to porphyry copper systems. They supply the bulk of a major metal, but individually there are endless "variations on a theme". The many styles of actual mineralizations that form tin orebodies are usually causally linked and one may lead to another. It is rather foolish to initiate an exploration program for, e.g., "tin skarns" and follow it blindly without taking into account that once a hydrothermal Sn-depositing system was set in motion, tin accumulated in many styles, skarns being just one of them, easily interchangeable for another style as the local conditions changed slightly.

Despite the many similarities in style and conceptual approach between "tin cupolas" and porphyry coppers, both systems are mutually exclusive and overlaps are extremely rare although examples have been recorded (e.g. in Central Kazakhstan and East Transbaikalia). This is clearly due to the geological setting and related petrogenesis of the parent "granites". While the bulk of the porphyry Cu affiliated "granites" are I- or "magnetite"-types, generated within or emplaced into the "transitional" crust of continental margins, the "tin granites" are overwhelmingly S- or "ilmenite"-types, with provenance within the continental crust. This is supported by the worldwide empirical experience, although competing ideas about mantle sources of tin (and tin granites) have also been suggested. This problem is reviewed in greater depth by Taylor (1979), and briefly touched upon in the earlier sections of this Chapter.

The tin granite mineralized systems have recently been reviewed by Hosking (1973, 1974), Štemprok et al., (1978), Taylor (1979) and by

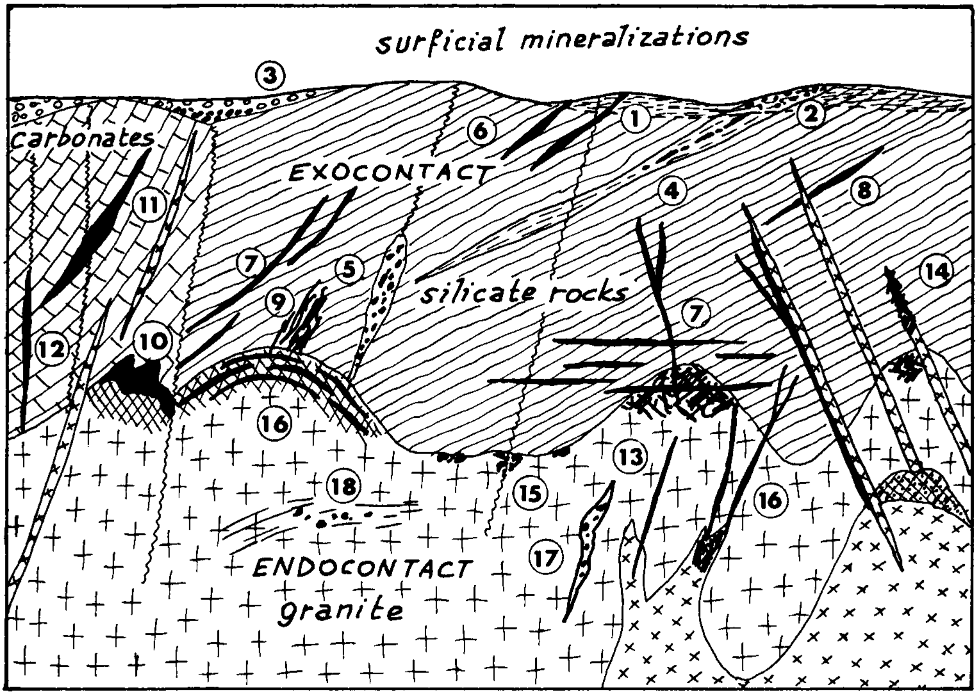


Fig. 28-59. The principal varieties of Sn(W,Bi,Mo,Be) mineralizations associated with high- to medium-level granitic plutons.

Surficial mineralizations: 1=gossans and oxidation zones; 2=regoliths; 3=transported placers (alluvial, beach).

Exocontact ores in silicate rocks: 4=relic mineralizations (unrelated to granite emplacement), e.g. paleoplacers, subaqueous hydrothermal stratiform deposits; 5=pipes, mineralized breccias; 6="distal" veins (no apparent connection with the "granite"); 7=proximal veins; 8=replacements in silicate rocks; 9=exocontact stockworks, disseminations.

Exocontact mineralizations in carbonate rocks: 10=exoskarns; 11=replacements in carbonates, mantos, pipes, etc.; 12=replacement veins.

Endocontact mineralizations: 13=stockworks, disseminations in cupolas; 14=ditto, in dikes; 15=small ore occurrences along contacts outside cupolas; 16=endocontact veins (sheeted flat veins); 17=pegmatites; 18=cassiterite disseminations in schlieren and inhomogenities. From Laznicka (1984).

the Soviet authors (Smirnov, ed., 1968; Smirnov 1969). The Russian-language authors brought many fresh ideas and contributed valuable descriptions of the Soviet and Mongolian tinfields, yet they used several conceptual approaches that differ from those common here. This led to several recent misinterpretations, the most usual one being consideration of the "apogranites" (essentially albitized granite apexes) as a petrochemically distinct magmatic rock.

It has to be emphasized that the concept of "tin granites" and "tin cupolas" is, to a considerable degree, an enigmatic one, and is confusing in many respects due to the variety of scales of consideration. The "main body" of the batholiths or plutons regionally associated with tin mineralization is usually an equigranular or porphyritic, monotonous biotite quartz monzonite (adamellite) with only slightly elevated tin contents (of the order of 3-5 ppm Sn) and virtually no associated ores (except when it was rejuvenated after intrusion). Such a precursor or "grandparent" granite (e.g. the Gebirge Granite in the Erzgebirge Tin Province) is then intruded or topped by a later stage, lesser volume more siliceous and leucocratic ("leucogranite") muscovite-biotite granite (e.g. the Erzgebirge Granite). This has the form of small epizonal massifs, stocks, dikes, etc. permissively formed just under the confining roof assemblage. The latter are rich in volatiles and the relatively impervious roof confinement prevented venting and volatile loss. Consequently, the volatiles including the metals they carried, accumulated in the apical regions. In some instances the "cupola granites" are not younger stage intrusions, but hydrothermally autometamorphosed apices of a single intrusive phase.

It appears that the depth modelling of magmatic systems applied to porphyry coppers ("volcanic" or subvolcanic, hypabyssal, plutonic) is immediately applicable to the tin (and some W,Be,Mo) deposits as well, and the absolute depth levels are also comparable (see Fig. 27-4). Table 28-7 gives the approximate balance of economic tin as related to mineralization styles and their depth levels. Also applicable to tin deposits is the analogy in multistage mineralization separated by a "barren interval" (as in Butte), where low-grade but more extensive disseminated or stockwork ore was partly upgraded into more restricted and higher-grade veins by a superimposed event (e.g. in the Cornwall; Panasqueira, Portugal; etc.). As in the Cu-mineralized fields, Sn ores occur, in relation to a granite body, in the endocontact or proximal exocontact (there, the association with a granite is intimate and immediately obvious), as well as in the distant exocontact where the granite is often not in sight but is usually postulated.

Two profound differences in comparison of porphyry Cu and Sn granite systems, however, stem from the fact that the ore components in the former are sulphides and in the latter are mostly oxides. The chemistry of the ore-bearing solutions and consequently the wallrock alterations are, therefore, to some extent different (high-sulphide Sn deposits are, however, transitional). A further difference is in the response of ores to weathering. The Cu sulphides are rapidly weathering degraded, while cassiterite is highly weathering resistant

Table 28-7. Approximate balance of tin in Phanerozoic deposits affiliated with mesozonal-epizonal granitic plutons

STYLE	TONNAGE IN:		
	1.BEDROCK DEPOSITS	2.PLACERS PROPORTIONALLY REASSIGNED TO BEDROCK SOURCES	3.TOTAL
Early endocontact ores			
in feldspathized apogranites	20Tt Sn	-	20Tt Sn
greisen,stockworks,veins	1,250	3,825Tt Sn	5,075
pegmatites	6	5	11
postmagmatic exocontact ores			
veins, stockworks	5,000	4,250	9,250
replacements in skarns	570	400	400
replacements in non-skarn carbonates	1,900		1,900
placers (considered independently)	8,500		
		GRAND TOTAL	17,226Tt Sn

so, in contrast to the Cu-depleted leached capping over porphyry coppers, similar weathering profiles over tin granites may preserve their hypogene Sn content, or may even be slightly residually enriched in tin.

28.8.2. Sn (W,Bi,Mo,Be, Ta-Nb) disseminations, stockworks and veins in altered granite cupolas and stocks.

This is the most distinct ("textbook") style of tin mineralization, but it is very unevenly distributed on a world-wide scale. It is the flagship of tin ores in the Erzgebirge, but elsewhere economic deposits of this style may be quite uncommon. This style, however, has the potential to supply low and very low grade tin ores in the future. In the literature, the content of this section is often treated under headings "greisen Sn deposits", "Sn apogranites", etc. The meaning of apogranites has been defined earlier. Greisens are hydrothermally altered felsic wallrocks (mostly granites), from which feldspar has been completely removed or altered to mica and/or topaz. The typical greisen assemblage is quartz, muscovite or zinnwaldite, topaz, frequently fluorite and apatite. Greisens commonly host disseminated or stockwork cassiterite or form alteration envelopes to ore veins.

In a "typical" tin-bearing granite cupola, the apogranitic feldspathic metasomatites and greisens are members of a generally low-sulphide alteration-mineralization system superimposed on leucogranites. In some sulphide-rich systems affiliated with quartz monzonites and granodiorites (as in the Sikhote Alin region, U.S.S.R.), the alteration pattern is different, resembling, in many respects, that in porphyry coppers.

"TYPICAL" (K/Na FELDSPAR, GREISEN) ALTERED GRANITE CUPOLAS

Cínovec (formerly Zinnwald) deposit in the Erzgebirge, N.W. Czechoslovakia (Štemprok and Šulcek, 1969; min. 150 Tt Sn/0.3%, 30 Tt W; Fig. 28-60) is an example of an almost ideal mineralized granite cupola that combines Li-enriched zones of feldspathization ("apogranite") with greisen alteration enveloping flat Sn,W,Li veins. The regularity is probably due to the fact that there is very little exocontact mineralization resulting from "leakage" of the mineralizing fluids into the roof.

The unaltered parent rock of the Cínovec cupola is a medium-grained porphyritic biotite granite, that is interrupted, in places, by microgranite zones generally parallel with the outer outline of the cupola. The intrusion dates from the Permian age and is generally considered to be one of the protuberances on the back of a much larger batholith that underlies the entire Erzgebirge region. The immediate roof to the Cínovec granite is a remnant of a formerly extensive pink rhyolite flow and ignimbrite sheet, locally intruded by granite porphyry dikes and stocks. The rhyolite is considered to be broadly comagmatic and only slightly older than the Cínovec tin granite.

The granite cupola has an elliptical cross-section, dipping gently (30°) in the north and south, steeply (80°) in the west. Hydrothermal alteration starts imperceptibly at a depth of about 730 m under the roof of the cupola, and is marked by the increase of initially intergranular, later K-feldspar-destructive albite, and by the formation of protolithionite-type micas. Higher in the profile the intensity of metasomatism increases and the albitization is locally complete so that almost pure albitites form as lenses and pipes, associated with zinnwaldite mica. The most common rock is albitized lithian granite composed of quartz, K-feldspar, zinnwaldite, sericite and kaolinite with accessory fluorite, topaz and rare disseminated cassiterite, zircon, columbite and other minerals. Approximately in the middle of the albitized profile, several bodies of K-feldspar metasomatites (metasomatic syenites) appear, and the entire contact of the cupola against the roof rhyolite is represented by a K-feldspar pegmatite lining ("Stockscheider"). There is no visible structural control to this early metasomatism other than the surfaces of concentric sheeting, and the alteration appears shortly to postdate

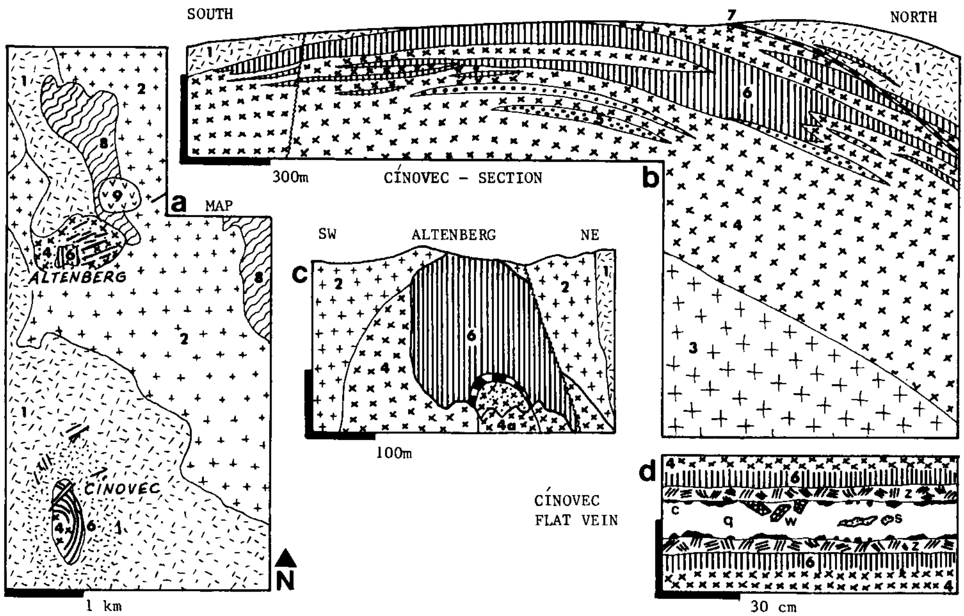


Fig. 28-60. Cínovec (Czechoslovakia) and Altenberg (East Germany) Sn(W) deposits hosted by greisen zones in feldspathized granite cupolas.
1=Fe rhyolite; 2=granite porphyry; 3=biotite granite (fine to coarse); 4=albitized zinnwaldite granite; 4a=younger phase at Altenberg; 5=metasomatic K-feldspar syenite; 6=greisen with flat ore veins; 7=border pegmatite (Stockscheider); 8=gneiss; 9=T_3 flood basalt.
Legend to Cinovec flat vein: c=cassiterite; q=quartz; w=wolframite; s=scheelite; z=zinnwaldite. Modified after Štemprok and Šulcek (1969), Chrt and Bolduan (1966); Rösler et al. (1968) and authors fieldwork, 1965.

the emplacement of the latest phase of the composite intrusion. The alteration regime was alkaline and is, in many respects, comparable with the K-feldspar alteration in porphyry coppers.

This was followed shortly afterwards by alteration due to acid fluids that was accompanied by formation of several parallel flat vein (lode) systems subparallel with the cupola surface, enveloped or interconnected by a quartz, zinnwaldite, lesser topaz and fluorite greisen. The veins filled and partly replaced dilations probably resulting from contraction of the intrusion during cooling. Minor, localized sericitization and argillization followed. Compared with porphyry coppers, greisenization is an "inserted" alteration phase between feldspathization and sericitization and is often gradational into silicification.

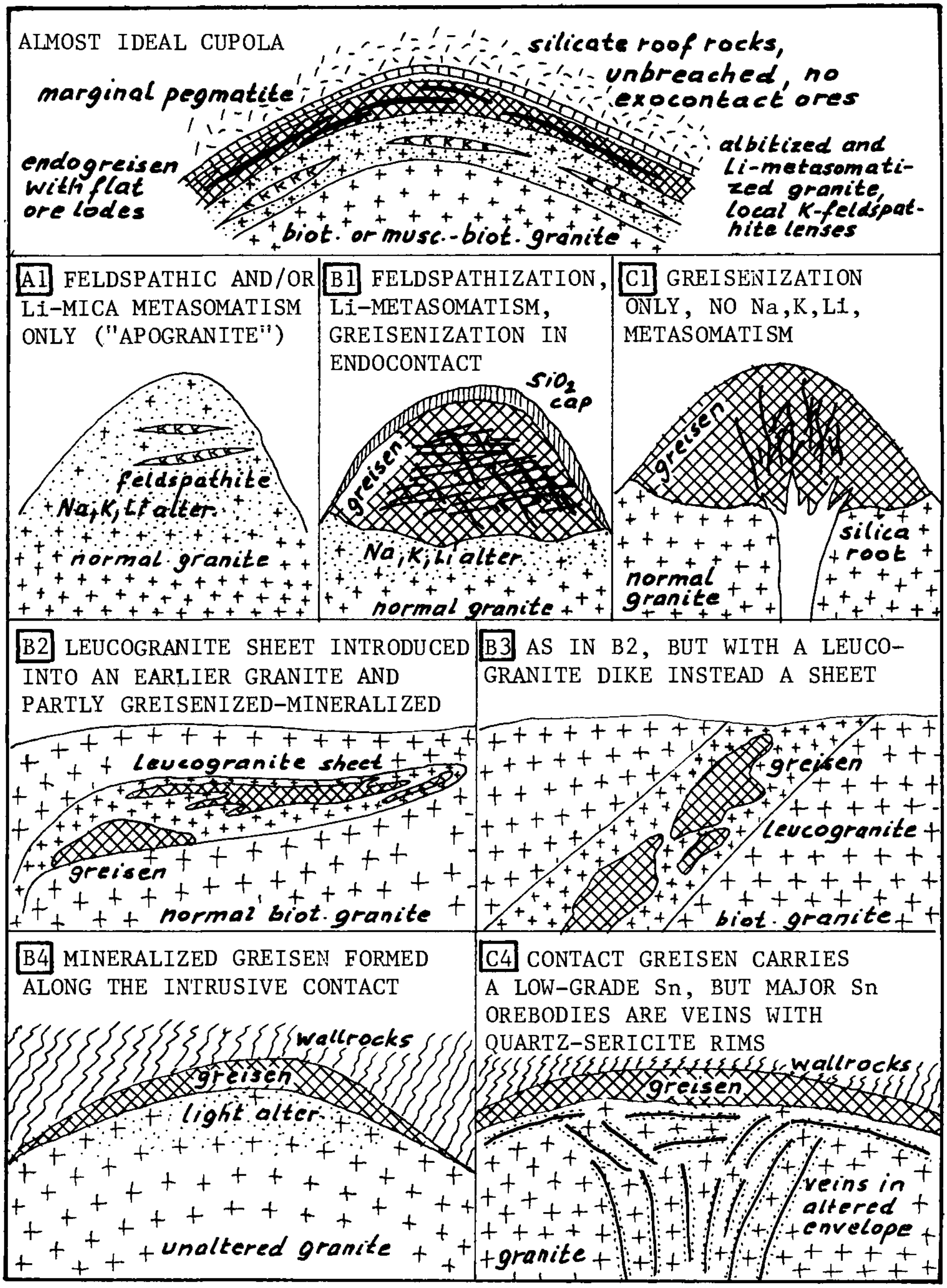
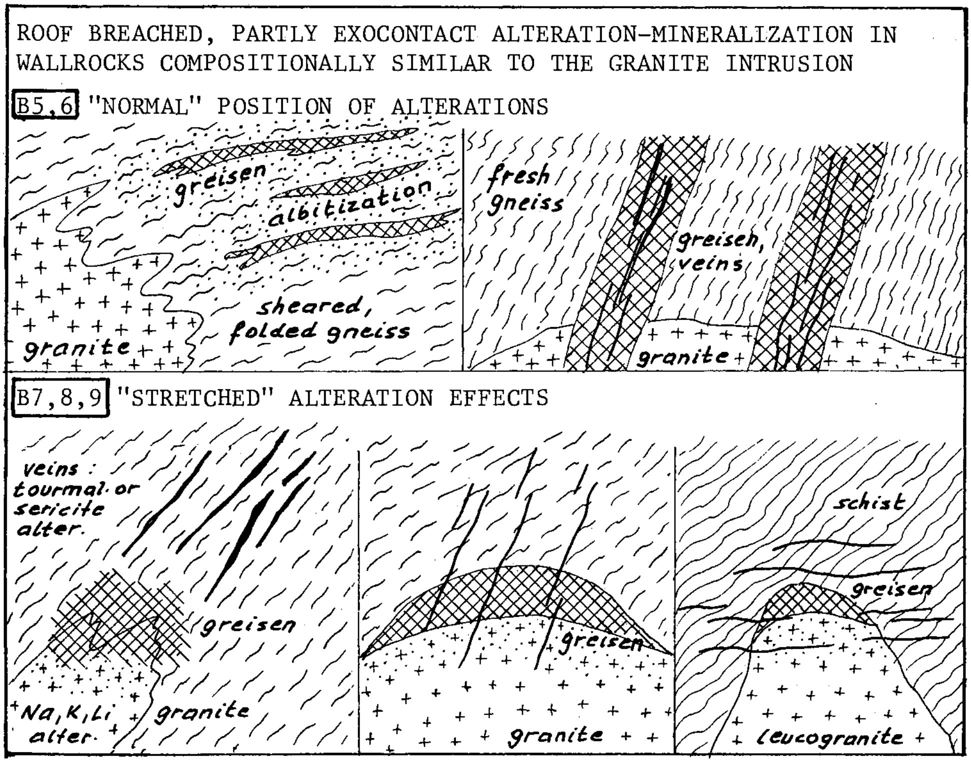


Fig. 28-61. Sn(W,Mo,Bi) mineralized altered granite cupolas, variations on a theme (see explanations in the text); from Laznicka (1984).



The ore minerals cassiterite, wolframite and minor molybdenite, bismuth, etc., may occur in three ways. These are as follows: (1) fine-grained disseminations in greisens. This constitutes a low-grade (0.1-0.2% Sn) but large tonnage ore; (2) coarse crystals of ore minerals scattered in zinnwaldite selvedges along the lode/greisen contacts or (3) large to very large crystals scattered in the flat quartz veins (Fig. 28-60d). The veins are up to 1 m thick, often symmetrical, and lesser quantities of scheelite, arsenopyrite, galena, sphalerite, stolzite, etc. are associated with wolframite and cassiterite. The thickness of the productive zone (veins and greisens) in Cínovec is about 200-300 m, but only a small proportion of this is an actual ore.

Other Sn(W,Bi,Mo) deposits in granite cupolas represent variations on a theme and many of the literature "subtypes" can be derived from the "ideal" example by adding and subtracting various attributes (Fig. 28-61). When only feldspathization and Li-metasomatism took place, sometimes mineralized "apogranites s.s." (A1) formed. (B1) is represented by a well developed endocontact greisen, crisscrossed by quartz veinlets and veins with scattered cassiterite, wolframite, aresenopyrite, and molybdenite (e.g. Hub Stock, Krásno and Altenberg). Greisenization grades into silicification and portions of the greisen are, in fact, masses of grayish-white vuggy and crystal-rich quartz with haphazardly scattered flakes of zinnwaldite and Sn,W,Mo,Bi,As ore minerals. The greisen is superimposed on the previously feldspathized granite, but this is often not apparent when mining or drilling was not carried out at a depth greater than the bottom of the productive zone. Occasionally, the greisen body changes downward into a quartz root (pipe).

(C1) shows greisen developed in a granite not previously albitized. Situations (B2) and (B3) show a leucogranite sheet or a late stage dike emplaced in an earlier granite, in which the dike suffered an autometasomatism terminating by the formation of endogreisen and/or a mineralized stockwork in it. The pre-greisen feldspathization was often light and inconspicuous and Li addition to the micas recognizable only analytically. At (B4), greisen is developed along the intrusive contact and at (C4) (as in Bukuka, Transbaikalia) a contact greisen with a low-grade Sn mineralization is developed, but the bulk of cassiterite is in a stockwork of endocontact quartz veins that have narrow quartz-sericite alteration rims, but are free of greisenization.

Increased variety of mineralization styles is the result of breach (rupture) of the roof to the granite cupola, that allows the fluids to migrate into the exocontact rocks of considerable lithological variety and uneven structural preparation. Fig. 28-61 cannot show more than a few "highlights". When the tin granite is emplaced in a wallrock compositionally similar to it (an older granite, gneiss; B5,6), the endocontact alteration can cross the contact and be developed on both sides of it (e.g. Čistá). In the remaining instances (B7-9) the alteration-mineralization system "stretches" and one may find feldspathization deep in the parent granite, greisenization at the very top of the granite or in the exocontact (exogreisen) and quartz-cassitetite veins in no further altered (or sericitized, tourmalinized) hornfelsed metasediments at some distance from the contact.

GRANITES (APOGRANITES, "A" in Fig. 28-61), FELDSPATHIZED ONLY, MINERALIZED BY Ta(Nb,Be,Sn,REE,Th)

Feldspathization modifies granite composition and petrochemistry and makes it more alkaline than it was at the end of the magmatic stage. When the existence of such post-magmatic alteration is not recognized, a calc-alkaline granite can be mistakenly placed into the alkaline or peralkaline family. The latter family, however, also contains apogranites, for example in Nigeria (Chapter 33). Apogranites of both petrochemical affiliations have been thoroughly described in the Soviet literature (e.g. Smirnov, ed., 1968), but the quality of description suffers from anonymous localities and a complete lack of quantitative data (witheld for state security reasons).

Most occurrences of apogranites that have been described correspond compositionally to the feldspathized zone at Cínovec and the pervasively but incompletely feldspathized bulk of the original granite is interrupted by fracture-controlled pods, pipes, lenses, sheets, fracture veinlets or stockworks of almost pure albitites (resembling aplite) or microcline-syenite metasomatites. The latter are commonly composed of the conspicuous light-green (the colour is particularly well developed when lightly weathered) microcline variety amazonite. These advanced feldspathites and their lithian mica (zinnwaldite, exceptionally lepidolite)-containing varieties, frequently contain scattered crystals of beryl, columbite-tantalite, ilmenorutile, monazite and other Be, Ta-Nb, REE and Th minerals. This suggests a convergence to and correspondence with the "rare metal pegmatites" that exist at greater depths. The ore minerals are too dispersed in most cases to constitute a currently economic ore, but they may have contributed much of the columbite and monazite recovered in many placer cassiterite fields of the world. Beryl, however, is rarely reported from tin placers. This is due to its low stability in the zone of weathering. Beryl accompanied by columbite, monazite, scheelite and other minerals, however, is present in several placers formed over apogranites in arid zones, as in Mongolia (e.g. Zhanchublin district; Marinov et al., 1977).

At some Mongolian apogranite localities (e.g. Buren-Tsogto tungsten deposit; Marinov et al., 1977), amazonite forms veinlets and veins in apogranite resembling pegmatite and it carries disseminated wolframite, beryl, fluorite, cassiterite and sulphides.

Of particular scientific interest (and readily accessible to the western visitors) are the apogranite cupolas at Montebras and Echassières in the French Massif Central (Aubert, 1968). The Montebras cupola is a ring dike measuring 350x200 m of a porphyritic muscovite-biotite granite emplaced by magmatic stoping into an older granite. It is surrounded by a pegmatitic (Stockscheider) and silicified envelope and a mica-greisen. It is heavily albitized. The albitized cupola and an adjacent separate intrusion of albite granite contain disseminated cassiterite associated with amblygonite-montebrasite and niobotantalite, but the Sn and Ta contents are subeconomic. Echassières is a biotite granite cupola 3 km in diameter, faulted after emplacement, and intruded by several volatile-rich younger intrusive phases including the Beauvoir albite-lepidolite apogranite. Lepidolite constitutes 10-20% of the granite and there are disseminated cassiterite, herderite, montebrasite, microlite and topaz. The disseminated ore represents 12 Mt of material with 0.14% Sn (16.8 Tt Sn), 0.97% Li_2O, 219 ppm Be and 117 ppm W. A wolframite stockwork in the exocontact schist represents 6.24 Tt W.

It appears that large masses of feldspathized and Li-metasomatized granites in the Sn and W provinces of the world may become important future low-grade, large tonnage resources of Ta and Be in their own right, or in combination with epigenetic vein or carbonate replacement bodies in the exocontact (e.g. Lost River, Alaska). Already at present, Proterozoic apogranites (in Egypt and Saudi Arabia) hold the largest known Ta resources of the world. These are treated in Volume 2.

An anonymous apogranite cupola located in the Sn-W-Mo province of East Transbaikalia and described in Smirnov, ed. (1968; p. 324, 325), appears to contain a Ta orebody economic at present. There, scattered crystals of columbite-tantalite, Mn-tantalite and rare microlite are hosted by a zone of lepidolite, amazonite, quartz, albite metasomatite 20-100 m thick, formed within a cupola of a Jurassic porphyritic biotite and muscovite-biotite granite, emplaced into a schist roof. The complex alteration zoning is of the Cínovec style, but the massif suffered an early post-magmatic faulting and fracturing that facilitated the movement of the metasomatizing fluids. The Ta_2O_5 grades in the uppermost zone (up to a depth of 20-70 m from the contact) range from 0.04 to 0.01%. If the zone is persistent, the deposit can easily contain 50 Mt ore with an average of 0.02% Ta (=10 Tt Ta), a significant accumulation.

DISSEMINATED AND STOCKWORK Sn (W,Be,Mo) ORES IN GREISEN-ALTERED GRANITE CUPOLAS ("B" and "C" in Fig. 28-61; Table 28-8)

Erzgebirge and Slavkovský Les tin province (Czechoslovakia and East Germany)

This N.E.-elongated province that straddles the Czech and German border is about 150 km long and 60 km wide (Chrt and Bolduan, 1966; Tischendorf et al., 1978). In the southwest, it is separated by the Ohře River graben from a smaller satellite Sn-W and U, polymetallic Slavkovský Les district. Cínovec, described earliers, is situated in this province. The province coincides with a fold- and metamorphic belt of late Proterozoic and Paleozoic metasediments and metavolcanics which are believed to be almost completely underlain by a Carboniferous to Permian granitic batholith dated 305 and 240 m.y. The older intrusive phase is mostly a porphyritic granite to quartz monzonite, the younger phase is the cupola-forming volatile-rich granite, believed to be responsible for most of the ores.

The granites crop out in several plutons over 20% of the territory and are in shallow subsurface elsewhere. The present level of erosion intersects probably the most optimal level of hydrothermal mineralization and almost a thousand occurrences of Sn,W, U, Pb,Zn, Ag, Cu, Fe and fluorite, barite are known in the granite aureole. Erzgebirge has been a classical area of economic geologic studies in past centuries (Agricola, v.Cotta, Stelzner, and others). About 200-300 Sn(W) occurrences within apical granites are known. This includes at least 3 deposits and ore fields containing over 100 Tt Sn (Table 28-8). The cumulative Sn tonnage is of the order of 1 Mt Sn (more when the very low-grade material around 0.1% Sn is included).

The largest single tin deposit in the Erzgebirge is Altenberg (Chrt and Bolduan, 1966; Rösler et al., 1968; Fig. 28-60). This deposit is only 5 km from Cínovec on the German side of the border and although both deposits are members of the same system, each orebody is separate. In Altenberg the ore is located in a mass of greisen formed within a cupola of a Permian granite emplaced into a comagmatic

Table 28-8. Disseminated and stockwork tin deposits and fields in greisen-altered granite cupolas. Selected examples

LOCALITY	WALL-ROCKS AND TIN GRANITE	MINERALIZATION	REFERENCES
Cínovec, Erzgebirge Mts.,N.W. Czecho-slovakia	Pe rhyolite, granite porphyry Pe biotite granite (apogranite) cupola	system of flat qtz.,zinnwaldite, cassit.,wolfr.,etc.lodes // with the cupola contour envel.by greisen; floored by alb.,Li-mica apogr. Min. 150Tt Sn/0.3%,30Tt W	Štemprok and Šulcek (1969)
Altenberg,Erzgebirge East Germany (adja-cent to Cínovec)	Pe rhyolite and quartz porph. Pe biot.granite,multiphase double stacked cupola	homogenous greisen body around younger apex; cassit.,wolfr., moly.,Bi,arsenop.,fill hairthin fract. 200Tt Sn/0.3% (est.600Tt Sn/0.1%)	Rösler et al. (1968)
Horní Slavkov,Krásno, Čistá zone, N.W. Czechoslovakia	Pt_3-PZ migmatite,gneiss,meta-quartz.,amphibolite; Pe biot.gran.,albitized,seric. altered	5 greiseniz.cupolas and sheets in endocont. have dissem.and stockw.cassit.,wolfr.,ars.,moly. etc. Minor Sn-W, import.U,Ag,Pb veins in exocont. Est.300Tt Sn	Chrt and Bolduan,(1969)
East Kemptville, S.W. Nova Scotia, Canada	Cm-Or quartzite,slate; D? biot.granite and qtz.monzon.	cassit.,pyr.,pyrrh.,arsenop., pods in mass.greisen and greis. selvadges // qtz.veins in gran. Minor fluor.veins;76Tt Sn/0.2%	Richardson et al.(1982)
Ardlethan, N.S.W., Australia	S,quartzite,micasch.,slate D,biot. to musc.-biot.granite	numerous zones of qtz.-tourm. alter. and topaz greis.along joints; pipes with dissem.cassi-ter.grade to pipes,stockw.,fiss. veins; 10.2Tt Sn/0.17%	Garretty (1953)
Anchor M.,Lottah, N.E. Tasmania,Austr.	S schist,phyllite; D older bio. gran.,sills of musc.-biot.gran.	700x160 m greis.zone with fine dissem.cassit.,cp.;7Tt Sn/0.3%	Groves and Taylor (1973)

granite porphyry and rhyolite. This cupola was thoroughly greisenized shortly after emplacement, and once more following the emplacement of another, younger phase granite stock (the "Inner Granite"). The latter is capped by a thin pegmatite body (Stockscheider) and the volatiles produced by the Inner Stock caused an autometasomatic alteration of its apical portion (including the pegmatite that was converted into an almost pure topaz), as well as additional greisenization and mineralization veining in the above-intrusion region of the older cupola. The earlier greisen is a dark topaz, quartz and Li-biotite rock (also called "Zwitter"), the younger greisen is light, bleached, hematite-pigmented rock. Cassiterite, wolframite, molybdenite, bismuth, bismuthinite, arsenopyrite and rarer minerals occur as fillings of hairline (0.06-0.1 mm) fractures in the greisen, giving the whole mass an average grade of 0.3% Sn.

Horní Slavkov, Čistá, Krásno (Ďurišová et al., 1969; Chrt and Bolduan, 1966) is a zone about 10 km long, of greisen stocks and sheets, developed within and over a Permian lithian albitized leucogranite (apogranite) emplaced into an earlier multiphase pluton, under the confining cover of a Proterozoic biotite gneiss (Fig. 28-62). Two adjacent mineralized stocks mined since the Middle Ages (Huberstock and Schnödenstock) had a massive quartz, topaz, zinnwaldite greisen bodies mineralized by stockwork and microscopic disseminated cassiterite, wolframite, arsenopyrite, chalcopyrite, molybdenite, etc. The intensity of greisenization diminishes downwards. The solid greisen changes into a system of flat greisenized lodes alternating with kaolinized and chloritized granite. The Huberstock alone is estimated to have contained originally about 150 Tt Sn and 70 Tt W.

The Čistá deposit at the western end of the zone is in relatively lightly albite feldspathized and Li-altered biotite granite (K-feldspars and even plagioclase are largely preserved, biotite is replaced by zinnwaldite and lithionite, topaz was added) under a migmatite roof. Several diffuse, elongated mica-rich greisen bodies subparallel with the intrusive grain are present, and they grade into a sericitized granite. Fine-grained cassiterite and minor wolframite and molybdenite impregnations form seven elongated zones up to 20m thick and 400 m long, subparallel with the contact. The ore zones have diffuse (assay) boundaries and are largely in the most intensively greisenized and sericitized wallrocks although their fringe is in megascopically virtually unaltered rocks. The orebodies, however, cross lithologic boundaries and follow faithfully the alteration zones. The Sn content is between 0.2 and 0.3%, W and Mo contents are less than 0.05%, but there is a high Ta content (up to 0.13%) locally. Minor stockworks and veins are superimposed.

The remaining Erzgebirge tin stockworks (Sadisdorf, Ehrenfriedersdorf, Tannenberg, Geyer, Schneckenstein, Krupka, Přebuz) are less important economically and are considered exhausted after more than eight centuries of mining.

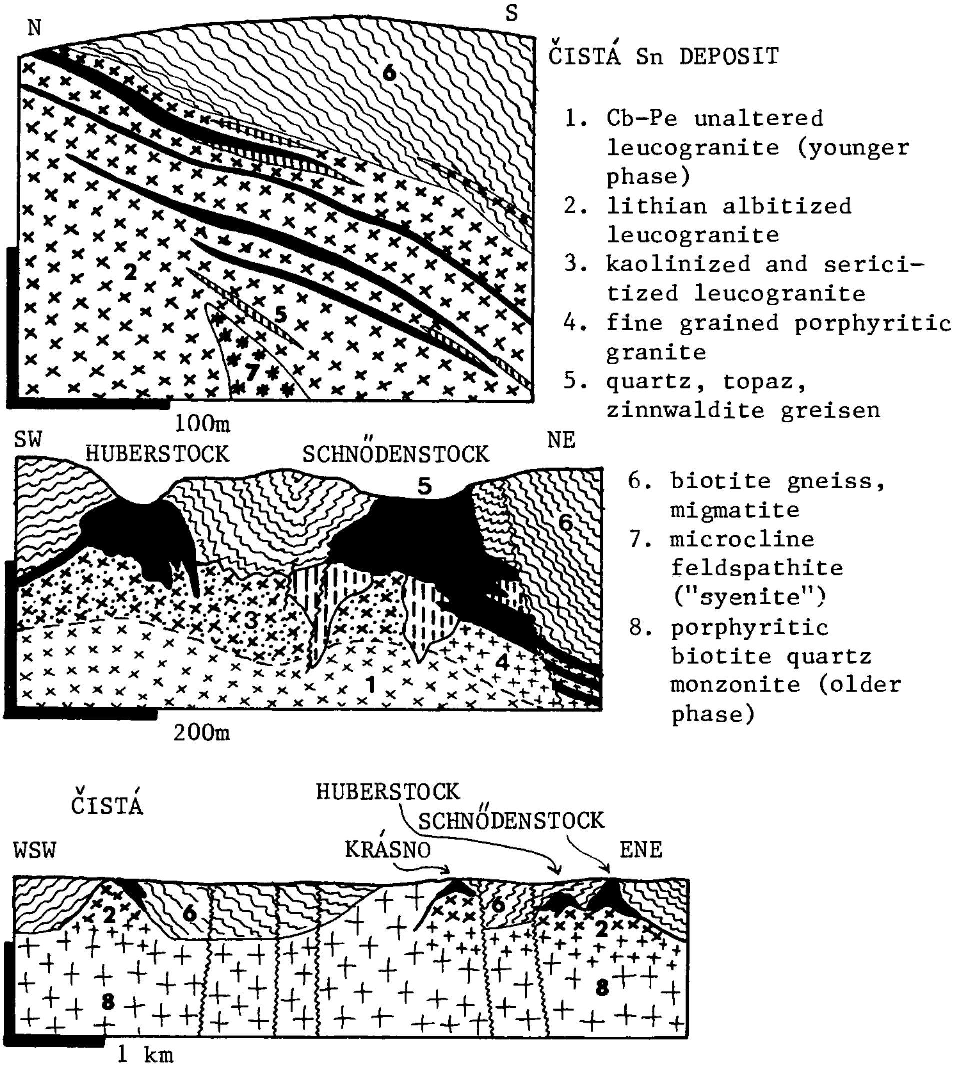


Fig. 28-62. Cassiterite and wolframite-bearing greisenized granite stocks in the Horní Slavkov-Čistá area, W. Czechoslovakia. Modified after Ďurišová et al. (1969) and Chrt and Bolduan (1966). Bottom section is diagrammatic from LITHOTHEQUE.

CORNWALL AND DEVON, S.W. ENGLAND

South-west England (Cornwall in particular) is a well-known classical tin mining area that has produced more then 2 Mt Sn. The bulk of the tin, however, came from exocontact veins (and from placers), so a more detailed locality description is provided in a subsequent Section. Mineralized cupolas, however, have recently become a favourite exploration target because of their supposed potential for containing large, low-grade deposits. Hemerdon, the largest such deposit so far discovered, is a tungsten mine with minor tin by-product (45 Mt ore with 0.136% W, 0.029% Sn) so is discussed later.

FRANCE, SPAIN, PORTUGAL

Massifs of Permo-Carboniferous "tin granites" appear throughout the western European Hercynian foldbelt and in the Hesperian Massif. The past production came mostly from veins and placers, but several endocontact stockworks have been discovered or evaluated recently. In western Spain, the large but very low-grade Baltar cassiterite and wolframite stockwork (50 Mt ore with 0.12% W, 0.08% Sn) is primarily a tungsten mine and so is the Panasqueira vein deposit in Portugal.

EASTERN SIBERIA AND N.E. MONGOLIA

This vast area contains several Sn,W,Mo provinces (Table 28-9 and Figure 28-63) genetically associated with Jurassic to lower Tertiary granites. Most orebodies are in the granite exocontact. Those having the form of stockwork in greisenized granite cupolas include the Kester deposit in the Ege Khaya field, Yakutia, described by Materikov (1974); Bukuka in East Transbaikalia (Magak'yan, 1968); Baga-Gazryn and Khara-Moritu in Mongolia (Marinov et al., 1977). The Butugychag Sn deposit in the upper Kolyma River (Materikov, 1974) departs from the usual style in that it has stockworks and parallel systems of quartz, albite, K-feldspar, cassiterite, wolframite and molybdenite veins filling what appear to be zones of torsion fracturing in a granite cupola. The host rock is an albitized apogranite, locally greisenized.

NOVA SCOTIA, CANADA

Recent geochemical exploration resulted in the discovery of a large but low-grade (38 Mt ore with 0.2% Sn) deposit of disseminated cassiterite in Devonian granite near East Kemptville (Richardson et al., 1982). This deposit is contained in a greisenized and sericitized granite just under the quartzite roof. It is notable that the ore occurs beneath an inflection of the roof, rather than in a

Fig. 28-63. Principal tin provinces of the world.

typical cupola. Albite alteration of the host granite outside the greisen has not been emphasized in the preliminary paper, but the presence of quartz-phosphate (triplite, apatite) suggests apogranite association.

SUNDALAND (S.E. ASIA) TIN BELT

Over 90% of the tin production and reserves in this extensive belt come from placers and the rest from exocontact veins, replacements and stockworks. Because of the humid tropical environment, bedrock outcrops are scarce. Several small endocontact cassiterite occurrences are known in Malaya (Hosking, 1973, 1974). On the Indonesian "Tin Islands", the Pemali deposit on Bangka (Schmidt, 1976; 12.22 Tt Sn/0.12%), is the only significant though small bedrock deposit. Cassiterite is in a greisen-hosted stockwork in the contact zone of a Mesozoic granite.

EASTERN AUSTRALIA

The Tasman orogenic belt of eastern Australia contains a series of tinfields distributed from northern Queensland to Tasmania, but in order of importance endocontact tin stockworks are in fourth place (after carbonate replacements, placers and exocontact veins). Over 100 occurrences of disseminated and stockwork cassiterite in small

Table 28-9. Phanerozoic plutonic tin provinces of the world, brief data

PROVINCE	GEOLOGY	MINERALIZATION	REFERENCES
Cornwall and Devon, S.W. England, U.K.	D-Cb slate,silts.,minor greenstone (metabasalt),limest., intr.by 295 m.y. qtz.monzon. pluton, 280-275 m.y. qtz. feldsp.porphyry dikes	X000 main stage(postdating dikes) fiss.and repl.cassit.,cp.,arsenp., pyrrh.,qtz.,tourm.,chlor.veins; minor wolfr.stockw.in greisenized cupolas,replac.shears. 2.5Mt Sn (portion from placers);2 Mt Cu; 250Tt Pb	Halliday (1980) Dunham et al. (1978)
Tin granite massifs in the Hercynian belt of France, Spain,Portugal	Pt_3-PZ high-grade to greensch. metased.and metavolc.,intr.by several phases of Cb-Pe granitic plutons; typical cupolas rare (e.g. Echassières)	mostly qtz-cassit. or wolfr. fissure veins in exo-and endocont.; rare stockw. in greisens (Baltar) and feldspathiz. Li apogranites (Montebras); about 70Tt Sn, 70Tt W	Taylor (1979)
Erzgebirge and Slavkovský Les Mts., W. Czechoslovakia and East Germany	Pt_3-D greensch.to amphib.fac. maf.metavolc.,metased. in a D-Cb deformed N.E. orog.belt; 305 m.y.mesozon.porph.granite to qtz.monzon.,240 m.y. epiz. "tin granites"	the bulk of econ.Sn comes from several large endocont.greisens with cassit.stockw.,dissem. and Li mica. X00 of qtz veins with cassit.or wolframite are less productive; placers. 1 Mt Sn, 3 dep.100Tt Sn+	Tischendorf et al.(1978) Chrt and Bolduan (1966)
Central Kazakhstan Sn Province (S.W. of Karaganda)	Or-S siltst.,shale,sandst. intr. by Cb_3-Pe qtz.monzonite,	numerous miner.centres in aureole of granite stocks and plutons; apogr.,endocont.greisens and veins, lesser exocont.veins, domin. by W-Mo; Sn is rare. Estim. 5Tt Sn, 50-100Tt W	Borukaev and Shcherba eds. (1967)
Kal'ba-Narym Ranges Sn Province, E.Kazakhstan, U.S.S.R.	D_1-Cb_1 shale, sandst.; Cb_3-Pe large gran.and qtz.monz.pluton, cont.dorsal ridges and cupolas of Sn granite; Pe-Te subaerial volcanism	endocontact greisens and stockworks with cassit.,minor apogranites with Ta,Be,pegmatites,placers. Estim. 30Tt Sn	Smirnov ed.(1968)

N.E. Mongolia, East Transbaikalia, U.S.S.R. province	PCm and PZ folded basement includes a PZ_3 granitic bathol. J-Cr meso-epizon.diorite to alaskite plutons, andes.-rhyol. continental volcanism	rare endocont.stockw. and veins (Bukuka); many exocont.veins,replac. and stockw.(Khapcheranga, Sherlovaya Gora). Qtz.,tourm.,chlor.,cassit. and sulphide-cassit. Est. 500Tt Sn	Materikov (1974)
N.E. Yakutia and Kolyma Basin Province, Siberia, U.S.S.R.	Tr flyschoid sandst.,slate,on margin of a median massif, intr.by J_3-Cr_1 granodiorite, granite	rare endocont.veins,stockw.(Kester, Butugychag);widespr.exocont.qtz., tourm.,chlor.,cassit.veins and stockw.,minor cassit.-sulph.bodies. Estim.min.300Tt Sn	Materikov (1974) Magak'yan (1968)
N.E.Chukotka, U.S.S.R., and west. Alaska, U.S.A.	Tr-Cr_1 litharen.,slate; J_2-T_1 dior.to alaskite. Sn related to Cr qtz.monz.,gran. and leucogr.,30-50 intrus.	in Lost River,Alaska,cassit.is in cupola and dike greis.,exocont. veins,skarn (with Be,fluorite,Li micas); similar in Siberia,where most import.qtz.-cassitt.,less sulph.-cassit.veins; placers. Est. min.250Tt Sn	Taylor (1979) Materikov (1974)
Komsomol'sk (Miao-Chai) distr.,Amur area, S.E. U.S.S.R.	J terrig.sedim.,basalt,diab., gabbro; Cr andes.,dac.,rhyol. volc.-sedim.; Cr dior.to granite plut.; Sn assoc.with diorite porphyries	qtz.,tourm.,cassit.replac.bodies along faults to qtz.-chlorite repl. cut by qtz.-cassit. and cassit.-sulph.veins. At Solnechnoe,ore zone is up to 8km long, 115m wide. Estim. 100Tt Sn	Materikov (1974)
Kavalerovo distr., Sikhote Alin, Soviet Maritime Province (Primor'e)	PZ_3-MZ sandst.,siltst.,minor lim.,chert,spil.,gabbro; Cr_1 terrig.sedim.; Cr_3-Eo buried bath.with gran.cupolas; Cr-T_1 contin. andes.-rhyol. volcanism	Eo, silicate (tourm.,chlorite) vein, lesser replac. cassiterite oreb. Biot.,seric.alteration envel. around granod.to granite stocks; ore veins, stockworks. Estim. 250Tt Sn, by-product Zn,Pb,Ag	Materikov (1974)

Table 28-9 (continued). Phanerozoic plutonic tin provinces of the world, brief data

PROVINCE	GEOLOGY	MINERALIZATION	REFERENCES
Southern Kiangsi (parts of Kwangsi, Hunan), China	Pt, Cm-S sandst.,shale,quartz. D,Cb limestone, intruded by J_{2-3} granite	numerous endocont.greisen stockworks mostly feeding placers; exocont.veins; recent large Sn,W, Be,Bi,etc.skarns (Xi Zhoyouang); min. 850Tt Sn, 650Tt W	Ikonnikov (1975) Juan (1946)
Yunnan, S.W. China (Kochiu)	Tr limest.,shale 85 m.y. granite intrusions	hematite,cassiter.,arsenop.,pyr., sphal.,gal.,massive replacem.in limest.;also residual and placer Sn 1.65 Mt Sn/3.65%	Juan (1946)
E.Thailand,Laos (Cholburi-Chantaburi; Nam Pathene)	PZ quartzite,limest.,shale Cb,Tr-J granite plutons	probably greisen,vein and skarn, but all prod.estim.to max.10Tt Sn comes from saprolite,alluv.and beach placers	Fontaine and Workman (1978)
Peninsular Burma, Thailand,Malaya tin belt	D_2-Cb_1 marine shale,sandstone (qtz.rich turbidite);Pe thin sandst.,shale,minor limest. Cb_1-T_1 biot.gran.,coarse two mica gran.with access.tourmal.	few bedrock mines (e.g.Sungei Lembing); complex cassit.exocont.veins greisens,skarns; thousands of small regolithic occurr.contrib.cassiter. to a variety of eluv.,alluv.,beach placers; 4.9 Mt Sn	Hosking (1973,1974)
Indonesian Tin Islands (Bangka,Belitung, Singkep)	Cb-Pe_1 sandst.,shale,siltst., minor tuff.seds.,hornfelsed; Tr_3 (213 m.y.) biot.and musc. biot.granite,tropic.weathered	hydroth.miner.198 m.y.,small greisen,skarns,veins; almost entire prod.and res.comes from onshore and offshore placers; 2.6 Mt Sn	Hosking (1973,1974)
N.E. Queensland Tinfields,Australia (Herberton,Cooktown, etc.)	S_2-Cb_1 sublitharen.,shale,minor carb.; Cb_1-Pe_3 acid cont. rhyodac.volc.,cauldrons,qtz. monz.to gran.bath.,cupolas	20-30 separ.miner.centres above cupolas above cryptobath. in Herberton field, 10 more elsewhere; greisens,pipes,veins,placers;163 Tt Sn	Taylor (1979) McLeod,ed. (1965)

New England tin-fields, N.S.W., Australia	PZ_1–Pe_1 folded terrigen.seds. Pe_3 rhyodacitic contin.volc., large qtz.monzon. and granite batholiths,minor cupolas	cassit.mostly as endo-and exocont. veins, greisen pipes,fract.stock-works in hornfelsed exocontact seds. The bulk of cassit.came from pla-cers; 210Tt Sn	Taylor (1979) McLeod, ed. (1965)
Lachlan belt tin fields, N.S.W. and Victoria,Australia	Or–D metased.,terrig.slate, qtz-rich litharen.,minor carb. S_3–D qtz.monzon.to granite batholiths	cassit.in small greisen bodies,less exocont.veins; the bulk came from placers; 53Tt Sn	McLeod,ed. (1965)
N.E.Tasmania (Ros-sarden,Blue Tier, Ringarooma, etc.)	PZ_1 (S) slate, qtz.-rich lith-arenite; D_3 qtz.monzonite, granite	cassit.in greisen (Blue Tier) and exocont.fiss.veins (Rossarden);the rest is from placers,mostly alluv. deep leads; 95Tt Sn	Williams (1978)
N.W. Tasmania (Re-nison Bell, Mt.Cle-veland, Bischoff)	Pt_3–Cm_1 siltst.,quartzite,mi-nor lim.,dolom.,greenst., ophiolites; D qtz.monzonite, leucogranite, qtz. feldsp.por.	3 large cassiterite-pyrrhotite repl. in carbonates; about 20 small grei-sen,vein and placer occurrences; 400Tt Sn	Williams (1978)
Nova Scotia batho-lith, Canada	PZ_1 quartzite,slate intr.by D granod.,qtz.monzon.bathol., 350 m.y. alaskite dikes	East Kemptville, low-grade cassit. dissem.in greisen and sericitiz. granite-hosted stockwork	Richardson et al.(1982)
Cordillera Real plutonic Sn provin-ce, Bolivia	Or–D gray slates interb.with qtz.-rich litharen. and quart-zites; Tr to Mi qtz.monzon.to granite batholiths, stocks	exocont. qtz.,tourm.,chlor.,cassit., wolfr.,sphal.,etc. veins are most common, followed by peneconc.mantos in quartzite and placers. 2Mt Sn	Ahlfeld and Schneider-Scherbina (1964)

endocontact greisen pipes are known but most are small (of the order of 10-100 t Sn; Fig. 28-64). They have, however, been of greater importance as suppliers of cassiterite to placers (e.g. at Gibsonvale, Cooktown, Tingha, Ringarooma, etc.).

The two largest deposits mined on their own have been Ardlethan, N.S.W. (10.2 Tt Sn/0.17%) and Anchor mine in the Blue Tier Batholith, Tasmania (7 Tt Sn/0.2-0.5% Sn). The latter deposit has been studied in detail (Groves and Taylor, 1973) and it consists of a very fine (practically invisible) disseminated cassiterite and some chalcopyrite in a light greenish-gray, quartz, mica, chlorite greisen. The greisen forms irregular, sheet-like bodies in the apical region of a thick sill-like intrusion of biotite-muscovite granite, emplaced in an unmineralized Devonian porphyritic biotite granite to quartz monzonite. The mineralized zone is about 700 m long, 160 m wide, and positioned within the upper 40 m of the granite sill.

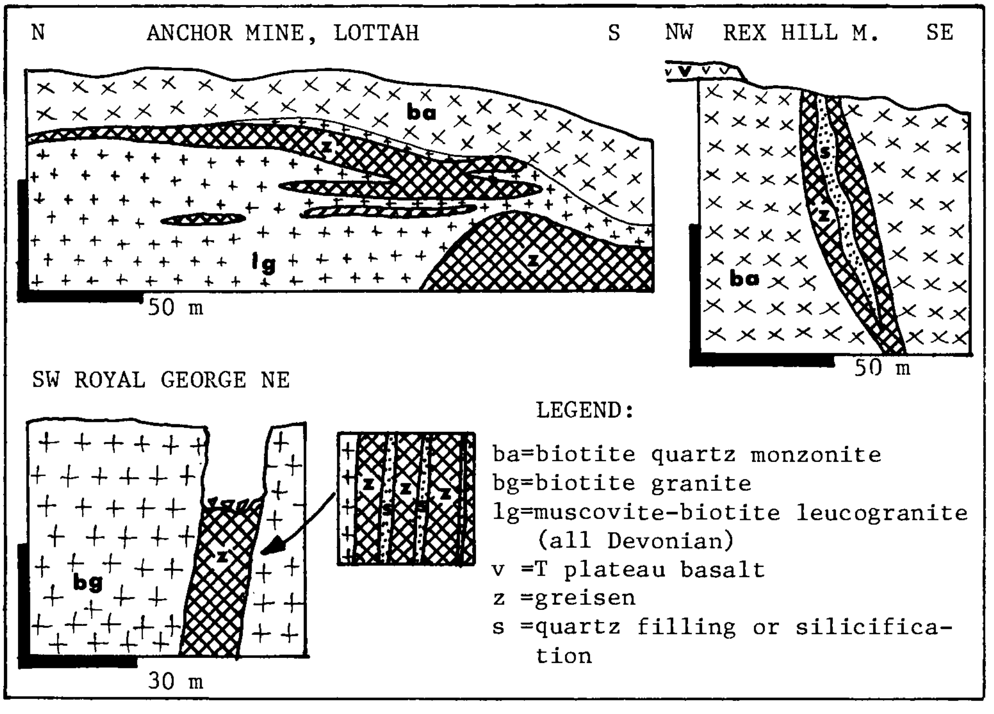


Fig. 28-64. Examples of small endocontact greisen Sn deposits in N.E. Tasmania. From LITHOTHEQUE, after Groves and Taylor (1973), Urquhart (1967) and authors fieldwork, 1971.

28.8.3. Postmagmatic Sn (W,Bi,Mo) veins, stockworks and replacements in granite aureoles (non-carbonate hosts; Table 28-10)

This is the mainstay of the plutonic tin association. Thousands of occurrences are known worldwide and although individual deposits are small to medium in size, the cumulative importance is significant because exocontact veins and similar bodies occur in every known plutonic tin province. The classical, narrow and small tonnage fissure veins have recently been joined by several "modern" styles: mineralized breccias and fracture (joint) stockworks in hornfelsed supracrustal rocks.

CORNWALL AND DEVON, S.W. ENGLAND

This N.E.-trending metalliferous area occupies a peninsula in the S.W. tip of England. It measures about 150x60 km (the same dimensions as those of the Erzgebirge) and has produced about 2.5 Mt Sn and 2 Mt Cu mainly from veins and placers. Cornwall is one of the sacred places of metalliferous geology (e.g. a craddle of the zoning theory), and it has recently been re-interpreted in a series of publications (Dunham et al., 1978 ; Jackson, 1979; Halliday, 1980). As in the Erzgebirge, the greater part of S.E. England is underlain by a major Carboniferous batholith exposed in five cupolas. Deformed, greenschist and contact-metamorphosed Devonian and Carboniferous "molasse" slates, litharenites, lesser greenstones and carbonates occur in the roof. Several thousand hydrothermal ore occurrences congregate in the immediate vicinity of the cupolas, at both sides of the contact (but more in the exocontact).

Halliday (1980) demonstrated that the ores kept forming for about 75 million additional years after the granite emplacement, according to the following time pattern:

295 m.y.: emplacement of major plutons;

285-280 m.y.: endocontact greisens with sheeted veins and Sn-W stockworks (rare);

280-275 m.y.: after fracturing, emplacement of granite porphyry dikes and shortly afterwards the majority of Sn, W and Cu lodes. Main Stage of mineralization;

270 m.y.: formation of most Pb,Zn,Sb,Ag, etc. veins (minor) and

220-230 m.y.: U and remaining polymetallic mineralization.

In S.W. England both the intrusive dikes and ore veins (lodes) follow the same fracture sets and shear zones, both in the endo- and exocontacts of the early granites (but in exocontacts of the younger generation of granitic stocks when such are present). When the "late" (postmagmatic) Main Stage veins are hosted by the older granite, they are recognizable from the earlier endocontact greisen apogranite association by their lack of intimacy with their host, by lack of control by the granite cupola morphology and contacts and by different mineral filling and alterations. Most reviews of the Cornish metallogeny recognize the following styles of the Main Stage and later

Table 28-10. Postmagmatic Sn (W,Bi,Mo,etc.) veins, stockworks, replacements, in granite aureoles (non-carbonate hosts); selected examples

LOCALITY	HOST ROCKS	MINERALIZATION	REFERENCES
Wheal Jane mine, Truro, Cornwall, Great Britain	D_1 slate, siltstone intr.by 280 m.y. qtz.feldsp.porph. dikes	up to 23 m thick complex N.E. striking replac. vein in shear along dike/wallrock contact. Cassit.,ars., local mass.pyr.,sphal.lenses. 62.5Tt Sn/1.25%	Rayment et al. (1971)
Dolcoath Main Lode, Camborne, Cornwall, Great Britain	D-Cb slate, siltst.,greenstone intr. by Cb granite	1.5 km long, 1 km deep, 0.3-12 m thick N.E. striking fracture filled by brecc. cementing qtz.,tourm., cassit. 93.5Tt Sn, 355Tt Cu	Jackson (1979)
Khapcheranga, East Transbaikalia, U.S.S.R.	Pe hornfelsed shale,quartzite; J,porph.biot.granite; Cr,T, gran.porph.,rhyol., dacite	over 20 fiss.filling and fault gauge replac. veins along N.W. tect.zone; pyrrh., fine cassit.,less arsenop.-cassit. and qtz.,calc.,chlor.,cassit. veins; ox.zone to 50m; 240Tt Sn/3.78%	Magak'yan (1968)
Ege-Khaya field, Yakutia, N.E. Siberia, U.S.S.R.	Tr folded terrig.litharen., slate, intr. by J_3-Cr_1 granodiorite	miner.fault brecc.and fiss.veins along N.E. crush zones; qtz.,tourm., chlor.,pyrrhot.,cassit.,arsenop., sphal.,cp.,stannite; zoned; min. 70Tt Sn, partly from placers	Magak'yan (1968)
Sungei Lembing mine Pahang, E.Malaya	PZ hornfelsed slate, quartzite intr. by Cb_3 granite	600 m wide band of hornfelsed sedim. // with granite contact, cut by complexly zoned veins with cassit., chlor.,arsenop.,cp.,sphal.,pyr., locally quartz	Hosking (1973)

Sn(W,Cu,etc.) ores (essentially the same styles are universal worldwide):

(1) Fissure veins

Veins supplied most of the metal production. They are usually tabular, several centimetres to about 2 m wide, traceable along a strike for 500-1,000 m (exceptionally up to 6 km), and followed to depths of up to 900 m. There is no persistent relationship between the granite form and vein trends. Some veins occupy the same fissures as dikes, but dike-cutting veins are more common. Most fissure veins have polyphase filling and many show metal zoning with depth. Cassiterite usually accompanied by chalcopyrite, chalcocite, specularite, sphalerite, wolframite and arsenopyrite is scattered in quartz, chlorite, tourmaline, feldspar, hematite or mica. Some major veins were high in Cu and low in Sn (e.g. the Dolcoath Vein produced 355 Tt Cu and 93.5 Tt Sn), others carried exclusively chalcopyrite and chalcocite (e.g. Devon Great Consols, 776 Tt Cu). There is no satisfactory explanation for the widely variable presence of Cu in the tin veins. The high-copper areas appear to correlate with abundant greenstone wallrocks (spilites, metabasalts), the most likely Cu sources.

The Dolcoath Main Lode near Camborne (Fig. 28-65), the most productive vein in the district, is a N.E.-trending, 50-90° S.W. dipping structure continuing for 1.5 km and tin-mineralized for over 1 km downdip. Its thickness varies from 0.3 to 12 m and the vein is filled by brecciated quartz, tourmaline and cassiterite at a depth where granite is the wallrock, and comb quartz, pyrite and chalcopyrite near the surface, in slate and greenstone wallrocks. The wallrock alterations include silicification, sericitization, tourmalinization and chloritization.

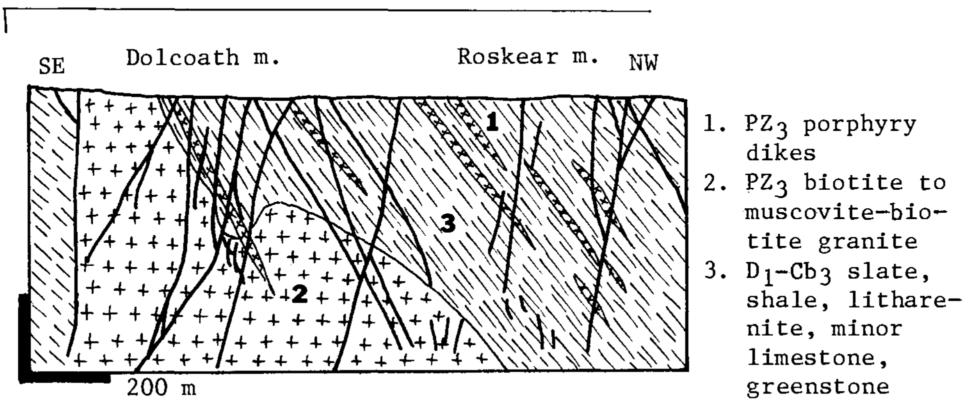


Fig. 28-65. Sn and Sn-Cu veins in the Camborne area, Cornwall. Simplified after Dines, ed., (1956).

(2) Replacement veins

Dunham et al. (1978) distinguished three varieties: (a) replaced wallrocks adjacent to a narrow fissure, (b) completely replaced selected horizons (e.g. carbonates) within the metasediments and (c) replacements of mylonite and gouge along faults and shears. The Great Flat Lode is an example of (a). It has been traced for 6 km and it consists of tourmalinized and silicified granite mineralized by finely disseminated cassiterite and minor sulphides, adjacent to quartz, tourmaline and cassiterite leaders. The lode width ranged from 1.3 to 4.5 m.

In the Wheal Jane mine near Truro, an example of (c) and one of the few recently producing Cornish deposits (Rayment et al., 1971; 62.5 Tt Sn/1.25%), unusually thick (up to 23 m) and complex lodes follow shears along the contact of gently N.W.-dipping quartz-feldspar porphyry dikes, emplaced into Devonian slates and siltstones. The thickest B lode is a shear zone replaced and impregnated by cassiterite, tourmaline, arsenopyrite, lesser chalcopyrite and pyrrhotite. In places it contains lenses of massive pyrite and sphalerite. The wallrock black slates are sericitized.

(3) Replacement pipes.

These are uncommon and of little importance. The largest pipe in East Wheal Lovell mine is roughly cylindrical, 130 m deep and 4 m in diameter, consisting of a 1 cm thick central stringer of quartz surrounded by silicified and sericitized granite with some disseminated cassiterite, sulphides and fluorite.

ERZGEBIRGE MOUNTAINS, CZECHOSLOVAKIA AND EAST GERMANY

In the Erzgebirge, veins and late postmagmatic tin stockworks are considerably subordinate in importance to mineralized greisens. Sn-W and W lodes were mined in the Pechtelsgrün field, Germany, Horní Slavkov (Gellnauer Vein), Rolava and Přebuz, Czechoslovakia and elsewhere. Tourmalinized stanniferous hornfelses formed by thermal metamorphism of phyllites at the contact with the Horní Blatná Stock in Podlesí (Roos, 1966), constitute a potential (0.6% Sn) tin ore. In the past, two small orebodies (2 m thic and 40 m long) marked by sporadic visible cassiterite, pyrite and arsenopyrite on occasional fracture veinlets, were mined. In the absence of associated fracture minerals the cassiterite is finely dispersed and megascopically unrecognizable. Similar hornfelses may form economically important deposits in the future.

EASTERN CORDILLERA TIN BELT, BOLIVIA

The "plutonic" share of the Bolivian Tin Province probably represents about 2 Mt Sn, most of it in exocontact veins, stockworks and replacements affiliated with Triassic to Miocene high-level granites. The Province has already been reviewed briefly in this book

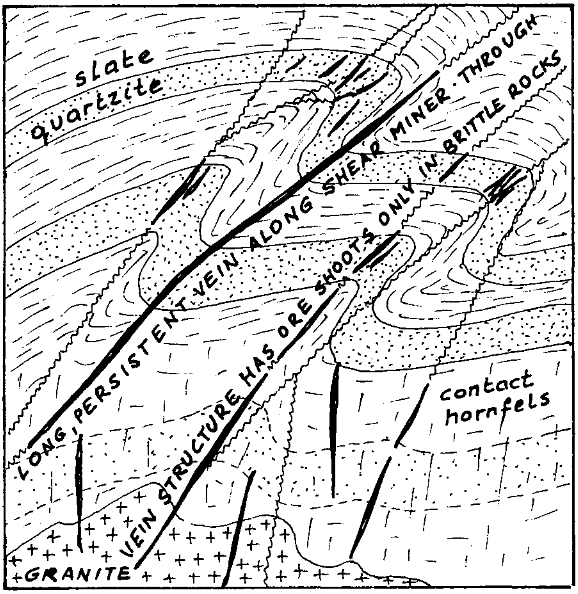


Fig. 28-66.
The usual control of the Bolivian exocontact veins by bedrock competency.

in connection with its distinct bedrock, composed of alternating shallow marine shales and quartzites (Section 19.7.1., Fig. 19-10). The vein morphology is strongly influenced by the competency of wallrocks (Fig. 28-66).

EAST TRANSBAIKALIA, U.S.S.R.

In East Transbaikalia where Sn,W,Mo ores are associated with Jurassic and Cretaceous granites, several stages of mineralization have been recognized just as they have in the Cornwall (Tomson et al., 1970). The early stage (165-170 m.y. at deposits in Khapcheranga and Bukuka) produced endocontact greisens with disseminated and stockwork cassiterite and wolframite. A later stage (148 m.y.) generated postmagmatic hydrothermal cassiterite-sulphide veins.

The Khapcheranga deposit (Magak'yan, 1968; min. 240 Tt Sn/3.78%) is in a Permian shale and quartzite intruded by Jurassic biotite granite stocks. The mineralization is located in the exocontact, along a set of parallel N.W.-striking fault zones over 2 km long. Several varieties of ore are present, the most important being massive pyrrhotite-cassiterite forming lenses replacing fault gauge. The cassiterite is very fine grained and invisible. Quartz, calcite, chlorite, cassiterite veins and cassiterite-arsenopyrite veins are alternative fillings. The oxidation zone is well developed to a depth of 50 m and it consists of a goethite-scorodite mass with relic cassiterite crystals.

In the Sherlovaya Gora deposit a quartz, chlorite, hematite, cassiterite, ferberite stockwork lies in a breccia, filled by upper Jurassic rhyolite fragmental material. The mineralization is fault controlled and about 600 m from a stock of lower Cretaceous granite porphyry.

SUNDALAND (S.E. ASIA) TIN BELT

This N.-S.-trending belt, approximately 3,000 km long, represents some 7.5 Mt Sn, most of it recovered from placers (Chapters 23, 24). The secondary cassiterite, however, comes entirely from a belt of Carboniferous to lower Tertiary granitic plutons and their aureoles. The Main Range Batholith has already been described as an example of mesozonal batholiths. Although several hundred bedrock tin occurrences are known and they span the entire range of styles discussed in this Chapter (Hosking, 1973, 1974), only about 5 major "bedrock" deposits are known and have been in production. One of them, the Sungei Lembing mine near Kuantan, eastern Malaya (Table 28-10), is of greatest importance. It contains a system of "Cornish-style" chlorite, cassiterite, arsenopyrite, chalcopyrite, etc. veins in hornfelsed sediments along a granite contact.

NEW ENGLAND, AUSTRALIA, THE MOLE GRANITE AUREOLE

The Mole Granite (Weber, 1974; Fig. 28-67) is a late Permian "tin granite", and one of the youngest intrusions of the composite New England Batholith. It is an elliptical body with an area of 800 km^2, emplaced in folded and hornfelsed Permo-Carboniferous sediments (originally shales, siltstones, sandstones) and in lower Permian continental volcanics. The batholith is in an early stage of unroofing as is borne out by the presence of a small roof pendant. About 150 mostly small Sn,W,Bi and base metal occurrences are scattered on top of the unroofed granite (these are small chlorite-cassiterite or quartz-wolframite pipes), in the pendant and on its flanks. A local speciality are ore occurrences in "silexite", resembling, in some respects, the "secondary quartzites" and formed largely by postmagmatic silicification of the granite along fractures and in the immediate exocontact.

At the Bismuth mine (Fig. 28-68A), the "silex" is a fracture-filling and wallrock-replacing white quartz, grading to coarse crystalline quartz, fluorite, topaz masses and a fine-grained greisen. It contains scattered crystals of wolframite and lesser molybdenite, bismuth, safflorite and skutterudite.

Of greater practical importance are large exocontact cassiterite stockworks, two of which are being mined near Emmaville, about 10 km south from the Mole Granite margin. The earlier known stockwork at the site of the Great Britain mine (Figs. 28-68, 69) is located in brittle, hornfelsed former Permian shales and felsic volcanics in the

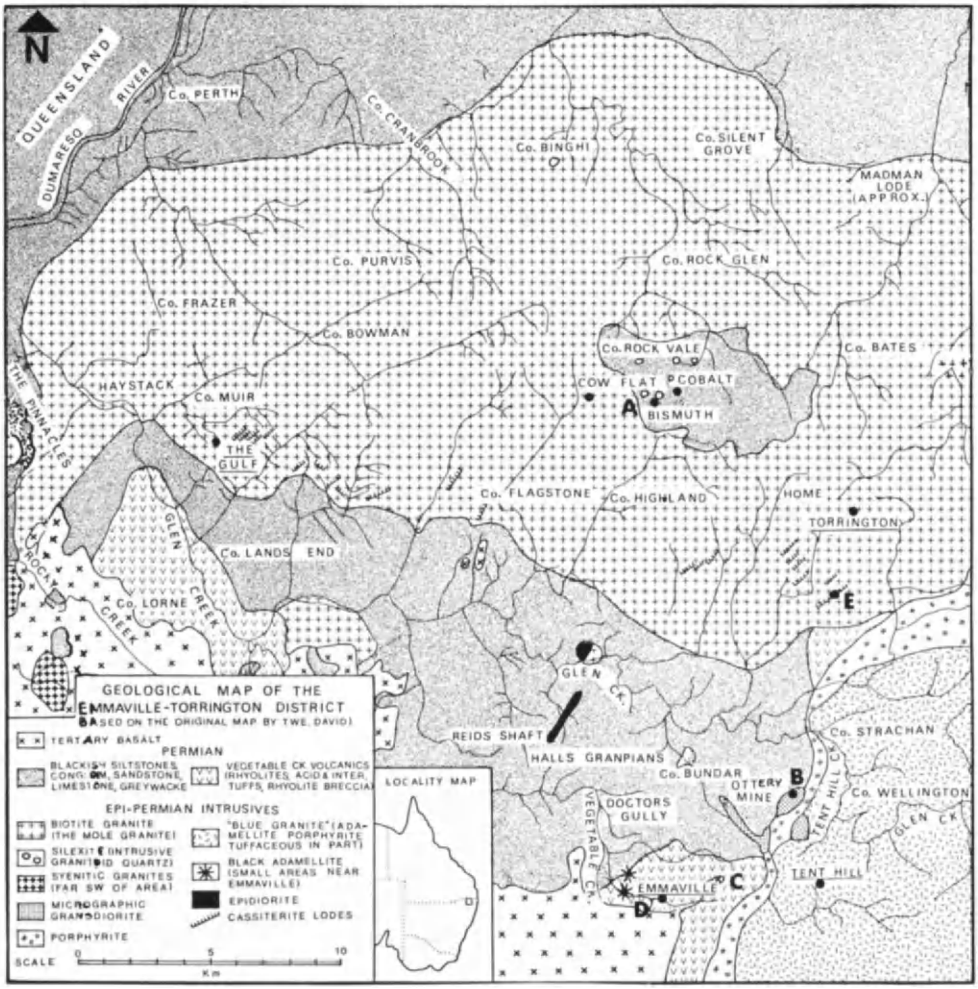


Fig. 28-67. Geological map of the Mole Granite massif and its aureole, N.S.W., from Lawrence (1975); courtesy of the Australian Institute of Mining and Metallurgy. Localities assembled in Figure 28-68 are marked by letters A to E.

immediate roof of a hornblende-biotite granodiorite. A system of parallel N.E.-trending, steeply dipping fractures extends over several square kilometres, having a density of 5 to 50 fractures per metre. The fractures are filled by thin white vuggy quartz veinlets, some of which contain scattered cassiterite crystals. Some fractures are dotted by flat cassiterite crystals without quartz. Every fracture is fringed by a bleached rim, 1-2 cm wide and some contain fine radial or fibrous black tourmaline. The overall appearance is very similar to the Bolivian mineralized quartzite mantos (e.g. Kellguani;

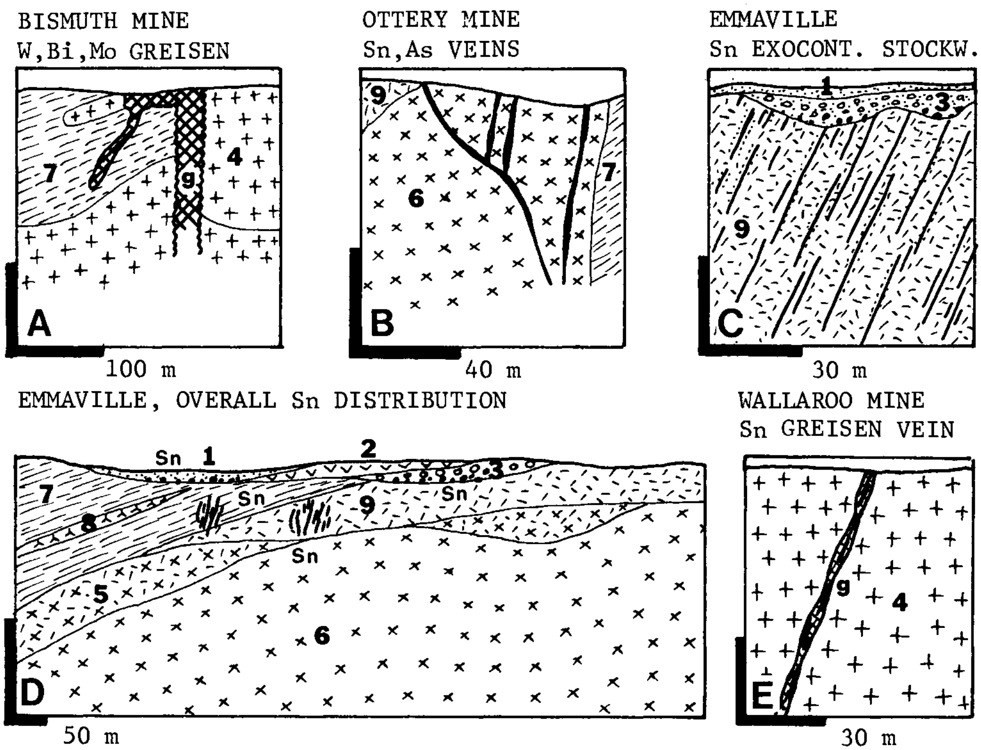


Fig. 28-68. Diagrammatic representation of the principal mineralization styles associated with the Mole Granite and its aureole, New England, N.S.W.
1=Q, Recent alluvium; 2=T plateau basalt, partly lateritized; 3=T, sub-basalt gravels; 4=Pe Mole Granite, coarse porphyritic biotite granite with a finer grained marginal facies; 5=black epidotized feldspar hornblende porphyry; 6=xenolithic hornblende biotite granodiorite; 7=Pe hornfelsed siltstone, conglomerate, sandstone; 8=greenstone; 9=rhyolite to rhyodacite flows, tuffs, breccia. From LITHOTHEQUE.

Chapter 19). The payable portions of the stockwork are irregularly distributed. 520 t Sn was produced between 1970 and 1973, and the overall recoverable tin content is probably of the order of several thousand tons.

In the nearby Grampians (Tarongo) deposit, the reserves of comparable ore are 17 Mt of material with 0.17% Sn, 0.05% Cu and 4.4 ppm Ag (=29 Tt Sn, 75 t Ag). Other deposits in the Mole Granite aureole (Fig. 28-68) include quartz, arsenopyrite, cassiterite fissure veins (Ottery mine, 2.4 Tt Sn); short quartz, chlorite, cassiterite

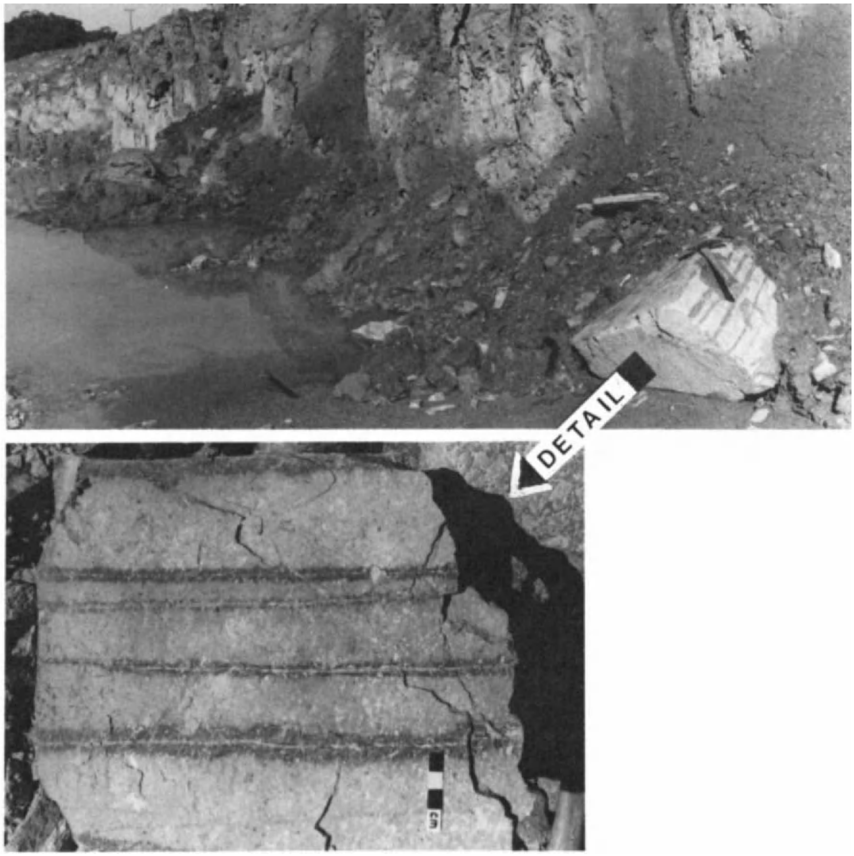


Fig. 28-69. Emmaville, New England, Australia, a quartz, cassiterite, lesser sulphides exocontact fracture stockwork and sets of parallel veins in hornfelsed Permian metasediments and metavolcanics. The ore minerals are located in thin fractures emphasized by narrow alteration rims.

veins in granite (e.g. Wallaroo mine); a Pb,Zn,Ag sulphide replacement in a dolomitic bed (Collisons) and others.

SIKHOTE-ALIN DISTRICT (U.S.S.R.) AND THE TIN-SULPHIDE DEPOSITS IN BIOTITE AND SERICITE ALTERATION HALOES

Sikhote Alin (or Kavalerovo) tin district (Materikov, 1974; Magak'yan, 1968) is near the Pacific coast of Siberia, facing Hokkaido over the Sea of Japan. It contains a variety of hydrothermal Sn and

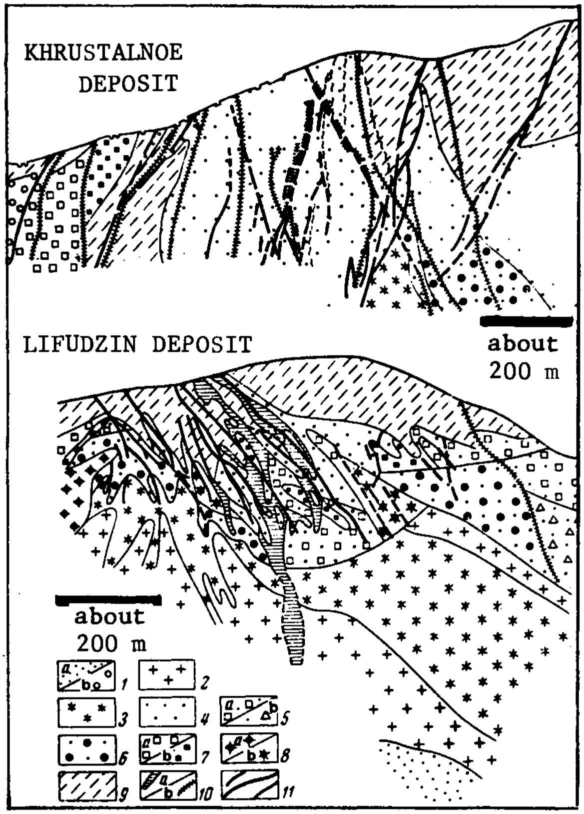
Pb-Zn deposits probably associated with Eocene high-level quartz diorite, granodiorite and granite stocks at a depth. The existing orebodies, however, are situated in the roof where only intrusive dikes are in evidence and they are controlled by alteration-zoned structural domes. A buried pluton is postulated to be present at a depth of 1.5-3.5 km.

The mineralized region is a synclinorium filled by a monotonous, folded upper Paleozoic and Mesozoic shale, siltstone, minor limestone, chert, spilite sequence (reminescent of the Cornish lithology), flanked on the west by an uplifted and deeply eroded late Cretaceous granitic batholith, and in the east by a Cretaceous continental margin andesite-rhyolite belt. The latter volcanics overlap into the ore-bearing sedimentary sequence.

The ore fields and deposits (Rudnoe, Smirnovskoe, Lifudzin, Khrustal'noe, Dalnee, Bol'shaya Sinancha) are associated with N.E. and N.S.-trending fault zones, and ore distribution is controlled by distinct alteration envelopes described and interpreted by Razmakhnin et al. (1974); Fig. 28-70. A typical domal alteration-mineralization complex in pelitic sediments has a core of an early intensive prograde biotitization, grading outward into a propylitic (mainly chlorite) zone. The biotites have an increased trace Sn content. On this are superimposed products of a later biotite-destructive acid leaching, consisting of sericite, quartz-sericite, quartz, chlorite and other assemblages containing biotitized relics. The best economic tin mineralization accumulated above the buried biotitized cores, and it has a vertical span of 200-600 m. Most commercial ores do not descend more than 200 m into the biotitized cores and those orebodies that do so have a strong envelope of sericitization.

The principal ore style comprises long (2-7 km) sets of thin, parallel fracture veins grading into stockworks and replacement veins. The tin ores are sulphide rich (arsenopyrite, chalcopyrite, galena, sphalerite, stannite), and cassiterite is usually finely crystallized and "invisible" except for the early stage quartz-tourmaline or chlorite, cassiterite veins and stockworks. The veins with high stannite content are difficult to process and they are of marginal economic importance.

As with other Soviet localities, the impossibility of an on-site inspection makes it difficult to ascertain the degree of uniqueness of the Kavalerovo district. Biotite formation is an integral part of the thermal metamorphism in the above intrusive zone everywhere where the granite was emplaced into a shale sequence, which is the most common case. Later-stage hydrothermal veins and stockworks hosted by the biotite hornfelses often are in the bleached and sericite-altered hornfelses. Razmakhnin et al. (1974), however, emphasized hydrothermal biotitization resulting in almost pure biotitites, so there is likely to be a degree of, at least quantitative, uniqueness.



1. biotite metasomatites and biotitized rocks
2,3. zone of hydrothermal leaching
2. light
3. strong
4–6. zone of simultaneous leaching and deposition represented by white silica metasom.
4. after propylites
5. after cryptic biotitization
6. after biotitites
7. cryptic biotitization
8. zones of "gathering" biotitization
9. propylitic rocks
10. dacites, andesites, diorite porphyries
11. orebodies

Fig. 28-70. The variety of hydrothermally altered rocks and metasomatites present at two deposits in the Kavalerovo district, Sikhote Alin, S.E. Soviet Union. From Razmakhnin and Razmakhnina (1973), approximate scale added.

28.8.4. Postmagmatic Sn (W,Bi,Mo) ores in skarn and altered carbonate

The development and success of the Renison Bell deposit in Tasmania focussed attention of geologists on the carbonate-hosted tin deposits, a previously little publicized style of mineralization. About 2.55 Mt Sn is believed to be present in metacarbonate-hosted orebodies. In the popular literature, all the tin ores in metacarbonates are often headlined as being in skarn or tactite and considered, implicitly or explicitly, to be contemporary with the formation of the "main stage" silicates. This is an oversimplification. Approximately half of the deposits are located in skarns or tactites but the rest are in recrystallized, dolomitized or silicified carbonates lacking the skarn silicates. In the former association the timing and characteristics of the tin mineralization conform to the general skarn model, reviewed earlier.

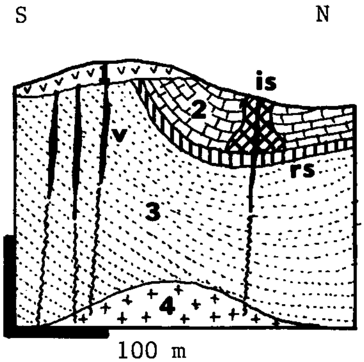
TIN-BEARING SKARNS

"Tin skarns" have recently been reviewed in Einaudi et al. (1981). In skarns tin can be (a) bound in the lattice of silicates, (b) present as fine but "invisible" cassiterite surrounded by a more common "carrier mineral" such as magnetite or pyrrhotite or (c) megascopically apparent in fracture fillings and veins. The (a) group is, at present, of questionable economic value, because the silicate tin cannot be economically recovered but if a large deposit of stanniferous silicates were ever discovered, a recovery process would certainly be found. The Doradilla deposit near Bourke (N.S.W., Australia) is said to contain 10-12 Mt of material with 0.3% Sn (=30 to 36 Tt Sn) largely in grossularite but also in malayite in skarn. The rest of the currently known occurrences of Sn silicates are small and have a patchy distribution. Most are located in the "gangue" of bodies of a later cassiterite. The silicates include Sn garnets (grossularite or andradite, up to 5.8% SnO_2); Sn-amphibole (up to 3% SnO_2); axinite, idocrase and few other minerals. Magnetite may contain up to 0.4% SnO_2. These minerals form in the earliest stage of skarn growth.

Stanniferous sphene, malayite ($CaSnSiO_5$) as well as nordenskioldine, högbömite and some other rare minerals, form in the later stages of skarn formation. Malayite is most widespread in wollastonite skarns and is an inconspicuous light-brown mineral of nonmetallic appearance resembling common sphene, grossularite or idocrase. Like scheelite, malayite is fluorescent under ultraviolet light. Because of its high tin content, malayite accumulations could be of practical importance.

The latest, hydrothermal stage of skarn development is the most important for tin deposition, and cassiterite accompanied by fluorite, amphibole, phlogopite, hematite, pyrrhotite and sometimes by scheelite, bismuthinite and molybdenite accumulates as stockwork veinlets and veins within and outside the skarn. Commonly, the late-stage stockworks in exocontact skarns are transitional into greisens in the endocontact, or into fluorite, quartz, tourmaline, axinite, datolite and other veins anywhere in the contact aureole.

In Moina, Tasmania (Kwak and Askins, 1981; Fig. 28-71) cassiterite with malayite, scheelite and bismuthinite occurs in a rhythmically banded idocrase, magnetite, fluorite skarn on the periphery of a pyroxene, idocrase, magnetite skarn. The skarn formed by replacement of an Ordovician limestone, 200 m above an altered cupola of tin granite. The tin-bearing skarn (45 Tt Sn/0.15%) was recognized only recently in what had been a small ore field producing Sn,W and Bi (689, 438, 90 t, respectively) from five E.-W.-trending fracture quartz, fluorite, topaz, muscovite, chlorite veins hosted mostly by quartzite.



1. Mi olivine basalt capping
2. Or, recrystallized limestone (marble)
3. Or, sandstone to contact meta-quartzite
4. D, altered granite cupola

rs=reaction garnet,pyroxene,magnetite skarn

is=rhythmic infiltrational fluorite, magnetite, vesuvianite, cassiterite, scheelite, sphene

v=quartz,fluorite,cassiterite veins

Fig. 28-71. Moina Sn-W skarn and vein deposit, Tasmania (diagrammatic, from LITHOTHEQUE).

The Lost River ore field in the York Mts., Seward Peninsula, Alaska (Dobson, 1982; Fig. 28-72) has close geological affinities with the Chukotka belt in Siberia rather than with the rest of Alaska. Ordovician limestone resting on earlier sediments was intruded by a late Cretaceous "tin granite" stock and a complex fluorite, Sn,W,Be mineralization formed in both the endo- and exocontact. The interesting fluorite-Be veins predate the granite emplacement and are reviewed in a later section. The granite-hosted greisen is of the "ordinary" type, composed of fine-grained quartz with topaz, tourmaline, cassiterite and sulphides.

The skarn is composed of an early andradite garnetite (up to 6% SnO_2 in andradite) which is cut by a layered fluorite, magnetite, idocrase vein skarn. The latter carries some helvite and malayite. The layered skarn, in turn, is often intersected by idocrase and garnet veins containing abundant sulphides (galena, sphalerite, chalcopyrite), some scheelite, and light-brown cassiterite. The latest abundant hydrothermal assemblage connected with the skarn development has fluorite, green biotite, lesser hornblende and white mica, and it forms veins and replacement veins in the earlier skarn as well as in the exocontact limestones. Sulphides (dominant sphalerite and pyrite) occur as massive zones and pods often intergrown with cassiterite. The late stages of skarn development were contemporary with the greisenization in granite. The published Sn and W reserves in the Lost River area are 40.5 Tt Sn/0.15%, 8.1 Tt W/0.03%, and there is some 4.4 Mt of fluorite.

Xi Zhoyouang mine in Hunan, S.E. China (Jovanović and Ramović, 1981) is truly a giant deposit if the published figures are correct (420 Tt Sn, 600 Tt W, 40 Mt CaF_2, 200 Tt of beryl, 230 Tt Bi,

Table 28-11. Skarn-hosted hydrothermal Sn (W,Mo,Bi,Be) deposits; selected examples

LOCALITY	HOST AND INTRUSIVE UNITS	MINERALIZATION	REFERENCES
Lost River, Seward Peninsula, Alaska, U.S.A.	Pt or Cm, slate,argill.limest., gabbro; Or, argill.limest. Cr_3 (71 m.y.) granite stock, porph. dikes, rhyolite	complex miner.system; Sn is high in andradite and malayite in skarn; cassit.is in endocont.greisen, late stage stockw. and veins in skarn. 40.5Tt Sn/0.15%; 8.1Tt W	Dobson (1982)
San Antonio mine, S.Eulalia, Chih., N. Mexico	Cr limest.converted to skarn; T_1 granite, rhyolite dikes	vertic.chimney of garn.,epid.,actinol. skarn has late stage qtz.,fluorite,topaz,cp.,cassit.veins in 2 km N.-S. zone; 8Tt Sn	Hewitt (1943)
Campiglia Marittima, central Italy	J limest.,shale; 5.7-4.7 m.y. qtz.monz.,tourm.gran.,porphyry	cassit.with sphal.,gal. dissem.or in late-stage veins in Mn-ilvaite, hedenb.skarns and marble; 4Tt Sn	Corsini et al. (1980)
Beatrice Pipe, Selibin,Perak,Malaysia	Pe limestone; Tr? tin granite	cassit.,ars.,cp.,in fluor.and barite gangue, late stage repl.masses in tremol.skarn; a pipe under a tin placer; 8Tt Sn	Hosking (1973)
Xi Zhoyouang dep., S.of Changsha, Hunan, China	PZ sandst.,shale; D-Cb limest. J (172, 139 m.y.) biot.granite	900x600x300 m complex skarn,superimp. stockw.of cassit.,scheel.,Bi, moly.,etc.;cassit.also dissem.in late stage skarn and greisen; 420Tt Sn,600Tt W, 230Tt Bi,40Mt fl.	Jovanović and Ramović (1981)
Doradilla near Bourke, N.S.W., Australia	Cm-Or slate,chert,marine metavolc.,rare limest.; D granite, greis.porph.dikes,leucogranite	15 km long, 3m wide horiz.of grossul.,wollast.,idocr.skarn with Sn-diops.,garnet,malayite; late stage Sn-magn.,cassit.,sulphides. 36Tt Sn/0.3%, partly in silicates	Plimer (1980)

Moina, N.W. Tasmania, Australia	Or,quartzite,limest.,hornfels; D, autometasom. tin granite at a depth of 200 m	cassit.,malayite, Sn-garnet in late stage assoc.in idocr.,magnet., fluor.skarn; also Sn,W,Bi veins outside of the skarn; 45Tt Sn/ 0.15%, plus 690 t vein tin	Kwak and Askins (1981)

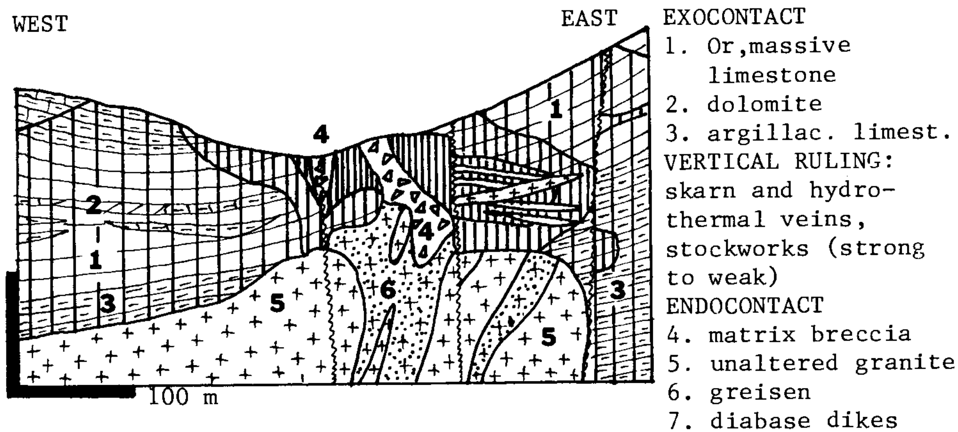


Fig. 28-72. Lost River mine, Alaska, hydrothermal plutonic cassiterite superimposed on greisen and skarn. Slightly modified after Dobson (1982).

110 Tt Mo), and it is a "variation on a theme" of lithophile metal skarn/greisen systems. The ores are contained in both the endo- and exocontact of a Jurassic biotite "tin granite" (two phases, 172 and 139 m.y.) emplaced in Devonian and Carboniferous limestones in a faulted anticline. The earliest skarn has a garnet, diopside, idocrase and wollastonite assemblage, followed by a hornblende-epidote skarn. These are only lightly mineralized by sporadic veinlets and nests with sulphides, cassiterite, chrysoberyl, tafeiite, helvite and beryl. The economic orebodies associated with the early skarn contain 0.238% W, 0.124% Sn, 0.105% Bi and 0.023% Mo.

The most important orebodies, as in the Lost River field, are contained in the transitional greisen-skarn zone dominated, in the exocontact, by late-stage veins and replacement masses of fluorite, garnet, diopside, hornblende, feldspar, quartz, scheelite, wolframite, molybdenite and bismuthinite. In this zone tungsten (0.465% W) is the dominant metal, and the tin content is 0.105%.

The remainder of the known tin skarns are all small deposits (Table 28-11); e.g. Campiglia Marittima, Italy, 4 Tt Sn; Santa Eulalia, Mexico, about 6 Tt Sn; Beatrice Pipe, Malaya, 8 Tt Sn).

TIN IN NON-SKARN CARBONATES (Table 28-12)

Cassiterite occurrences in altered carbonates lacking extensive skarn zones are most extensively developed in the trio of important deposits (Renison Bell, Mt. Bischoff and Mt. Cleveland) in north-western Tasmania (Figs. 28-73, 28-74). There, cassiterite is always associated with predominant massive pyrrhotite, to the point of being completely "invisible". All three major deposits and additional small occurrences (e.g. Mt. Razorback; Chapter 7) are hosted by a Cambrian and latest Proterozoic sedimentary and volcanic marine sequence of quartzite, slate, minor pillowed metabasalt greenstone, litharenite, bedded chert, limestone and dolomite. These low-grade metamorphosed but locally strongly deformed and tectonite serpentinite intruded rocks, occur in a broad N.E.-trending synclinorium (Dundas Trough), confined between two Precambrian "highs" (Williams, 1978). A series of late Devonian to lower Carboniferous quartz monzonite and granite plutons, small stocks and dikes with thermal aureoles up to 2.5 km broad, have been emplaced in the supracrustal rocks. About 20 small cassiterite occurrences of the common styles (endocontact greisens, exocontact veins) are associated with the potassic leucogranite phase, and there is little doubt that the tin accumulations in carbonates have the same affiliation, despite occasional statements to the contrary.

Renison Bell, the largest deposit (Patterson et al., 1981; 282 Tt Sn/1%; Fig. 28-74) contains a series of massive pyrrhotite, lesser chalcopyrite and cassiterite sheet (manto)-like orebodies hosted by three horizons of impure dolomite interbedded with Cambrian quartzite, shale and minor volcaniclastics. Lesser discordant orebodies of disseminated, veinlet and bleb pyrrhotite and cassiterite are situated

Table 28-12. Carbonate-hosted non-skarn hydrothermal tin deposits; selected examples

LOCALITY	HOST AND INTRUSIVE UNITS	MINERALIZATION	REFERENCES
Renison Bell, N.W. Tasmania, Australia	Cm_1 shale,siltst.,sandst.,minor tuff,3 impure dolomitic beds; D qtz.monzon.,granite,qtz. porphyry (not in cont.with ore)	set of dolom.-replacing pyrrh., cp.,cassit. manto oreb.,extending from faults; minor discord.orebod. 282 Tt Sn/1%	Patterson et al. (1981)
Mt.Bischoff, Waratah, N.W. Tasmania Australia	Pt_3 or Cm_1 quartzite,slate,minor dolom.interbeds; D, qtz.feldsp.porph. dikes	massive pyrrh.,qtz.,talc,cassit. replace dolom.; dissem.cassit.,pyr. sphal. in altered porphyry dikes; minor qtz.-cassit.veinl.; 80Tt Sn	Groves (1972)
Mt.Cleveland, Luina, N.W. Tasmania, Australia	Cm, low-grade met.argill.,litharen.,chert,spilite,maf.tuff, limest.; intr.by gabbro,diab. D, granite plut. 4 km away; altered,W,Mo miner.granite dike, at lower mine levels	system of parallel dissem.to mass. pyrrh.,cp.,cassit. lenses in calc-silic.hornf.("chert") and marble, underl. by qtz.,fluor.,wolfr.,Bi, molybd. stockw. in altered porphyry 31.2Tt Sn, 10Tt Cu	Collins (1981)
Kochiu, Yunnan, southern China	Tr limest., shale, underl. by PCm gneiss, schist, phyllite; Cr_3 (85 m.y.) granite cupolas of biot.-tourm.granite, believed floored by a major cryptobatholith	replacem.bodies of hemat.,cassit., ars.,pyr.,sphal.,gal. in limestone; in endocont. apogranite and greisen cont. feldspathite veins, lepidolite, lithionite, qtz. veins; minor vesuv.-wollast. skarns; 1.6 Mt Sn/3.65%	Meng et al. (1937)

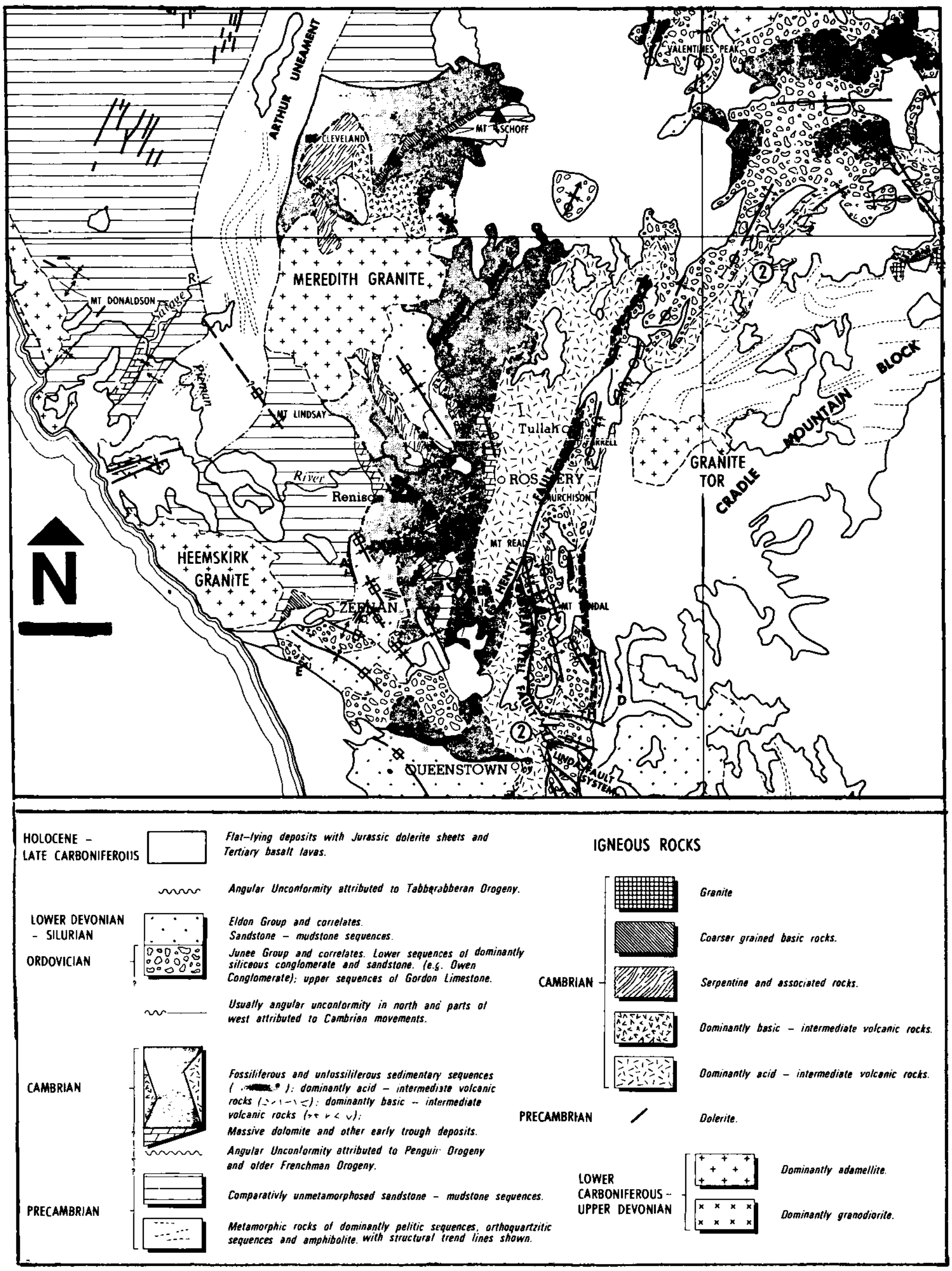


Fig. 28-73. The metalliferous area of N.W. Tasmania, showing the location (by triangles) of the three important sulphide cassiterite replacement deposits in carbonates. From Williams (1978).

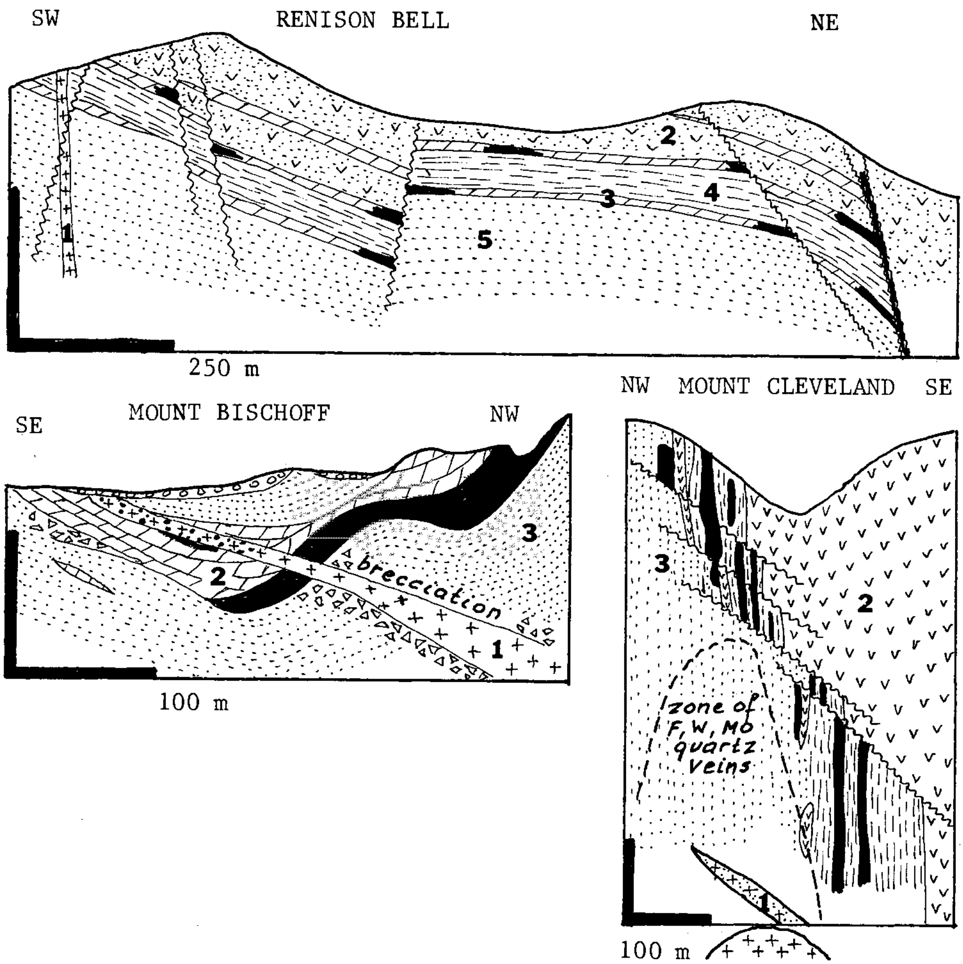


Fig. 28-74. Replacement pyrrhotite-cassiterite deposits in carbonates, N.W. Tasmania.

Mount Cleveland: 1=D altered granite porphyry body (diagrammatic only); 2=Cm greenstone (meta-spilite); 3=Cm meta-argillite, siltstone, shale, graywacke.

Mount Bischoff: 1=D quartz feldspar porphyry dike; 2=Pt_3 or Cm_1 dolomite; 3=quartzite and slate.

Renison Bell: 1=D quartz feldspar porphyry; 2=Cm basaltic volcarenite, siltstone; 3=ferroan dolomite layers; 4=thinly bedded quartzite, siltstone, shale, sandstone; 5=quartzite, sandstone.

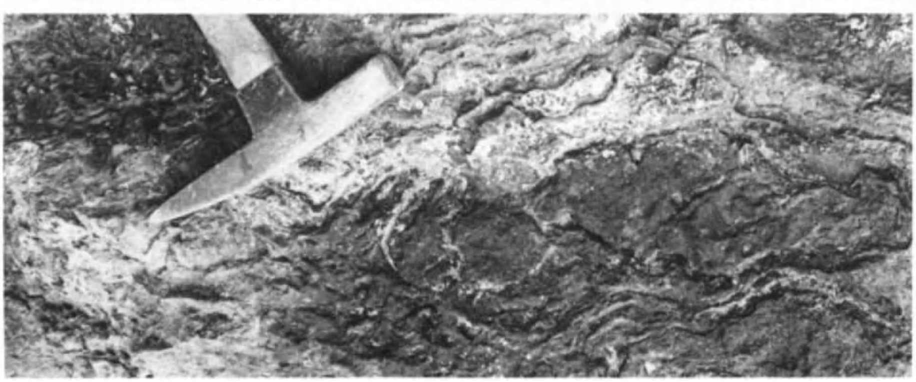
From LITHOTHEQUE, after Newnham (1976), Groves (1972), Collins (1981) and 1980-81 property tours.

in talc-altered and coarse-recrystallized dolomite along a fault zone. When a quartzite bed is present in the mineralized sequence, it is often replaced by alternating bands of tourmaline, quartz and pyrrhotite. Small stocks of Devonian biotite granite and quartz monzonite, and several dikes of quartz porphyry including one that is greisenized and contains minor cassiterite, occur in the vicinity and probably represent the concentrator rock suite to Renison Bell. The ore was interpreted as having precipitated from hot stannous chloride complexes at 350° C.

Mount Bischoff, Waratah (Groves, 1972; Figures 28-74, 75) was discovered in 1871 and it produced 60 Tt Sn. Several tens of separate orebodies are arranged at both sides of the contact of a probably Eocambrian dolomite and Devonian altered quartz-feldspar porphyry dikes. The most important orebodies were irregular pyrrhotite, quartz, talc, fine cassiterite masses , replacing dolomite. Next in importance were patches of pervasively disseminated cassiterite with pyrite and marmatite, in argillized and topaz-tourmaline altered quartz-feldspar porphyry endocontacts.

Mount Cleveland in Luina (Collins, 1981; 31.2 Tt Sn; Fig. 28-74) is in Cambrian deep marine ("oceanic") mafic volcanic-sedimentary association (spilitic greenstone, mafic pyroclastics, argillite, chert, litharenite, limestone) of the type described in Chapter 10. The lower greenschist-metamorphosed host unit is in fault contact with ophiolites, and is intruded by diabase and gabbro dikes. A Devonian granite pluton crops out 4 km south of the mine and probably underlies the mine field in depth. The ore consists of a series of vertical to steeply dipping lenses of massive to disseminated pyrrhotite and fine-grained (invisible) cassiterite (and chalcopyrite), peneconcordant with the relic bedding of a calc-silicate hornfels. The ore grades to replacement sulphide masses in a relatively pure former limestone. In the footwall of the peneconcordant sulphide lenses is a stockwork of quartz, fluorite, wolframite, molybdenite, bismuthinite and minor cassiterite veins hosted by a litharenite. In the deepest mine levels, the stockwork enters an altered (silicified) Devonian quartz porphyry dike. The origin of Mt. Cleveland is enigmatic but much less so now than it was in the past, when the presence of a mineralized granite in depth was unknown. The lithophile metals accumulation is hardly "stratiform" or "exhalative" as suggested by some, but the Fe and Cu sulphide orebodies are in the "right" lithological association to make such an origin possible and could be pre-granite.

Fig. 28-75. Mount Bischoff tin deposit, Waratah, Tasmania. Top and centre: general view and one of the workings. The white material is weathering-argillized altered porphyry. The dark rock is altered dolomite with remnants of pyrrhotite-cassiterite replacements.



The Kochiu district, Yunnan, southern China, by far the largest carbonate-hosted tin accumulation (1.6-2 Mt Sn/3.65%) has been mined for over 100 years, but there are few modern published data available in European languages. The fragmentary information (Meng et al., 1937; Ikonnikov, 1975) indicates that the district contains complex ore near a late Cretaceous apogranite, complete with albite, lepidolite and protolithionite zones. Known orebodies occur in greisen, in quartz, cassiterite, wolframite veins in the granite and in Precambrian basement metamorphics and in Triassic carbonate. Monotonous Triassic limestones are much in evidence in the area, and they are mineralized at and close to a contact with granite cupolas. A portion of the cassiterite (and also probably Sn-silicates that are not recovered) is situated in a late-stage idocrase-wollastonite skarn, but the bulk come from "sausage-like" and manto replacement orebodies peneconcordant with the limestone bedding.

28.8.5. Relic (pre-granite) Sn(W,Mo) orebodies in granite aureoles

In plutons-affiliated ore fields, the most frequently reported relic mineralization is in the supracrustal rocks, with which it is more or less conformable ("stratiform"). Such mineralization can be preserved almost intact (only isochemically metamorphosed), or suffer remobilization of variable intensity. The cassiterite mineralized quartzites at several localities in Bolivia which are interpreted as being paleoplacers, have already been treated in Chapter 19. More reported examples of relic Sn ores or anomalous enrichments in metamorphosed volcanic-sedimentary supracrustal associations are currently interpreted as former "exhalites" (=hydrothermal, seafloor sediments).

The Gierczyn-Nové Město pod Smrkem (Poland and Czechoslovakia) and Halsbrücke-Bräunsdorf (Erzgebirge) zones are treated in Chapter 29. More examples are known and Plimer (1980) reviewed the problem of "exhalative" precursors to the granite-associated Sn and W deposits. In several instances when cassiterite is present in a conformable massive sulphide or in iron formation horizons, it is epigenetic and superimposed (e.g. Zlatý Potok, Erzgebirge). There is a close analogy with the setting of cassiterite in skarns.

28.9. TUNGSTEN (WOLFRAMITE AND SCHEELITE) VEINS, STOCKWORKS AND DISSEMINATIONS IN NON-CARBONATE ROCKS IN GRANITE AUREOLES

28.9.1. Introduction

The economic tungsten supply comes approximately equally from (1) wolframite and lesser scheelite veins and stockworks in silicate rocks and (2) scheelite skarns in carbonates. The geological difference between tungsten veins and scheelite skarns is more than just the variety of host rocks, mineralogy and style of deposition. In contrast to Cu skarns which, in most cases, are just a "special" wallrock variety of porphyry coppers and Sn-skarns that are often an exocontact extension of greisens, the bulk of W veins and scheelite skarns are mutually exclusive and do not occur together (there are, however, exceptions as, for example, at the Xi Zhoyouang deposit).

The bulk of wolframite and scheelite veins in provinces that also carry tin, are associated with potassic leucogranites rooted in large quartz-monzonite to granite batholiths. The granites are of the "S" (ilmenite) type and the regional geological history is marked by events of fragmentation and reconstitution of an earlier continental crust (doming, initial rifting, collisions). Scheelite skarns, on the other hand, are genetically associated with quartz diorite to quartz monzonite (mostly granodiorite) plutons of continental margin belts, and their parent intrusions show I (magnetite) type tendencies, although this is not always conclusive. No appreciable quantities of tin are associated. There is also a significant contrast in the level of emplacement. Scheelite skarns belong to the "deep" (depth of formation around 12 km) skarns, W veins formed at epizonal and upper mesozonal intrusive levels.

Ferberite and hübnerite (end members of wolframite) vein deposits are not, with some exceptions (e.g. Dzhida, Transbaikalia; Rwanda) members of the Sn-W vein/stockwork provinces, and have a transitional setting.

28.9.2. Wolframite-bearing greisens and veins in W-Sn provinces

This mineralization style is a complete analogue of the cassiterite deposits in greisens described earlier. Cassiterite is usually present as an accessory component in wolframite greisens and complete transitions exist between both. Most tin deposits listed in Table 28-8 produced some tungsten as well. In some systems of granite cupolas with a greisen and exocontact roof sediments with veins, the former preferentially carry Sn, the latter W. In Cornwall this zonality is reversed and most endocontact greisens (e.g. Hemerdon) carry W deposits, whereas the bulk of the tin occurs in veins. Examples of interesting tungsten deposits in Sn-W provinces are briefly reviewed here and in Table 28-13, but the reader should consult the previous sections for data on the provinces.

Hemerdon, located just 11 km N.E. of Plymouth, (Anonymous, 1979b) is the largest W deposit in the metalliferous region of S.W. England. There, a dike-like body of Devonian biotite granite intrudes hornfelsed siltstone, mudstone and mafic volcanics. The granite is partly greisenized, silicified and tourmaline-altered, and pervaded by a stockwork of thin quartz, K-feldspar, hematite veinlets and veins. The veins range in thickness from several millimetres to several centimetres. Wolframite, arsenopyrite and rare cassiterite are scattered in the veins in a most irregular fashion ("few nuggets in some bands, then nothing for some distance") that makes exploration difficult. The outcrop is marked by a kaolinized saprolite down to a

Table 28-13. Wolframite-bearing greisens grading to veins; selected examples

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Hemerdon, Devon, S.W. England	Cb-Pe granite intruded into D hornfelsed siltst.,mudst. and marine metavolcanics	qtz.,microcline,hemat.,wolfr.,arsenopyr.,cassit. stockwork grading into veins in greiseniz.granite; 61.2Tt W/0.136; 13.05Tt Sn/0.029	Anonymous (1979b)
Baltar deposit, western Spain	Cb-Pe stocks of greiseniz. leucogran.intrus.into coarse biot.and musc.granite	large,low-grade stockw. of quartz, wolfr.,cassit.veinlets; 60Tt W/0.12% 40Tt Sn/0.08%	Min.Magaz. June 1980
Panasqueira, S. Portugal	Cb-Pe gran.to qtz.monzon. greiseniz.cupola,intr.into Pt_4 or Cm hornf.argillite and litharenite	290 m.y.; 200-300 m thick horiz. swarm of qtz.,wolfr.,lesser cassit., cp.,veins at a level of cupola; W miner.postdate granite and greisen; 42Tt W, by-product Cu,Sn	Kelly and Rye (1979)
Akchatau, central Kazakhstan,U.S.S.R.	S_1-Cb_1 sandst.,siltst.,argill.,andes.,rhyol.tuff; Pe biot.qtz.monzon. intr. by leucogran.bodies	clusters of qtz.,musc.,topaz greisen and vein bodies in 4 belts; 300 separate bodies with scatter.wolfr., fluor.,tourm.,molybd.	Shcheglov and Butkevich (1974)
Antonova Gora, East Transbaikal, USSR	J sandst.,shale; J med.grained musc.granite	series of // qtz.,musc.,fluor.,wolf. veins 0.6-0.7 m thick, up to 1 km long, in apical part of gran. stock	ditto
Bukuka, East Transbaikal, U.S.S.R.	J_2 sandst.,shale; J_3 biot.granite stock,dikes	80 qtz.,wolfr.,lesser sphal.,cp.,pyr. gal.,bismuth veins and stockw. in greiseniz.,silicif.,seric.granite	ditto
Dzhida, East Transbaikalia, U.S.S.R.	Cm schist,metavolc.,ophiolites; PZ qtz.dior.,gabbro, granite; Tr syen. Tr-J_1 leucocr.gran.,gran.porph.	140 m.y. qtz.,hübnerite,lesser scheelite and sulphide veins.	ditto

Yugodzyr, S.E. Mongolia	PZ, sandst.,slate; PZ_3–J_1 granite, dikes; 210–220 m. y. aplite,tourm.pegm., greiseniz.gran.porphyry	1)gently dipping qtz.-wolfr. veins in exocont.; 2) moly. dissem.and stockw. in endocont.greisen; dissem. moly, wolfr.,lesser scheel.,helvite,pyr., ars. Est.min. 30Tt W, 50Tt Mo	Marinov et al. (1977)
Iul'tin, Chukotka Pen.,Siberia, U.S.S.R.	Cb_1–Tr_2 schist,marble,gabbro overl.by shale,siltst., sandst.; Cr_1 granod.,qtz. dior.porph.,biot.granite	104 short,en-echelon veins, up to 1.2 km long ore zones; qtz.,musc., lesser albite,fluor.,wolfr.,cassit., sulph. in hornfels. exocontact	Shcheglov and Butkevich (1974)
South Kiangsi W distr.,S.E. China; SELECTED DEPOSITS:	PZ, N.E. trending sandst. and hornf.slate,intr.by J_2 and Cr granitic bathol.	160–180 m.y. mineraliz. assoc. with granites, in endo- and exocontacts. 5.5 Mt W (minor quant. from placers)	Ke-Chin Hsu (1943) Kazanskii (1972)
Sihuashan, near Tayu	biot., musc.-biot. granite, alaskite, intruded to hornfelsed pelites	qtz.,wolfr.,feldsp.,musc.,moly.,cp., in about 200 // fiss. veins N80°W grad.to stockw.,dissem.,in endocont. 891Tt W/0.64%	
Pankushan	D, thick-bedded quartzite, S.W. dipping	E.-W. vertic.fissure veins of qtz., wolfr.,bismuth,arsenop.,zinnwald., scheel. in exo- and endocontact; 112Tt W/1.2%	
Yachishan		fissure qtz.,wolfr.,ars.,bismuth. veins in endocont.; 118Tt W	
Kweimeishan	Cm-Or dark gray quartzite, phyllite interbeds, near granite cupola	closely spaced N20°E qtz.,wolfr. veins grading to sheeted miner.zone; 1,500x500 m; 107Tt W	
Tachishan	Or-S phyllite, argillite, quartzite, diorite dikes	N65–80°W // veins to sheeted zone, qtz.,wolfr.,zinnwald.veins filling joints in tourmaliniz.hornfelses; 52Tt W/2%	

depth of 40m.

In the Erzgebirge, Pechtelsgrün (East Germany; Rösler et al., 1968) is an often quoted cupola wolframite deposit. There, a coarse-grained porphyritic Carboniferous biotite granite is intruded at a depth of 340 m by a younger "inner" leucogranite stock, the apical portion of which is capped by the marginal pegmatite, and greisenized. The tungsten mineralization is located in a N.W.-trending fracture zone up to 8 m thick and 1,200 m long, containing a large amount of narrow quartz, muscovite, feldspar, wolframite, arsenopyrite, etc. veinlets forming a stockwork. At some depth, these veinlets gradually unite to form several discrete veins. The ore zone is contained in the older granite and dissapears upon reaching the inner granite cupola. In the greisen, pyrite is abundant but the W and Mo contents are unimportant.

Panasqueira, Portugal (Kelly and Rye, 1979) has been the most productive western European tungsten mine for some time. There, a large number of near-horizontal parallel fissure veins occur in hornfelsed phyllite at a level of a greisenized granite cupola topped by a silica cap. The veins are, however, younger than the granite and composed of quartz with scattered wolframite and lesser cassiterite and chalcopyrite. The ore originated from NaCl-rich brines well below their critical temperature. The veins cut sharply across the steep foliation of their hosts and there is only an inconspicuous alteration.

In the W(Sn,Mo) province of central Kazakhstan, U.S.S.R. (Shcherba, 1968), wolframite is in the "conventional" style of stockworks and veins in granite endo- and exocontacts (e.g. Akchatau, Bainazar, Boguty). The Bainazar deposit is comparable, in many respectss, with Pechtelsgrün, only the ore band is substantially wider and is hosted by hornfelsed sandstones and slates in the exocontact above a greisenized leucogranite cupola. The parallel but discrete veins in the stockwork (quartz, molybdenite, wolframite) loose identity once they reach the granite cupola, and change into a mineralized fracture stockwork in the zinnwaldite, topaz, quartz greisen. There is an increase in the proportion of molybdenite with depth.

Eastern Transbaikalia and Mongolia contain a large number of W, W-Sn, and W-Mo deposits associated with Jurassic and Cretaceous granites. Yugodzyr, the largest tungsten deposit in Mongolia (Marinov et al., 1977), is in the Nukut-Daban Range in the south-eastern part of the country. There, a stock of lower Jurassic quartz porphyry topped by a small cupola is emplaced in lower Paleozoic hornfelsed slates and sandstones. The cupola as well as a younger phase of granite porphyry dikes are greisenized. The ore comprises two types: (1) disseminated and stockwork molybdenite, lesser wolframite, scheelite, arsenopyrite, etc. assemblage in greisens and (2) several systems of discrete parallel quartz, muscovite, wolframite, beryl, molybdenite (in the exocontact) and quartz, molybdenite, fluorite, ankerite, pyrite, lesser wolframite (in the endocontact) fracture veins. The veins are horizontal to gently dipping and the deposit morphology is strongly reminescent of Panasqueira.

Tumen-Tsogto deposit near Bayan-Oba, E. Mongolia (Marinov et al., 1977) is associated with a middle-upper Jurassic granitic complex intruded into Permian and Triassic continental felsic volcanics, Devonian terrigenous sandstones and limestones, and late Paleozoic metamorphics. Several apogranite cupolas with early albitites and pegmatites (or amazonitic K-metasomatic syenites) contain small quantities of beryl and wolframite. The most important ore from an economic point of view, however, is contained in a lens up to 30 m thick, 150 m long, of faintly banded ? replacement quartz, rimmed by greisen and situated near the contact of fine and coarse granites. Wolframite is the main ore mineral, present in the form of scattered, relatively large, tabular crystals. Additional W and Mo occurrences are situated in greisen zones. In the Buren-Tsogto W deposit, Mongolia, amazonite and albite apogranites are cut by quartz, wolframite, muscovite, beryl, fluorite, scheelite, cassiterite and sulphide veins.

On the Soviet side of the border in Transbaikalia, the Dzhida tungsten field is best known (Shcheglov and Butkevich, 1974; Fig. 28-76). There, 140 m.y. old quartz, hübnerite, scheelite and sulphide veins and stockworks intersect Paleozoic quartz diorite and granodiorite, Triassic syenite and lower Jurassic leucocratic granite and dikes. There is a considerable time gap between the termination of the intrusive activity and the hydrothermal veining. At the Kholtoson deposit, 140 subparallel veins have been recorded, 70 of them economic.

In the Bolivian plutonic tin belt, most cassiterite deposits produced lesser quantities of tungsten, the largest producers having been Chojlla (8 Tt W; Fig. 28-77)and Viloco (35 Tt W, 60 Tt Sn). There is, however, no large wolframite deposit.

The situation in the Tasman orogen of eastern Australia is similar. Mt Carbine, 50 km W.S.W. of Cairns, Queensland, has recently been explored as a large but very low grade deposit (15-25 Mt ore with 0.072% W = 14.4 Tt W; Plumridge, 1975) that gives it the distinction of being probably the world's lowest-grade hydrothermal tungsten deposit considered for production. There, a swarm of nearly vertical parallel quartz, K-feldspar, wolframite, lesser scheelite and minor sulphide veins striking 135°, is hosted by Devonian to Carboniferous hornfelsed slates with minor volcanics, 1 km from a Carboniferous granite contact. The veins represent 9.8% by volume of the ore to be mined in bulk.

28.9.3. Wolframite-bearing greisens and veins, outside of major tin provinces

NAN-LING RANGE (S. KIANGSI) TUNGSTEN PROVINCE, S.E. CHINA

The N. E.-trending Nan-Ling Range in the Kiangsi, Hunan and Kwangtung Provinces (about 200-400 km north from Canton) is estimated to contain about 5.5 Mt of tungsten in several hundred plutonic vein

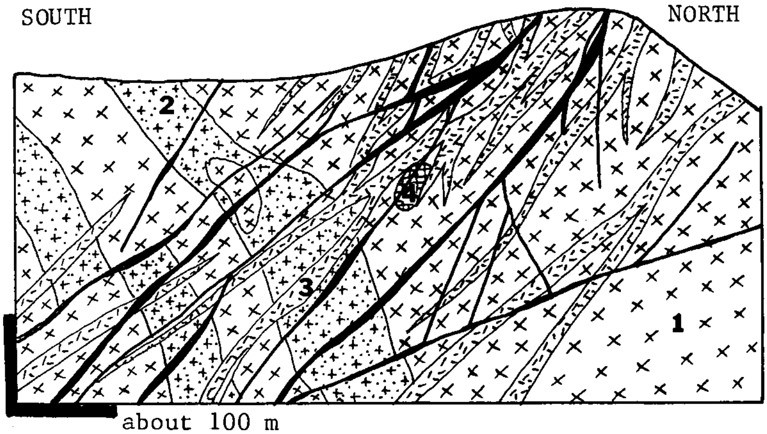
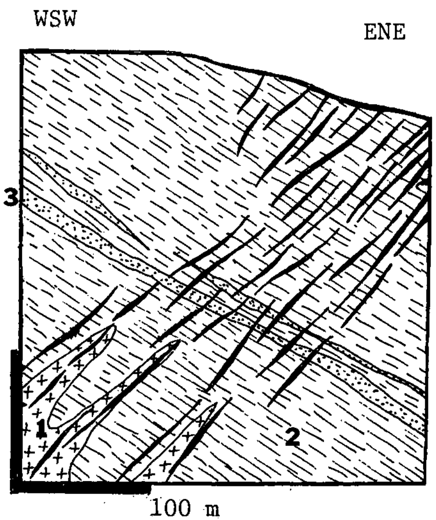


Fig. 28-76. Kholtoson W deposit, Dzhida field, East Transbaikalia, U.S.S.R. 1=PZ_3 quartz diorite; 2=J_1 granite porphyry; 3=J_1 lamprophyre; 4=PZ_1 hornblendite relics; 5=quartz–hübnerite veins. After N. K. Nefedov in Vakhromeev (1961).



1. 190 m.y. altered leucogranite (partly greisen) in apical portion of a granitic pluton
2. Or, gray slate transferred to knotten schist and biotite hornfels in granite aureole
3. Or quartzite interbeds

BLACK: lenticular quartz veins with scattered wolframite and cassiterite

Fig. 28-77. Chojlla Sn-W mine, Cordillera Real, Bolivia. From LITHOTHEQUE, based on data in Ahlfeld and Schneider-Scherbina (1964) and mine tour, 1977.

occurrences distributed over an area of about 350x150 km (Kazanskii, 1972). Over 90% of this wealth is in the Southern Kiangsi region (36,000 km^2; Fig. 28-78). Geologically, this is a part of the Kuei-Hsiang-Kan orogenic belt. This belt consists of lightly metamorphosed lower Paleozoic marine sandstones and shales marginal to and resting on a Precambrian crystalline basement, continuing here from the Cathaysian Platform in the west. The folded rocks are partly topped by Devonian to Triassic platformic sediments including quartz arenite, shale and limestone and intruded by Jurassic and Cretaceous granitic rocks. Most of the region is probably floored by a large quartz monzonite and biotite granite batholith with a large number of cupolas. Numerous wolframite vein deposits are mostly hosted by the lower Paleozoic detrital sediments in the aureole of Jurassic granites. Further west, in the thick platformic carbonate sequence in Hunan, there are numerous skarn and carbonate replacement Pb-Zn and occasional Sn-W deposits (e.g. Xi Zhoyouang). As expected, modern non-Chinese literature on this province is scarce, and the classical paper by Ke-Chin Hsu (1943) is still widely quoted.

The tungsten deposits are mostly veins in granite (44% of old production) and in the sedimentary exocontact (56% of production), near the apex of granite cupolas. As elsewhere, greisens are common in the endocontact, while tourmalinization is the most common alteration of the sedimentary wallrocks. The veins typically fill systems of parallel E.-W. fissures filling tension joints perpendicularly or at an angle to the metasedimentary bedding. The vein persistence and regularity is one of the peculiarities of the enormous cumulative tungsten concentration. The veins are composed mainly of massive quartz, muscovite, tourmaline, K-feldspar, wolframite, lesser molybdenite, chalcopyrite, arsenopyrite and Bi-minerals. At Chiulungnau, a quartz lens, up to 50 m wide, was emplaced along the granite-phyllite contact and is lined by a greisen on the endocontact side. The quartz contains swarms of small wolframite crystals. A small proportion of tungsten came from "pegmatites", more probably hydrothermal quartz, K-feldspar, fluorite, lithian mica, topaz, wolframite and cassiterite veins that accompany the quartz veins. The richest deposit, Sihuashan (891 Tt W) has dimensions of 2 x 1.2 km and is entirely contained within a small granite stock.

NORTH AMERICA

In the Americas (except Bolivia) granite and greisen associated wolframite deposits are conspicuously scarce. This contrasts with the large and abundant scheelite skarns in the Cordillera. In the Appalachian belt, wolframite veins are represented by the small Burnt Hill deposit in New Brunswick (over 30 short quartz, muscovite, topaz, wolframite veins in hornfelsed lower Paleozoic argillite and quartzite above a Devonian granite cupola), and by the Hamme mineralized zone in the Carolina Slate Belt. The latter locality (Foose et al., 1980;

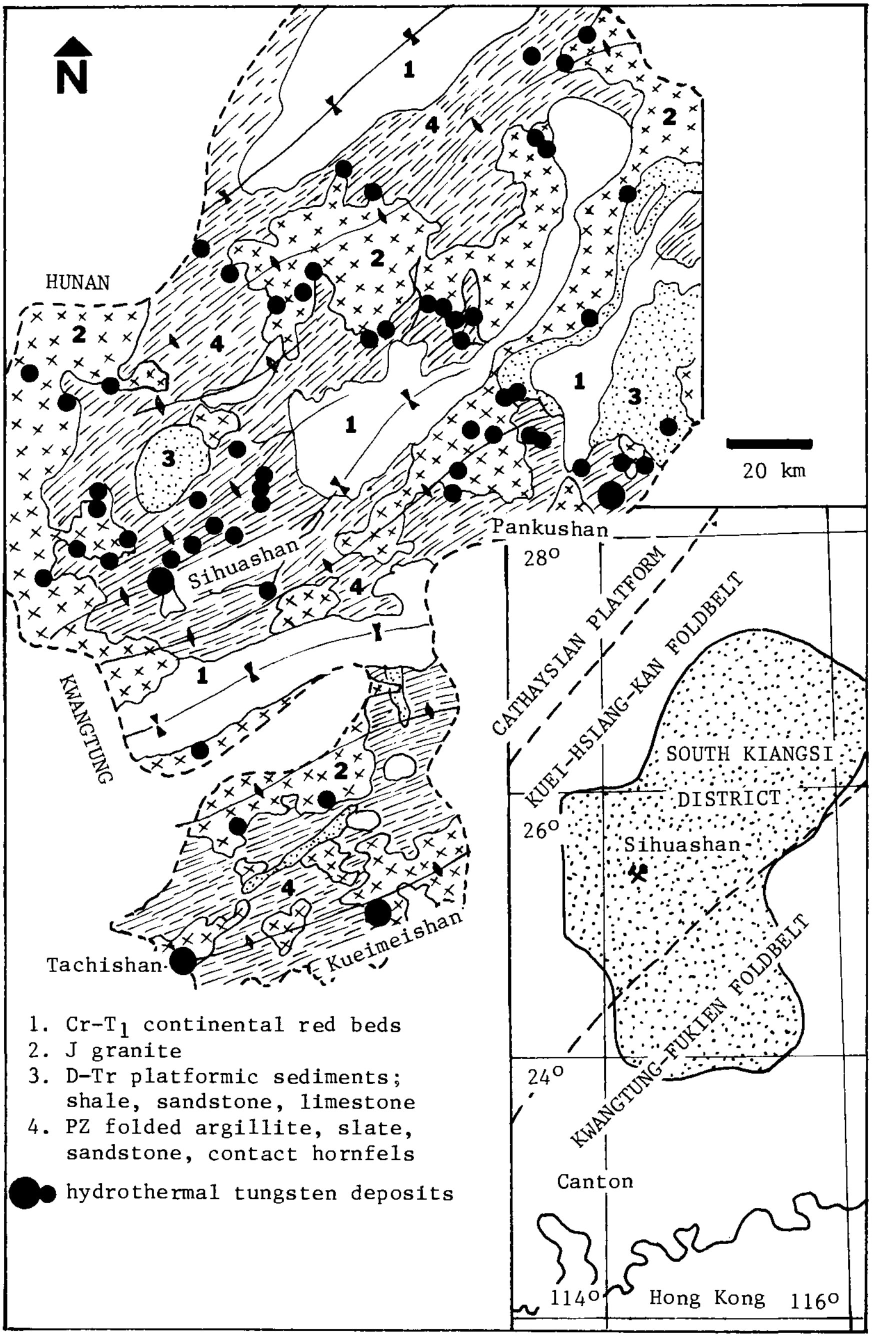


Fig. 28-78. The wolframite vein and stockwork district of South Kiangsi, southern China. After Ke-Chin-Hsu (1943).

7.2 Tt W) has a series of steeply dipping quartz-hübnerite veins, concentrated along a lower Paleozoic granite-slate contact. The N35°E trending vein band is about 3.5 km long and it contains eight en-echelon lodes fringed by a thin alteration envelope of quartz-sericite greisen. The orebody has been folded and locally penetratively deformed along a series of shears.

In the western Cordillera, the Red Rose mine near Hazelton, British Columbia (Sutherland Brown, 1955; 850 t W) is located at the eastern edge of the Coast Batholith (Section 28.2.3.), hosted by a Mesozoic diorite near a lower Tertiary porphyritic granodiorite and felsite dike swarm. The orebody is a vein, 1.2-13 m thick, filling a N35°W striking, 65° S.W. dipping shear, and is composed of a massive, drusy quartz with lesser amounts of feldspar, biotite, hornblende, tourmaline, ferberite, scheelite and chalcopyrite.

The Boulder County (Netherland) tungsten district in Colorado (Lovering and Tweto, 1953; 12 Tt W) has orebodies in Proterozoic gneissic quartz monzonite as well as minor schist and gneiss, associated with middle Tertiary felsite, aplite and "pegmatite" dikes. The orebodies are N.E. and E.N.E.-trending fissure, shear and breccia filling low-temperature (200-300° C, i.e. epithermal) veins. They are composed of ferberite and lesser pyrite, sphalerite, tetrahedrite and adularia scattered in drusy and cherty horn quartz to hematite-pigmented jasper. The veins grade into barren silica-cemented "reefs" or into gold-telluride veins. The wallrock alteration consists of a thin sericitized or silicified selvedge, rapidly passing out into an argillized margin. This is a high-level mineralization probably related to an intrusive stock in depth and substantially different from the "greisen-style" lodes reviewed so far.

SOUTH AMERICA

The Pasto Bueno deposit in the northern Andes of Peru (Landis and Rye, 1974) is more interesting for its geology and geochemistry than for its economic importance. It is a tungsten-polymetallic deposit (monthly concentrate production in the 1970s: 20 t W, 40 t Cu, 45 t Pb, 189 kg Ag), surrounded by a halo of K-silicate (feldspar and biotite), greisen, phyllic, argillic and propylitic alteration. It is associated with a 9.5 m.y. old quartz monzonite stock having I-type characteristics. The ores are in a near-vertical quartz, fluorite, sericite, carbonate, wolframite, tetrahedrite, sphalerite and galena vein system in the endo- and exocontact of the stock. The Pasto Bueno Stock is a separate intrusion located about 50 km N.E. of the main body of the Andean batholith, reviewed in Section 28.2.2.

In Argentina, several hundred small quartz, wolframite, scheelite, bismuthinite, etc. orebodies occur in uplifted blocks of the old crystalline basement east of the main Andean ranges (in Cordillera Frontal, N. Patagonian Massif), but their aggregate tonnage is only about 7.5 Tt W. The largest deposit, the Los Condores mine in the

Sierra de San Luis (Haude and Weber, 1975; 4,592 t W, 173 t Bi) contains three parallel veins, 0.5-2.5 m thick, in phyllite and schist, parallel with pegmatite injections.

28.9.4. Scheelite veins and stockworks in non-carbonate rocks

Accessory scheelite is a common mineral in tin and tungsten veins as well as in some molybdenite and gold deposits. Hydrothermal veins and stockworks in which scheelite is the only or dominant mineral are, however, uncommon and also inconspicuous (Fig. 28-79).

(1) Disseminated and stockwork scheelite in granite endocontacts (in cupolas and dikes) which is reminescent of porphyry coppers, has been reported in several small occurrences such as the Victory mine near Gabbs, Nevada, or Haut-Auxelles in the Vosges Mountains, N.E. France (Fluck et al., 1975). At the latter locality, scheelite is located in an intensely silicified and less sericitized, tourmalinized dike of Carboniferous microgranite, intruded into lower Carboniferous continental volcanics and sediments. A stockwork of quartz or quartz-feldspar veinlets occupies 80% of the rock and a very fine, inconspicuous scheelite is scattered throughout. Up to 30% of sulphides (pyrite, pyrrhotite, arsenopyrite, molybdenite) are present locally.

Stockworks of crosscutting veinlets are gradational into swarms of parallel quartz-scheelite veins, or into few "strong" veins in both endocontact (2) and exocontact (3). This style is represented by the very low grade (0.05-0.07% W) vein swarms in the Permo-Carboniferous granite near Barruecopardo, W. Spain, as well as in the Boguty deposit, S. Kazakhstan.

Boguty (Shcheglov and Butkevich, 1974) is in production and it is probably the largest currently operating scheelite vein/stockwork deposit known. There, a flysch-like Ordovician sequence of dominant sublitharenites and minor slates and limestones was folded and intruded by a composite pluton which is probably of Permo-Carboniferous age. The earlier intrusive phase produced biotite-hornblende quartz monzonite and the later phase albitized and greisenized leucogranites. Early K-feldspar, biotite and tremolite alteration surrounds the intrusion. Later stage scheelite is situated in an N.E.-trending altered and mineralized fracture zone, up to 2.5 km long and 200 m wide, located along the granite/metasedimentary contact, largely on the exocontact side. In the stockwork, several large and relatively persistent veins are accompanied by a complex network of fine veinlets. The veins and veinlets are composed of quartz, muscovite, purite and scheelite. Wolframite, molybdenite, chalcopyrite, galena, pyrite, tourmaline, fluorite and K-feldspar occur in small quantities. Most of the scheelite is located in selvedges, whereas the central portions of thicker veins are visually unmineralized. Within the stockwork, quartz, sericite, chlorite alteration is most common. The Verkhnye Kairakty deposit in Kazakhstan is similar.

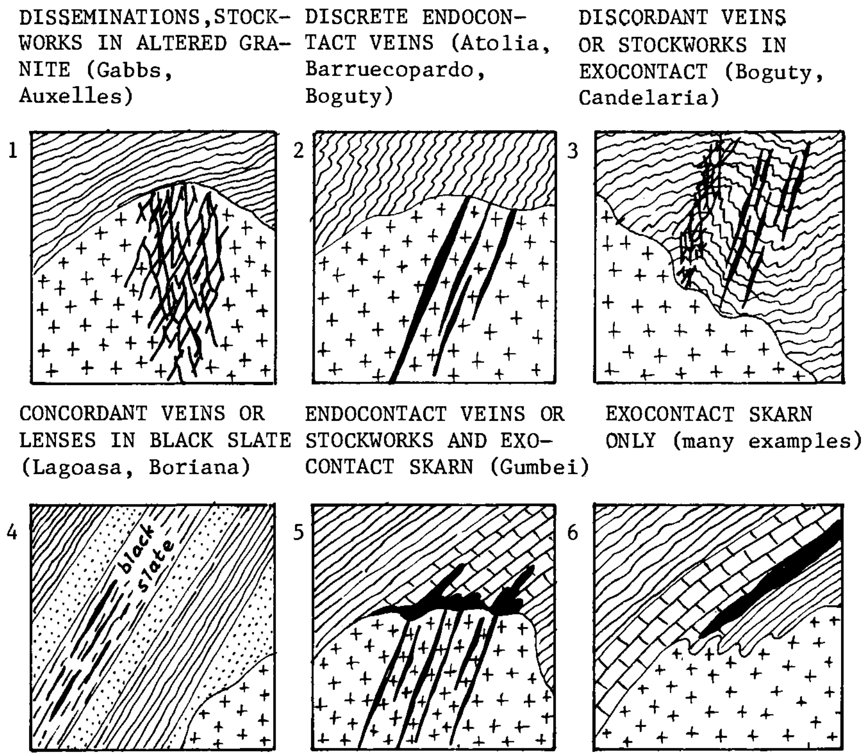


Fig. 28-79. Diagrammatic representation of the varieties of epigenetic hydrothermal scheelite deposits associated with granitic plutons.

The recently discovered Logtung property at Logjam Creek (close to the Yukon-British Columbia border, Canada; Tempelman-Kluit, 1981) is a large, low-grade "porphyry scheelite-Mo" deposit. It contains geological reserves of 162 Mt ore with 0.0952% W and 0,032% Mo (i.e. 152.3 Tt W and 50 Tt Mo). The deposit consists of scheelite and molybdenite disseminated in a stockwork of quartz veins in a Cretaceous quartz monzonite stock, a member of the Seagull group of intrusions.

Orebodies consisting of quartz-scheelite lenses and stringers running parallel to foliation and/or bedding of black metasediments (slates, phyllites) in granite aureoles (style 4) are known in several localities, for example, Lagoasa in Portugal. Such occurrences are generally considered (re)mobilized stratiform tungsten enrichments and these were recently reviewed by Denisenko and Rundkvist (1977). The low-temperature (epithermal) scheelite veins in quartz monzonite near Atolia, California, were reviewed in Chapter 26. When carbonates are available in the exocontact of scheelite-mineralized granites (style 5; e.g. Gumbei deposit in the Urals), both endocontact veins and exocontact scheelite skarns result. In the large scheelite skarn deposits reviewed in the next section, the granite endocontacts frequently contain mineralogical quantities of scheelite, but this is rarely of economic significance.

28.10. SCHEELITE SKARNS

Phanerozoic scheelite skarns contain about 950 Tt W, a significant increase from virtually nothing before World War II. The potential for new discoveries is good, mainly because of the relatively deep-seated origin of this mineralization style. Scheelite skarns have been reviewed recently by Einaudi et al. (1981). From the associational point of view, scheelite skarns (SS) can be subdivided into (1) high-level skarns (hypabyssal or aposkarns, associated with epizonal and upper mesozonal plutons) and (2) deep-seated (abyssal) skarns. Skarns of type (1) are associated with greisenized granite cupolas and scheelite is almost always accompanied by substantially more widespread cassiterite or sulphides. These have been reviewed sufficiently earlier and will not be considered again here.

Skarns of type (2) are the "typical" scheelite skarns, believed to have formed at depths ranging from 5 to 15 km, at the level of lower mesozonal or even katazonal granites. Because of their deep origin, SS now exposed are almost entirely hosted by Triassic and older carbonates and related to Cretaceous and older intrusions. In complex orogenic belts, scheelite skarns often survive in the deepest eroded cores of major batholiths, as in the Sierra Nevada, California. The SS are rarely associated with other metalliferous skarns and hydrothermal deposits except, sometimes, the "hypothermal" gold-quartz lodes and later-stage, superimposed ores. As summarized by Einaudi et al. (1981), the properties of scheelite skarns are as follows:

(a) They are associated with coarse-grained, K-feldspar megacrysts containing porphyritic granodiorite to quartz monzonite stocks and batholiths. Aplites and pegmatites are common; (b) the plutons are largely unfractured, permissively emplaced; (c) endoskarns are narrow and unimpressive, containing diopside, plagioclase, epidote; (d) SS are hosted either by a "black association" of argillaceous carbonates converted to calc-silicate hornfelses alternating with thermally hornfelsed pelite, or by pure marbles; (e) the above rocks are overprinted by infiltration and diffusion metasomatic skarns that are typically zoned. A barren pyroxene, plagioclase, lesser epidote skarn fringed by an outer amphibole zone forms in a hornfels, mineralized garnet-pyroxene skarn with an outer wollastonite-idocrase zone, forms in the marble; (f) SS are often manto-shaped, peneconcordant ("stratiform"), and tend to follow specific stratigraphic units (usually the stratigraphically lowest marble bed if more beds are present); (g) SS are either "reduced", formed in a "black" exocontact association and at a greater depth, or "oxidized", formed in light or hematitic hosts. Reduced skarns contain hedenbergite, almandine-rich garnet, biotite and hornblende. Oxidized skarns contain andradite and epidote; (h) early, anhydrous phases of skarns are usually overprinted by subsequent retrograde hydrous phases with biotite, hornblende, actinolite, epidote, sphene and apatite; (i) early anhydrous skarns are more persistent, and contain low-grade but consistent mineralization of fine grained, high-Mo disseminated scheelite, accompanied by disseminated pyrrhotite and accessory molybdenite. Molybdenite is sometimes a helpful megascopically visible indicator of scheelite presence. Retrograde skarns are patchy, coarser-grained, and contain low-Mo, coarse scheelite with masses of pyrrhotite and chalcopyrite. Rich ore masses are often located at the outer skarn-marble contact, replacing marble.

Fig. 28-80 is an idealized example of a composite "reduced" SS developed in a "black shale"-impure limestone and minor greenstone association, intruded by granodiorite. In this example, the supracrustal association is predominant in terms of volume. In many cases, however, SS crop out as thin screens on the surface of an exposed eroded pluton or form isolated rafts or xenoliths within the "granite" (as in Sierra Nevada, California). In the latter case, the "granite" is predominant and scheelite-mineralized remnants can be expected anywhere within the batholithic body. Commonly, SS occurrences within a deeply eroded batholith form long, discontinuous belts.

Mactung deposit located in the Macmillan Pass region of the N.E. Canadian Cordillera (Dick and Hodgson, 1982; Fig. 28-81) is a major tungsten accumulation (reserve figure is given as either 216 or 479 Tt W/0.9% WO_3). It is hosted by a lower Cambrian to Devonian association of gently dipping hornfelsed micaceous phyllite, slate and limestone, intruded by Cretaceous quartz monzonite stocks. The SS are peneconcordant with the bedding, replacing relatively pure limestone beds interlayered with non-calcareous, commonly graphitic hornfels. Scheelite is concentrated in a hedenbergite-almandine rich garnet skarn, locally retrograded to actinolite-biotite and clinozoisite-plagioclase assemblages. It is accompanied by abundant pyrrhotite, lesser chalcopyrite and rare sphalerite and ferberite. Minor quantities of scheelite are located in quartz veinlets in hornfels and in the quartz monzonite endocontact.

The Cantung deposit (81 Tt W/1.28%; Fig. 28-82) located farther south in a comparable setting is smaller and has three separate orebodies, two of them high-grade. The Pit orebody is in a coarse garnet, diopside, epidote skarn. The East orebody is essentially a banded pyrrhotite mass in marble with much tremolite but few other dark silicates in the matrix. Scheelite and lesser chalcopyrite are disseminated in the pyrrhotite.

The tungsten skarns of the Sierra Nevada, California, a classical region, have recently been summarized by Newberry (1982). There, scheelite occurrences are contained within a N.W.-S.E.-trending belt measuring 250 x 80 km, at or near contacts of late Triassic to middle Cretaceous granodiorite and quartz monzonite plutons and lower

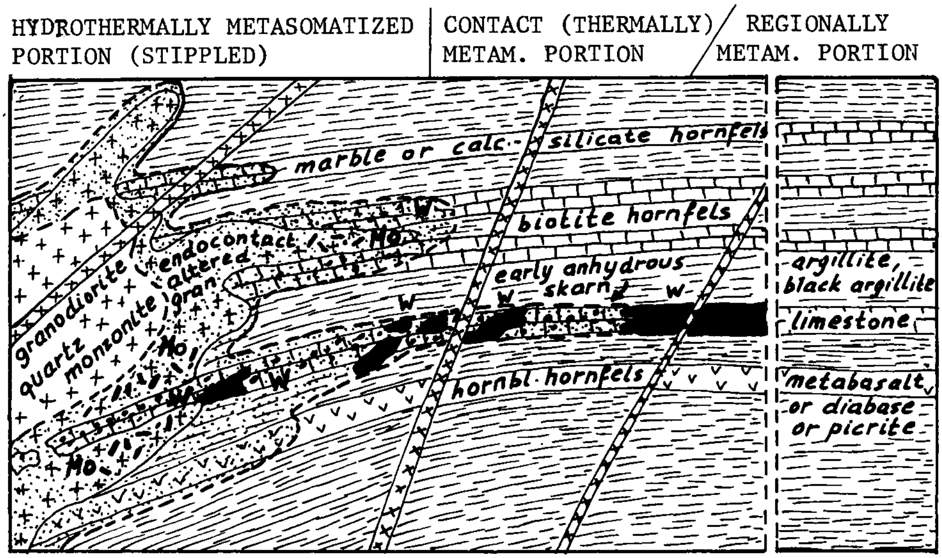
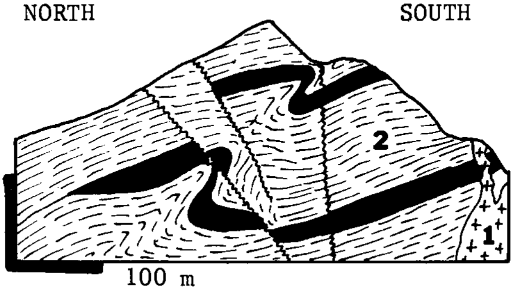


Fig. 28-80. Usual setting of a deep-seated "reduced" scheelite skarn in a "black" carbonate, pelite, lesser greenstone exocontact association. BLACK: late retrogressively hydrated skarn with patches of rich scheelite; W and Mo: erratic, subeconomic disseminations of scheelite and molybdenite. From Laznicka (1984).

Cambrian to upper Triassic carbonate metasediments. The largest deposit, Pine Creek mine near Bishop (27 Tt W/0.4%) is contained in a 1,200 m long septum of Paleozoic metasediments forming rafts and roof pendants within the plutonic rocks. Comparable skarns mined in the Osgood Mountains, one of the Basin and Range blocks in western Nevada, were described in detail in a memoir by Hotz and Willden (1964; Fig. 28-83). There, SS are on the contact of Cambrian to Pennsylvanian metacarbonates with lower Cretaceous granodiorites.

Salau in the French Pyrenees (Derre et al, 1980) is a zone of discontinuous skarn lenses in Ordovician marble, about 1,600 m long, in the roof of what is probably a Carboniferous granodiorite. The scheelite is disseminated in the central portion of pyrrhotite masses enveloped by a scheelite-free pyrrhotite. Pyrrhotite, in turn, is hosted by a diopside-idocrase skarn, particularly by pyroxene-biotite bands within it. Stratabound Pb-Zn occurrences are situated in the same sedimentary horizon at a greater distance from the contact.

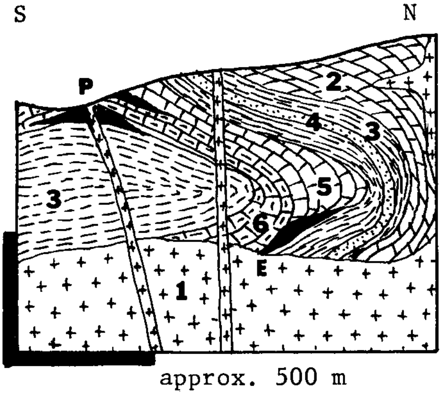
Tyrny Auz, located at the northern slopes of the Great Caucasus Range, U.S.S.R. (Pek et al., 1970; Pokalov, 1974; Fig. 28-84), has been the most significant Soviet W and Mo deposit of the "early generation" of discoveries. This is actually a geologically complex polygenetic and multistage field, that departs considerably from the



1. Cr (89 m.y.) biotite quartz monzonite
2. Cm-D hornfelsed metasediments (biotite hornfels, black graphitic hornfels, minor calc-silicate hornfels

BLACK: scheelite skarn

Fig. 28-81. Mactung mine, Macmillan Pass, N.W.T., Canada. From LITHOTHEQUE, slightly modified after Dick and Hodgson (1982).



1. Cr granodiorite, qtz.monzonite, dikes and a stock
2. Cm dolomite
3. contact hornfelsed argillite
4. quartzite
5. gray and white banded limestone marble
6. spotted calc-silicate hornfels

BLACK: scheelite skarn orebodies
P=Pit ore body; E=E orebody

Fig. 28-82. Cantung scheelite deposit, Tungsten, N.W.T., Canada. From LITHOTHEQUE, based on data in Dick and Hodgson (1982) and N. Cawthorne, guided tour, 1975.

"typical" model of SS shown earlier. The stratigraphic sequence there starts with a Proterozoic or a lower Paleozoic basement, overlain successively by early Devonian shale and limestone, lower Carboniferous ophiolites and bimodal (spilite-keratophyre) volcanic-sedimentary association. This is topped by late Carboniferous and Jurassic continental sediments. These were intruded by a series of granitic intrusions ranging in age from Jurassic to Pliocene, and emplaced at various levels ranging from a probably

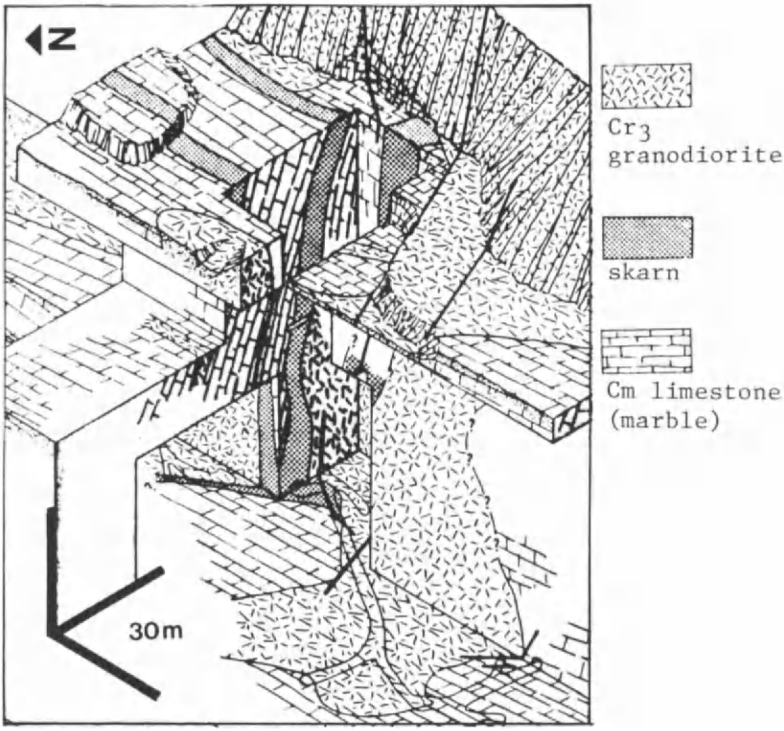
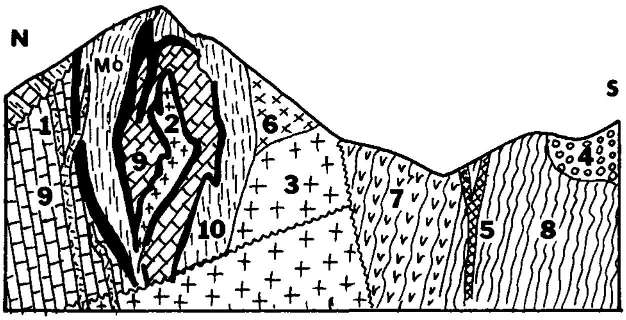


Fig. 28-83. Pacific mine scheelite skarn, Osgood Mts., Nevada. From Hotz and Willden (1964).

middle mesozone to surficial volcanic extrusions.

The two styles that are economically the most important at Tyrny Auz are scheelite skarns and molybdenite stockworks. The latter are younger, superimposed on the former. The principal scheelite orebodies are in the roof of a probably Cretaceous porphyritic biotite granite intruded by a younger leucogranite. Scheelite skarns occur along the contact of hornfelsed pelites and marbles. Scheelite and minor molybdenite are disseminated in garnet, idocrase and wollastonite skarns formed from relatively pure limestones. Molybdenite is concentrated in quartz-molybdenite veins and veinlets, forming a dense stockwork superimposed on the biotite hornfels adjacent to the SS, and partly on the skarn itself. A variety of late-stage veins with sulphides of base metals carrying Au,Ag, and Sn appear to be contemporary with a late-stage fracture-controlled retrogressive skarn assemblage, containing stanniferoue ilvaite.

Sangdong, the best known ore deposit of Korea (Farrar et al., 1978; 105 Tt W/0.56%) is in the popular literature headlined as a major SS, but the mineralization is much more complex and controversial.



1. Cr-Pl (80-2 m.y.) rhyolite dikes
2. leucogranite
3. porphyritic biot. granite
4. J_1 conglomerate
5. J_1 peridotite
6. Cb? qtz.diorite
7. Cb_1 ophiolites, spilite-keratoph.
8. Cb_1 phyllite
9. D, marble; D, biotite hornfels

BLACK: scheelite-Mo skarn; Mo=molybdenite stockwork

Fig. 28-84. Tyrny-Auz, N. Caucasus, U.S.S.R., scheelite-Mo skarn and Mo stockwork. After Pek et al. (1970).

The principal orebody is a narrow, persistent zoned stratabound horizon 3.5-5 m thick and 1.5 km long, a member of a lower Cambrian alternating shale, sandstone and impure limestone unit. The central zone in this horizon has a quartz, biotite, muscovite assemblage, grading outward to hornblende-quartz, minor biotite and ultimately to diopside-garnet skarn. The ore consists of closely spaced quartz-scheelite and quartz, scheelite, sulphide veinlets in the quartz-mica core, that has a grade of 1.5-2.5% WO_3. This drops to 0.3-1.5% WO_3 in the hornblende-quartz zone, and to sub-economic contents in the skarn. Farrar et al. (1978) interpreted the mineralization as upper Cretaceous, epigenetic, introduced from outside but 20 m.y. later than the age that corresponds to the closest known granitic stock. Alternative interpretations consider the deposit as stratiform (metamorphosed and partly remobilized hydrothermal sediment); epigenetically mineralized shear zone and other. Discordant tension fractures filled by earlier quartz, scheelite, molybdenite and later quartz, bismuthinite, tetradymite, chalcopyrite, etc., are widespread in the mine field and contribute important quantities of the by-product bismuth.

King Island tungsten field off Tasmania is the most important of the current Australian W producers (71.5 Tt W), and an example of a "completely zoned" SS recently described by Kwak and Tan (1981). The largest No.1 and Dolphin orebodies form a system of mineralized lenses, broadly conformable within two stratigraphic horizons in a contact metasomatized assemblage of Cambrian mafic volcanics, argillites, carbonates and what is possibly a tillite, in the contact aureole of a lower Carboniferous quartz monzonite intrusion. The total length of the E.-W.-trending zone is about 1.5 km, the width is about 50 m. The grade distribution varies and within the ore zone several barren "horses" occur. The main ore mineral, Mo-rich scheelite, is associated with abundant pyrrhotite and minor molybdenite and chalcopyrite. The scheelite has the form of fine to coarse disseminated and erratically scattered crystals in andradite, andradite-hedenbergite, and grossularite-calcite skarn. Less frequently, coarse crystalline scheelite forms masses and grains along crosscutting calcite veinlets.

Although alternative genetic interpretations of the King Island SS have been offered (e.g. remobilized stratiform "exhalite"), the epigenetic, granite-related postmagmatic nature of the ore is demonstrated beyond doubt by the crosscutting relationships and sharp contacts within the host marble beds. The lithologic peculiarities of the exocontact association have already been discussed in Chapter 17.

Table 28-14 gives a brief summary of the major SS deposits of the world.

28.10. STOCKWORK MOLYBDENITE DEPOSITS

28.10.1. General

Stockwork molybdenite deposits (SMD) in high-level intrusions represent some 7 Mt of contained economic (or nearly economic) Mo at present. They stand about half way between the porphyry Cu-Mo deposits (that represent some 8 Mt of by-product Mo) and stockwork W-Sn(Mo) deposits (some 200 Tt of by-product Mo), in many aspects of geotectonic setting, petrochemical affiliation, ore mineralogy, etc. The North American Cordillera and, in particular, a small segment of the Colorado Rocky Mountains is a "home" for the majority of stockwork Mo deposits, so it is no wonder that most recent descriptions, systematics and genetic models regarding these deposits originated there (Clark, 1972; Soregaroli and Sutherland Brown, 1976; White et al., 1981; Mutschler et al., 1981; Westra and Keith, 1981).

In North America at least, it is possible to subdivide the SMD into two subcategories, showing a good deal of mutual independence in character and setting. The "granite molybdenite systems" (Mutschler et al., 1981) or "Climax-type" deposits (White et al., 1981) are on one side, genetically affiliated to "true" granitic magma. The "granodiorite (or quartz monzonite) systems" are on the other. The former, although a unique class, have generally high trace or accessory contents of W and Sn (recovered in Climax), so they are on the more "sialic" side of the porphyry Cu-stockwork Mo-cupola Sn sequence. The "granodiorite" Mo stockworks, on the other hand, are gradational into porphyry coppers. Some Mo deposits, particularly those outside North America and of pre-Tertiary age, appear transitional and there is not enough data to determine clearly their affinities. In multiphase intrusive complexes the older phases may be granodiorites to quartz monzonites and the youngest phases granites, so the classifier has a choice of placing the Mo occurrences into either category. The B.C. Moly deposit in the Alice Arm district placed, in the literature, in the granodiorite-quartz monzonite class, is associated with true granite.

28.10.2. Granite-associated stockwork molybdenite deposits

These deposits (Table 28-15) contain a greater share of Mo than the "granodiorite molybdenums" (5 Mt against 2 Mt). Westra and Keith (1981) characterized the "granite Mo stockworks" as associated with alkali-calcic, metaluminous to peraluminous granitic differentiates. Their source plutons contain from 25 to over 250 ppm Nb, 200 to 800 ppm Rb, less than 125 ppm Sr, less than 0.2% TiO_2, and are enriched in F,Sn,W and Mo. Molybdenite and pyrite are the main ore minerals, minor W is present as wolframite or hübnerite, tin is in cassiterite, and monazite is relatively common. Quartz and sometimes K-feldspar are the dominant gangue minerals, but fluorite and topaz occur occasionally. K-feldspar metasomatism and silicification are intense in the core of mineralization systems. The further proposed subdivision of the "granite Mo stockworks" into a "Climax subtype" and "Questa subtype" based on the degree of differentiation of the parent magma, is not recommended for global empirical purposes, because of the transitionality. Molybdenite stockworks hosted by peralkaline or alkaline (alkalic) granites and syenites (or set in alkaline provinces) are treated separately in Chapter 33.

"Granite molybdenite deposits" are most common in tectono-magmatically rejuvenated old sialic blocks ("terrains of autonomous activation" of the Soviet writers). These may be positioned on the continental fringe of broad marginal orogens (e.g. the Colorado Rocky Mountains), or in an intracratonic setting having a long history of doming, block faulting and rifting (East Transbaikalia). The difference between the two above settings is, at best, quantitative anyway. Comparable regions in the Fore-Cordilleran Ranges in Argentina, the "diwa" (activated) terrains in S.E. China and elsewhere, are the probable sites of future stockwork Mo discoveries.

Most of the Colorado stockwork Mo deposits are hosted by high-level intrusions of high silica rhyolite and granite porphyry, having the form of intrusive domes, cylindrical stocks and less frequently of ring dikes, radial dikes, breccias, etc. Many are positioned as protuberances on the "back" of a buried regional batholith, much the same as in the cassiterite-bearing systems. Multiple intrusions are even more common here. The host (roof) rocks into which the intrusions were emplaced, are mostly old high- to medium-grade metamorphics (gneisses, migmatites, amphibolites, as in Colorado). Some are interrupted by tectonic grabens filled by continental felsic volcanics and volcaniclastics, broadly coeval with the mineralized intrusions. The contact metamorphic alteration affecting the metamorphics can be virtually undetectable. Tectonic control (grabens, horsts, lineaments, block faults and their intersections) is important. The "prime time" of exposure of the hypabyssal mineralized complexes is Miocene to Cretaceous.

Table 28-14. Scheelite skarns in Phanerozoic carbonates, selected example localities

LOCALITY	HOST AND INTRUSIVE UNIT	MINERALIZATION	REFERENCES
Macmillan Pass (Mactung), N.W.T., Canada	Cm_1-D altern.marble and hornf. often black argill.,loc.brecc. 80-87 m.y. qtz. monzonite stock	scheel.,pyrrh.,lesser cp.,sphal., ferber. forming lenses in a pene-con. horiz. of hedenb.,garnet skarn; 479Tt W/0.76%	Dick and Hodgson (1982)
Cantung, Tungsten, N.W.T., Canada	Cm_1 interb.hornf.argill.,lim., dolom.,minor quartzite, greens. 92 m.y. granod. and qtz. monz. stock	3 ore lenses cont. dissem.scheel. two are in garn.,diops.,epidote skarn, one is mass.pyrrhot. in tremol. skarn and marble away from cont.; 80.9Tt W/1.28%	ditto
Salmo, S.British Columbia, Canada	Cm hornfelsed black argill., gray limestone; J_3 qtz.monzo-nite, aplitic granite	hedenb.,garn.,biot.,hornbl.skarn lenses with pyrrh.,cp.,scheel., gal.-sphal. replac. in marble out-side of contact; 2,439Tt W/0.47%	Little (1959)
Osgood Mts., W. Ne-vada, U.S.A.	Cm-Pe hornf. limest.,shale, chert, quartzite, interm. to mafic volc.; 69 m.y. granod. with qtz.dior.border facies	dissem.scheel.in garn.-epid.skarn at immed.granod./marble contact; irreg.to tabul.oreb.,minor scheel. in granod. 5,040t W	Hotz and Willden (1964)
Pine Creek mine, Sierra Nevada, California,U.S.A.	PZ_3 hornf.argill.,limest., quartzite, rafts and roof pen-dants in 92 m.y. porph. qtz. monzon. with pegmatite pods	contact lenses and sheets of gar-net,idocr.,wollast.,hornbl.skarn with dissem. scheel.,cp.,moly., magn.,pyr. 24Tt W/0.4%	Newberry (1982)
Salau, Pyrenees, France	Or, hornf.marble, shale, sand-stone; Cb? granod. to qtz.dio-rite at margin	lenses and columns of mass.pyrrh. with dissem.scheel.in diops.-ido-crase skarn and pyrox.-biot.bands 10.15Tt W/1-1.6%	Derré et al. (1980)

Uludağ mine, Bursa distr., N.W. Turkey	Pt_3? schist, marble, amphibolite; T? granodiorite	scheel. with pyrrhot. in diops.-garnet skarn, peneconc. lenses along strat. horiz.; minor quartz-wolfr. veins; 28Tt W/0.28%	Schumacher (1956)
Tyrny Auz, N. Caucasus, U.S.S.R.	D hornf. shale, limest., quartzite; Cr porph. biot. gran. plut., leucogran. stocks, followed by Cr-Pl rhyol. porph. dikes	garn., idocr., wollast. skarn at marble cont. carry scheel. and lesser moly.; superimp. qtz.-moly. stockw. and late stage Pb, Zn, Sn, Au, Ag veins. Est. 70Tt W, 50Tt Mo	Pokalov (1974) Pek et al. (1970)
Chorukh-Dairon, Tadzhikistan, U.S.S.R.	D_3-Cb_1 limest. xenol. and rafts in Cb qtz. dior., granod., gran. porph., aplite, pegm. pluton	2 km ore zone, vein and layer-like retrogr. scapol. skarns repl. garn., pyrox., amphib., epid., scheel. endo- and exoskarn; Est. 20Tt W	Shcheglov and Butkevich (1974)
Sangdong, South Korea	Cm, hornf. shale, sandst., impure limest.; Cr qtz. monzon. intr. 4 km away	peneconc. zoned horiz. in metased. miner. by qtz., scheel., sulph. veinlets in its centr. zone (qtz., biot., musc.), fringed by skarn. Interpr. as hydrotherm. replacem. 105Tt W/0.56%, 9Tt Bi, 6.5Tt Mo	Farrar et al. (1978)
King Island off Tasmania, Australia	Cm, hornf. argill., limest., mafic metavolc., breccia (tillite ?); Cb_1 qtz. monzonite	Mo-rich scheel. dissem. in several lenses of andrad.-pyrox. and grossul.-calcite skarn along two stratigr. horizons; 71.5Mt W	Kwak and Tan (1981)

Table 28-15. Stockwork molybdenum deposits, 1: granite affiliation ("Climax-type")

LOCALITY	HOST AND INTRUSIVE UNIT	MINERALIZATION	REFERENCES
Climax, Colorado, U.S.A.	Pt_{1-2} biot.schist to gneiss, qtz.monzon.; 33-18 m.y. multiple intrus.,coaxially stacked conical gran.to rhyol.porph.	3 stacked annular stockw.oreb.of qtz. moly.,pyr.,topped by a tungsten (hübnerite) zone, in exocontact above intrus.apex; 2Mt (or 4.8Mt)Mo/0.33%	Wallace et al.(1968)
Red Mountain (Henderson and Urad deposits), Colorado,U.S.A.	Pt_{1-2} qtz.monzonite; 28-23 m.y. compos.high-level multiph.intrus.suite of granite + rhyol.porph.,minor intrus.breccia	small Urad oreb.is in an early stage subvolc.porph.plug at surface; Henderson is a large Climax-like blind stockw.in depth, in K-feldsp.altered porphyries; 1.5Mt Mo/0.3%	White et al. (1981)
Mt.Emmons-Redwell Basin,Colorado, U.S.A.	MZ sandst.,shale; T, hornf.sedim.,rhyolite; 17 m.y. rhyol. porph.,felsite, ign.breccia	2 oreb.; circular,inverted teacup-shaped oreb.,760 m diam.,90 m thick (Mt.Emmons); moly. stockw.below an intrus.brecc.pipe (Redwell Bs.) Mt.Em. only: 409Tt Mo/0.264%	White et al. (1981)
Questa, New Mexico, U.S.A.	Pt gneiss, gran.,pegm.,quartz. T_2 rhyol.,andes.,latite,sedim. 23 m.y. hornbl.and biot.gran., biot. leucogranite	pyr.,moly.,qtz.veinlets,fract.coat., fiss.veins in K-feldsp. to biot.-seric.alter.arcuate and linear shell along granite-andes.cont. 250Tt Mo/ 0.11%	Clark (1972)
East Kounrad, N. Lake Balkhash, U.S.S.R.	PZ_1 sedim.,volcs.;D_{1-2} silic. volc.,granod.,qtz.diorite Pe,coarse leucogran.,aplite, pre-ore apogranite	W.N.W. system of parallel veins grading into stockw.;qtz.,moly.; qtz., wolfr.; qtz. mica greisen. Estim. min. 70Tt Mo	Pokalov (1974)
Bugdaya, East Transbaikalia, U.S.S.R.	PZ granite, granosyen.; J_{1-2} shale, sandst.; J_3 continent. volc.,granod.,qtz.dior.; J_3 leucogran.,qtz.porph.,apl.	circular stockw.of qtz.,moly.,pyr., Mo-scheelite, fluorite in sericitiz. granite enveloping barren silicif. core. Est.min. 40Tt Mo	Pokalov (1974)

Deeper-seated (plutonic) equivalents of the Colorado cylindrical mineralized intrusions probably exist in the East Transbaikalia and central Kazakhstan Mo provinces, but are often difficult to distinguish from the granodiorite-affiliated Mo stockworks. The plutonic Mo deposits tend to be linear or rectangular in form, and densely veined stockworks are usually substituted by bands of closely spaced veins. Mo stockworks are, as a rule, very proximal to their concentrator intrusion, being in their apical portions or, more frequently, immediately above the apex in the above-intrusion roof. In single phase intrusions, the above-intrusion orebodies are in metamorphics, in basement granites or in felsic volcanics. In multiple intrusion/mineralization systems such as Climax, the top orebody is in the roof rocks and the lower orebodies are in the earlier intrusions. The very intensive silicification and K-feldspar alteration associated with orebodies often obliterates the former intrusion/roof contact, so that it may appear that the entire orebody is in the intrusive endocontact.

Most of the known Mo stockwork deposits occur alone (no other ores are directly associated), although there are exceptions. At Red Mountain, Colorado, embryonal epithermal Mn,Pb,Zn,Ag mineralization is to be found in the late stage porphyries above the Henderson and Urad stockworks. In Tyrny-Auz (Greater Caucasus; Section 28.10), Mo stockworks are superimposed on an earlier scheelite skarn and adjacent hornfelses, in the exocontact of a granite stock. A stockwork Mo deposit is postulated (although not yet proven) under the U(Mo) veins near Marysvale, Utah. Pb-Zn veins and replacements as well as gold deposits may be broadly contemporary with stockwork molybdenum deposits and be present in the same metallogenic belts, as in the Colorado Rocky Mts.

Supergene alteration and its zoning over stockwork Mo deposits is poorly developed and imperfectly known. To a considerable degree this is the result of the setting of the major deposits which is in recently glaciated terrains, from which most of the fossil weathering crusts have been stripped away. The orebody outcrops at Climax, Questa, etc. are marked by fracture coatings of the bright yellow ferrimolybdite, and portion of the released Mo is in jarosite and goethite coatings and infiltrations. No equivalents to the zone of sulphide enrichment over porphyry coppers have been reported.

Climax, Colorado, is the largest, richest and oldest known representative of this clas (Wallace et al., 1968; 2 Mt Mo/0.33%; Fig. 28-85). It is a complex of three coaxial Oligocene intrusions of granite and rhyolite porphyry, emplaced into Proterozoic biotite schist and quartz monzonite. The intrusions are arranged in such a way that each progressively younger intrusion is emplaced at a lower level into the roof of an older intrusion. Intrusive dikes corresponding to each phase as well as the mineralization and alteration are in the roof above each intrusive phase. In Climax, there are two separate, arcuate, concave downward annular ore shells capping the apex of the two lower (younger) intrusive stocks, and an erosional remnant of a third (upper) shell. Taken together, these

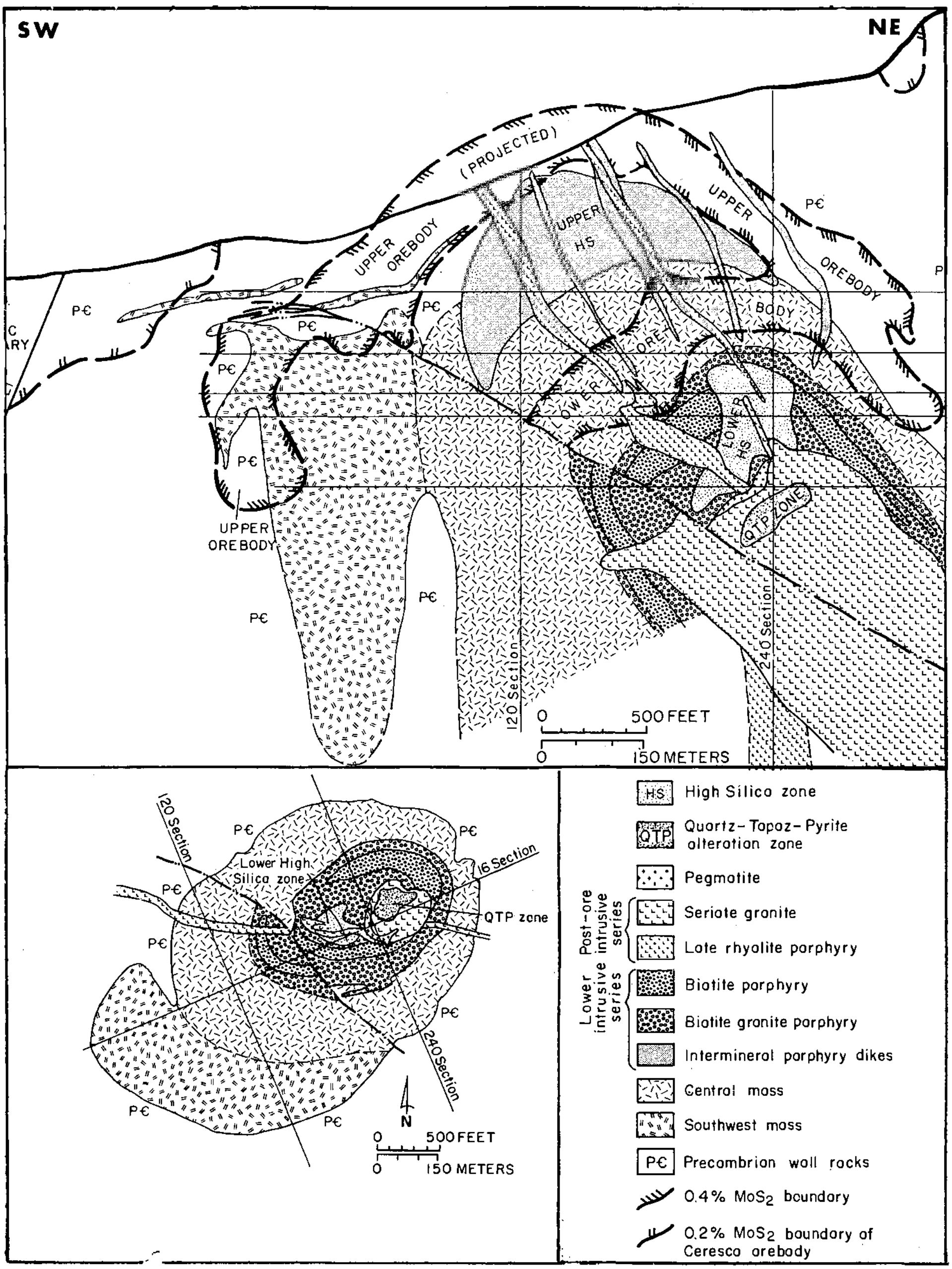


Fig. 28-85. Climax Mo deposit, Colorado; generalized geology and ore zones in section and a map. From White et al. (1981), courtesy of Economic Geology.

orebodies form an inverted hollow cone with upper and lower diameters of 1,400 and 750 m, respectively, and a height of about 450 m.

An orebody is composed of a stockwork of crisscrossing quartz, molybdenite, pyrite veinlets less than 3 mm thick, hosted by a silicified and K-feldspar altered beige granite or rhyolite porphyry in the centre. Quartz, sericite, pyrite alteration marks the outer fringe. Each molybdenite orebody is accompanied by a tungsten zone located above, from which the by-product hübnerite and cassiterite are recovered. In the pre-Quaternary relict oxidation zone at Climax, ferrimolybdite, Mo-"limonite" and Mo-jarosite are present in place of molybdenite, without a marked enrichment or impoverishment in Mo.

The Urad-Henderson twin deposits (White et al., 1981; Fig. 28-86) are located on and under Red Mountain, a short distance N.E. of Climax. Urad is a small (12 Mt ore with 0.38% MoS_2) orebody discovered in an outcrop. Henderson is a large (272 Mt ore with 0.49% MoS_2), blind orebody discovered in depth, 900 m under the surface. Both deposits are members of a multistage late Oligocene probably vented system (probably a stratovolcano) emplaced into the wallrock of a Proterozoic quartz monzonite. The system consists of a downward-widening composite stock of rhyolite, granite and aplite porphyries, many of which crop out at the Red Mountain summit. The Urad orebody is located in an early subvolcanic porphyry plug, dike swarm and intrusive breccia, and it is a relic of an initially larger body destroyed by intrusion of the Red Mountain porphyry. The latter is altered and impregnated or veined by rhodochrosite.

The deep-seated Henderson Mo deposit is similar in shape to the lower Climax orebodies, is younger than Urad and draped over a four-phase mass of a granite porphyry (Primos porphyry) as well as a cupola of Henderson Granite. The Mo stockwork contains much pure molybdenite coating, without quartz, hairline fractures, and also molybdenite flakes in quartz, pyrite and fluorite veinlets. Greater portion of the orebody coincides with K-feldspar alteration zone, but occurs also in silicified rocks. Among the unusual alteration zones at Henderson are topaz-magnetite, greisen, and spessartite garnet zones. The latter is not a skarn, but an associate of a late-stage hydrothermal galena, sphalerite and rhodochrosite suite.

Two Permian "granite Mo stockworks" in central Kazakhstan, Koktenkol' and East Kounrad (Pokalov, 1974), differ from the Colorado deposits by their predictably deeper erosional level and widespread greisenization. Koktenkol' is above a large granite cupola rooted in a more extensive buried pluton. The quartz-molybdenite stockwork is elongated parallel with a N.N.W.-trending shear zone, and wolframite is locally abundant in the quartz-molybdenite veins. The wallrock is K-feldspathized and there are greisen patches and vein rims.

The East Kounrad deposit is unusual because being set in what is a porphyry copper province, associated with Carboniferous granodiorites (e.g. Kounrad; Section 28.2.2.). Despite its proximity (about 10 km) to the porphyry copper field, East Kounrad is related to a younger, Permian, petrochemically different suite of biotite granite and leucogranite. This is a plutonic level deposit, located in a

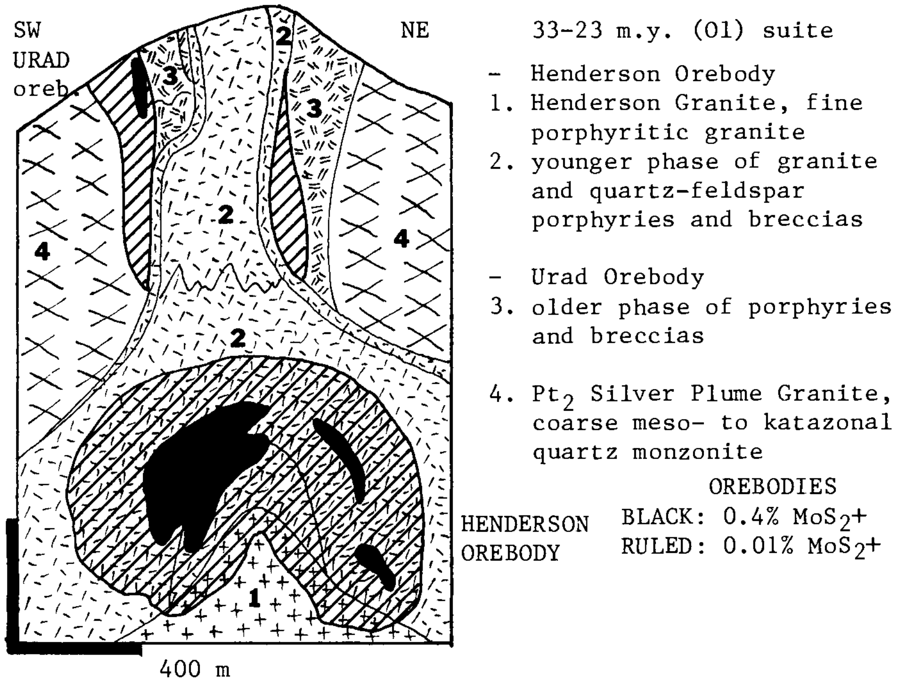


Fig. 28-86. Red Mountain stockwork Mo mineralized complex, Colorado. From LITHOTHEQUE, simplified after Wallace et al. (1978).

considerably eroded granite cupola, and most orebodies are swarms of parallel, discrete quartz, molybdenite, lesser wolframite veins in K-feldspar altered, greisenized and sericitized granites.

28.10.3. Granodiorite (quartz monzonite) associated stockwork molybdenum deposits

This ore category (Table 28-16) is associated with calc-alkalic and high-potassium calc-alkalic magma series and peraluminous mesozonal to epizonal plutons. This is the same association that produced the majority of porphyry Cu-Mo deposits. Geochemically, these rocks have less than 20 ppm Ni, 100-800 ppm Sr and 100-350 ppm Rb. They are most common in a continental margin setting in which the majority of rocks is believed emplaced under compressive conditions (Westra and Keith, 1981). There, SMD favour small, late-stage stocks emplaced into older, polyphase and deeply eroded major batholiths (such as the Coast Batholith of British Columbia; Section 28.2.3.) at a much higher crustal level. Such stocks are easily overlooked in the "sea" of the relatively monotonous "granite" mass. Similar stocks occur on flanks

Table 28-16. Stockwork molybdenite deposits 2: granodiorite-quartz monzonite affiliation

LOCALITY	HOST AND INTRUSIVE UNIT	MINERALIZATION	REFERENCES
Quartz Hill, S.E. Alaska, U.S.A.	J-Cr foliated granod.,tonal., migmat.,schist, sillim.gneiss; 27-30 m.y. compos.stock,biot. gran.to porph.,aplite	hypabyssal miner.,all in endocont. molybd.in fract.coatings,qtz.-moly. veinlets; silicif.,K-silicate alt. 1.2Mt Mo/0.08%	Hudson et al. (1979)
Alice Arm field, N.W. British Columbia, Canada	J_3-Cr_1 argill.,siltst.,grayw., hornfelsed; 48-54 m.y. qtz. monzon.,granod.porph.,alaskite plugs, stocks	cylindrical stockw.,qtz.,moly.,pyr.; K-feldsp.,biot. alter.,phyllic outer zone; cluster of 13 dep.and occurr.; late stage Zn,Pb,Cu veins; 225Tt Mo	Woodcock and Carter (1976)
Adanac, 40 km N.E. of Atlin, northern British Columbia	Cr plutonic rocks,deep-seated; 62 m.y. qtz.monzon.,qtz. monz. porph.,alaskite	elliptical, lens-shaped stockw.of qtz.veins, veinlets,with moly.,pyr. Weak qtz.,seric.,pyr.alteration; 91Tt Mo/0.1%	Soregaroli and Sutherland Brown (1976)
Hudson Bay Mt. near Smithers, central Brit. Columbia	$J_{1,2}$ hornfelsed marine shale, andes.metavolc.,granodiorite; 70-84 m.y. qtz.monz.porph., quartz latite, cylindr.stock	extens.tabular stockw.of qtz.,moly., pyr.veins and veinl. in biot.,silica, seric.alteration. 109Tt Mo/0.12% or 6Mt Mo/0.05%	Bright and Jonson (1976)
Endako, central British Columbia Canada	137-141 m.y. granodior.bathol. 141 m.y. elong. qtz.monz.body	stockw.and set of subparallel qtz., moly.,pyr. veins in K-feldsp.,biot., seric. and argill. alter.envelope; 248Tt Mo/0.09%	Kimura et al. (1976)
Mačkatica-Surdulica, S.E. Yugoslavia	PZ gneiss,schist,migmatite; T subvolc.dacite,nearby granodiorite pluton	several small pipe-like qtz.,moly., pyr.stockw. in silicif. and seric. altered dacites; 20Tt Mo/0.1%	Janković (1982)
Zhireken, East Transbaikalia, U.S.S.R.	PZ granite bathol.,J_{2-3} biot. hornbl.granod.pluton; J_3 gran. porph.stock,dikes;dacite porp. dikes	qtz.,moly.,pyr.veinlets in K-feldsp. stockw.in apical zone of granite endocont.; access.cp.,qtz.,tourm., wolfr.veins; est.min. 50Tt Mo	Pokalov (1974)

of major batholiths, emplaced into supracrustal volcanics or into sedimentary associations. Stockwork molybdenum deposits can be found within or on the fringe of porphyry copper provinces, or alternatively in terrains noted for scheelite skarn occurrences. This is reflected in the accessory minerals. Chalcopyrite is common and scheelite occasional, but there is no wolframite or cassiterite. Some deposits such as Brenda, British Columbia, stand, in terms of geochemical concentration, about halfway between porphyry coppers and stockwork Mo's.

In the Canadian Cordillera (Soregaroli and Sutherland Brown, 1976), hypabyssal stockwork Mo's are associated with composite, silicic, leucocratic quartz monzonite stocks (e.g. Boss Mountain, Alice Arm district). Plutonic stockworks occur in later stages of composite quartz monzonite batholiths. Their ages range from 140 m.y. to 8 m.y. Most stocks were emplaced in marine pelitic rocks and are surrounded by biotite hornfels. The orebodies occur in both endo- and exocontact, are largely fracture-controlled, and range from stockworks of crisscrossing veinlets in the hypabyssal bodies to zones of closely spaced parallel veins in the plutonic deposits (Endako). K-feldspar and biotite alteration is associated with ore in the former, sericite alteration in the latter, styles. Silicification is widespread.

Endako deposit, 160 km W. of Prince George, British Columbia (Kimura et al., 1976; 248 Tt Mo/0.09%; Fig. 28-87), is the largest operating Mo mine in Canada. The ore is located in a late Jurassic quartz monzonite, a phase of a large composite batholith, emplaced in Triassic marine andesitic volcanics and sediments. The orebody is an irregularly elongated, N60°W-trending mass of densely fractured and diked quartz monzonite, containing a series of en-echelon N.E.-striking ore bands. It is 3.4 km long. The bands consist of discrete, 15-100 cm wide ribboned quartz-molybdenite veins, and stockworks of thin quartz-molybdenite and molybdenite veinlets. Magnetite, pyrite and lesser chalcopyrite are associated. The large veins are bordered by a narrow (3-5 cm) pink K-feldspar altered envelope. The thin veinlets and the stockworks as a mass are quartz, sericite, pyrite altered.

Hudson Bay Mountain (also Glacier Gulch, Yorke-Hardy) deposit near Smithers, British Columbia (Bright and Jonson, 1976) is under a local landmark (Fig. 28-88). It is under and adjacent to a glacier. It may contain as much Mo as Climax or more, but in about 10 times lower concentration (2 Mt Mo/0.07%). The deposit is located above a flank of a late Cretaceous quartz monzonite stock or cupola, intrusive into domed and hornfelsed Jurassic marine metavolcanics and metasediments. The roof rocks were earlier intruded by a thick granodiorite sheet and a composite subvolcanic plug composed of rhyolite porphyry, intrusive breccia and dikes. The plug is truncated at depth by the quartz monzonite stock and a block of various rocks in the exocontact of the stock contains erratically distributed molybdenite on hairline fractures and in two generations of quartz-molybdenite veinlets and veins. The dimensions of the mineralized block are 1.5 x 2.5 x 2.1 km. There is no striking, localized alteration within the system

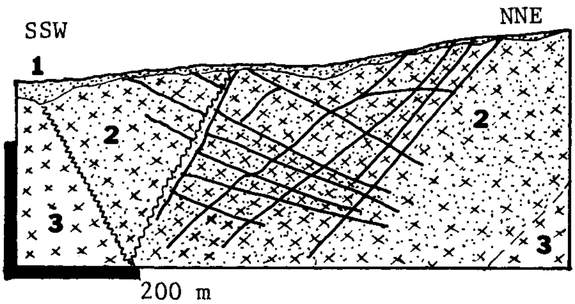


Fig. 28-87. Endako, British Columbia, multiple vein to stockwork Mo deposit. From LITHOTHEQUE, simplified after Kimura et al. (1976).

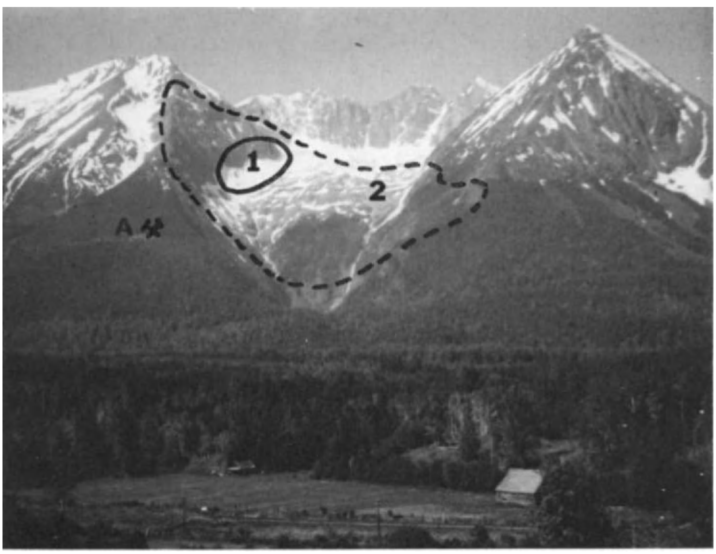


Fig. 28-88. Hudson Bay Mountain near Smithers, British Columbia, from the north-east. 1=Higher-grade molybdenite stockwork projected to surface; 2=approximate outline of a weak surface mineralization. A=adit.

(except for contact hornfelsing, bleaching and intense silicification within the early breccia plug), and no focussed and dense network of fractures. Bright and Jonson (1976) pointed out that if the entire 8.5 km^2 block is considered to be a low-grade ore (with an arbitrarily assigned grade of 0.05% MoS_2), then there are some 6 Mt Mo in the system. The potentially economic orebody is a U-shaped sheet of rocks with a greater density of quartz, molybdenite, lesser scheelite, chalcopyrite, pyrite, carbonate and K-feldspar veinlets with a grade better than 0.12% Mo.

Alice Arm district in the S.W. corner of British Columbia (Woodcock and Carter, 1976) is unusual in having a cluster of some thirteen stockwork occurrences. Normally, these deposits tend to occur in isolation. The Mo stockworks are associated with small oval and elongated high-level stocks of quartz monzonite to granite porphyry, most of which are multiple intrusions. These were emplaced in Jurassic to Cretaceous hornfelsed metasediments. As a rule, quartz monzonite is the oldest and most widespread phase. It is bordered by granodiorite and quartz diorite, and intruded by younger dikes and irregular masses of alaskite or, occasionally, intrusive breccia. Quartz, pyrite, molybdenite stockworks and veins are in the zone of potassic alteration and small, late stage quartz, carbonate, pyrite, galena, sphalerite, tetrahedrite, etc. veins are associated with most occurrences.

Additional Cordilleran localities are summarized in Table 28-16, and many more deposits and showings are known there (e.g. Thompson Creek, Idaho, 136 Tt Mo/0.15%; Cannivan, Montana, 178 Tt Mo/0.096%; Opodepe, Sonora, Mexico, 109 Tt Mo/0/08), but not enough data are available so far.

In Europe, the best-known stockwork deposits are near Mačkatica in the Serbo-Macedonian massif of Yugoslavia (Janković, 1982). There, quartz, pyrite, molybdenite veinlets comprise numerous irregular, pipe-shaped orebodies in a silicified and sericitized Tertiary subvolcanic dacite intrusion, emplaced in Paleozoic basement metamorphics. The dacite is located near the Surdulica granodiorite complex and could be a surficial manifestation of a more complex intrusive system at depth.

East Transbaikalia, U.S.S.R., contains several deposits that appear transitional between the "granite" and "granodiorite" stockwork molybdenums. At Zhireken (Pokalov, 1974), a quartz-molybdenite stockwork is located in an apical portion of a small, late Jurassic, composite stock of a fine grained granite porphyry as well as in a dacite dike swarm emplaced in an early Jurassic granite batholith. The orebody is situated in a K-feldspar alteration zone overprinted by argillization. This deposit contains a relatively high concentration of accesory chalcopyrite (recovered as a by-product) as well as tungsten (associated with quartz-tourmaline veinlets).

In the rest of the world, stockwork Mo deposits occur in the Okcheon orogenic belt, South Korea (e.g. Yongwol, 192 Tt Mo/0.24%), in south-eastern China and elsewhere, but the information available here is patchy.

28.11. MOLYBDENITE (WULFENITE) VEINS AND SMALL PIPES

Separate and discrete quartz and quartz, feldspar, molybdenite fissure veins associated with granitic plutons were mined on a small scale before the World War II, at the onset of the wave of discoveries of stockwork molybdenum deposits in the Cordillera. Not a single vein produced more than 5,000 t Mo (most produced several tens to hundreds t Mo), despite the frequently high grade (1-3% Mo). Locality examples include Olalla, Lost Creek and other small deposits in British Columbia, Daito-Yamasa area in Japan, Pupio in Chile and others. At present the only practical importance of small molybdenite veins in mesozonal to epizonal granite terrains is as an indicator of a possible "leak" from a more extensive stockwork system in the subsurface, so they should be examined as a possible exploration guide. In Endako and Alice Arm fields such veins were known to exist before the discovery of the large "bulk" deposits.

Wulfenite ($PbMoO_4$) forms minor accumulations in some replacement Pb-Zn deposits in carbonates (e.g. Mapimi, Mexico) and rare small vein deposits in silicate rocks. The best known American locality is the San Anthony vein near Mammoth, Arizona (1,700 t Mo). It was a late-stage quartz, adularia, galena, sphalerite, wulfenite, etc. fissure vein in the roof of the large San Manuel-Kalamazoo porphyry copper. The main economic importance of the few small known wulfenite occurrences is as a source of crystallized mineral specimens to collectors, although some may be indicative of possibly buried Mo or Cu-Mo stockwork, or Pb-Zn vein or replacement deposits.

Small quartz-molybdenite replacement and breccia-cementing pipes in granites near their roof contacts, are best known in eastern Australia and were mentioned earlier. Their importance is minimal.

28.12. MOLYBDENUM SKARNS

Skarns mined for molybdenum only are rare, yet Einaudi et al. (1981) managed to list eleven example localities worldwide. Cumulatively, they represent some 30 Tt of Mo, to which should be added the larger quantity of Mo present in skarns that are minor exocontact variations of mineralized intrusive stocks (e.g. Little Boulder Creek, Idaho, about 90 Tt Mo/0.09%; Cannivan Gulch, Montana). By-product Mo is also recovered from scheelite, Sn-W-Mo-Be skarns and Pb-Zn skarns. Molybdenum skarns are not a unique mineralization style (as, e.g., are the scheelite skarns) and can be anticipated whenever a Mo-mineralized complex interacts with exocontact carbonates. Molybdenite is the only major Mo mineral and pyrrhotite, pyrite, chalcopyrite, scheelite, bismuthinite, are often associated. The igneous intrusion may range from granodiorite to granite.

At the Yangchiachangtzu mine (Liaonong, China; Hsieh, 1950; 21 Tt Mo/0.3%), a Mo-skarn was discovered by chance at depth under a Pb-Zn replacement deposit in carbonates. The Mo orebody consists of veinlets, disseminations and lumps of molybdenite with magnetite, pyrite, sphalerite and galena in a garnet-dioside and later stage skarn lens, peneconcordant with bedding in a Cambro-Ordovician "black" limestone-shale sequence.

The Coxey mine near Rossland, British Columbia (Eastwood, 1967b), produced 1,653 t Mo from a small mineralized system involving a Tertiary brecciated and altered granodiorite dike emplaced in a brecciated diopside skarn. Molybdenite stockwork was superimposed over both rocks across the contact.

28.13. POSTMAGMATIC Be DEPOSITS

28.13.1. General

Hydrothermal-plutonic beryllium deposits are an entirely post-Lindgren and post-Schneiderhöhn class of ores, missing from the classical textbooks. Before and shortly after World War II the only beryllium resource was beryl from pegmatites, and the world Be reserves were estimated to be about 7.1 Tt Be in 1952 (of this, 525 t Be were contained in U.S. pegmatites). In the past thirty years, a variety of non-pegmatitic Be deposits has been found (Fig. 28-89; Table 28-17), of which the subvolcanic bertrandite deposits at Spor Mountain, Utah (Chapter 26, 24 Tt Be) are of greatest importance.

Beryllium deposits associated with granitic rocks for which some tonnage estimates have been made (Warner et al., 1959), represented 6,530 t Be in the United States only (when epithermal deposits are included; 4,780 t Be when the latter are excluded). Beryllium reserves in the Xi-Zhoyouang skarn deposit, Hunan, China (Section 28.8.4.) correspond to 7,7 Tt Be. There are no quantitative data on the Soviet Be reserves but a guestimate based on the six or so unnamed major plutonic Be deposits repeatedly described in the literature, is about 15 Tt Be. Altogether, non-pegmatitic Be deposits associated with Phanerozoic granitic rocks may represent some 30 Tt Be. Be affiliated to alkaline and peralkaline intrusions will be treated in Chapter 33, and is not included in the above figures.

Classification of granite-hydrothermal Be deposits is highly subjective and mostly based on mineral associations (parageneses; e.g. Zabolotnaya, 1974). Shcherba (1968b) proposed a classification of Be deposits affiliated with greisens that included also the exocontact metasomatites such as skarns. On the grounds of intrusive petrochemistry, the bulk of Be deposits tend to be associated with "tin granites" or similar alkali-calcic, highly siliceous, peraluminous granites. In the distal accumulations (subvolcanic and epithermal), this cannot be determined easily. It is possible that Be deposits have, like the Mo stockworks (Section 28.10) dual affiliation and in addition to true granites, they may be also related to quartz monzonites as in the Basin and Range province, western United States and its extension into Mexico. In the latter case, it is hard to imagine the Be accumulation to be the result of magmatic differentiation alone. The western U.S. "berrylium belts" (Warner et

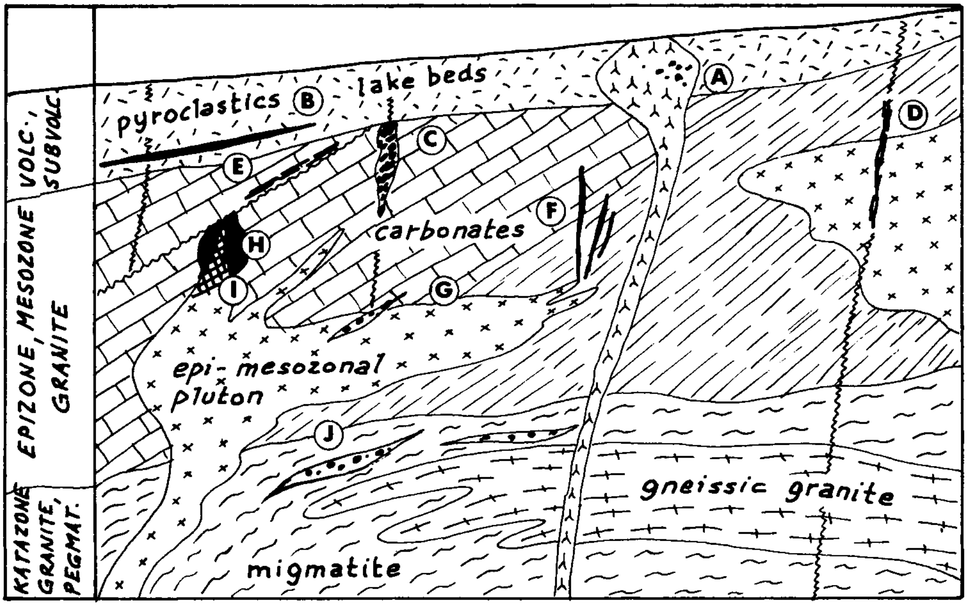


Fig. 28-89. Principal styles of Be deposits associated with calc-alkaline magmatism (see Table 28-17 for explanation of letter codes).

Table 28-17. Principal styles of Be deposits affiliated with calc-alkaline magmatism (emphasis on independent postmagmatic deosits related to epi- and mesozonal granites and quartz monzonites; compare also Fig. 28-89)

VOLCANIC-SUBVOLCANIC LEVEL (described in Section 26.6.11)	
(A)	disseminated beryl in subvolcanic rhyolite
(B)	disseminated bertrandite in water-laid tuff (e.g. Spor Mountain; about 30 Tt Be)
(C)	fluorite-bertrandite pipes, veins, replacements
(D)	epithermal quartz, adularia, bertrandite veins (e.g. Gold Hill; about 1,750 t Be)
EPI- AND MESOZONAL PLUTONIC LEVEL	
(E)	quartz, fluorite, scheelite, phenacite, bertrandite fault-filling veins and replacements (Mt. Wheeler, 260 t Be)
(F)	quartz, tourmaline, fluorite, wolframite, beryl, helvite, etc. veins (300 t Be)
(G)	high-level pegmatites with minor beryl
(H)	skarns with Be-andradite, Be-idocrase, helvite
(I)	greisens with accessory beryl
KATAZONAL SYSTEMS	
(J)	Be pegmatites (10 Tt Be)

al., 1959) seem to correlate with a Be-anomalous Precambrian crystalline basement.

From the associational point of view, the largest and most complex group of Be deposits occurs in the intrusion and over-intrusion complexes of "tin granite" cupolas, involving apogranites, greisens, skarns and veins. The rest are scattered, lonely localities, giving few clues as to their grand system affiliation, if any. Each category will be reviewed separately.

28.13.2. Be deposits in granite cupola endocontacts and exocontacts

The anatomy of "tin granite" cupolas has already been discussed. Here, only the setting of Be deposits will be considered (Fig. 28-90, Table 28-18). The "normal" (unaltered) granite (marked A on Fig. 28-90) associated with Be ores is likely to have a high trace Be content (of the order of 20 ppm Be), and may contain sparsely scattered beryl grains within its principal mass, or in pegmatite bodies.

The post-magmatically feldspathized portion of the cupola (apogranite), may reach up to 200-300 ppm Be in its partly but evenly albitized main body (B), and small crystals of beryl and rare bertrandite may be present. Greater accumulation of coarser beryl crystals can be found in metasomatic veins and pods of almost pure albitite ("albite aplite", C); microclinite ("amazonite syenite, D), or in mineralogically variable fracture veins (E). No currently economic Be accumulations, however, have been reported from this setting, nor from the marginal pegmatite (Stockscheider, F) of the cupola perimeter.

The feldspathized granite is terminated by a greisenized capping, and among the greisen facies distinguished by Shcherba (1968b), muscovite-quartz (G); topaz-quartz (H); mica (muscovite) only, (I) and quartz-tourmaline (J) greisens are most characteristic. They could be zonally arranged, but more often they form patches. Almost completely silicified masses (K) are sometimes considered to be a special facies of greisens. Beryl may be present as an accesory mineral in all the greisen facies, always accompanied by wolframite, cassiterite, molybdenite and other metallic minerals. Exclusively beryl-bearing greisens are not known. Shcherba (1968b) listed a late-stage bertrandite, sericite, fluorite association superimposed on greisen or formed along its fringe. As a source of Be, greisens are of limited importance.

Economically the most important accumulations of Be in granite intrusive and over-intrusive systems occur in exocontacts in carbonate rocks. About 80-90% of the postmagmatic plutonic Be comes from them. In the early skarns (L), Be usually accumulates in idocrase (Be-idocrase, up to 1.09% BeO) as in the Snake Range, Nevada and Iron Mountain, New Mexico, or in grossularite. Helvite group minerals $R_8(BeSiO_4)_6S_2$; R in helvite is Mn, in danalite Fe, in genthelvite Zn) are common in late stage skarns (M), e.g. in ribboned magnetite, fluorite, helvite skarn at Iron Mountain, New Mexico. Local variations of Be associations in skarn have been described, almost all in the late stage skarn or in retrograde veins and replacements superimposed on skarn.

In the large polymetallic skarn deposit Xi-Zhoyouang, Be accumulated in the beryl-epidote zone of late skarn, and in feldspar, helvite, chrysoberyl, tafeiite, bertrandite, cassiterite veinlets superimposed on skarn. Shcherba (1968b) listed a variety of mineral assemblages of late stage veins and stockworks superimposed on skarn in Kazakhstan and the Soviet Far East: (1) phenacite, chrysoberyl, fluorite, muscovite, tourmaline, calcite, scheelite, euclase, beryl, sulphides; (2) beryl, mica, fluorite, phenacite, scheelite, cassiterite, albite and (3) helvite, vesuvianite, fluorite, beryl, danalite, chrysoberyl, fluorite. Simple fluorite, scheelite, beryl and quartz, beryl veins are superimposed over skarn in the Victoria mine, New Mexico (Warner et al., 1959) and fluorite-helvite veins are found in the Grandview mine, New Mexico.

Exocontacts in alumosilicate rocks (N) are less exciting as sites of Be accumulations. Disseminated beryl rarely occurs in fracture veinlets superimposed on biotite or tourmaline hornfelses. Exocontacts in mafics (amphibolite, gabbro, serpentinite; O, P) are getting much attention in the Soviet literature (Shcherba, 1968b; Zabolotnaya, 1974) because they are well developed at several localities in the Urals (e.g. Takovaya). There, however, they are a source of a gem quality chrysoberyl (alexandrite) and emerald, rather than a bulk Be ore. Usually, two endocontact zones may be distinguished along mafic or ultramafic contacts (O): inner, more proximal, phlogopite and/or amphibole (actinolite, tremolite, anthophyllite) zone; (P) outer zone of chloritization and talc alteration. Shcherba (1968b) listed two Be associations, most likely to be present in the late-stage veins superimposed over both zones: (1) beryl, chrysoberyl, phenacite, bavenite, phlogopite, biotite, fluorite, feldspar, quartz and (2) phenacite, bavenite, beryl, albite, phlogopite, etc.

Above-intrusion veins and/or replacement bodies in carbonates (S, T) that are more or less independent of the skarn/greisen profile along the immediate contact, are common and economically important. At Lost River, Alaska (Sainsbury, 1969; this deposit contains the largest calculated reserve of granite-affiliated hydrothermal Be in the United States), the fluorite, white mica, diaspore, tourmaline, chrysoberyl veins date from an earlier period than the skarns and greisens. Fluorite, phenacite, bertrandite; and fluorite, mica, beryl associations, are most common in carbonate replacement veins and masses in the U.S.S.R.

In alumosilicate exocontacts, quartz, K-feldspar, molybdenite, wolframite, etc. veins and stockworks carry beryl as an accesory mineral, but no exclusively Be-mineralized veins have been reported.

The Lost River ore field, western Alaska (Sainsbury, 1969; Dobson, 1982; 4,050 t Be/0.2%) is also an important tin locality, already mentioned earlier. A granite cupola below the Lost River tin deposit contains some phenakite in greisenized and argillized granite. The exposed greisen bodies are virtually Be-free, but a fluorite, tourmaline, cassiterite-bearing rock in selvedges along the greisen/carbonate contact contains up to 3.3% BeO largely bound in chrysoberyl. The early stage andradite, magnetite, idocrase skarn is generally Be-poor, except for the local contents of up to 0.45% BeO in idocrase. Banded fluorite-magnetite skarn at the Tin Creek locality carries Be in helvite. The bulk of the economic Be in the Lost River area is contained in fracture filling and replacement veins in Ordovician carbonates, relatively distant from the granite. The veins are controlled by thrust faults, normal faults and zones of brecciation, and their usual mineralogy consists of dominant fluorite with lesser quantities of white to lilac mica, Be-diaspore, tourmaline

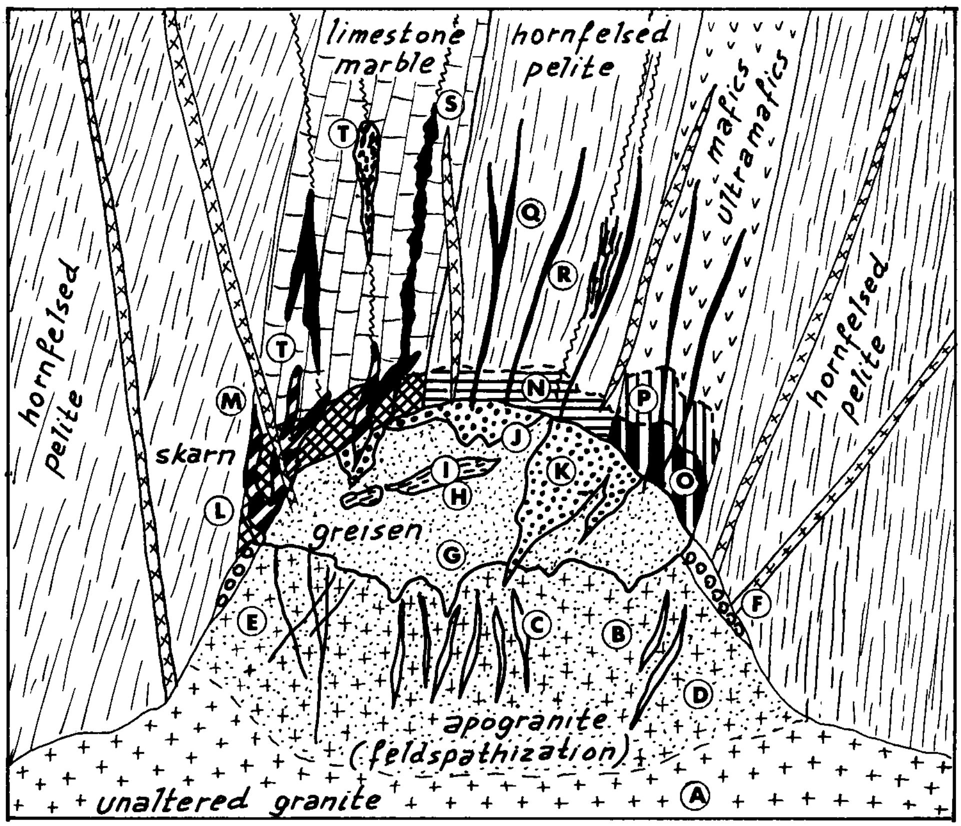


Fig. 28-90. The setting of Be deposits in intrusive and overintrusive region of granite cupolas. See Table 28-18 for an explanation of letter codes. From Laznicka (1984)

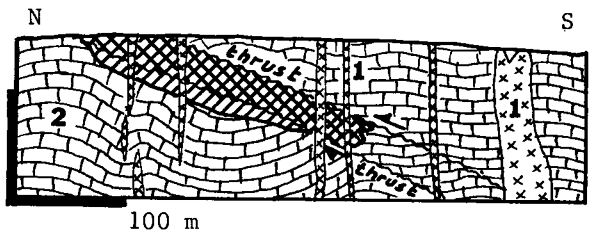
Table 28-18. The setting of Be deposits in the intrusive and over-intrusive regions of granite cupolas

(A)	NORMAL GRANITE; high trace Be or beryl disseminations in weathered granite
	FELDSPATHIZED GRANITE (APOGRANITE)
(B)	small crystals of beryl or bertrandite disseminated in evenly albitized apogranite
(C)	"albite aplite"-style replacement veins containing disseminated beryl
(D)	"amazonite syenite" replacement bodies with beryl
(E)	fissure veins
	MINERALIZED GREISENS (X00 localities, X00 t Be)
(F)	occasional disseminated beryl in all varieties of marginal pegmatite (Stockscheider)
(G)	muscovite-quartz greisen
(H)	topaz-quartz greisen
(I)	monomineralic mica (muscovite, lithionite) greisen
(J)	tourmaline-quartz greisen
(K)	silicified masses, pipes
	IMMEDIATE EXOCONTACT IN CARBONATES
(L)	early stage skarn; Be-andradite, Be-idocrase; X0 localities, X00 t presently uneconomic Be
(M)	late-stage skarn, superimposed veins (fluorite, magnetite, helvite; beryl, epidote; etc.); X0 localities, about 20 Tt Be
(N)	IMMEDIATE EXOCONTACT IN ALUMOSILICATE ROCKS: biotite, tourmaline, etc., hornfels
	IMMEDIATE EXOCONTACT IN MAFICS, ULTRAMAFICS
(O)	amphibole, phlogopite, sphene, etc. metasomatites, beryl (also emerald), chrysoberyl; several localities, X00 t Be
(P)	chlorite, talc-altered rocks; Be minerals in superimposed quartz, tourmaline, etc. veins
	ABOVE-INTRUSION VEINS, REPLACEMENTS; Be occurs in a variety of associations, of which fluorite, quartz, tourmaline, crysoberyl, phenakite, beryl, etc. orebodies are most common; X localities, about 10 Tt Be
(Q)	fissure veins
(R)	stockworks
(S)	replacement veins
(T)	replacement masses, pipes, mantos

and chrysoberyl. Euclase, bertrandite, phenakite and beryl may be present in minor quantities. Fluorite is colourless to light-green and inconspicuous. The largest lode system at Camp Creek is a tabular body up to 800 m long and 70 m thick, gently dipping south beneath a thrust fault. Numerous ore veins and veinlets are located within the fractured and brecciated limestone and dolomite (Fig. 28-91).

Iron Mountain near Socorro, New Mexico (Jahns and Glass, 1944; 300 t Be/0.15%) is a frequently quoted, readily accessible locality. There, a Paleozoic limestone and calcarous shale were intruded by a Tertiary rhyolite, granite and aplite complex, and a small skarn zone formed in the exocontact. The early massive magnetite-garnet skarn grades into a marginal, banded "ribbon rock" composed of fluorite, magnetite and helvite replacing carbonate. Helvite is yellowish-brown or reddish-brown. It is inconspicuous and megascopically difficult to tell from garnet or idocrase. The higher-grade "ribbon rock" contains about 0.7% BeO, the lower-grade material has 0.2% BeO. Lesser quantities of Be occur in the same assemblage superimposed along shears and breccia zones on the earlier skarn.

The Soviet Be deposits are considered to be of great strategic importance, so their names, locations, tonnages, etc. have not been released. Descriptions and illustrations of anonymous localities lacking even such elementary detail as scales, orientations, names of stratigraphic units, etc., are pitiful and will not be reviewed here. The reader is referred to the original source (Zabolotnaya, 1974; Shcherba, 1968b). Only the general setting of the Soviet localities can be gleaned, after an exhaustive search for clues. Several occurrences are in the Chukotka Tin Belt of eastermost Siberia (western extension of the Seward Peninsula of Alaska), and these are comparable in many respects with the Lost River field. Beryllium albitites superimposed on Precambrian metamorphics are probably located in the Aldan Shield. The beryl-containing greisens are found in the East Transbaikalia (also at the Chulun-Khuriete showing in adjacent Mongolia), and in the Central Kazakhstan W-Mo-Sn belt.



1. Cr lamprophyre, porphyry dikes, stocks
2. Or limestone, dolomite

Be. fluorite, diaspore, mica, tourmaline, chrysoberyl veins, veinlets

Fig. 28-91. Rapid River Be deposit, York Mountains, W. Alaska. After Sainsbury (1969).

The Be occurrences at granite/ultramafic contacts are located in the central Urals.

28.13.3. Independent Be occurrences

Many small occurrences of hydrothermal Be minerals are isolated, one-of-a-kind entities that cannot be fitted into the granite cupola model. Most are exocontact veins or replacements.

The California Vein at Mt. Antero (Sawatch Range, Colorado; Dings and Robinson, 1957) is a quartz, beryl, pyrite vein 215 m long and at most 1 m wide. The beryl is light-green to bluish and there is an accesory molybdenite. Several quartz, hübnerite, molybdenite veins are known in the vicinity and stockwork molybdenum deposits have been discovered in the area recently.

The Mount Wheeler deposit, Nevada (Stager, 1960) probably contains a minimum of 260 t Be/0.26%. There, Cambrian black limestone and interbedded shale are faulted, silicified and some of the E. or N.E.-trending fault zones are filled by "linear stockworks of quartz veinlets and parallel veins mineralized by scheelite. Quartz monzonite to granodiorite body is postulated to be present at a depth of less than 300 m. A pale blue beryl was detected in veinlets and small isolated crystals in hornfelsed shale below the main mineralized zone originally mined for scheelite, but the presence of the two most widespread minerals phenacite and bertrandite, was discovered much later. Both minerals are colourless to white and resemble quartz. They are accompanied by fluorite, pyrite, Mn-siderite and scheelite. The Be mineralization was traced for over 800 m downdip, and 1,300 m along the strike. The ore shoots are up to 3.3 m thick, extend vertically for 5 to 7 m and average about 1% BeO.

Additional Be localities, many listed by Shawe (1966) include quartz, beryl, wolframite and fluorite veins mostly associated with quartz monzonite stocks (e.g. Little Dragon Mts., Arizona; Sheeprock Mts., Utah; Victoria Mine, New Mexico; etc.), fluorite-helvite veins (Grandview Mine, New Mexico) and others. Volcanics and subvolcanics-hosted Be accumulations have been described in Chapter 26.

28.14. Pb-Zn(Ag) DEPOSITS IN "GRANITE" AUREOLES

28.14.1. General

Pb-Zn(Ag) ("polymetallic") deposits and occurrences are the most common variety of ores to be found in "granite" aureoles. At least 100 districts and large ore fields carry polymetallic deposits, worldwide. Considering the frequently large number of individual veins or orebodies present in a single field or district (e.g. 1100 veins in the Freiberg district, Erzgebirge, about 100 of them producing), the figure of over 10,000 producing Pb-Zn(Ag) orebodies in the world is probably a conservative estimate. These orebodies represent some 80 Mt Pb, 70 Mt Zn, 200 Tt Ag plus a considerable quantity of by-product Cd,Sb,Cu, As,Bi,Au, Sn,W,Mo, Hg,Te,Se, In,Ge,Ga, etc.

Although several colleagues would nominate a symmetrically filled quartz, galena, sphalerite vein as a "typical postmagmatic-hydrothermal orebody", not all veins are alike. There is a great variety of geometries, mineral associations and settings of the polymetallic orebodies and their origin continues to be controversial. No single model can accomodate this variety, and almost every summary statement made subject to scrutiny can be proven to include numerous exceptions. This is the price one pays for generalization and for the convenience of having a 20 page summary representing an ore category treated in no less than 50,000 pieces of literature.

Hydrothermal Pb-Zn(Ag) deposits have been traditionally (e.g. Schneiderhöhn, 1955; Park and McDiarmid, 1975) placed into the mesothermal, epithermal and telethermal categories on the grounds of assumed or demonstrated temperature of the ore-forming solutions, and into the subvolcanic and plutonic associations by their presumed level of emplacement and derivation. The high-level epithermal deposits hosted, by or spatially associated with, continental volcanic terrains have been thoroughly reviewed in Chapter 26. Most epithermal deposits studied recently by modern methods have been proven to have formed in the waning stage of volcanism or post-volcanically from convecting fluids mostly heated by an evolving intrusive body in the subsurface. Consequently, there is no qualitative difference between the "subvolcanic" and "plutonic" deposits and both categories overlap.

The recent advances in ore petrology, particularly the progress in the study of strata-related deposits (these have been extensively reviewed in the 14 volumes of the Handbook of Stratiform and Strata-bound Ore Deposits, edited by Wolf, 1976, 1981 and 1985), further demonstrated the considerable variety and transitionality of the Pb-Zn deposits. Not long ago, the peneconcordant massive sulphide ores in volcanic-sedimentary associations (e.g. Chapter 14) as well as the Mississippi Valley and Appalachian "types" (Chapter 20) were considered granite-related, postmagmatic. Now we know better...(do we really ?).

In many cases the style and origin of Zn-Pb ores correlates with the host lithologic association (e.g. sedimentary ores are in sediments), the "granites" being the most notable exception. Because of the distal position of postmagmatic-plutonic Pb-Zn orebodies with respect to their "emanative centre", such orebodies are hosted by older (pre-granite) rocks rather than by the concentrator intrusion. When a "granite" hosts orebodies (mostly veins), it is an old granite acting as a passive host, genetically unrelated to the mineralization. Several minor, economically unimportant or marginal exceptions, are reviewed in the following paragraphs. Parent/daughter relationships between plutonic intrusions and hydrothermal Pb-Zn deposits located in their aureole are difficult to demonstrate exactly. Numerous modern determinations based on isotopic age data indicate considerable gaps between the ages of igneous crystallization and ore emplacement (of the order of tens to hundreds of millions of years; about 100 m.y. in the Stříbro district, Czechoslovakia). Pb-Zn deposits occur particularly frequently in the tectono-magmatically "activated" (block faulted, stretched, rifted) terrains the formation of many of which shortly postdated termination of the continental granitic plutonism. In such terrains, metalliferous veins may have resulted from hydrothermal convection driven by other than granite-provided heat sources (geothermal heat, mafic dikes, small alkaline intrusions, younger buried granitic intrusions) and in most cases such a source is impossible to determine. A prospector should realize that although many Pb-Zn(Ag) deposits are undisputably members of a postmagmatic suite related to an evolution of an igneous intrusion and occur orderly in its aureole, there are many exceptions and departures from such a scenario some of which may, by their setting, mimic the former. In addition to this, relic, remobilized and mobilized Pb-Zn(Ag) deposits are unusually frequent. One should bear in mind the limitations of the aureole ore distribution model and be ready to see beyond it. The uncertainities and limitations mentioned in general above naturally overprint into the contents of the present book section as well. Indeed it cannot be demonstrated that all the examples treated here in the framework of plutonic deposits, are beyond doubt "granite"-affiliated.

Regarding geotectonic setting and host association, all Pb-Zn districts and "belts" formed in regions underlain by a relatively mature continental crust at the time of intrusive emplacement and ore generation. The most favourable terrains are "activated" portions of former platforms or "miogeoclines" such as the eastern portion of the Great Basin in Eastern Nevada and Utah; uplifts bordering "eugeoclinal" and "miogeoclinal" domains in orogenic belts (e.g. the Omineca belt, British Columbia); uplifts within the "ensialic" portions of continental margin orogenic belts and median massifs (e.g. the Bohemian Massif, Massif Central); ancient sialic continental blocks within island arcs (e.g. N. and C. Honshu, Japan); intracontinental uplifts, grabens, aulacogenes, rifts in their early stage of development (before the appearance of widespread basalts) and others.

The supracrustal lithologic associations treated in Chapters 11,12,14, 17,19,20, 26,28 and 30, typically host postmagmatic Pb-Zn deposits. Small isolated Zn-Pb occurrences may be present in the remaining associations. Some Zn-rich skarns and veins containing virtually no Pb are transitional into Cu skarns and veins and are hosted by "granite"-intruded intermediate to mafic marine volcanic-sedimentary suites of continental margins.

28.14.2. Pb-Zn sulphide deposits in non-carbonate hosts

STOCKWORKS, DISSEMINATIONS

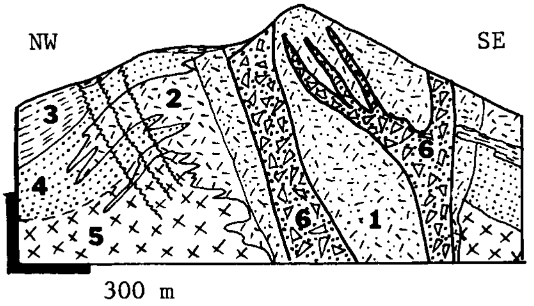
In contrast to the disseminated or stockwork Sn,Mo,Cu,W, and other deposits, Pb-Zn ores normally do not accumulate in a similar way in the immediate contact area of their concentrator intrusion. Several minor examples of "porphyry" (or stockwork) Pb-Zn(Ag) occurrences are largely due to unusual interactions, are very local and, to date, of no economic importance. Most are high-level (subvolcanic; e.g. disseminated sphalerite in porphyry dikes, Mt.Bischoff; disseminated galena and sphalerite in felsic subvolcanic stocks and dikes, locally in the Cartagena and Mazarron districts, Spain).

The disseminated, very low grade occurrence at Hahns Peak, Colorado (Young and Segerstrom, 1973; Fig. 28-92) is often quoted as an example of this type of mineralization. There, pyrite, galena, sphalerite, lesser tetrahedrite, chalcopyrite and proustite are sporadically scattered in certain zones of an altered (silicified, sericitized, kaolinized) breccia pipe intruded by an 11 m.y. old porphyry stock and dikes. This deposit is estimated to contain 6.39 Tt Ag, 639 Tt Pb and 387 Tt Zn at grades of 9.7 ppm, 0.1 and 0.06%, respectively. Similar occurrences although not of much economic importance in themselves at present, may indicate concealed mineralized apical intrusions (e.g. stockwork Mo).

FISSURE FILLING VEINS

Fissure veins are the most characteristic style of Pb-Zn deposits in non-carbonate hosts. All varieties of vein filling structures and textures treated in economic geology textbooks (symmetrical, banded, breccia cementing, cockade, etc.) are represented. The veins occur at some distance from the concentrator intrusion. When such an intrusion is a granite cupola intruded into pelitic sediments, the bulk of Pb-Zn veins tend to be located outside the thermally hornfelsed fringe, in rocks showing only minor effects of thermal metamorphism. A considerable variety of vein-filling mineral associations has been recorded (Tables 28-19, 20). Quartz, carbonate (calcite, dolomite, siderite) and barite gangue; galena, sphalerite, pyrite sulphides; and alteration sericitization, silicification, carbonatization, argillization and bleaching are most common. The alteration envelopes to veins tend to be narrow and developed in the immediate vein vicinity.

Some veins show mineralogical or geochemical zoning, most commonly showing an increasing Zn:Pb ratio and increase in the Cu and Au contents with depth (in many subvolcanic veins, on the other hand, gold is at its highest concentration near the top). Pb-Zn veins commonly follow dikes and are often preferentially hosted by them (e.g. in Příbram, Czechoslovakia). The economic importance of Pb-Zn(Ag) fissure veins has diminished considerably in the past four



1. T,bleached,silicified rhyolite porphyry
2. dacite, quartz latite. rhyolite porphyry
3. Cr shale, sandstone
4. J_3-Pe red beds
5. Pt_1 crystalline rocks
6. mineralized and altered breccia zones

Fig. 28-92. Hahn's Peak, Colorado, a low-grade disseminated Ag,Pb,Zn sulphide deposit. After Young and Segerstrom (1973).

or five decades mostly due to exhaustion and a labour-intensive method of mining. Individual veins tend to be small or, at best, medium-sized orebodies (several tens to hundred thousand tons of ore), but an aggregate tonnage of multiple vein fields could be significant. Compared with the many "modern" orebodies, veins tend to have high Pb and Zn grades and high silver contents. In the Oberharz district, West Germany, the Grund vein deposit was more profitable than the massive sulphide Rammelsberg, in the 1970's (H. Sperling, pers. commun.,1975).

REPLACEMENT AND RELIC OREBODIES IN NON-CARBONATE HOSTS

Replacement Pb-Zn(Ag) orebodies in silicate wallrocks occur at only a few localities but at least one of them (the Coeur d'Alene district, Idaho) is of substantial economic importance. There, steeply dipping narrow veins composed of fine crystalline galena, sphalerite, pyrite, pyrrhotite, ankerite, siderite, quartz, tetrahedrite and other minerals, are located in bleached siliceous Proterozoic slate, phyllite and sericite quartzite. At Coeur d'Alene and elsewhere, fault gouge to mylonite were most commonly replaced. Sometimes, replacement orebodies enclosed in silicate wallrocks formed by complete substitution of carbonate lenses, or by selective replacement of the carbonate component in, for example, a limy shale or a limy tuff.

Many Pb-Zn sulphide orebodies formerly interpreted as hydrothermal replacements in the "granite" aureole have subsequently been re-interpreted as relic stratiform deposits. Examples include several localities in Mexico (Fresnillo, San Martín, Plomosas and others; De Cserna, 1976a), Peru (Lehne and Amstutz, 1982) and elsewhere. This subject has been reviewed in Section 17.6.2. In addition to little modified earlier relic orebodies, one can expect a

Table 28-19. Pb,Zn,Ag multiple vein deposits, fields and districts; selected examples

LOCALITY	HOST AND INTRUSIVE UNITS	MINERALIZATION	REFERENCES
Elsa-Keno Hill field, Yukon, Canada	PZ_3 or MZ micasch.,gray to black phyll.,m-quartz., m-diabase sills; Cr_3 qtz. monzonite	28 vein zones N.E./S.E., in 1.6-20m wide gouge and brecc.filled zones; sider.,gal.,sphal.,pyr.,freiberg., pyrarg.; light (bleaching) to none alt. 190Tt Pb,123Tt Zn, 4.5Tt Ag	Douglas, ed., (1970)
Slocan-Kaslo distr. S. British Columbia Canada	Tr black slate, m-quartzite litharen.,minor limest., greenst.; J_1 granod.,qtz. dior., qtz. monzonite	many fiss. veins, rare limest.replac. sider.,qtz.,calc.,sphal.,gal.,pyr., tetr. 198Tt Zn; 164Tt Pb; 1,077 t Ag	Douglas, ed., (1970)
Coeur d'Alene distr. Idaho, U.S.A.	Pt_2 phyllite, siltst., m-quartz.; Cr_3 qtz. monzon. and dior. stocks, dikes	9 N.N.W. trending, miner.fault contr. "belts"; replac.lodes, sider.,anker., gal.,sphal.,pyrrh.; qtz.,sider.,Ag-tetrahedr. Main miner. period Cr_3-T_1, early Pt_2 miner.; possibil.of remobil. 6.9 Mt Pb; 3Mt Zn; 140Tt Cu; 31Tt Ag	Fryklund (1964)
Colorado Mineral Belt (Rocky Mts., U.S.A.)	Pt_1 gneiss,migmat.,amphib. Pt_2 qtz. monzon.,granite Cr_3-T_2 qtz. monz. stocks, dikes;granod.,lamproph.	almost contin.belt of fissure veins; qtz.,pyr.,gold; qtz.,carb.,pyr.,sphal. gal. Short, impersistent ore shoots. 250Tt Pb; 130Tt Zn; 2.8Tt Ag; 210 t Au (signif. portion of Au from placer)	Lovering and Goddard (1950)
Park City field, Utah, U.S.A.	Ps-Tr limest.,dolom.,shale sandst.,folded,faulted, thrusted; T_1 dior.,diorite porphyries	replac.mantos in jasperoid // with bedd.planes; fiss.and replac.veins; qtz.,rhodochr.,rhodon.,pyr.,sphal., gal.in veins; Ag-bonanzas. 1.15Mt Pb, 600Tt Zn, 50Tt Cu, 6.76Tt Ag, 28t Au	Barnes and Simos (1968)

Santa Barbara, Chih.,Mexico	Cr_1 limest.,Eo,contin. andesites; Eo-Ol rhyol., qtz. monzonite in depth	pyr.,gal.,sphal.,qtz.,fissure veins in sedim. and andesites. 1.1 Mt Pb/3% 1.7 Mt Zn/4.8%; 266Tt Cu/0.75%; 5.2 Tt Ag	Busch (1980)
Fresnillo, Zacat., Mexico	Tr_3 andes.pillow lava, greenst.; Cr_1 limest.,shale; Cr_3 flysch sediments; Eo_3? granod.,qtz.monzon., rhyolite	bedded replac. or relic ? mantos; N.W. fissure veins, stockw.; py,sph., gal.,cp.,lesser pyrrh.,ars.,tetr.,pyrarg. Veins have qtz.,calc.,sider. gangue. 980Tt Zn, 920Tt Pb; 7.75 Tt Ag	DeCserna (1976b)
San Martin, Zacat., Mexico	MZ blue limest.,hornfelsed shale; T granod. porphyry	N.E./45-70°W up to 1.5 m thick veins; qtz.,calc.,fluor.,sphal.,cp.,gal., argent.,Ag; 669Tt Zn/5.75%; 180Tt Pb; 162 Tt Cu/1.35%; 4.2Tt Ag/150 ppm	Busch (1980)
Mina Matilde, northern Bolivia	D gray folded slate, sandstone; no intrus.known.	2 fiss.veins N23°E/90° up to 1.2-7 m thick, banded; sider.,gal.,sphal. 540 Tt Zn, 180Tt Pb, 12 Tt Cu, 120t Ag	Ahlfeld and Schneider-Scherbina (1964)
Oberharz district (Clausthal),Harz, West Germany	D slate,limest.,sandst.; Cb_1 litharenite, slate; Cb_3-Pe_1 and later: buried granite ?	16 N.N.W. discont.miner.fault zones; qtz.,sider.,calc.,gal.,sphal.,lesser bourn.,tetr.,Ag-sulphosalts. 1.8Mt Pb, 700Tt Zn, 4.7Tt Ag	Buschendorf et al.(1971)
Freiberg, Erzgebirge, East Germany	Pt_3 biot.gneiss, migmatite; Cb-Pe cryptobatholith	1,100 N.-S. and W.-E. fissure veins. 2 major miner. stages (PZ_3 and Tr-T); qtz.,sider.,gal.,sphal.,Ag-sulphosalts (see Table 28-20); 1.7Mt Pb, 7Tt Ag	Baumann (1976)
Rheinische Schiefergebirge, W.Germany (Ramsbeck,Enns, Holzappel,Bensberg)	D qtz.rich grayw.,slate, quartzite; deformed, cleaved, but no known granitic intrusions are present	fissure,shear,bedding veins, some may be remobiliz.relict oreb.; barite, carb.,sphal.,pyr.,gal.,lesser tetr., ars. 2.74Mt Zn; 1.22 Mt Pb; 1.1Tt Ag	Schneiderhöhn (1941)

Table 28-19 (continued). Pb,Zn,Ag multiple vein deposits, fields and districts; selected examples

LOCALITY	HOST AND INTRUSIVE UNITS	MINERALIZATION	REFERENCES
Příbram district, Czechoslovakia	Pt_3 slate,graywacke,greenstone (spilite); Cm litharenite; Cb-Pe buried pluton,qtz.diorite,diabase	2 parallel N.E. trending fault zones containing N.N.E. fiss.veins up to 1.7 km deep in fract.feathering from master faults; qtz.,sider.,carb.,gal., sphal.,boulang.,Ag-sulphosalts; estim. 1.2Mt Pb, 700Tt Zn, 4.5Tt Ag	Kutina (1963)
Sierra Morena district, Spain (Linares,San Quintin,La Carolina,etc.)	Pt_3 schists; Or, quartz., litharen.,slate,schists; Cb_1 grayw.,slate; Cb-Pe granod.,qtz. monzonite	subvert.fiss.veins in vein zones up to 12 km long; veins 1-2 m thick, qtz., anker.,carb.,gal.,sphal.,boulanger., Ag-sulphosalts; in metased.and granite 2.9Mt Pb, 670Tt Zn, 4.2Tt Ag	Schneiderhöhn (1941)
Leadhills-Wanlockhead d.,Scotland	Or grayw.,black slate, volcaniclastics; Cb-Pe buried plut., dikes	Pe_3; 70 W.N.W. to N.W. banded fissure veins up to 5 m thick; dolom.,calc., gal.,sphal.,pyr.,chalcop. 300Tt Pb	Dunham et al. (1978)
English Lake District.,N.W. England	Or, shale, grayw.,marine andes.,rhyol.; D_1 granite pluton; Cb-Pe cryptobath.?	fissure veins (e.g. Greenside vein); qtz.,bar.,sphal.,gal.,cp.; 230Tt Pb	Dunham et al. (1978)
Central Wales district, Great Britain	Or,Si folded slate, litharenite; unknown intrus.	356 m.y. miner.,low-temp.fissure veins 275 occurrences; qtz.,pyr.,sphal.,gal. cp. 382 Tt Pb, 75Tt Zn, 109t Ag	Dunham et al. (1978)
Rhodopen district, S.Bulgaria (e.g. Madan)	Pt gneiss,amphib.,marble; PZ deep-seated granite; Ol qtz.monz.,granod., syenite, rhyolite	swarms of fissure veins in 43 groups, minor marble replac.; qtz.,carb.,gal., sphal.,pyr.; 2.77Mt Pb/2-3%; 2.18Mt Zn; 240Tt Cu; 4Tt Ag	Iovchev (1961)
Zeehan-Dundas d., S.W. Tasmania Australia	Pt_3-Cm slate, quartzite; Cm-D slate,greenst.,sd., limest.;D tin granite	D; about 30 N.N.W. and N.N.E. fissure veins of qtz.,sider.,gal.,sphal.,pyr.; minor stann.,cassit; 324 Tt Pb 900t Ag	Blissett (1962)

Table 28-20. Selected examples of single Pb-Zn-Ag fissure veins

VEIN	HOST ROCKS	AGE, FILLING, MINERALOGY, ALTERATIONS, MAGNITUDE, TONNAGE, ETC., OF THE VEIN	REFERENCES
Neue Hoffnung Gottes Freiberg, E.Germany (noble quartz assoc.)	Pt_3 gray gneiss, biotite gneiss	Cb-Pe; qtz.,sphal.,ars.,pyr.,pyrrh.,lesser cassit.,pyrarg.,miarg.,stephanite,polybasite. Seric.,silicif.; N.N.E.,2 km long, up to 2 m wide, 460 m deep; X00 t Ag	Schneiderhöhn (1941,1955)
Himmelfahrt, Freiberg East Germany (Edle Braunspathformation)	Pt_3 gray gneiss biotite gneiss	Cb-Pe; sider.,lesser calc.,gal.,sphal.,qtz., tetr.,freibergite,pyrarg.,proustite; N.N.E., 600-1,000 m long, 0.75-1.5 m wide; X00 t Ag	ditto
Silbernaler Gang, Grund, Harz Mts., West Germany	Cb_1 litharenite, slate	Cb_3-Pe_1; qtz.,lesser calc.,dolom,sider.,bar., gal.,sphal.,lesser cp.,pyr.,tetr.,pyrargyrite; banded and brecciated; W.N.W., 6 km long, up to 50 m wide; 11.5 Mt ore	Buschendorf et al. (1971)
Holzappel Hauptgang, Rhein. Schiefergebirge, West Germany	D litharen.,slate,diabase sill, porphyroid	Cb?; qtz.,sider.,sphal.,tetr.,gal.,lesser pyr.,cp.; qtz.-seric.alter.; 3.4 km long, 0.6-7 m thick, 1,017 m deep;	Schneiderhöhn (1941,1955)
Main Vojtěch Vein, (Hlavní Vojtěšská) Příbram,Czechoslov.	Cb diabase dikes in Cm litharenite; in depth Pt_3 slate,greenst.	Cb?; sider.,gal.,sphal.,bournon.,Pb-Sb sulphosalts; in depth: fine qtz.,sider.,gal.,sphal., cp.; pyrarg.,steph.,polybasite throughout. Seric.,carbonatiz.,bleaching alter.; N.N.E./ 70-85°E; 2 km long, depth to 1,700 m	Kutina (1963)
Greenside Vein, English Lake Distr. Great Britain	Or, marine andesite,rhyol.,qtz. porph.stocks	PZ_3; barite,qtz.,sphal.,cp.,gal.; single N.-S. east dipping fault filling vein, 1.3 km long, up to 10 m wide, 600 m deep; 167Tt Pb, 65 t Ag	Dunham et al. (1978)
Mayflower Vein, Park City field, Utah, U.S.A.	Ps-Pe limestone, dolomite; T_1 diorite	T_1; quartz,lesser calc.,rhodochr.,rhodon.,pyr., sphal.,gal.,small shoots of enarg.,tetr.,cp.; silicif.,qtz.-seric.alter.; N70°E/65°N, 670 m depth.	Barnes and Simos (1968)

variety of (re)mobilized mineralizations, always controversial and difficult to interpret. The Coeur d'Alene district (Gott and Cathrall, 1980) described in greater detail later, illustrates a case where (re)mobilization has been frequently assumed, but not yet convincingly proven.

28.14.3. Zn-Pb sulphides in carbonates: skarns

Zn-Pb skarns (Table 28-21) represent some 12 Mt Zn and 9 Mt Pb, worldwide. Their Zn:Pb ratio varies widely. As a rule, the skarns near intrusive contacts are high in Fe-sphalerite (marmatite) and low in galena, but they may contain significant amounts of chalcopyrite. Distal skarns tend to be Pb-rich, particularly in orebodies formed in carbonates outside the skarn envelope.

Zn-Pb skarns were briefly reviewed by Einaudi et al. (1981), and these authors summarized their most distinctive features as follows: (1) frequent occurrence of Mn-rich skarn silicates (johannsenite, bustamite); (2) common occurrence in distal position to intrusive contacts; (3) location along structural or lithologic contacts; (4) preferential association of sulphides with pyroxene, rather than with garnet; (5) absence of significant metamorphic aureoles around the skarn and (6) retrograde minerals represented by Mn-rich ilvaite, pyroxenoids, subcalcic amphibole and chlorite.

The skarns are mostly calcic, although few examples of magnesian skarns are known. They are all related to high-level intrusions (upper mesozone to subvolcanic) ranging from granodiorite through quartz monzonite to leucogranite, and from holocrystalline plutons through small stocks and porphyry dikes to breccia pipes (Trepča, San Antonio Mine, Chih.). Some skarns lack known associated intrusive rocks, but are located along structurally or lithologically controlled solution pathways. The skarns vary in shape from irregular masses through chimneys and pipes to peneconcordant mantos. Selective replacement of thin carbonate lenses or beds sandwiched between silicate rocks (e.g. shales, quartzites) results in orebodies that may be confused with stratiform deposits. Some isochemically metamorphosed Zn-Pb deposits in supracrustal rocks, on the other hand, may correspond compositionally to skarns. Relic supracrustal Zn-Pb orebodies overprinted by skarn and partly remobilized, are virtually indistinguishable from true metasomatic skarns. Fig. 28-93 shows selected examples of Zn-Pb skarns and

28.14.4. Zn-Pb sulphides hosted by carbonates: no skarn assemblage

Disseminated (scattered) to massive galena, sphalerite, pyrite, pyrrhotite and other sulphides lacking the skarn silicates, form large and rich orebodies in many mining fields throughout the world (Table 28-22), in which high-level plutons and subvolcanic bodies intruded sedimentary carbonates. They represent some 25 Mt Zn and 27 Mt Pb.

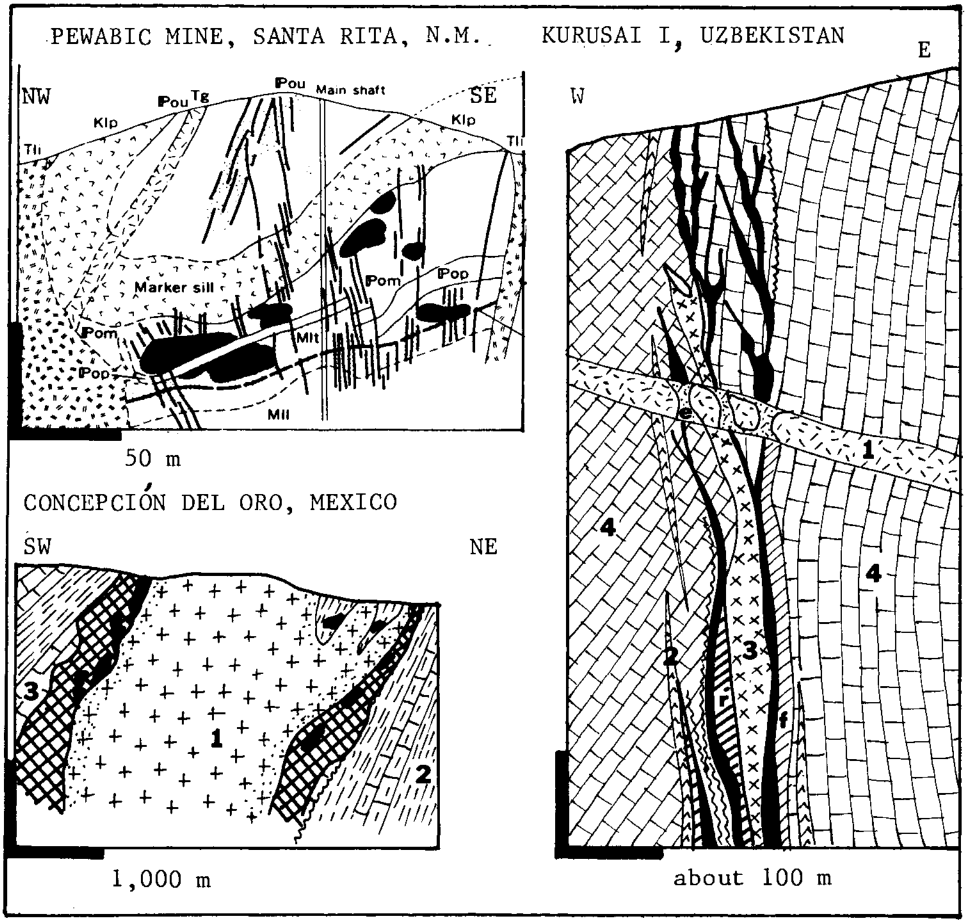


Fig. 28-93. Examples of Zn-Pb and Zn-Cu skarns.

Pewabic mine: Tli=T_1 rhyodacite porphyry; Tg=epidotized granodiorite porphyry; Klp=Cr_3 hornblende quartz diorite; Pou, Pom=Ps limestones; Pop=Ps shale; Mlt, Mll=Ms limestone.

Concepción del Oro, Mexico: 1=Eo-Ol granodiorite; 2=Cr_3 thin bedded limestone and black shale; 3=J limestone. Black area: mineralized grossularite skarn; grid: wollastonite skarn and marble.

Kurusai I (Kurama Range, Uzbekistan): e=epidote endoskarn; r=reaction skarns; f=forsterite calcite hornfels; 1=Pe syenite porphyry; 2=quartz porphyry and diabase; 3=diorite, syenodiorite; 4=Cb_1 marble; 5=D3 marble; black: vein skarn with sulphides. From Jones et al. (1967), LITHOTHEQUE (diagrammatic) and Lukin et al. (1968).

Table 28-21. Zn-Pb skarns, selected examples of deposits and ore fields

LOCALITY	HOST UNITS AND INTRUSIONS	MINERALIZATION	REFERENCES
Hanover, Santa Rita distr., New Mexico, U.S.A.	Cb limestone; T_1 granod.stock, granod.porphyry dikes	sphal., lesser gal., cp., pyr., moly., in garn., pyrox., amphibole skarn; 920Tt Zn/14%; 132Tt Pb/0.3%; 70Tt Cu/1%; 658t Ag/112 ppm	Einaudi et al. (1981)
Naica, Chihuahua, N.Mexico	Cr_1 folded limest., shale; T rhyol. dikes, qtz.-feldspar porphyry	42 chimney and manto oreb. of dissem. pyr., gal., sphal., lesser cp., arsenp., pyrrh., scheel. in wollast., garnet, idocr., hedenb. skarn; fault control. 620Tt Pb/4.4%; 550Tt Zn/3.9%; 47Tt Cu/0.37%; 1,875t Ag/133 ppm;	Stone (1959)
Concepción del Oro, N. Mexico	J-Cr limest., shale, sandstone; hornf., skarnized; 40-38 m.y. porph.granod., qtz.monzonite	dissem. and mass. magn., specul., pyr., cp., sphal., gal. in garn., epid.. diops., wollast. rim skarn. 300Tt Cu, 30t Au; 633 Tt Pb; 546 Tt Zn	Buseck (1966)
El Mochito mine, Honduras	Cr limest., red-beds clastics, shale, skarn; block-faulted, graben; T diab.dikes, granod. stock postul. in depth	fault-control. distal skarn; pipe-like bodies of magn., sphal., gal., pyr., cp., pyrrh. in Mn-hedenb., andradite, ilvaite, bustam. skarn; 857Tt Zn/8.2%, 508Tt Pb/4.84%; 1,617t Ag/154 ppm	Eng. and Min. November 1977
Aguilar, northern Argentina	Cm quartzite, limestone; T_1 quartz monzonite stock	sphal., gal., pyr., ars., pyrrh. mantos and columns // intr.cont. and faults in hedenb., garn., wollast., rhodonite, amphib., chlorite skarn; 1.8 Mt Zn/16%; 1.38Mt Pb/11%; 2.7Tt Ag	Angelelli (1950)
Kurama Range, Uzbekistan, Soviet Central Asia	D_2-Cb_1 limest., dolom., andes., tuff, rhyol.porph.; Cb_2 granodior., gran.porph., stocks, dks.	sphal., gal., pyrrh., magn., cp., in mantos and pipes fringing porph. dikes, in skarn and marble. Est. 2Mt Zn, Pb	Smirnov and Gorzhevsky (1974)

Tienpaoshan, Sikang, China	Or, limestone; MZ quartz monzon. stock	sphal.,gal.,cp.,pyr. masses and mantos in hedenb.,epid.,fluor.skarn; min.180Tt Zn, 150Tt Pb, 56Tt Cu	Hsieh (1950)
Shuikoushan, Hunan, China	Pe limestone; MZ-T quartz monzonite stock	sphal.,gal.,pyr.,cp.,irregular masses in contact garnet,pyrox.,epid. skarn; 750Tt Zn, 690Tt Pb, 900t Ag	Hsieh (1950)
Yeonhwa, Ulchin distr., South Korea	Pt_1 basem.granite; Cm-Or folded carbonate,quartzite,shale; 94-50 m.y. granod.,qtz.monzon. porphyry	several skarn oreb.in a 25 km long E.-W. belt; pyrrh.,sphal.,lesser gal.,cp.,in high-Mn pipe-like bodies of grandite-andrad.,rhodon.,bustam., Mn-pyrox. 723Tt Zn, 84Tt Pb	Yun and Einaudi (1982)
Tetyukhe, Sikhote Alin, south-eastern U.S.S.R.	Cb to Cr_1 shale,sandst.,limestone incl.silic.karst brecc., Cr_3-T_1 contin.andes.,dac.,rh. T_1 qtz.porph.,dior.,granod.	sphal.,gal.,pyrrh.,dissem.and masses in skarn mantos and pipes (Mn-hedenb.,ilvaite skarn) and replac. in marble; min.2Mt Zn,1.6Mt Pb, 2 Tt Ag	Magak'yan (1968)
Kamioka, N.C. Honshu, Japan	Pt_1 hornbl.and biot.gneiss, marble,calc-silic.gneiss; Cb-Pe amphibolite,m-gabbro, m-quartzite; J? granitization; Cr,qtz. and gran.porph.	80 small sphal.,gal.,cp.,pyr.,graphite,pyrrh.oreb. in hedenb.skarn and partly in marble; 3 major clusters; 4.44Mt Zn/5.7%; 624Tt Pb; 2.7Tt Ag; 6,240 t Bi; 338t Te	Nishiwaki et al. (1970)
Chichibu mine, C. Honshu, Japan	Cb-Pe litharen.,slate,chert, limest.,maf.tuff,m-basalt; hornfelsed,cont.skarn; Mi, qtz.dior.porph.,qtz.porph.dk.	pyr.,pyrrh.,magn.,cp.,in skarn; pyr.,sphal.,gal.,cp.,stibn.,bismuthin.,Au, etc.in brecc.superimp.on skarn and limest.; 53Tt Zn, 9Tt Cu	Miyazawa (1970)
Nakatatsu mine, C. Honshu, Japan	Cb_2 limest.,black slate, diabase; J_2-Cr_1 sandst.,shale; Cr_3-T_1 (60 m.y.) gran. porph.	sphal.,lesser gal.,cp.,in a penecon-cord. manto in clinopyrox. skarn; 385Tt Zn/5.5%; 35Tt Pb/0.5%; 21Tt Cu/0.3%; 210 t Ag/30 ppm	Shimizu and Iiyama (1982)

Table 28-22. Pb-Zn replacement sulphide deposits in carbonates, selected examples

LOCALITY	HOST AND INTRUSIVE UNITS	MINERALIZATION	REFERENCES
Bluebell mine, Riondel, British Columbia, Canada	Cm_1 calcite to dolom.marble, m-quartzite, micasch.,graph. sch.,calc-silic.hornfels, tactite; 170-30 m.y. qtz. monz.plut.and stocks in area	tabular replaced ore mantos in 3 zones, not in direct cont.with intrus. Coarse pyyrh.,sphal.,gal.,knebelite, quartz, calcite; 280Tt Pb	Ohmoto and Rye (1970)
La Encantada, N.W. Coahuila, Mexico	Cr, limest.,shale; recryst., partly skarn; T qtz.monzon. stock in depth	high-grade ore chimney; gal.,sphal., magn.,pyr.,proustite in limest.,underlain by sulph. skarn. Almost all prod. comes from oxid.zone with cerussite, argentojaros.,angles. 769Tt Pb/12%; 2.52Tt Ag/400 ppm	Lozej and Beales (1977)
Providencia, Zacatecas, Mexico	J_3-Cr limest.,shale; folded, hornfelsed; Ol (40 m.y.) granodior. stock	elong. replac. pipes; sphal.,gal.,pyr. calc.,quartz; high proport.of oxidiz. ore; 633Tt Pb/6.5%; 546Tt Zn/13%; 3.24Tt Ag/200 ppm	Sawkins (1964)
Cerro de Pasco, central Peru	Tr_3-J_1 black limest.,dolom., silic.shale resting on D black phyllite; Mi_2 (14.4-14.2 m.y.) vent breccia, qtz. monzonite dikes	early stage mass.repl.bodies of pyrrh. sphal.,arsenop. and pyr.,silica in carbonate, followed by late stage qtz. pyr.,enarg.,luzonite veins and Ag-bonanza formed by hydroth. leaching; 100Mt pyr.,7 Mt Zn; 3Mt Pb; 48Tt Ag	Einaudi (1977)
Trepča, Kosovska Mitrovica, Yugoslavia	Or-S marble, phyll.,qtz.-seric. sch.,m-quartzite; Mi vent fac.brecc.pipe comp. of qtz.-seric.alter.trach., dacite fragm.,carbonate; dacite-granod. plugs	massive, coarse sphal.,gal.,pyrrh., arsenop.,cp.,etc. in pipe-like or irreg.bodies replace marble or early skarn near vent; 3Mt Pb/6%; 2Mt Zn/4%; 5Tt Ag/100 ppm	Janković (1982)

Olympias mine, Chalkidiki Pen., Greece	Pt,PZ micasch.,gneiss, amphibolite, marble; T aplit.granite,granod.	peneconc.tabular replac.body 400x 1,500x12 m; pyrrh.,pyr.,sphal.,gal., ars.,cp.; Mn-oxide rich gossan; 450Tt Zn; 360Tt Pb; 240Tt As; 1.3Tt Ag; 70 t Au	Marinos (1982)
Laurium, Attica, Greece	PZ marble, micasch.; MZ slate, congl.,limest.,greenstone metavolcanics; Mi? granod.porph.sills,buried stock; minor skarn	gal.,sphal.,pyr. replac. of carbonate along faults and bedd.planes,less superimp.on skarn; karsting,oxid. zone rich in Ag; 497Tt Zn, 1.21Mt Pb, 8,010 t Ag	Marinos (1982)
Argun R.belt (Nerchinsk), East Transbaikalia,USSR	Cm_1 black argill. dolom., limest.,shale; J_{2-3} qtz. porph. dikes, stocks	pipe,vein,lens replac. in jasperoid and dolomitiz. limest.; gal.,sphal., pyr.,arsenop.,stannite, tetr.; 2.3Mt Pb; 1.5Mt Zn, 800t Ag	Smirnov and Gorzhevsky (1974)

NOTE: North American fields Metaline, Leadville, Gilman,Tintic, Santa Eulalia, are treated in Table 20-8.

Virtually all the orebodies are distal with respect to intrusive plutons or stocks, but could be in immediate contact with minor porphyry dikes or sills (as in Leadville).

The orebodies are strongly structurally and lithologically controlled, and the most common alteration associated with the ore is pervasive or partial silicification resulting in jasperoid (metasomatic chert). When jasperoid is developed, the sulphides either occur as fine disseminations in jasperoid giving it a gray to black colour (e.g. in the Taylor ore field, Nevada), or they form rich, often coarse crystalline masses, outside the jasperoid on the site of replaced marble masses or as cavity fillings. Jasperoid and its characteristics have been treated in detail by Lovering (1972). In a later paper (Lovering and Heyl, 1974) the difference between a barren and mineralized jasperoid and application of jasperoid as a guide to concealed ore, have been discussed.

The characteristic shapes of Pb-Zn sulphide orebodies are peneconcordant sheets to lenses (mantos) controlled by lithology (stratigraphy) and also by bedding plane dilations and paleokarst; subvertical chimneys and pipes and a variety of mineralized breccias, veins and stockworks (Fig. 28-94). Until recently, it has been automatically assumed that all the carbonate-hosted orebodies are replacements, but this is no longer the only possible explanation. Callahan (1977) suggested that many of the well-known "mantos" in the western Cordillera are hydrothermally modified and reconstituted earlier deposits of the Mississipi Valley-"type". The most important piece of evidence applied by Callahan was the widespread presence of karst features such as open caves, solution collapse breccias, etc. at many localities, recorded in earlier publications (e.g. in Leadville, Tintic, Goodsprings). This genetic alternative together with some description and cross-sections of the example localities is treated in Section 20.10.1. and will not be repeated here. Even if the Zn-Pb ores were not earlier and were introduced by granite-related hydrotherms, they could have still precipitated in a paleokarst so this represents an important structural control.

The carbonate-hosted Zn-Pb orebodies may occur alone (no skarns present), or alternatively may coexist with skarns. In the latter case, skarns occur in closer proximity to the intrusion. Transitional orebodies between true skarns and carbonate replacements are also known. In the Bluebell mine, British Columbia (Ohmoto and Rye, 1970), coarsely crystalline pyrrhotite-marmatite rich massive to disseminated

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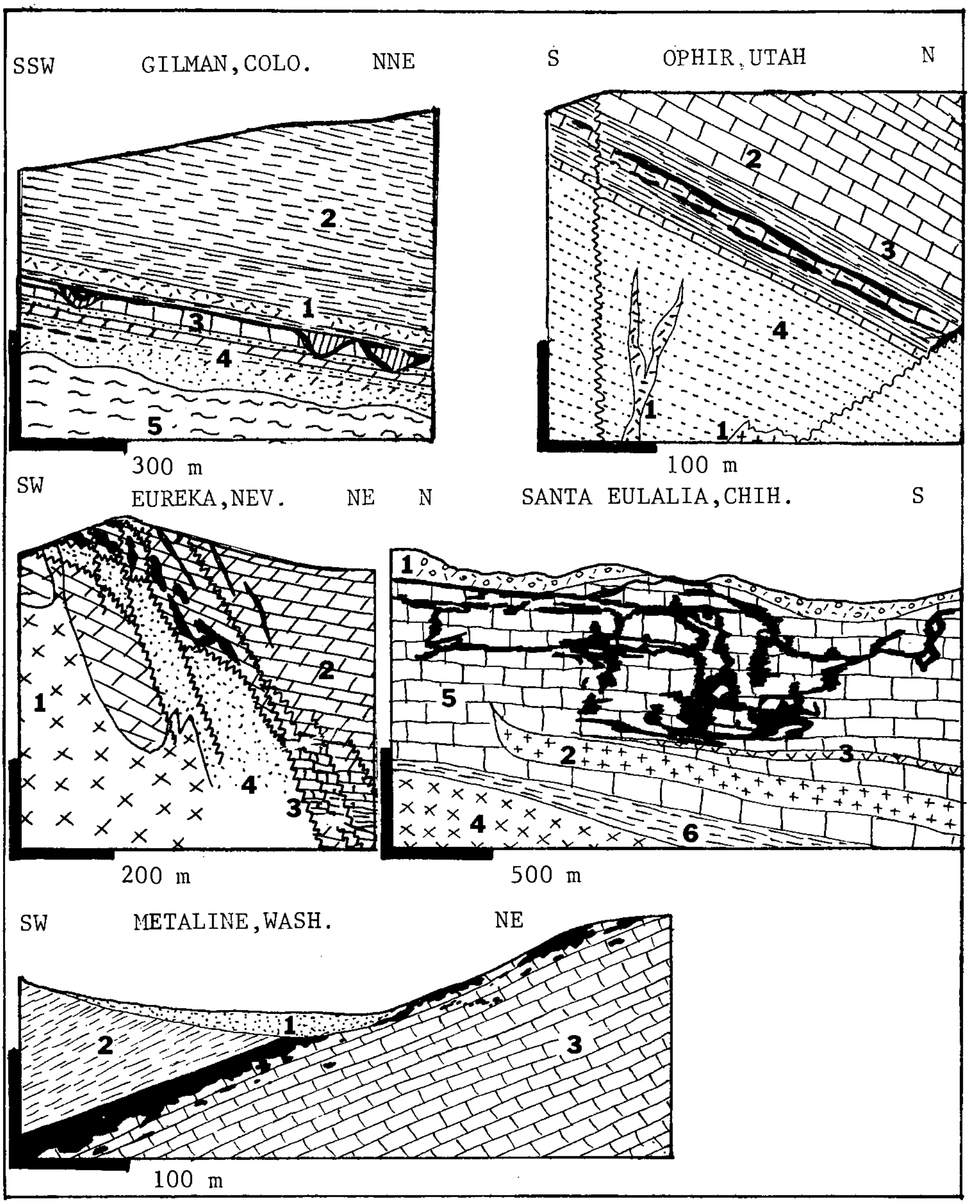
Fig. 28-94. Selected examples of Zn-Pb sulphide manto and chimney deposits in carbonates in granite aureoles.

Gilman: 1=Cr_3-T_1 quartz biotite porphyry; 2=Ps shale; 3=Ms_2 dolomitized limestone; 4=Cm_3-Ms_2 quartzite, sandstone, shale, dolomite; 5=Pt_2 metamorphics.

Ophir: 1=Ol rhyolite and quartz monzonite porphyry; 2=Cm_{2-3} limestone, dolomite; 3=Cm_1 hornfelsed shale, shaly limestone; 4=Cm_1 quartzite.



Eureka: 1=Cr_3 quartz diorite; 2=Cm_2 massive dolomite and limestone; 3=Cm_2 black limestone and shale; 4=Cm_1 quartzite.

St. Eulalia: 1=T,Q conglomerate, tuff, volcanic flows; 2=T_2 rhyolite, microgranite; 3=T_2 diabase, microdiorite; 4=granodiorite; 5=Cr thick-bedded limestone; 6=MZ carbonate evaporite association.

Metaline: 1=Q cover; 2=Cm slate and argillite; 3=Cm gray limestone.

From LITHOTHEQUE, after Radabaugh et al. (1968), Gilluly (1932), Nolan (1962), Hewitt (1943), Dings and Whitebread (1965).

sulphides replaced Cambrian limey to magnesian marble beds enveloped by metaquartzite and micaschist. Quartz, calcite and knebelite (Fe-Mn olivine) occur in the ore, and tremolite, diopside and talc have a patchy distribution in the marble and form beds of a calc-silicate hornfels.

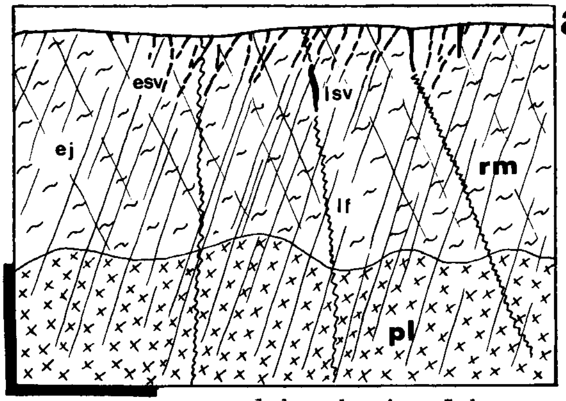
28.14.5. Examples of Pb-Zn(Ag) deposits and districts (Tables 28-19 to 22, Fig. 28-95)

FREIBERG, SAXONY (EAST GERMANY); A STRUCTURALLY CONTROLLED VEIN FIELD IN THE ROOF OF A BURIED PLUTON

Freiberg ore field, Erzgebirge (Baumann, 1976; Figs. 28-95 and 96) is hosted by monotonous and lithologically uniform biotite gneisses and migmatites. These metamorphics form a gentle dome, believed to be underlain in depth by a late Paleozoic granitic pluton. The field contains about 1100 discrete mineralized fissure veins, of which about 100 were productive. The bulk of the veins occur within a 5x12 km N.N.E.-trending belt situated approximately at the centre of the dome. The remainder are located in a less distinct E.-W. system along the dome fringe.

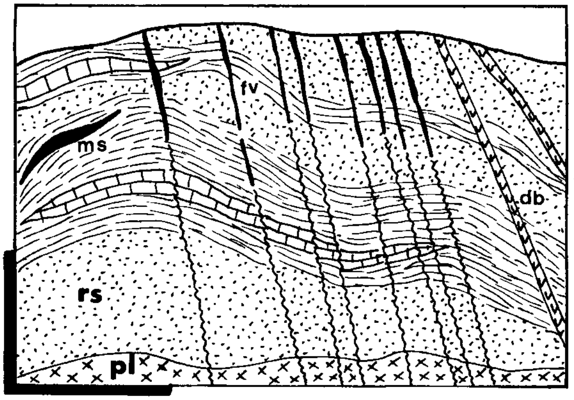
Baumann (1976) distinguished two types of fissures which he interpreted as shear joints and feather joints. The shear joints (fissures) have a great strike extension (up to 20 km) and dip vertically. Their width ranges up to 6m, and they are filled by breccia, rock powder and mylonite. The ore minerals they carry have often a form of impregnations. The feather joints trend N.W.-S.E., dip 30-70^{o} S.W., are shorter (average 2km), and filled by massive to banded ore veins.

The hydrothermal veins belong to two major depositional cycles: (1) Late Paleozoic (Permo-Carboniferous) post-magmatic cycle, associated with the "granite" and (2) Triassic to Tertiary cycle of a high-level "activation" (Fig. 28-97). Two major vein associations formed during the first cycle: (a) quartz, arsenopyrite, pyrite, sphalerite, galena and (b) siderite, pyrite, galena, freibergite, jamesonite, Ag-sulphosalts and native silver. The wallrock alteration was a comparatively light sericitization, silicification and carbonatization. The second cycle produced the following association: (c) fluorite-barite, hematite, lesser galena, sphalerite and marcasite; (d) cherty quartz, carbonate, skutterudite, niccolite, proustite, argyrodite and (e) quartz, hematite, Mn-oxides. The alteration was gentle bleaching, argillization and quartz impregnation. The zoning pattern is indistinct, expressed in terms of the maxima of metal concentration, from the centre outwards: ZnPb-PbAg-AgSb.



vert. 1 km, horiz. 5 km

a Mineralization in two regular systems of joints filled by early stage veins (esv) above buried granite (pl). Some veins were rejuvenated (lsv) along faults (lf). rm=roof metamorphics (Pt). Freiberg, Saxony, East Germany. Permo-Carboniferous and some Mesozoic Pb,Zn,Ag minor Cu,Sn ores.



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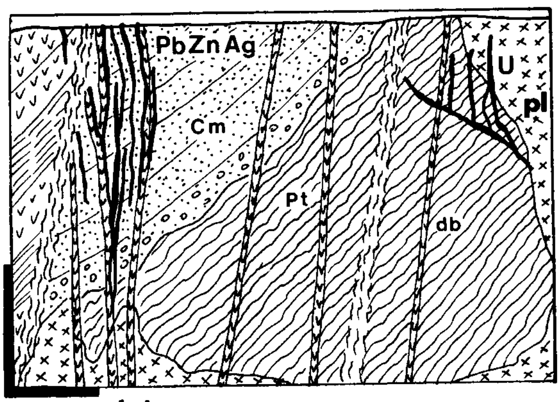
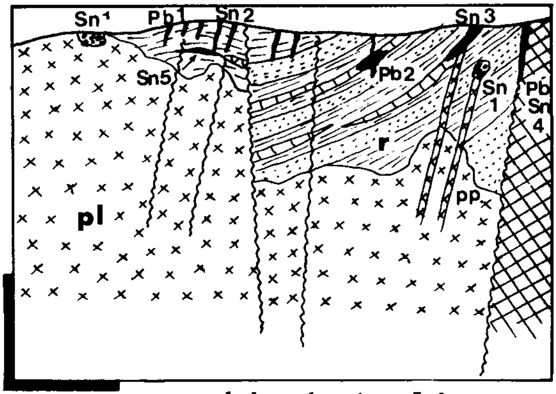
b Mineralization in fissure veins (fv) filling faults and fault zones in Cb_1 "graywacke" and slate. Stratiform massive sulphide orebody (ms; Rammelsberg) is in D_2 slates. db=diabase rs= D_1-Cb_1 roof sediments; pl=postulated buried pluton. Oberharz district, West Germany; Cb_{2-3} ores



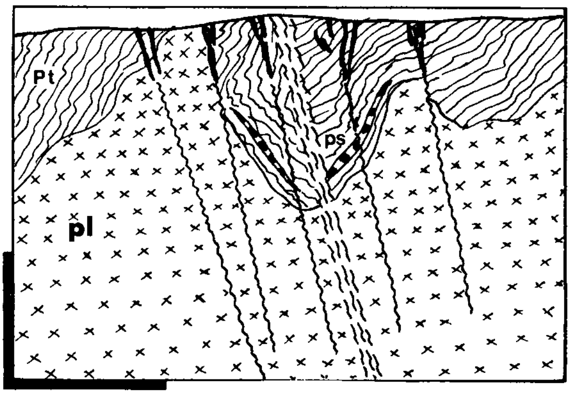
1 km

c Fissure Pb-Zn-Ag veins (on the left) are closely affiliated with diabase dikes along fissures, branching from a major N.E. fault. U veins (on right) with lesser Pb,Zn,Ag,Cu are along faults and shears near a plutonic (pl) margin. db=diabase. Příbram district, Czechoslovakia; Cb to MZ? ores



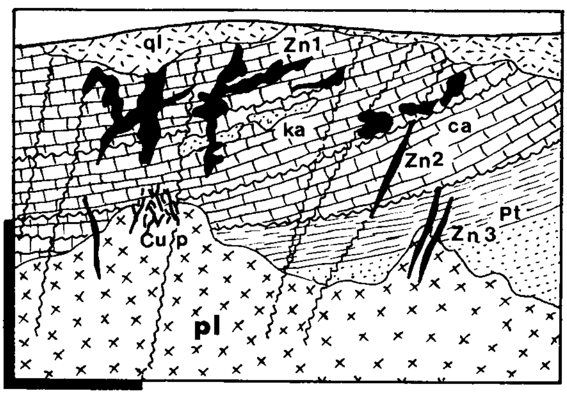
vert. 1 km, horiz. 5 km

d A variety of Pb-Zn-Ag (=Pb) and Sn ores hosted by Pt_3-D sediments and minor volcanics, intruded by D quartz monzonite and granite (pl), Zeehan-Renison Bell area, W.Tasmania. pp=porphyry r=roof rocks; op=ophiolite Pb 1=fissure veins; Pb 2= carbonate replacements; Sn 1=greisens; Sn 2=stannite veins; Sn 3-cassiterite-pyrrhotite replacements; PbSn 4=replacemens in altered ultramaf.



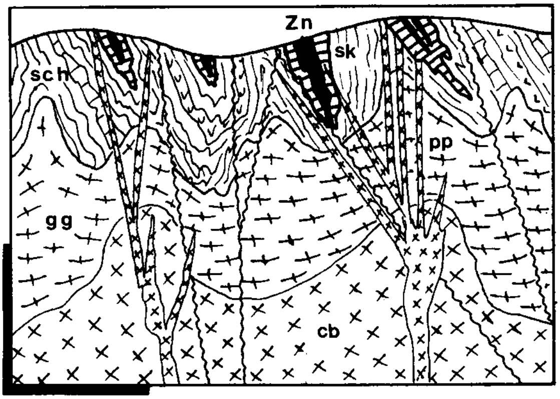
vert. 1 km, horiz. 5 km

e Galena-sphalerite and siderite-tetrahedrite replacement veins in bleached Pt_2 fine detrital sediments, along faults above Cr_3-T_1- pluton (pl). ps=concordant pyritic slate. Coeur d'Alene district, Idaho



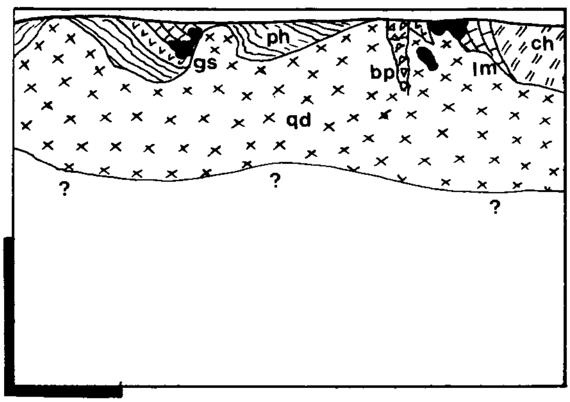
vert. 1 km, horiz. 2 km

f Zn-Pb replacement bodies in silicified (jasperoid) Cm-Cb carbonate (Zn 1); replacement veins (Zn 2); fissure veins in altered PCm basement (Zn 3); Cu p=porphyry Cu in Ol qtz. monzonite pluton (pl); ka=karst cavities,solution collapse breccias; ca=carbonate. Tintic district, Utah



vert. 1 km, horiz. 2 km

g Replacement sphalerite, galena, pyrrhotite, pyrite etc. masses in skarn (sk) in Pt_2-PZ high-grade metamorphics (sch) at and near contact with Cr porphyry dikes (pp) believed related to a cryptobatholith (cb). gg=J ? katazonal granite, granitization. Kamioka district, Honshu, Japan.



vert. 1 km, horiz. 2 km

h Zn-Cu, minor Pb, skarn orebodies at contact of Cb-Pe marbles (lm), members of phyllite (ph), greenstone (gs), chert (ch) association with Mi ? quartz diorite (qd). Chichibu Mine, Honshu, Japan.

Fig. 28-95. Diagrammatic representation of the major styles of postmagmatic Zn-Pb ore fields, genetically associated with buried and exposed granitic plutons. Not accurate in detail. The dimensions of important features (orebodies, fault zones) are exaggerated and telescoped. The approximate scale represents the overall dimension of the area considered only. From LITHOTHEQUE, based on references listed in the text and field reconnaisance.

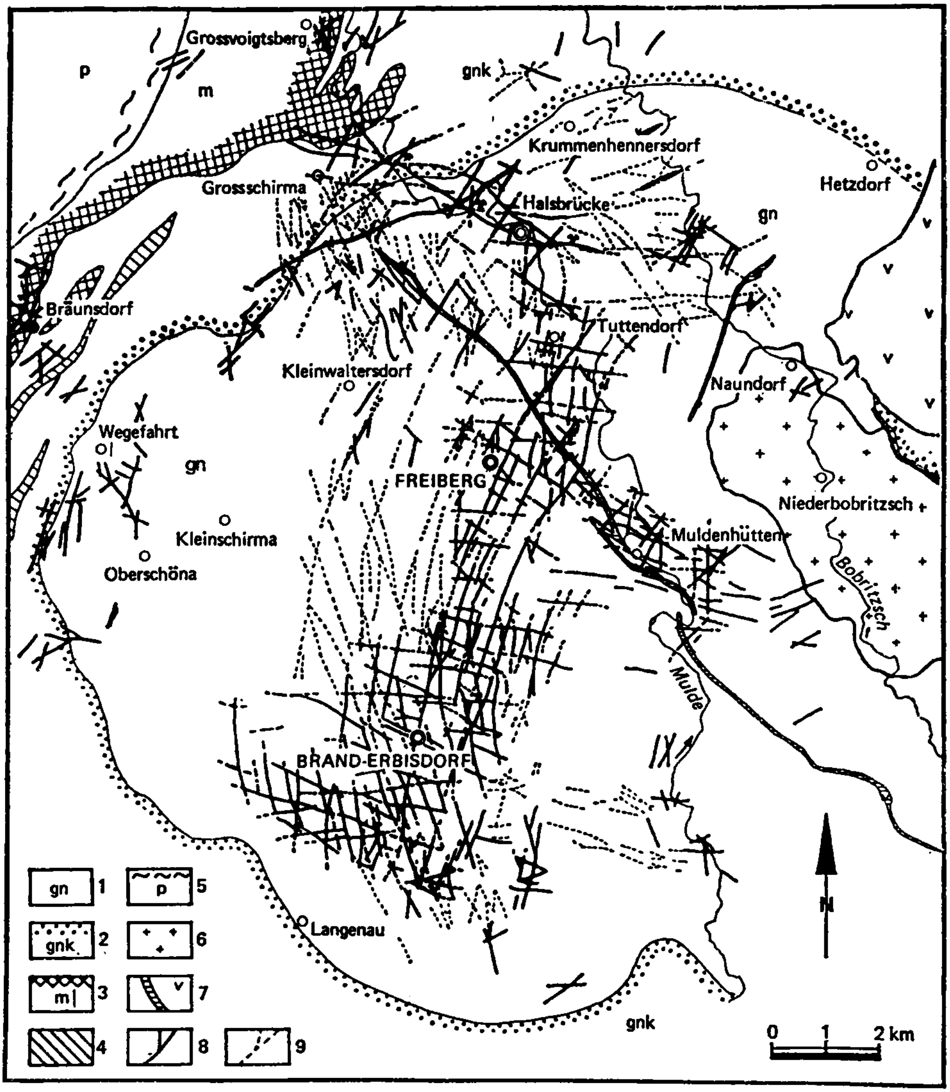


Fig. 28-96. Central part of the Freiberg (Erzgebirge) polymetallic vein ore district. 1=Biotite gneiss; 2=mica gneiss; 3=micaschist; 4=red gneiss; 5=phyllite; 6=PZ_3 granite; 7=porphyry; 8=ore veins; 9=tectonic structures. From Baumann (1976), courtesy of the Scottish Academic Press.

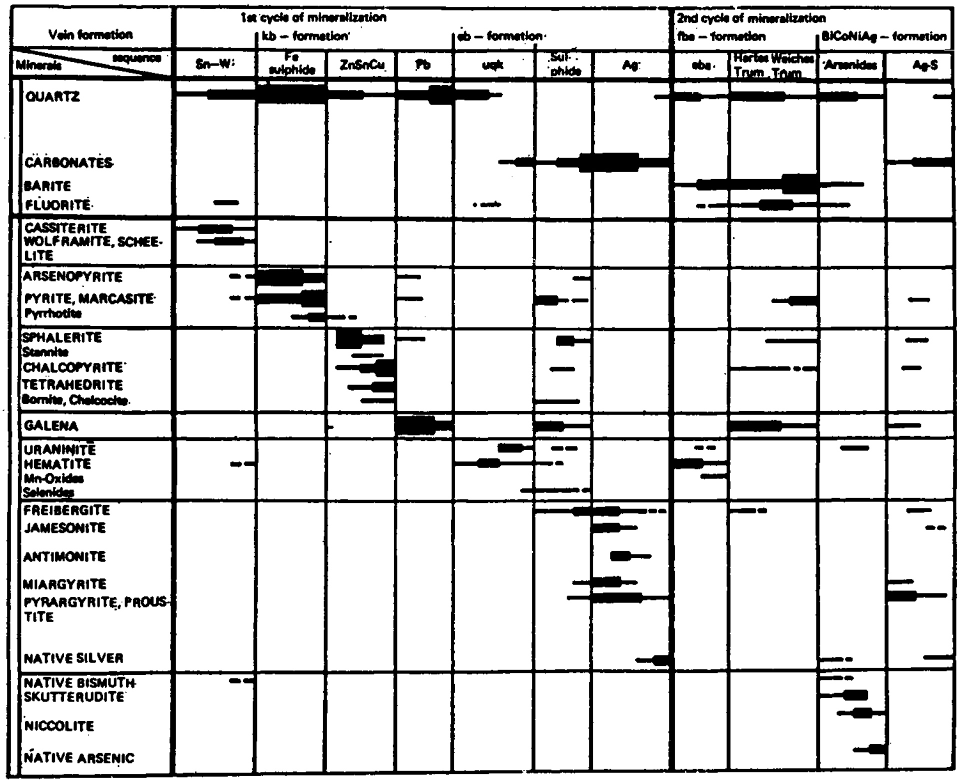


Fig. 28-97. Mineral associations and sequence of mineralization in the Freiberg (Erzgebirge) polymetallic ore veins. kb=pyritic sphalerite–galena association; eb=precious metals and siderite association; uqk=U, quartz, calcite association; eba=Fe-barite association; fba=fluorite-barite association. From Baumann (1976), courtesy of the Scottish Academic Press.

OBERHARZ DISTRICT, WEST GERMANY: A SYSTEM OF PERSISTENT, SUBPARALLEL MINERALIZED STRIKE-SLIP FAULTS (Fig. 28-95b)

Oberharz (Upper Harz, or Clausthal-Zellerfeld district) is a mineralized area, measuring 22x25 km in the northwestern extremity of the Harz Mountains (Buschendorf et al., 1971). This is part of the late Paleozoic foldbelt consisting of a sequence, several thousand metres thick, of Devonian marine sandstones, slates and minor limestones, unconformably topped by lower Carboniferous siliceous slate and quartz-rich litharenite interbedded with slate. The middle Devonian black slates contain the important stratabound massive sulphide deposit Rammelsberg near Goslar, described in Chapter 17. At the end of Devonian the supracrustal sequence was folded, faulted and intruded by a bimodal association of diabase and keratophyre.

In the upper Carboniferous period, the complex was intruded by granite, disrupted by a system of subparallel W.N.W.-trending strike-slip faults with a variable vertical downthrow component, and mineralized. The ore deposition took place in four or more phases of open space filling and intra-vein metasomatism. The vein structures are up to 20 km long and up to 50 m wide, filled by breccia, rock flour and gouge, but the economic ore was situated in more restricted sectors (up to 6 km long). Nine major fields exploiting one or more veins, have produced 1.8 Mt Pb, 700 Tt Zn, 4.7 Tt Ag and about 32 Tt Sb, till 1980.

The Grund field alone, producing from three vein structures, accounts for about one half of the production (Sperling, 1973; 950 Tt Pb, 400 Tt Zn, 2 Tt Ag). There, the ore shoots consisted of mineralized fault breccia, banded veins and linear fault zone stockworks. Quartz is the most common gangue, followed by siderite, calcite, barite. Sulphides are represented by several generations of sphalerite and galena, lesser bournonite, boulangerite, tetrahedrite and Ag-sulphosalts. The wallrock alteration is light: sericitization, local light silicification, ankerite or siderite impregnation or veining and bleaching.

COEUR D'ALENE DISTRICT, IDAHO: Pb,Zn,Ag REPLACEMENT VEINS WITH A 1.4 B.Y. HISTORY OF MINERALIZATION

Coeur d'Alene district (near Kellogg and Wallace, N.Idaho; Fryklund, 1964; Gott and Cathrall, 1980; Figs. 28-95e, 28-98) represents 6.9 Mt Pb, 3 Mt Zn, 140 Tt Cu, 31 Tt Ag and at least 70 Tt Sb in terms of metal quantities accumulated in its ores. The core of the district is a system of subparallel W.N.W.-trending "mineral belts", developed on both sides of the major Osburn Fault. The latter is a strike-slip and normal fault with a lateral displacement of up to 26 km and some 5,000 m of vertical offset. The district has approximate dimensions of 40x20 km and covers an area of 780 km^2. The bulk of orebodies are hosted by a sequence of monotonous middle Proterozoic marine detrital sediments (slate, argillite, siltstone, quartzite) at least 7,000 m thick, deposited on a stable continental margin basement ("miogeocline"), and later metamorphosed in the lower greenschist facies. The sediments have been strongly deformed during the "Laramide orogeny" and intruded by several small stocks and dikes of quartz monzonite, diabase and lamprophyre of Cretaceous to lower Tertiary age that may be a part of a larger buried pluton.

The eight or so Coeur d'Alene "ore belts" are W.N.W.-trending, south dipping second-order fault structures, parallel with the Osburn Fault. Both shears and tensional fractures are represented. The principal faults as well as branching third order fissures are mineralized. Most characteristic are the steeply dipping veins replacing fault gouge, mylonite and breccia. The veins tend to have been narrow at outcrop, but many widened with increasing depth. The productive veins shortly postdate emplacement of the "Laramide"

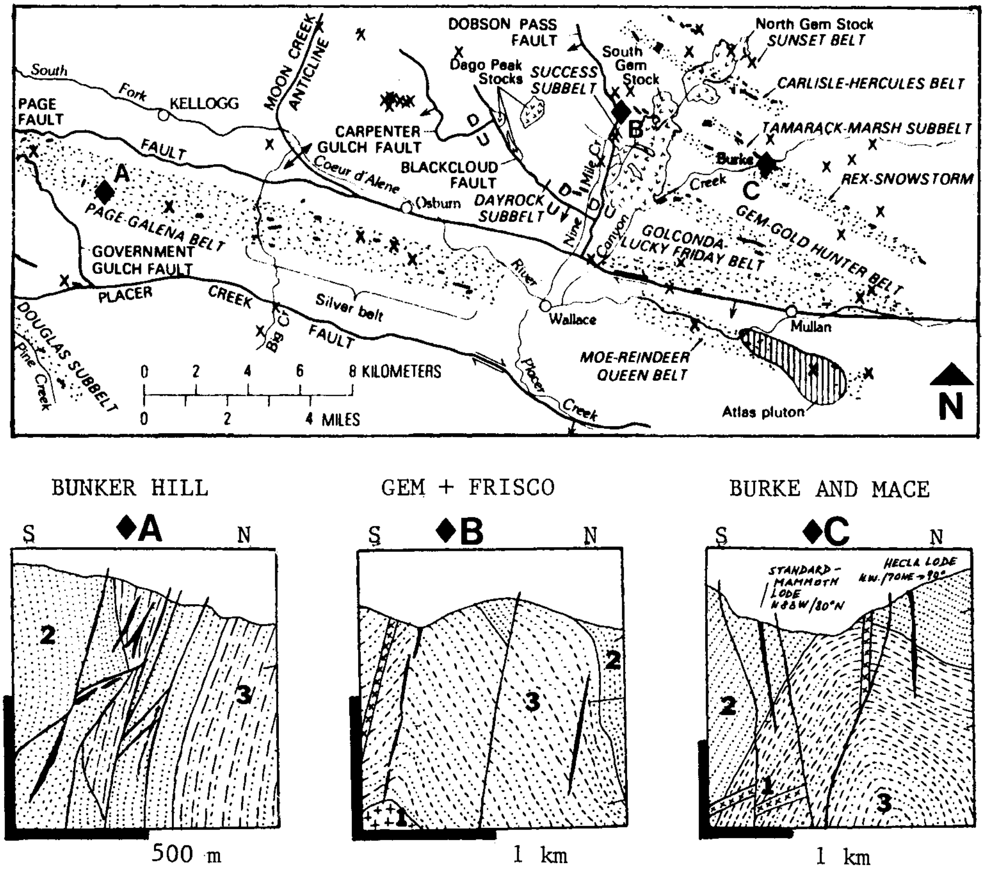


Fig. 28-98. Coeur d'Alene Pb,Zn,Ag district, Idaho. TOP: location map, from Gott and Cathrall (1980). BOTTOM: examples of deposits, from LITHOTHEQUE: 1=Cr_3-T_1 quartz monzonite; 2=Pt_{2-3} quartzite; 3=Pt_{2-3} argillite, siltite, quartzite interbeds.

intrusive stocks, and two mineral associations are of the greatest importance. These are as follows: (1) siderite, ankerite, galena, sphalerite with occasional biotite, garnet and grunerite gangue, and pyrrhotite, magnetite, tetrahedrite (e.g. the Bunker Hill mine) and (2) quartz, siderite, Ag-tetrahedrite veins (e.g. Sunshine, Galena mines).

The former are thick and account for all the lead and zinc produced plus some silver. The latter are thin, but they produced the bulk of the silver. Gold-quartz, stibnite and uraninite veins have been of little importance. The most widespread and conspicuous wallrock alteration in the district is a bleaching, ranging from slight sericitization to a mere pigment removal, as well as impregnation and thin veining of the wallrocks by siderite or ankerite. The bleaching is a consequence of the prevalent wallrock composition, that already includes a rock-forming sericite that remained stable in the presence of mineralizing fluids. In the few examples of "granite"-hosted veins, the alteration is a feldspar-destructive sericitization. There have been six dated periods of vein mineralization in the district, ranging from Precambrian (uraninite veins) to Tertiary.

Widespread occurrences of stratabound copper mineralization are known in the host sequence outside of the Coeur d'Alene district, and the basal sedimentary unit in the district (Prichard Formation) contains several horizons of pyritic phyllites and it correlates stratigraphically with the unit hosting the important Sullivan orebody, British Columbia (Volume 2). This, as well as the "ancient" isotopic lead composition and the low temperature of the ore fluids (130-175^{o} C) makes it tempting to assume some form of remobilization of metals initially brought in during the Proterozoic, by the "Laramide" intrusions.

ZEEHAN, TASMANIA; Pb-Zn-Ag VEINS IN THE ROOF OF A "TIN GRANITE"

Zeehan ore field is in western Tasmania and has dimensions of about 15x15 km (Blissett, 1962; 190 Tt Pb, 780 t Ag; Fig. 28-95d). There, block-faulted late Proterozoic and Cambrian quartzite, slate, siltstone and minor greenstone and Ordovician to Devonian sandstone, limestone and slate, are believed to be located in the roof of a Devonian (Mt. Heemskirk) granite pluton. About 30 fissure veins and an isolated carbonate replacement orebody formed along N.N.W. and N.N.E. faults. The veins carry relatively short (X0-330 m) and narrow but rich ore shoots composed of quartz-siderite or siderite and galena, brown sphalerite, pyrite, lesser chalcopyrite and tetrahedrite. A small replacement galena, pyrite and sphalerite orebody in Mn-siderite envelope is hosted by Ordovician limestone in the Oceana mine.

The Heemskirk Granite west of the Zeehan field contains small relics of cassiterite greisen and vein orebodies. Near Zeehan, in the granite roof, tin accumulated in the Stannite Lode, a thin quartz-pyrite fissure vein containing scattered stannite, arsenopyrite, minor cassiterite, tetrahedrite, molybdenite, bismuthinite and galena. The calculated content of metals in this vein was 775 t Sn, 941 t Cu and 60 t Bi, although not all these metals have actually been produced. In the same group of mines, several overlapping thick lenses of pyrite closely associated with greenstones (meta-spilite) contained 0.3-0.4% Sn, mostly in the form of dispersed cassiterite. About 1 Mt of 1% Sn ore has recently been discovered in the vicinity. The Renison Bell replacement tin deposit in carbonates (Section 28.8.4.) is located about 8 km N.E. from the margin of the Zeehan field, probably above a buried Devonian granite cupola.

TINTIC ORE FIELD, UTAH; CARBONATE REPLACEMENTS IN THE AUREOLE OF AN INTRUSIVE STOCK WITHIN AN ERODED PALEOVOLCANO.

Tintic (Morris, 1968; Morris and Lovering, 1979; 1.01 Mt Pb, 167 Tt Zn, 127 Tt Cu, 8.3 Tt Ag, 82.5 t Au; Fig. 28-95f) is in a north-trending fault block range near the eastern margin of the Great Basin, central Utah. The host rocks range from Precambrian quartzite and argillite through a 3.3 km thick section of Cambrian to Carboniferous sediments, over 60% of which are limestone and dolomite. The remainder consists of quartzite and sandstone. The sediments have been extensively thrust-faulted during the late Cretaceous period, and carried eastward for as much as 160 km. The thrusts were subsequently folded and faulted. During the Oligocene period, a composite volcano including a caldera stage, buried the sedimentary range under a thick pile of latite ash flow tuffs, flows and agglomerates.

Several quartz monzonite stocks, plugs and dikes intruded the sediments and a portion of the volcanic pile. A widespread hydrothermal activity followed emplacement of the Silver City quartz monzonite. The earliest, pre-intrusion solutions converted many faulted limestone bodies to hydrothermal dolomite and caused chloritization and propylitization of the volcanics. This may have produced numerous cavity openings ("hydrothermal karst"), although the possibility of an earlier karst complete with Mississippi Valley-"type" Zn-Pb deposits was considered by Callahan (1977).

The early postmagmatic solutions were acidic, and they caused widespread advanced argillic alteration of silicate rocks along the faults. Slightly later fluids caused widespread pyritization, sericitization and silicification (jasperoid) in the carbonates. Metallic mineralization was associated with the latest, potassic alteration in the alumosilicate rocks (adularia, zunyite) and Mn introduction into the carbonates.

Over 90% of the metals produced came from large, irregular orebodies that have replaced the Paleozoic carbonates along faults above the quartz monzonite stocks and breccia pipes. The replacement bodies are composed of a cherty jasperoid containing barite, rhodochrosite, and scattered to massive sphalerite, galena, pyrite, lesser enargite and argentite. Economically the most important are large columnar masses (chimneys), followed by mantos and a variety of irregular bodies. Replacement veins in carbonates and fissure veins in the alumosilicate rocks are rare. The existence of a porphyry copper mineralization in one of the intrusive stocks has recently been revealed at some depth.

The Pb-Zn-Ag ores resulted from solutions that rose from numerous centres in the field, and spread in a manner resembling the trunk of a tree. The orebodies at higher elevations branch and divide, extending along bedding faults. In the downward direction, several of the "ore trunks" terminate in breccia masses, invaded by intrusive plugs and dikes.

CERRO DE PASCO, PERU; MASSIVE PYRITE, Zn,Pb,Cu REPLACEMENT IN CARBONATES ALONG A MARGIN OF A MIOCENE VENT

Cerro de Pasco is a giant deposit located in the metalliferous belt of central Peru (Einaudi, 1977; 100 Mt pyrite, 7 Mt Zn, 3 Mt Pb, 1.5 Mt As, 48 Tt Ag; see Fig. 17-7). It is hosted by an upper Triassic-lower Jurassic limestone and dolomite with interbeds of siliceous shale, unconformably resting on Devonian black phyllites. These sediments were block faulted and intruded by a Miocene (14.4 m.y.) vent facies breccia-conglomerate, followed by quartz monzonite porphyry dikes (14.2 m.y.). The dikes probably make contact with a buried intrusive stock. A large, N.-S. elongated funnel-shaped orebody, 1,800 x 300 m long, composed of almost massive pyrite mixed with chert, chalcedony and quartz, formed by replacement of Mesozoic limestone and minor Tertiary volcanics along a margin of the Cerro vent.

Einaudi (1977) interpreted the massive sulphide body as being an initially pyrrhotite, marmatite, arsenopyrite mass, altered by late fluids to pyrite-marcasite and FeS-poor sphalerite. The silicification and pyrite deposition in carbonates was contemporary with quartz-sericite, pyrite alteration of quartz monzonite and the volcanics. The sulphide mass is mineralogically zoned and the greatest accumulation of sphalerite and galena is on the fringe and above massive pyrrhotite pipes. The massive sulphide deposition was followed by a second stage of hydrothermal deposition, that produced quartz, sericite, pyrite, enargite and luzonite veins fringed by quartz-sericite alteration envelopes. Late-stage, low temperature hydrothermal leaching resulted in the formation of collapse breccias and the open spaces were mineralized by pyrite, hematite, gratonite, baumhauerite, aramayite, argentite, freibergite and light (low Fe) sphalerite and galena. This assemblage contains silver bonanza orebodies. Supergene secondary enrichment generated mantos of chalcocite-covellite, and a silver-rich limonitic gossan.

Trepča (Stari Trg) deposit near Kosovska Mitrovica, (Janković, 1982) is the largest Pb-Zn deposit of Yugoslavia (3 Mt Pb, 2 Mt Zn, 5 Tt Ag) and is somewhat reminescent of Cerro de Pasco in terms of association with a breccia-filled vent. The orebodies are irregular to pipe-shaped, coarse sphalerite, galena, pyrite, pyrrhotite, lesser chalcopyrite, magnetite and arsenopyrite masses. They replace Ordovician to Silurian limestone marble and an earlier hedenbergite, andradite, ilvaite, epidote, etc. skarn. The orebodies are situated immediately at the contact of a Miocene breccia pipe and dacite-granodiorite plug, or along a limestone-phyllite contact. The pipe fill is intensively silicified, sericitized, pyritized and carbonatized, and hosts minor occurrences of chalcopyrite, enargite and arsenopyrite.

CHICHIBU MINE, JAPAN: Zn,Cu,Fe SKARN IN A MAFIC VOLCANICS-CARBONATE ASSOCIATION

Deeper marine basalt (spilite), shale, litharenite, chert, limestone and often keratophyre association and its mineralization have been treated in Chapters 10 and 12. There, stratabound iron deposits (magnetite, hematite, siderite), Mn carbonates and Fe,Cu,Zn massive sulphides, constituted the distinct mineralization styles. When similar associations containing abundant limestone was later intruded by "granitic" plutons, skarn and carbonate replacement orebodies formed. Postmagmatic, "granite"-related ore-bearing complexes often display a remarkable degree of metallogenic heritage with respect to their supracrustal hosts (e.g. coexistence of Fe, Zn-Cu and Mn orebodies), the causes of which range from direct, in-situ remobilization of the earlier volcanic-sedimentary orebodies, to proximal mobilization of anomalous metal contents from the supracrustal unit.

The Chichibu ore field in central Honshu, Japan (Miyazawa, 1970; 4.7 Mt ore with 35.5% Fe, 1.12 % Zn, 0.19 % Cu, 0.07% Pb; Fig. 28-95h) is located in a Permo-Carboniferous suite of litharenite, slate, chert, lesser limestone, varicoloured tuff ("Schallstein") and metabasalt flows. These rocks have been intruded by a Miocene quartz diorite pluton and by quartz-porphyry dikes. All the supracrustals in the contact aureole have been extensively hornfelsed and a two-stage skarn (1: garnet-hedenbergite; 2: idocrase, wollastonite, ilvaite) formed along carbonate contacts. Tourmalinization, axinite alteration and silicification followed by sericitization and propylitization are widespread. About 12 small orebodies are located along the quartz diorite-carbonate contact, and they consist of an earlier pyrite, pyrrhotite, magnetite and chalcopyrite masses in skarn, and superimposed pyrite, sphalerite, galena, chalcopyrite, stibnite, bismuthinite and gold fillings in brecciated skarn and also as limestone replacements outside the skarn limit. The Mn ores are represented by rhodochrosite, Mn-ankerite and Mn-siderite replacing limestone, and by secondary oxides.

KAMIOKA, JAPAN: Zn-Pb SKARN IN A PRECAMBRIAN HIGH-GRADE METAMORPHIC TERRAIN, RELATED TO GRANITE PORPHYRY DIKES AND A PROBABLE CRYPTOBATHOLITH

The Kamioka ore field (Nishiwaki et al., 1970; 4.44 Mt Zn, 624 Tt Pb, 2,707 t Ag; Fig. 28-95g) is the largest zinc producer in Japan. About 100 small to medium-sized orebodies are hosted by hedenbergite, lesser epidote, garnet, actinolite, diopside and ilvaite skarn, and also by marble, in three major clusters. The ore field, about 8x4 km in cross-section, is situated in the crystalline Hida Block, composed of a lower Proterozoic core of tonalitic gneiss, migmatite and marble, with infolded Permo-Carboniferous mafic metavolcanics (now amphibolites), metacherts (quartzites) and metagabbros. The foliation strikes N.N.W., but turns almost 300° to N.N.E. owing to a composite anticline.

The metamorphics have been intruded and partly granitized by a foliated katazonal granite, probably dating from the Jurassic period and an augen gneiss. Following a rapid uplift and high-level open faulting in Cretaceous or Tertiary, quartz porphyry and granite porphyry dikes and small stocks probably related to a cryptobatholith penetrated along faults and produced skarn metasomatism in the marble. The skarn forms numerous horizons interfoliated with the alumosilicate rocks, and adjacent horizons often coalesce along anticlinal and synclinal axes and along drag folds. About 10% of the skarns carry ore, in the form of scattered sulphide and magnetite grains grading to almost massive pods. Much of the skarn contains relic graphite, recovered as a by-product. The porphyry dikes contain widespread scattered molybdenite flakes, and small localized stockworks. There is a strong possibility that there exists a Mo-stockwork mineralized cupola under the present ore field.

28.15. HYDROTHERMAL-PLUTONIC SILVER DEPOSITS

In plutonic association, silver deposits are substantially less conspicuous as a class than the epithermal "bonanza" Ag(Au) veins in the subvolcanic setting, treated in Chapter 26. The following styles of silver mineralizations can be recognized:

(1) Epithermal argentite, silver, Ag-sulphosalts identical with those described in Section 26.6.1., but hosted by the "basement rocks" (including older "granites") with few continental volcanics penecontemporary with the mineralization in evidence (e.g. Austin, Nevada; Fig. 28-99).

(2) Epithermal enargite-luzonite or tennantite-tetrahedrite veins hosted by the "basement" rocks (Cerro de Pasco, partly Butte).

(3) Ag-tetrahedrite (freibergite) veins, fracture stockworks and carbonate replacements in non-volcanic areas (e.g. Sunshine and Galena mines, Coeur d'Alene, Fig. 28-100).

(4) Silver-rich tops of Pb-Zn vein or replacement systems formed by supergene enrichment or a late-stage hydrothermal leaching and precipitation (e.g. Chañarcillo, Fig. 28-101).

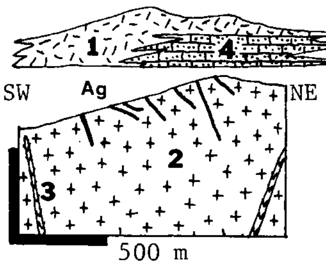
(5) Silver-rich "Main Stage" and "Late Stage" veins or shoots in essentially Pb-Zn fields (Příbram, Kutná Hora, Czechoslovakia; Freiberg, Erzgebirge; Keno Hill, Yukon; Beaverlodge and Silbak Premier mine near Stewart, British Columbia, Fig. 28-102).

(6) Silver-only (no base metals) low-temperature veins, stockworks, replacements; Batopilas, Mexico, partly St. Andreasberg, Harz Mts.

(7) Disseminated ("porphyry") silver deposits, e.g. Rochester, Nevada, Fig. 28-103; partly Hahns Peak, Colorado.

(8) Ag,Co,Ni,Bi,U,As association veins (treated separately in Section 28.16.).

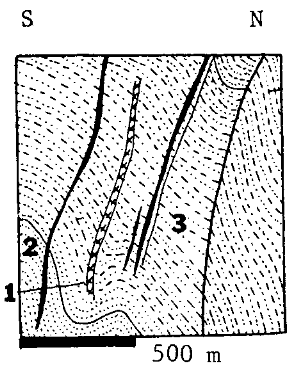
An ore deposit has to contain a substantial amount of silver minerals undiluted by substantial amounts of base metal sulphides, or



(top out of scale)

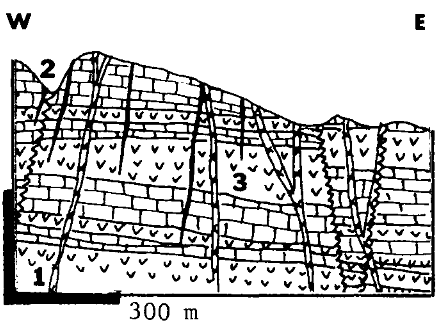
1. T, felsic lavas and pyroclastics
2. J ? quartz monzonite
3. J-T lamprophyre, aplite, pegmatite dikes
4. Cm? carbonatic arenite to sandy limestone

Fig. 28-99. Austin (Reese River) Ag vein field. Diagrammatic, from LITHOTHEQUE.



1. T_1 diabase and diorite dikes
2. Pt_{2-3} meta-quartzite
3. thin-bedded quartzite gradational into and interbedded with argillite, siltite and dolomitic, calcitic quartzite

Fig. 28-100. Sunshine Ag mine, Big Creek, Coeur d'Alene district, Idaho. From LITHOTHEQUE, based on data in Fryklund (1964).



1. Cr_{1-2} (100 m.y.) granodiorite and diorite stocks and dikes
2. Cr_1 black, gray and white limestone, minor hornfelsed shale
3. Cr_3 andesite to keratophyre pyroclastics

Fig. 28-101. Chañarcillo Ag field, Atacama, Chile. From LITHOTHEQUE, after Whitehead (1919).

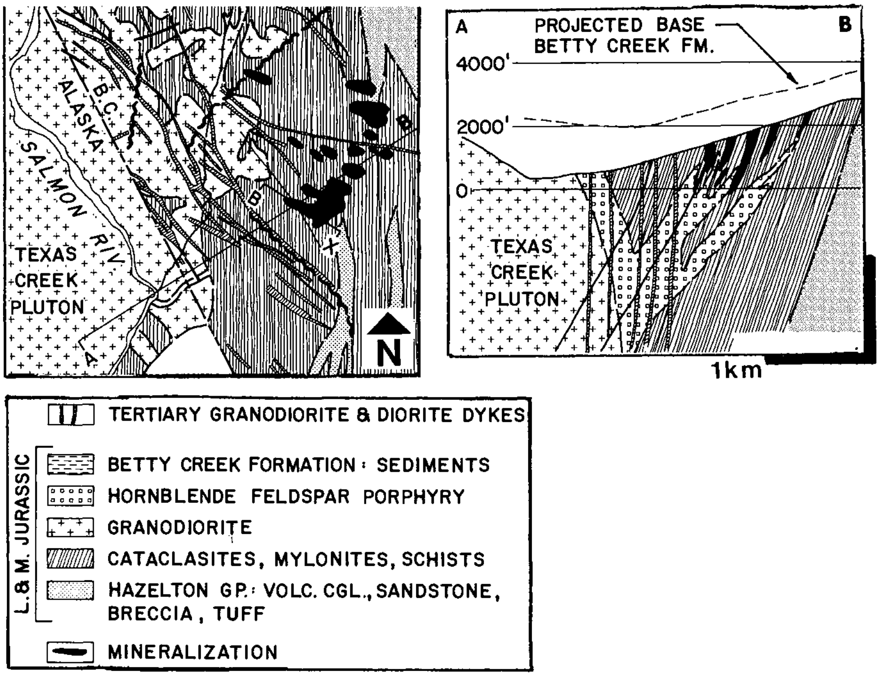


Fig. 28-102. Silbak Premier Au-Ag mine near Stewart, N.W. British Columbia. From Barr (1980), courtesy of the Canadian Institute of Mining and Metallurgy and the author.

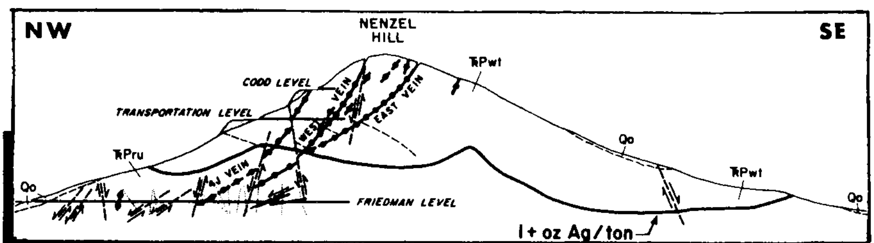


Fig. 28-103. Low-grade disseminated Ag mineralization, Rochester field, Nevada. Qo=Q alluvium; TrPwt=Tr-Pe rhyolite ash-flow tuffs and volcaniclastic rocks; TrPwf=rhyolite flows; TrPru=rhyolite flows and tuffs, undivided. From Vikre (1981), courtesy of Economic Geology.

must grade about 280 ppm Ag (=10 oz/t) or more, to qualify as a silver deposit. Many silver deposits of the above listed styles have been reviewed already in other sections, so selected examples only are considered briefly below.

Chañarcillo, 50 km S. of Copiapó, central Chile (Whitehead, 1919), produced 2,300 t of silver from a 40-150 m thick zone of supergene sulphide enrichment (argentite, native silver, dyscrasite, stephanite, amalgam), topped by a mineralized oxidation zone (cerargyrite, iodobromite, bromyrite, embolite, iodyrite). The hypogene ore is situated in a system of nearly vertical, parallel N. to N.E.-trending fracture or replacement veins containing only a low-grade, scattered galena, sphalerite, pyrite, chalcopyrite, proustite and pyrargyrite in calcite and barite gangue. The veins are located in a zone of facies transition between lower Cretaceous marine black limestone and partly continental andesite tuff, intruded by 100 m.y. old granodiorite and diorite stocks and dikes.

Austin, Nevada (Ross, 1953) had about 100 narrow, discontinuous N20-40°W striking, east-dipping fracture and shear veins, and minor silicified (replacement) ribs, hosted by a quartz monzonite massif (? mesozonal pluton) of probably Jurassic age. Quartz and pyrite are the most common vein minerals, and rhodochrosite, sericite, calcite, dolomite, galena, sphalerite, tetrahedrite, argentite, pyrargyrite, stephanite and polybasite are rare. Quartz, sericite and pyrite alteration is limited to the immediate vicinity of the veins. Most of the past production (600 t Ag, 540 t Pb, 60 t Cu, 0.5 t Au) came from proustite and tetrahedrite-rich shoots. The ores have epithermal characteristics and are probably related to high-level Tertiary intrusions, rather than to the postmagmatic phase of the host "granite".

Nenzel Hill, Rochester field, Nevada. This is a large, low-grade ("bulk") disseminated Ag(Au) deposit, described by Vikre (1981; Fig. 28-103) and estimated to contain about 100 Mt of 28 to 57 ppm Ag ore. It is hosted by Permo-Triassic rhyolite flows, ash-flow tuffs and volcaniclastics intruded by quartz monzonite to granodiorite stocks, related to the upper Cretaceous fringe of the Sierra Nevada Batholith. The intrusive exocontact is intensively quartz, sericite, pyrite or tourmaline altered, and there are sectors with dumortierite-andalusite (advanced argillic) alteration. The mineralization is located in a few quartz, K-feldspar, sericite, pyrite, sphalerite, Ag-tetrahedrite, stromeyerite, pyrargyrite, etc. higher grade and persistent veins mined in the past, as well as in thin stockwork veinlets of similar composition, in wallrock pyrite and in supergene "limonite". The latter is estimated to contain 80% of the available reserves.

St. Andreasberg, Oberharz, Germany. This is an ancient deposit (Schneiderhöhn, 1941; 313 t Ag) hosted by lower Carboniferous "graywacke" and siliceous slate, unconformably resting on Devonian slate, black slate, metabasalt and carbonate. The deposit lies in a contact aureole of a Permo-Carboniferous "granite". The ore veins fill N.W. or E.-W. fissures. They are under 1 m thick, and are filled by gray calcite with fine disseminated sulphides, arsenides and native elements (stibnite, breithauptite, arsenic, antimony, niccolite, smaltite, löllingite, sphalerite, galena). Three superimposed mineralization phases produced drusy, coarse crystalline aggregate of quartz, fluorite, Ag-tetrahedrite, chalcopyrite, galena, sphalerite, millerite, native silver, Ag-sulphosalts, realgar and crystallized zeolites. The wallrock alteration is very light (chloritization, calcite impregnations).

Batopilas (Chihuahua, Mexico; Wisser, 1966; 1.550 t Ag) has calcite, quartz, barite, arsenopyrite, sphalerite, galena, native silver, Ag-sulphosalts, safflorite and rammelsbergite veins, hosted by a fine-grained Tertiary diorite and quartz porphyry dikes, intruding andesitic volcanic breccias and flows. The veins were under 50 cm thick, close to the basement and low in base metal sulphides and in gold.

28.16. THE Ni,Co,Bi,Ag,U,(As) ASSOCIATION

The "Five Elements" association accumulated in hydrothermal veins has been popular mostly with the German-language geologists (e.g. Schneiderhöhn, 1941 and earlier works of the Freiberg Mining Academy Staff), because of its numerous classical occurrences in the Erzgebirge Mts. Close to fifty Phanerozoic localities of this association are now known worldwide, and it is estimated that they account for about 10 Tt Ag, 50 Tt Ni, 70 Tt Co, 3 Tt Bi and 50-100 Tt U. These ores have always been a genetic enigma, particularly because they bring together metals that possess a contrasting geochemical and environmental affiliation like the basaltophile and ultramafics-related Ni and Co, and granitophile U. Alternatively, all five metals plus As could conceivably accumulate together in certain marine sediments e.g. black shales and phosphorites. The fahlbånds (metalliferous schists) near Schladming, Austria, contain stratabound and remobilized niccolite, glaucodote, smaltite, bismuth, arsenic, Ag-tetrahedrite, etc. More examples are known in the Precambrian terrains (Cobalt, Ontario; Modum, Norway; Volume 2).

The known Ni,Co,Bi,Ag,U,As occurrences and incomplete, related metal combinations (e.g. Co-As, Ni-As, Co-Ni-As, U-Ag, etc.), although locally unique, appear to be variations on a theme. All are low-temperature, multistage mineralizations having a carbonate (calcite, dolomite), jasper, chalcedonic quartz, fluorite or barite gangue. All occur in block-faulted terrains, and the faults are high-level, filled by graphite-rich gangue, mylonite or breccia. The host terrains are invariably marked by an early stage of development involving mafic marine volcanics, black metalliferous pelites, minor carbonates, ultramafics, gabbros, and diabase dikes. This was followed, usually after a considerable time gap, by emplacement of "granites". The "granites" are of several age generations and include synorogenic tonalites and post-orogenic granodiorites to biotite granites. Skarns are frequently present. Although the "Five Element" veins usually occur in "granite" aureoles, they tend to be substantially younger than the hydrothermal phase of the "visible" granites, and usually superimposed. In Freiberg (Baumann, 1976) and Jáchymov (Chrt and Bolduan, 1966), the "Five Element" veins are Mesozoic to Tertiary, in contrast to the spatially associated late Paleozoic Pb-Zn and Sn postmagmatic veins and granite cupola stockworks. Post-granite diabase, lamprophyre or porphyry dikes often overlap with the Ni,Co,Bi,U,Ag veins.

The Jáchymov-Abertamy ore field on the Czech side of the Erzgebirge (Mrňa and Pavlů, 1967; Figs. 28-104, 105) is a historically important locality quite apart from its geological importance. Formerly known under the German name Joachimsthal, it was the home town of Georg Bauer (Agricola), craddle of the dollar (the local 16th century coinage was known as "Joachimsthaller", abbreviated to thaller, taller, dollar) and the first known uranium deposit of the world, in whose ores uranium was first discovered by Klaproth and Ra and Po by the Curies. The field started as a medieval silver-mining camp and subsequently passed through Co (for porcelain paints), Ra and U mining stages. The metal quantities in about fifty veins located within an area of 12x6 km are estimated to have been between 30-50 Tt U, about 2 Tt Ag, 5 Tt Co and 300 t Bi. 240 grams of Ra was recovered in the pre-war period.

The ore field is located in a Cambro-Ordovician micaschist-dominated series with interbeds of graphitic schist, metachert, metacarbonate, acid and mafic volcanics, situated in the roof of a Permo-Carboniferous granitic pluton. The bedrock is intersected by a system of N.W. and E.-W. faults, many of which are followed by granite porphyry and lamprophyre dikes. Erosional remnants of late Tertiary continental basalts and their feeder dikes are preserved over less than 10% of the area.

Postmagmatic mineralization along granite contacts and in their thermal aureole is represented by several swarms of quartz, cassiterite, wolframite veins and greisens, outside the limits of the Jáchymov-Abertamy field. Several bodies of magnetite, sphalerite, pyrite, chalcopyrite mineralized skarns are known within the field. The numerous post-granite hydrothermal ore veins are located in portions of gouge-filled E.-W., N.-S., and N.W. fractures. The veins are up to 1 km long, up to 1 m wide, and congregate in six clusters ("ore knots") separated by barren ground. Ore shoots are most common at fault intersections, and have often the form of columns composed of en-echelon ore lenses. The ore and gangue lenses are often separated from the wallrocks by altered fault clay, and in many cases the fault gouge is dispersed in the vein filling. The wallrock alteration ranges from silicification and sericitization around veins filled by the early quartz-sulphide stage to chloritization, argillization, hematitization and pyritization.

The hydrothermal ores are the result of six mineralization stages, from oldest to youngest: (1) quartz, arsenopyrite, pyrite, galena, sphalerite, chalcopyrite; (2) quartz-hematite; (3) dolomite, pitchblende, lesser pyrite, fluorite; (4) quartz, silver, skutterudite, rammelsbergite, niccolite, safflorite, bismuth;

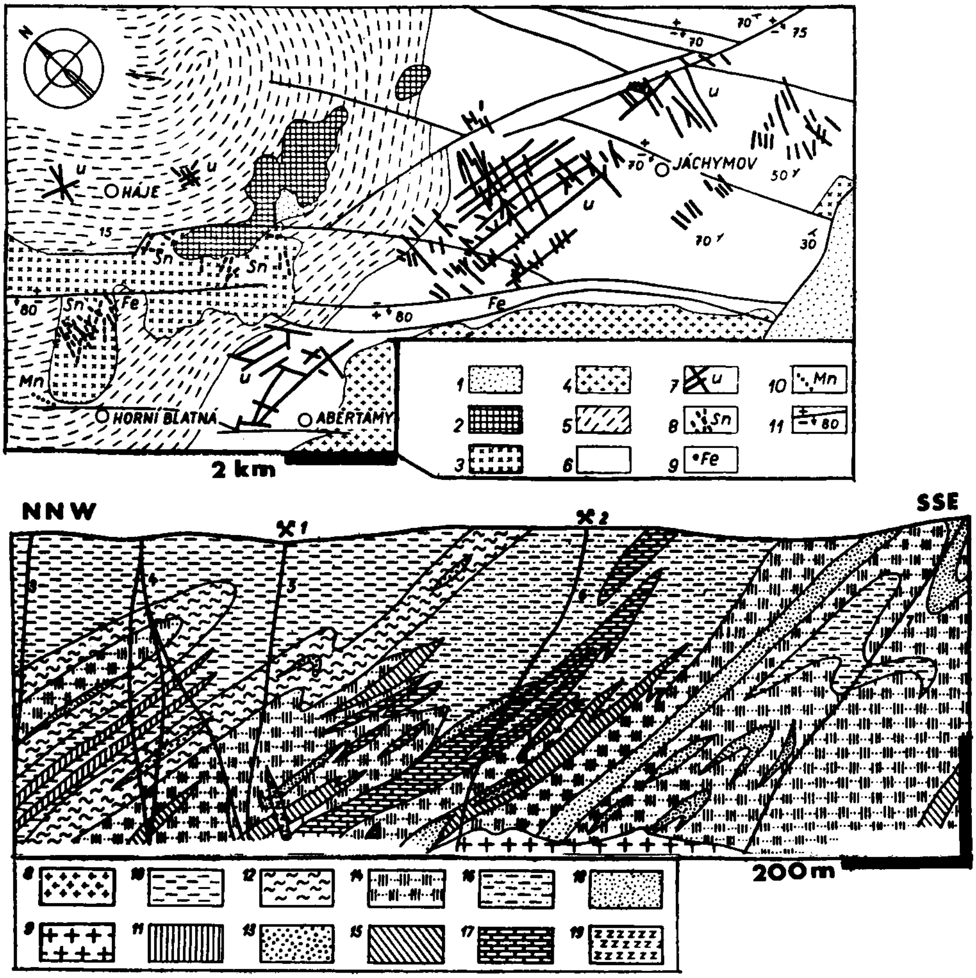


Fig. 28-104. Jáchymov-Abertamy U and Ag,Ni,Co,Bi vein field, N.W. Czechoslovakia (top) and a section through the Svornost (Einigkeit) mine in Jáchymov. After Mrňa from Mrňa and Pavlů (1967) and Mrňa (1963), courtesy Ústřední Ústav Geologický, Praha. Map legend: 1=Q,T sediments; 2=T plateau basalts; 3=Cb-Pe porphyritic granite (older mesozonal phase); 4=Pe epizonal leucogranite; 5=PZ_1 phyllites; 6=PZ_1 micaschists; 7=veins of Ag,Bi,Co,Ni,U association; 8=greisens with cassiterite; 9=quartz hematite veins; 10=Mn oxide veins; 11=fault zones. Section legend: 1=Svornost mine; 2=Josef mine; 3=Dorotea vein; 4=T basalt; 5=Kraví vein; 6=Geier vein; 7=Šindler vein; 8=granite porphyry; 9=granite. 10=PZ_1 (top unit) biotite-muscovite schist; 11=biotite schist; 12=PZ_1 (middle unit) biotite-muscovite schist; 13=biotite schist; 14=PZ_1 or Pt_3 (lowest unit) biotite muscovite schist; 15=biotite schist; 16=phyllite and micaschist; 17=calc-silicate hornfels; 18=metaquartzite; 19=lamprophyres.

Fig. 28-105. Jáchymov (formerly Joachimsthal), "the town that gave you the dollar" (and also U,Ra,Po isolated for the first time from its pitchblende). City centre with the shaft Svornost on the right.

(5) dolomite, arsenic, proustite, argentite, sternbergite, stephanite and (6) calcite, pyrite, galena, sphalerite, chalcopyrite, realgar. Brecciation and intravein metasomatism are widespread.

Jáchymov-style Ni,Co,Bi,Ag,U,As veins having a comparable geological as well as cultural history, have been mined at numerous localities on both the Czech (Potůčky, Přísečnice, Vejprty, Horní Slavkov) and East German (Schneeberg, Marienberg, Johanngeorgenstadt, Oberschlemma, Annaberg, Buchholz, Aue, Freiberg) sides of the Erzgebirge and Slavkovský Les. Similar deposits are known in the Příbram district in central Bohemia, in the Czech and Polish Sudeten (Kowary, Zálesí), in the Schwarzwald, Germany (Wittichen), in the French Alps (Chalanches), Pyrenees (Gistain), New Mexico (Black Hawk) and elsewhere.

The Khovu-Aksy field in the Tuva region, S. Siberia (U.S.S.R., close to the Mongolia border; Krutov, 1974) has Co-Ni arsenide veins superimposed on skarn and is reportedly a site of a large mining-metallurgical complex. The ore field has dimensions of about

4x2 km and is located in a geologically extremely complex block situated in a zone of deep N.-S. faults. The stratigraphically lowest units are lower Cambrian marine basalts, andesites, limestones and dolomites, intruded by plagiogranites and ophiolitic ultramafics. This is topped by Silurian to Devonian conglomerates, sandstones, siltstones and limestones. A 4 km long horizon of Silurian carbonate is almost completely converted into skarn in the exocontact of a lower Devonian granitic pluton.

The Co,Ni,Bi,Cu (and possibly U) orebodies are almost entirely contained in a series of N. and N.E.-trending fissure veins, superimposed on skarn and on Silurian siltstone. The veins are several hundred metres long and composed of chalcopyrite, smaltite-chloanthite, safflorite, lesser niccolite, rammelsbergite, löllingite, bismuth and emplectite in dolomite, ankerite and chlorite gangue. Most of the veins are compositionally banded, and chloritization is a common wallrock alteration.

Other localities with Ni-Co arsenides

Smaltite, chloanthite, cobaltite, gersdorffite, rammelsbergite and similar arsenides are present in small quantities in at least 100 hydrothermal vein and replacement deposits, worldwide. They are relatively most common in siderite orebodies and in the past, small quantities of Ni-Co concentrates have been produced as a by-product of siderite benefecation. The Siegerland siderite district of West Germany and the Spiš-Gemer area of Slovakia, were the best known producers. A small siderite-gersdorffite deposit near Dobšiná (Dobschau), Slovakia, yielded about 1,000 t Ni.

28.17. GOLD DEPOSITS

28.17.1. GENERAL

Many (perhaps 40-50%) of the postmagmatic hydrothermal deposits treated earlier (e.g. porphyry coppers, Pb-Zn veins) contain small quantities of gold, which is recovered as a by-product. Such deposits may grade into mineralizations in which the Au:base metal ratio (expressed in units of metal value, not in weight units !) is about one. Ultimately they may grade into deposits in which gold is the dominant or the only commodity recovered. "Gold deposits" thus cannot be differentiated sharply and in this section we concentrate on ores in which gold is the dominant commodity under an average economic climate.

Gold is frequently and characteristically associated spatially with "granitic" plutons, but this does not automatically guarantee a direct genetic connection. Its setting is a most elusive one. Of all metals, gold has the broadest range of intrusive rock types with which it is (presumably) genetically associated, and the broadest range of possible host rocks. Almost all alteration assemblages have been found at least once with gold. Gold accumulations have the greatest vertical range of formation and occurrence of all metalliferous deposits ranging from the deep katazone to the subvolcanic and even volcanic level and, curiously, at least one style of a significant gold accumulation can be distinguished at either level. The old prospector's adage "gold is where you find it" perhaps best expresses the heterogeneous nature of gold metallogeny and furnishes a plausible excuse for the lack of universal workable models of field gold association. "You could write books about gold deposits alone", a colleague remarked, and this is precisely what Boyle (1979) and before him Emmons (1937) and other writers have done. The reader is advised to consult the above compilations and the original literature for detail. The material in this section is just a brief summary.

Gold deposits spatially associated with Phanerozoic granitic plutons represent some 12,000 t Au and this includes placer gold presumably derived from corresponding bedrock sources. This figure overlaps with those given for "interaction gold" in some earlier chapters. In the Sierra Nevada Foothills, for example, gold is associated with both the characteristic slate-greenstone suite and tonalite-granodiorite intrusions, and the share of either association on the gold accumulation cannot be accurately expressed quantitatively.

Hydrothermal gold deposits can be classified and subdivided in many ways and the classical way based on the presumed temperature of hydrothermal solutions and mineral association (e.g. Schneiderhöhn, 1955; Bateman, 1951; Park and McDiarmid, 1975) is probably the most popular (at least in university courses). It is, however, one not particularly suitable for exploration and one that is outright misleading and contradicts the research results from the past twenty years (e.g. some greenstone-hosted peneconcordant deposits now interpreted as reconstituted hydrothermal sediments or metamorphogenic mobilizates, are placed into the "hypothermal" class. Here the temperature is the temperature of metamorphism, not precipitation from freely moving postmagmatic fluids). Simple substitute classification, however, does not exist. One can distinguish a variety of gold orebodies identical to orebodies of the metals treated so far (disseminations or stockworks, veins, carbonate replacements, etc.). One can subdivide gold deposits on mineralogical grounds (there is a two end-member sequence between Au hosted by entirely sulphide carriers and free Au only in quartz; Table 28-23 lists sample mineralogical associations of plutonic gold deposits). One can arrange gold deposits by membership in the regional "metal belts"; Table 28-24) and one can arrange gold deposits by lithologic associations as has been done in this book. The brief treatment of gold deposits in this section is arranged by mineralization styles within and outside a plutonic aureole, regardless of the supracrustal rock association.

In each association, gold in ore can be present as free-milling, visible or invisible, or as a gold in the lattice of sulphides (mainly arsenopyrite and pyrite). The latter is more expensive to extract. The gold bullion has a variable purity, ranging from about 995 (per mil) to around 500.

Table 28-23. Sample mineral associations of hydrothermal gold deposits associated with Phanerozoic granitic plutons

quartz, lesser pyrite, chalcopyrite, pyrargyrite, gold (Balei, epithermal)
quartz, stibnite, lesser siderite, pyrite, sphalerite, gold (Zlatá Idka, Slovakia)
quartz, carbonates, pyrite, lesser galena, sphalerite, chalcopyrite, tennantite, pitchblende (Central City, Colorado)
quartz, ankerite, calcite, lesser pyrite, arsenopyrite, galena, sphalerite, chalcopyrite, gold (Grass Valley, California)
quartz, ankerite, fluorite, lesser galena, sphalerite, gold tellurides, gold (Jamestown, Colorado)
quartz, tourmaline, pyrite, lesser chalcopyrite, arsenopyrite, freibergite (Klyuchi, East Transbaikalia)
quartz, pyrite, arsenopyrite, scheelite, bismuthinite (Au is located in pyrite and arsenopyrite); Zarmitan, Uzbekistan
quartz, calcite, lesser pyrite, arsenopyrite, pyrrhotite, scheelite, chalcopyrite, gold (Jílové, Czechoslovakia)
quartz, ankerite, calcite, albite, lesser arsenopyrite, pyrite, pyrrhotite, gold (Bendigo, Victoria)
quartz, carbonate, pyrite, lesser arsenopyrite, galena, sphalerite, stibnite, gold (Ballarat, Victoria)
pyrite, chalcopyrite, pyrrhotite, lesser quartz, calcite, gold (Rossland, British Columbia)
pyrrhotite, pyrite, chalcopyrite, molybdenite, bismuth, tetradymite, Au tellurides (Ol'khovo, Sayan Range, Siberia)

Table 28-24. Hydrothermal-plutonic gold deposits arranged by association with "belts" and "provinces" of other metals, sometimes resulting in mixed provinces (e.g. Au-Sn; Au-Mo; etc.)

Pb,Zn,Ag	Colorado Front Ranges, e.g. Georgetown, Silver Plume, Breckenridge; quartz, carbonate, pyrite, galena, sphalerite, arsenopyrite, gold veins
Mo	E. Transbaikalia Au-Mo belt, e.g. Klyuchi, Darasun; quartz, tourmaline, pyrite, molybdenite, sulphides, gold stockworks and veins
Cu	porphyry copper fields with zonally associated gold-quartz veins; e.g. Panguna, Bougainville; Almalyk, Uzbekistan
Sb	auriferous quartz, stibnite, pyrite, arsenopyrite veins; La Lucette, France; Milešov, Magurka, Dúbrava, Czechoslovakia
W (scheelite)	quartz, scheelite, gold veins, e.g. Moose River, Nova Scotia; Zarmitan, Uzbekistan
Sn	Yana-Kolyma belt, Siberia; gold-quartz lodes overlap with quartz-cassiterite veins and greisens
Hg	complex quartz, carbonate, tetrahedrite, amalgams, gold veins; Los Mantos mine, Punitaquí, Chile
Ag	common epithermal, less common plutonic association

28.17.2. Disseminated and stockwork gold in granitic stocks and breccia pipes or dikes

This ore style is most common in Tertiary volcanic or subvolcanic settings (Chapter 26) and also in the Precambrian greenstone belts (Volume 2). Boyle (1979) mentioned only two Phanerozoic plutonic-associated deposits. More localities, however, are known and with the increasing gold price and application of new techniques of low-grade gold extraction (e.g. in-situ and heap leaching), interest in low-grade "disseminated" gold deposits increases.

The small gold stockwork in quartz monzonite at the Jessie Mine, Colorado (2 t Au) has already been described briefly (Section 28.2.2.). In the Central City gold vein field in the same region, a large pipe-like stockwork ("The Patch"; Sims, Drake and Tooker, 1963) composed of quartz, pyrite, sphalerite, chalcopyrite, tennantite, galena and gold filling thin fracture veinlets, is located in a pyrite-sericite-altered quartz monzonite.

The Klyuchi deposit (East Transbaikalia Au-Mo belt, U.S.S.R.; Borodaevskaya and Rozhkov, 1974) is a network (stockwork) of auriferous veinlets and larger veins in Jurassic granite and granodiorite porphyry. The host high-level intrusion is emplaced into Paleozoic granite gneisses. The veinlet composition is quartz, tourmaline, pyrite, chalcopyrite, arsenopyrite, freibergite, and other minerals. Gold is located mostly in pyrite, and the wallrocks are intensively sericite altered. The large, low-grade Kidston deposit in northern Queensland, Australia (20 Mt ore with 2.5 ppm Au=50 t Au) is similar.

In the Permian Zarmitan granosyenite intrusive complex, Uzbekistan (Garkovets et al., 1979), gold is situated in quartz, pyrite, arsenopyrite, scheelite, bismuthinite veins and stockworks. Most of the gold is carried by pyrite and arsenopyrite, and the stockwork is located in a zone of pervasive microcline and albite metasomatism.

28.17.3. Gold vein fields around small central hypabyssal intrusions

Gold deposits equivalent in overall geometry to the granite cupola-controlled Sn deposits or Mo-mineralized intrusive stocks, are relatively rare. The high-level Darasun field in the East Transbaikalia Au-Mo belt, is an example (Borodaevskaya and Rozhkov, 1974; min. 90 t Au). This deposit is located within a Paleozoic crystalline basement (gabbro, amphibolite, intruded by late Paleozoic granodiorite, granite and syenite), block-faulted and activated in the Mesozoic. The gold is to be found in about 200 thin but persistent N.E. and N.W.-trending fissure veins, hosted by gabbros and other Paleozoic rocks in the exocontact of a small middle-upper Jurassic plagiogranite stock and intrusive breccia. The veins are filled by quartz, carbonate, tourmaline, chlorite, sericite, pyrite, arsenopyrite, sphalerite, galena, tetrahedrite, Pb-sulphoantimonides, bismuthinite, Au-tellurides, etc. The wallrock alteration is quartz-sericite and propylitic and there is a distinct metal and mineral zoning apparent on the surface as a series of overlapping concentric zones (from centre outward the series runs as follows: quartz-tourmaline, pyrite-arsenopyrite, galena-sphalerite, chalcopyrite-bournonite, sulphoantimonides).

In the Jamestown ore field near Boulder in the Colorado Mineral Belt (Lovering and Goddard, 1950; 29 t Au, 235 t Ag), swarms of mineralized fissure veins surround an almost circular small stock of Oligocene sodic granite (1 km in diameter). The host rocks to the veins are a small pluton of lower Tertiary granodiorite and a Proterozoic granite. Gold occurs in two types of veins: (1) quartz, fluorite, gold tellurides, gold and (2) pyrite, chalcopyrite, fine gold.

The Central City field in the same belt (Sims, Drake and Tooker, 1963; 116.4 t Au; Fig. 28-106) contains over a hundred veins. The bedrock is a Proterozoic crystalline terrain composed of biotite gneiss, migmatite and pegmatite intruded by many small dikes and irregular high-level plutons of an early Tertiary intrusive suite. The latter includes granodiorite, quartz monzonite and bostonite porphyries. Abundant, closely spaced intersecting faults produce a meshlike network. The veins are largely fault fillings and range from simple, tabular bodies to complex branching lodes in subparallel fractures. Most veins are 0.3-1 m wide, filled by quartz and chert with minor carbonate, fluorite and barite.

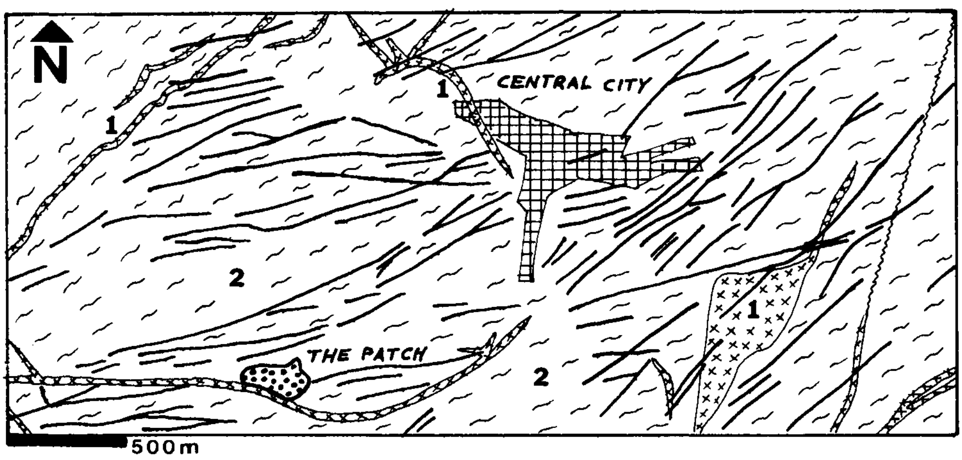


Fig. 28-106. Central City field, Rocky Mountains, Colorado, Au(Pb-Zn,U) veins. 1=T_1 granodiorite, quartz monzonite, granosyenite, bostonite, trachyte dikes and stocks; 2=Pt_{1-2} biotite sillimanite gneiss, migmatite. From LITHOTHEQUE, after Sims, Drake and Tooker (1963).

Pyrite is the dominant metallic mineral, and there are variable quantities of galena, sphalerite, chalcopyrite, tennantite, enargite and pitchblende. Gold occurs as free metal, or in pyrite. Wallrocks adjacent to the veins are usually sericitized, and sericitization is succeeded outward by argillization. A faint mineralogical zoning in the district is represented by the dominance of pyritic veins in the core, surrounded by a peripheral zone rich in galena and sphalerite.

28.17.4. Gold veins in and around moderately eroded mesozonal plutons

It has frequently been observed that gold-quartz veins of simple mineralogy often occur in moderately to deeply eroded "granitic" (mostly quartz diorite to granodiorite) plutons, in a setting in which other metals (except scheelite skarns) rarely accumulate. In the classical model of the 1930s, such veins were placed into the hypothermal or katathermal categories but more recent studies (e.g. Coveney, 1981) have demonstrated that the filling temperature range of similar veins was much broader (from about 200° to 491° C).

Grass Valley-Nevada City gold field, California (Johnston, 1940; Albers, 1981; 330 t Au/7-14 ppm, 90 t Ag; Fig. 28-107) is a classical locality now exhausted (but one mine has been preserved as a state park). This field is in the N.W. extension of the Mother Lode Belt, hosted by and probably associated genetically with a Mesozoic granodiorite pluton emplaced in late Paleozoic and Mesozoic slate, litharenite, greenstone and serpentinite terrain. The gold-bearing veins form a conjugate N. and N.W.-striking system. The veins in granodiorite have gentle dips (aver. 35°), those in the supracrustals as a rule are steep. The veins fill both normal and reverse faults and fissures, marked by shattered wallrock. Quartz is the principal vein mineral, associated with carbonates (ankerite, calcite) and pyrite, arsenopyrite, lesser sphalerite, chalcopyrite, galena and gold.

Gold deposition was contemporary with galena, and both minerals are closely associated. The veins were remarkably persistent and no change in mineralogy was observed over a vertical interval of more than 1,300 m. The wallrocks are strongly altered. Sericite, pyrite and ankerite alteration assemblage adjacent to veins grades away into propylitization (chlorite-epidote). Aplite, porphyry and lamprophyre dikes, both pre-ore and post-ore, are widespread in the field.

Deposits very similar in style and environment to those in Grass Valley include the Stepnyak field in northern Kazakhstan (gold-quartz veins in a diorite pluton, intruded into mafic volcanic meta-arenites); Dorozhnyi in the Yana-Kolyma belt; Milešov-Krásná Hora, Czechoslovakia; Bralorne, British Columbia; Segovia (Antioquía, Colombia) and others (Table 28-25).

The important <u>Kochkar ore field</u> in the S.E. Urals, U.S.S.R. (Magak'yan, 1968; min. 120 t Au; Fig. 28-108) is in a large Carboniferous plagiogranite pluton, emplaced in a lower Devonian to middle Carboniferous greenstone (mafic volcanic-sedimentary) suite.

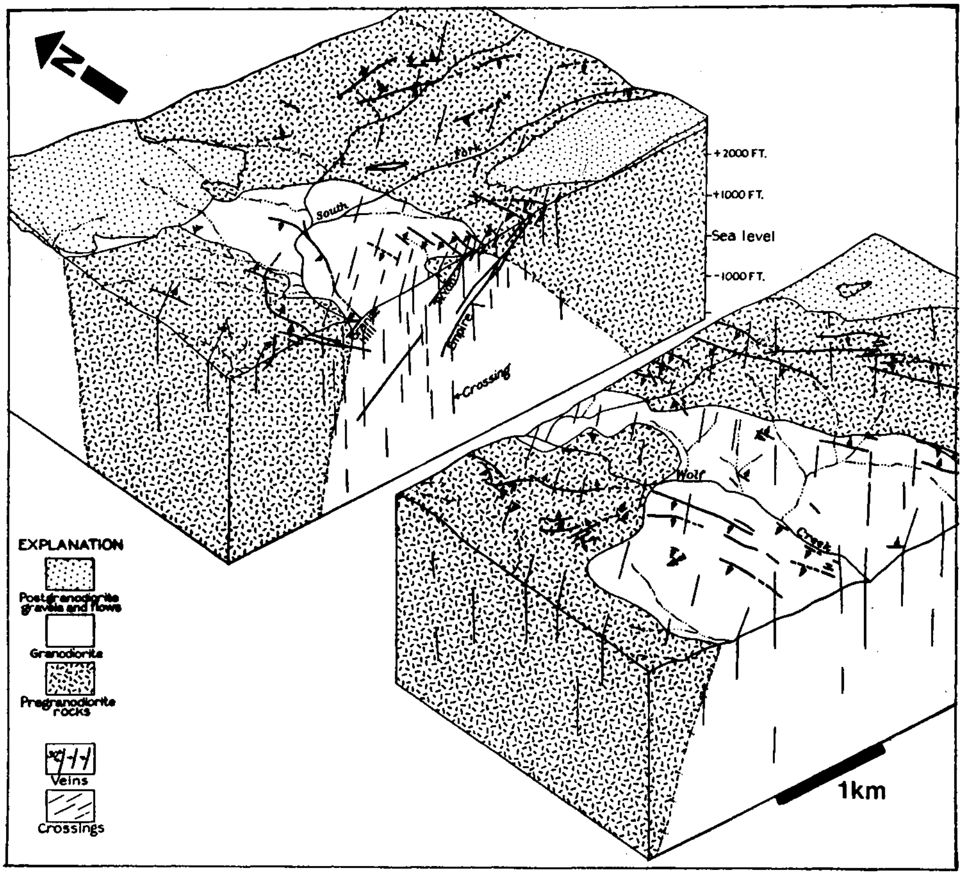


Fig. 28-107. Gold quartz veins in the Grass Valley, Nevada City field, California. From Johnston (1940).

A younger intrusive phase of microcline granite (quartz monzonite) is believed affiliated with the gold mineralization. The field contains over 1,500 veins (200 of them economic) in the microcline granite exocontact, that are controlled by two conjugate systems of E.N.E. shear fractures. The bulk of the ore veins are hosted by carbonatized dikes of diorite, diorite porphyry, plagiogranite porphyry, syenite porphyry, felsite and diabase. The ore veins are 0.4 to 2 m wide and tens to hundreds of metres long. The filling is quartz, lesser tourmaline, ankerite, calcite, pyrite, galena, chalcopyrite, tetradymite. The gold occurs in both free milling form and bound in pyrite and arsenopyrite. Portion of it is contained in tellurides. The gold bullion contains up to 10% Pt.

Rossland ore field, British Columbia (Barr, 1980; 80.1 t Au/13.35 ppm, 106 t Ag/17 ppm, 62 Tt Cu/1%) is an example of sulphide-gold

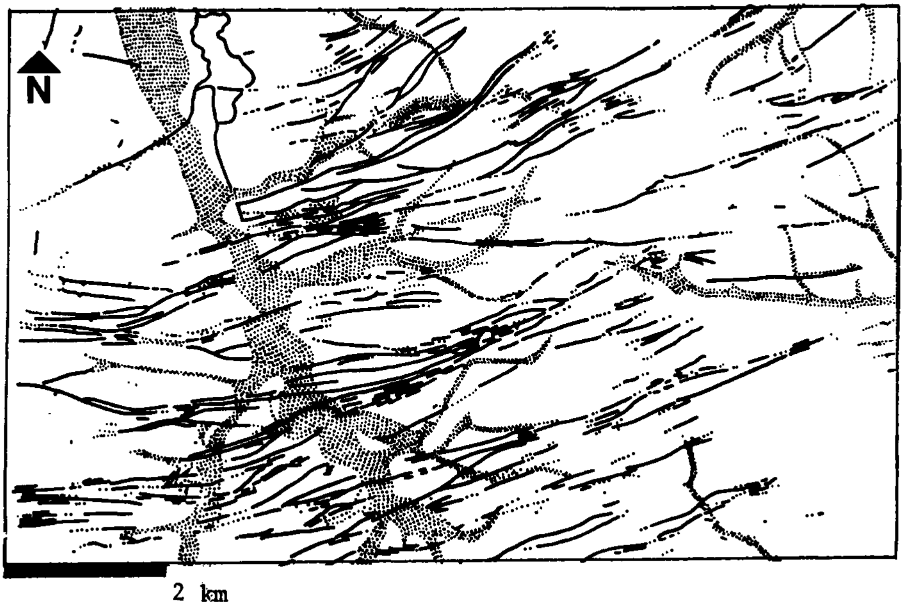


Fig. 28-108. A portion of the Kochkar goldfield, the Urals, U.S.S.R. Black area: Au-bearing veins; stippled: Q valley sediments, containing alluvial placers; blank: Cb_1 plagiogranite massif intersected by E.N.E. altered dikes. From Magak'yan (1968).

veins within and along the contact of an eroded intrusive pluton. The basement is formed by Carboniferous siltstone, sandstone, conglomerate and minor limestone, topped by Jurassic intermediate to mafic volcanic pile composed of andesite volcanic breccia, ash-flow tuff, augite porphyrite and volcaniclastics. The supracrustal rocks were intruded by several plutons and stocks between the Jurassic and lower Tertiary periods , and the intrusive rocks range from quartz diorite through monzonite, granodiorite, granite to syenite. The Rossland orebodies cross the intrusive contact between the monzonite and augite porphyrite, and are believed to be related genetically to a minor stock of Eocene (48 m.y.) quartz diorite and a swarm of diorite porphyry and lamprophyre dikes.

The ore veins are controlled by E.N.E. and S.E. sets of fractures and ore shoots in the veins commonly terminate against the northerly set of dikes. Although the vein zones extend for 1.3 km or more, the ore shoots are short and narrow and composed of almost massive pyrrhotite, chalcopyrite, lesser pyrite and native gold. The vein width is very variable, ranging from several centimetres up to 43 m, and it would be tempting to assume remobilization of an earlier volcanogenic or subvolcanic relic mineralization in the origin of these veins. No sufficient evidence, however, is available.

28.17.5. Gold veins in distal plutonic exocontacts, or predating the "granite" emplacement

These are by far the most common and productive variety of auriferous veins. Both gold-quartz and sulphide-gold end-members of filling occur, although the former is the dominant one. In this setting, the veins display a considerable lithological (associational) and structural-metamorphic control, and several distinct lithologic associations treated in this book carry the bulk of the veins. They are: (1) greenstone-phyllite or slate gold belts (e.g. Juneau, Klondike, Mother Lode, Piedmont Gold Belt, Jílove, and others; Section 10.4.3., Figs. 10-6 and 10-11); (2) felsic metavolcanic belts (e.g. Howie, Haile, Hay Mt. mines, S. Piedmont; Section 12.5.) and (3) slate belts of "flyschoid" character (Meguma Group of Nova Scotia; Victoria Goldfields, Australia; Yana-Kolyma belt; Chapters 16, 19).

In all the regions listed above, penetratively deformed and low-grade metamorphosed supracrustal rocks host the ore veins that fill (or replace) shears, faults, fractures as well as dilations conformable with foliation. "Granites" are invariably present within the mineralized fields or adjacent to them. In fact, it appears that in most of the supracrustal belts a sizeable pluton underlies the metasediments and metavolcanics. The genetic relationships between the "granites" and the veins, however, remain controversial and in some instances (in Nova Scotia, Yana-Kolyma, etc.) it has been demonstrated that some of the gold veins are older than the local "granites", which dismember and contact metamorphose them.

The gold deposits that have already been reviewed will not be discussed again here, but basic data on several example localities are summarized briefly in Table 28-25.

28.17.6. Gold-bearing skarns and carbonate replacements

Many Cu, Pb-Zn, Bi, and other skarns yield gold as a by-product, but only a few skarn deposits have ever been mined for gold as the sole, or the main, product. Gold in skarns is always associated with sulphides (arsenopyrite, pyrite, rarely pyrrhotite) that accumulate in the late-stage infiltrational skarn or are superimposed on the earlier garnet, hedenbergite, epidote, amphibole, etc. skarn in the form of veins or fracture stockworks.

<u>The Hedley ore field</u>, British Columbia; (Barr, 1980; 49.2 t Au/12.4 ppm; Fig. 28-109) is underlain by late Triassic marine andesite tuff, breccia, volcanic argillite, arenite, and impure limestone. The supracrustal rocks were folded, intruded by middle to upper Jurassic and Cretaceous quartz diorite and granodiorite stock and dikes as well as by augite diorite and quartz gabbro. The latter rocks could, at least in part, be hybrids, created by mingling of the supracrustal basaltic andesite and intermediate intrusions. The granitic intrusions produced contact hornfelses out of the silicate sediments, and converted the limestone into garnet, hedenbergite,

axinite and epidote skarn.

In the principal Nickel Plate zone, the orebodies are sheet-like, overlapping en-echelon masses of skarn within 80 m of the skarn/marble contact, mineralized by disseminations, scattered blebs and masses of arsenopyrite and minor pyrite and sphalerite. The arsenopyrite carries the gold, and its content in the ore was most commonly between 10 and 50% by volume. Arsenic was not recovered and is not included in the statistics, but if the average As grade were 5% As (a conservative estimate), there would have been about 200 Tt As in the ore.

Boyle (1979, p. 250-251) briefly reviewed more localities of auriferous skarns in the western United States (Cable, Montana; Ouray, Colorado; Battle Mountain, Nevada), Nicaragua (Rosita, La Luz), southern Siberia (Sinyukha, Lebedskoe, Natal'evskoe, Tardanskoe), Sarawak (Bau) and North Korea (Suian). At most localities, copper sulphides were abundant. Gold tellurides are important in the Soviet deposits. In Bau stibnite is associated with

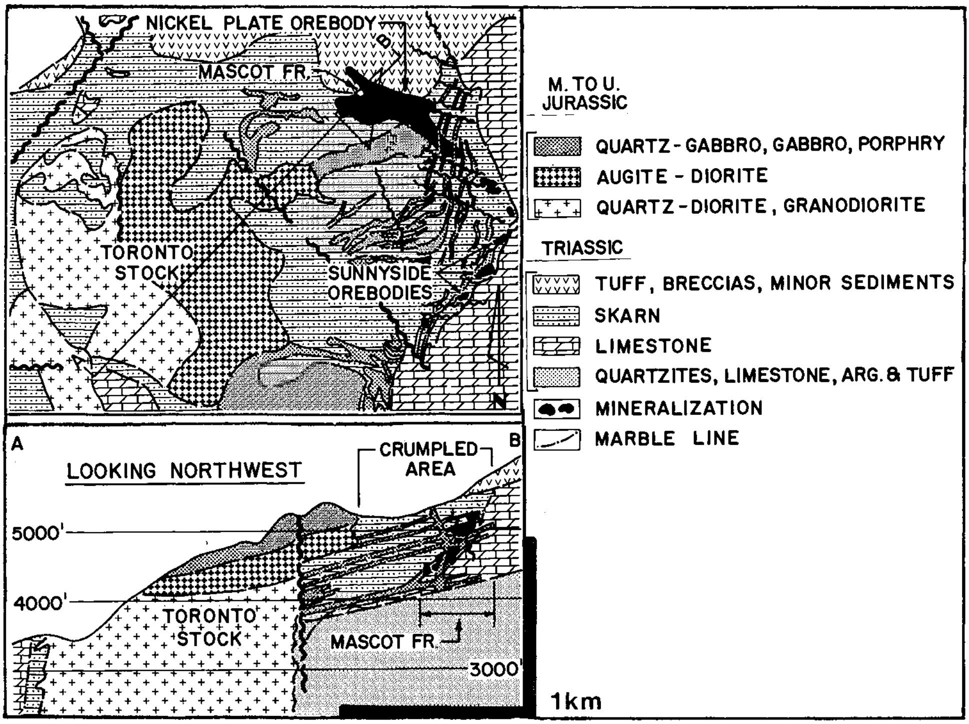


Fig. 28-109. Hedley field gold skarns, southern British Columbia. From Barr (1980), courtesy of the Canadian Institute of Mining and Metallurgy and the author.

Table 28-25. Essential data on the more important plutonic and interaction-plutonic Phanerozoic gold deposits, districts and belts of the world. Abstracted from MANIFILE (Laznicka, 1973)

1.LOCALITY	2.CL.	3.ST.	HOST UNIT			
			4.AGE	5.MT.	6.CH.	7.HOST ROCKS
Willow Creek, Alaska, U.S.A.	OF	FV,SV	PZ,MZ	A	29	gneiss,schist
Nome, Alaska, U.S.A.	DT	PL,FV	PZ	G,A	17,29	schist,gneiss
Fairbanks, Alaska	DT	PL,FV	Pt,PZ	A	29	gneiss,schist,qtzt.
Chicagoff Island, Alaska, U.S.A.	OF	SV,FV	Cr	1G	13,16	andes.tuff,grayw., slate
Juneau, Alaska	OF	RV,SV	Tr_3	Z-1G	10,16	slate, graywacke, greenstone
Premier near Stewart British Columbia	DP	SV,FV	J_{1-2}	Z-1G	13	andes.tuff, slate, argillite
Zeballos,Vanc.Isl. British Columbia	OF	SV,FV	Tr_3	Z-1G	13	andesite tuff
Bralorne, British Columbia, Canada	OF	SV,FV SW	Pe,Tr	Z-1G	10,7 13	chert,slate,serpen. greenst.,andesite
Hedley, British Columbia, Canada	OF	SK	Tr_3	Z-1G CT	13,16	limest.,quartz., argill.,andesite
Rossland, British Columbia, Canada	OF	RV,FV SV	J_2	Z-1G	13	andes.tuff,argill.
Wells (Cariboo dist) lodes, Br.Columbia	OF	FV,SV RV	Cm	G	19,17	schist,m-quartzite argill.,limestone
Salmo-Ymir, southern British Columbia	OF	FV	Cm_1	1G	19	quartzite,phyllite, limestone
Klamath Mts.,Oregon and Calif.,U.S.A.	DT	PL,SV FV	PZ	G,A	12,29 7	gneiss,greenst., micasch.,limest.
Blue Mts.,Oregon, U.S.A.	DT	PL,SV FV	PZ	G,A	12,10	schist, greenst., slate
Boise Basin, S.W. Idaho, U.S.A.	DT	PL,FV	J-Cr_1		28	granodiorite, quartz monzonite
Marysville, Montana U.S.A.	OF	PL,FV	Cr_3		28	qtz.dior.,granod., granite
Rimini, Montana U.S.A.	OF	FV,PL	Cr_3		28	qtz.dior.,qtz.monzon.,granodior.
Elliston, Montana U.S.A.	OF	PL,FV SV	Cr_3		28	qtz. monzonite

CONCENTRATOR INTRUSION			OREBODIES	
8.ST.	9.AGE	10.PETROGRAPHY	11.MINERALOGY	12.TONNAGE
1	Cr_3-T_1	qtz.diorite	qtz,py,ar,sf,tetr,ga,Au	17.24t Au
2	Cr_3-T_1	granod.,granite	qtz,py,ar,Au	100.7t Au
2	Cr_3-T_1	qtz.dior.,gran.	qtz,py,ar,sf,sb,sch	87.3t Au
2	Cr	dior.,qtz.dior., granodiorite	qtz,py,Au	22t Au
3-4	Tr_{2-3}	qtz.dior., granodiorite	qtz,py,ar,ga,sf,cp,Au	187.2t Au
3-4	J_2?	qtz.diorite porphyry	qtz,py,ga,sf,cp,tetr, pyrargyrite,Au	50.54t Au
2	J_2	granod.,qtz. diorite	qtz,py,sf,cp,ga,po,Au	12t Au
1-2	J_1	plagiogranite, dior.,qtz.dior.	qtz,carb,py,ar,Au	95.2t Au
3-4	J	granodiorite	ar,po,cp,py,sf,Au	44.3t Au
3-4	J-T_1	dior.,monzon., granodiorite	qtz,po,cp,py	82.5t Au
5	J-Cr?		qtz,ank,py,ar,sch,sf, ga,Au	74.8t Au
3-4	J_1	qtz.dior.,gran., granodiorite	qtz,carb,py,ga,sf,cp,Au	35t Au
3	J-Cr_1	dior.,qtz.dior., granodiorite	qtz,py,ar,cp,sf,ga,Au	162t Au
3	Cr_2	qtz.diorite, diorite	qtz,py,cp,ar,sf,ga,sb, Au	110t Au
1	Cr_1	qtz.monzon., granod.,porph.dk	qtz,py,ar,sf,tetr,sb,Au	79.24t Au
1	Cr_3	qtz.dior.,dike rocks	qtz,py,tetr,cp,ga,sf,Au	42t Au
1	Cr_3	qtz.monzonite	qtz,ga,sf,py,ar,Au	112.6t Au
1	Cr_3	qtz.monzonite, porph. dikes	qtz,ga,sf,py,Au	33t Au

Table 28-25 (continued).

1.LOCALITY	2.CL.	3.ST.	HOST UNIT 4.AGE	5.MT.	6.CH.	7.HOST ROCKS
Basin and Boulder, Montana, U.S.A.	OF	BR,FV	Cr_3		28	qtz.monzonite
Winston, Montana U.S.A.	OF	PL,FV	Cr_3		28	qtz.dior.,granod., qtz.monzonite
Virginia City, Mont. U.S.A.	OF	PL,SV	Pt	A	29	gneiss,schist
Grass Valley-Nevada City,Calif., U.S.A.	OF	SV,FV RV	Cb-J	G-1A CT	10,12 7	micasch.,greenst., serpentinite
Mother Lode, Sierra Nevada, California	MB	SV,FV RV,PL	Cb-J	G-1A	10,12 7	slate,schist,greenstone,serpentinite
Central City, Colorado, U.S.A.	OF	FV,SV	Pt_2	A,UM	29	gneiss,migmatite, granite,pegmatite
Idaho Springs, Colorado, U.S.A.	OF	FV,SV	Pt_2	A,UM	29	as above
Antioquía Gold Province, Colombia	MA	PL,FV SV	PZ PZ-Cr	G,1A	10,12 16,17	slate,greenstone, ophiol.,tonalite
Segovia mine (incl. in above)	DP	FV	Cr_3		28	qtz.diorite, dacite porphyry
Berlin mine (incl. in Antioquía)	DP	FV	PZ	G,1A	12	greenschist, chlorite schist
Pataz-Parcay area, eastern Peru	DT	SV,FV PL	Pt,PZ	G,A	16,17 29	phyllite,schist, granite
Nova Scotia goldfields, Canada	MA	SR,SV FV	Cm	1G	16	slate,sublitharen. quartzite
Southern Piedmont gold belt, U.S.A.	MB	SR,SV FV,PL	Cm	1G	16	slate,graywacke
Jílové, western Czechoslovakia	OF	SV,FV SW	Pt_3	Z-1G CT	12	m-keratoph., greenst.,plagiogr.
Roudný mine, Zvěstov W. Czechoslovakia	DP	RV,SW	Pt_2	A,UM	29	biot.-sillim.gneiss calc-sil.gn.,amphib
Berezovsk, Ural Mts. U.S.S.R.	OF	FV,RV SW	Cm_1-Cb	1g,A	10,12 7,28	serp.,greenst,qtz-seric.sch.,plagiog.
Kochkar, Ural Mts., U.S.S.R.	OF	FV,RV	Cb_1 Or-D_1	G,A	28,10 12	plagiogr.,m-basalt m-andesite
Muruntau, S.Tian-Shan, U.S.S.R.	OF	SW,FV SV	Pt? S?	G	12,16 17	slate,phyllite, sandstone (quartzt)
Kommunard, Altai-Sayan, U.S.S.R.	OF	SW,SK SV,FV	Cm	G	10,12 28	m-basalt,m-keratop. diorite,gabbro

CONCENTRATOR INTRUSION			OREBODIES	
8.ST	9.AGE	10.PETROGRAPHY	11.MINERALOGY	12.TONNAGE
1	Cr_3	qtz.monzonite, porph.dikes	qtz,py,ga,sf,cp,tetr,Au	75.6t Au
1	Cr_3	qtz.monzonite, porph.dikes	qtz,py,ga,sf,ar,tetr,Au	56.6t Au
2-3	Cr_3-T_1	granod.,quartz monzonite	qtz,py,ga,sf,tetr,sb,Au	74t Au
1	Cr_3	granodiorite	qtz,ank,alb,sct,py,ar,cp, Au	330t Au
3-4	J-Cr	qtz.dior., granod.,qtz.mnz	qtz,ank,alb,py,ar,sch,Au	440t Au
2-3	T_1	qtz.monzon.porp bostonite	qtz,carb,py,sf,cp,tetr, ga,Au	116.4t Au
2-3	T_1	as above	qtz,py,cp,sf,ga,ar,Au	51.1t Au
2	Cr_3	tonalite	qtz,ga,sf,py,ar,Au	1,450t Au
5	post Cr_3		qtz,carb,py,sf,ga,Au	45t Au
4	Cr_3?	tonalite	qtz,py,ga,sf,po,ar,cp	14.6t Au
3-4	PZ?	granodior.,qtz. diorite	qtz,py,ar,tetr,sf,ga,Au	280t Au
3,4	D	granod.,qtz. monzon.,granite	qtz,py,ar,sch,Au	26.3t Au
3,4	D	granod.,quartz monzon.,gran.	qtz,py,src,chl,ar,Au	80t Au
3	D-Cb	granodiorite, qtz.diorite	qtz,carb,py,ar,po,Au	est.12t Au
5	PZ_3		qtz,dolom,ar,py,Au	10t Au
2	Cb	qtz.porph., granod.dikes	qtz,tourm,py,tetr,ar,cp, sch,Au	est.200t Au
2,3	Pe	microcl.granite	qtz,ar,py,cp,ga,sf,Au	est.120t Au
3-4	MZ?	plagiogr.porph. dk.,granod.	qtz,py,ar,Kf,biot,carb, tourm,sch,Au	est.250t Au
2	PZ_1	diorite	qtz,calc,py,po,ar,cp, tetr,magn,Au	est. 50t

Table 28-25 (continued)

1.LOCALITY	2.CL.	3.ST.	HOST UNIT 4.AGE	5.MT.	6.CH.	7.HOST ROCKS
Darasun, East Trans-baikalia, U.S.S.R.	OF	FV	PZ	G-A	28,29	granod.,gabro, gr. syen.,amphib.
Yana-Kolyma belt, Siberia, U.S.S.R.	MB	Pl,FV	Cb_3-Cr_1	Z-G	16	litharenite,slate
Croydon, N.W. Qld., Australia	OF	FV,SW	PCm	A	29	gneiss,amphibolite
Charters Towers, Qld.,Australia	OF	FV,SV	PZ_1? Pt?	A	29	micasch.,chlorit. sch.,quartzite
Gympie,southern Qld.,Australia	OF	FV	PZ	1G	16?	slate,argillite
Beechworth-Myrtle-ford, Victoria,Aus.	OF	PL,FV	Or_{2-3}	G	16?	phyllite,shist, hornfels
Walhalla, Victoria Australia	OF	SV,FV	D_1	1G	16	shale,sandstone, graywacke
Wood's Point, Victo-ria, Australia	OF	FV,SV	D_1	1G	16	slate,sandstone, graywacke
Victoria Goldfields, Australia	DT	SV,FV SR,PL	Or_1	1G	16	slate,black slate, qtz-rich litharen.
Beaconsfield, N.Tasmania, Austral.	OF	FV	Cm,Or	Z	16?	litharen.,conglom., greenst.,ophiolite
Reefton, Westland, New Zealand	OF	SV,FV	Pt?	G	16	graywacke,argillite phyllite

EXPLANATIONS:

Column 2, CLASS; DP=deposit; OF=ore field; DT=district; MA=metalliferous area; MB=metalliferous belt

Column 3, STYLE; BR=breccia; FV=fissure vein; MR=massive replacement; RV=replacement vein; SR=saddle reef; SV=shear vein; SW=stockwork; PL=placer

Column 4, AGE=geological age

Column 5, METAMORPHIC INTENSITY; Z=zeolite (and slates); 1G=lower greenschist; G=greenschist; 1A=lower amphibolite; A=amphibolite; UM=ultrametamorphism (granitization); CT=contact

Column 6, CH=Chapter in which the lithologic association is treated in this book

CONCENTRATOR INTRUSION			OREBODIES	
8.ST	9.AGE	10.PETROGRAPHY	11.MINERALOGY	12.TONNAGE
2	J_{2-3}	plagiogr.,gra-nod porph.dikes	qtz,carb,tourm,chl,sct,py, ar,sf,ga,cp,tetr,Au	est. 80t Au
2-4	J_3	dior.,albitite, porph.dikes	qtz,py,ar,sb,sch,Au	min.1,800 t Au
3,4	Pe_3	granite dikes	qtz,carb,py,ar,Au	21.7t Au
1	PZ_1	granod.dikes	qtz,calc,py,ga,sf,cp,ar, tellurides,Au	192t Au
4	Pe_3	granod.,gabbro diorite	qtz,py,Au	96.2t Au
2	D_3	granite,qtz. monzonite	qtz,py,Au	118.2t Au
2	D_3	diorite dikes	qtz,ank,py,ar,born,Au	41.85t Au
1	D_3	diorite dikes	qtz,ank,py,ar,cp,Au	16t Au
4	D	granodiorite	qtz,ank,alb,py,ar,Au	2,081t Au
3,4	D	lamprophyre dikes	qtz,py,cp,ga,sf,Au	24.2t Au
3-4	MZ		qtz,cp,py,ar,sb,cp,ga	57t Au

Column 8, STATUS; intrusive unit 1=hosts all or most orebodies; 2=hosts some ore; 3=present in ore endocontact; 4=distant from orebody; 5=not established

Column 11,MINERALOGY; qtz=quartz; py=pyrite; ga=galena; sf=sphalerite; ar=arsenopyrite; alb=albite; sct=sericite; sb=stibnite; cp=chalcopyrite; sch=scheelite; cl=chlorite; ank=ankerite; carb=carbonate; Au=gold or electrum the gold, and in Suian the skarn is particularly high in boron minerals such as kotoite and ludwigite.

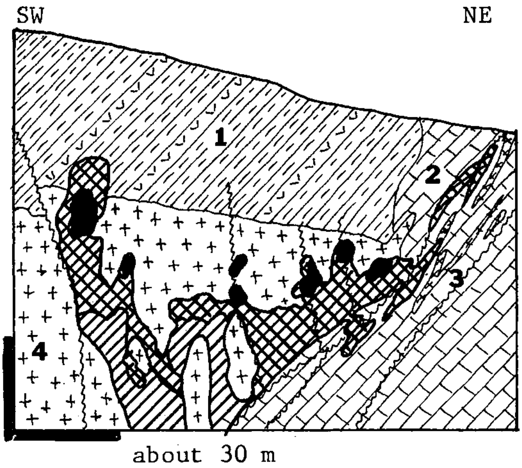
Złoty Stok (formerly Reichenstein; min. 12 t Au) in the Polish Silesia (Schneiderhöhn, 1941) is an enigmatic mineralized skarn in which gold is carried by löllingite as much as by arsenopyrite. The orebodies are contained in magnesian (diopside, tremolite, chondrodite, forsterite) skarn formed by replacement of a dolomite, considerably retrogressively hydrated into a meta-serpentinite. Masses of löllingite, arsenopyrite, pyrrhotite, magnetite and chalcopyrite are situated in a compact ore lens measuring 40x35 m and the grade was between 5 and 35 ppm Au. The skarn formed along the contact of Proterozoic or lower Paleozoic schist, amphibolite and marble sequence, intruded by late Paleozoic syenite and diorite.

The small "skarn" gold deposit at Junction Reefs near Mandurama, N.S.W., Australia (Section 13.6.) is contained in peneconcordant layers interbedded with meta-andesites and volcaniclastics. This could be a thermally metamorphosed volcanogenic mineralization.

Auriferous sulphide replacements in carbonates lacking the skarn association also occur. Like their Pb-Zn counterparts, they may be associated with widespread silicification (jasperoid), or they may be accompanied by another kind of alteration such as recrystallization, Fe or Mn introduction, hydrothermal dolomitization, etc. Purely gold occurrences in metasomatic jasperoid are uncommon. In the Drum Mts. (N.W. of Delta, Utah), gold occurs with pyrite in jasperoid, replacing Cambrian carbonates near a small Tertiary diorite, monzonite, andesite and quartz latite stocks and dikes. Spot contents of 56-85 ppm Au have been reported.

Gold-bearing massive pyrrhotite (visually indistinguishable from a massive pyrrhotite associated with replacement deposits of cassiterite, scheelite, etc.) with lesser pyrite, chalcopyrite, molybdenite, bismuth, tetradymite and gold tellurides, is mined in the Olkhovo deposit in E. Sayans, Siberia (Shakhov, 1972; Borodaevskaya and Rozhkov, 1974; Fig. 28-110). There, replacement sulphide masses containing a variable proportion of quartz, carbonate, sericite, chlorite and serpentinite gangue, are located in lower-middle Cambrian limestone and dolomite (members of a volcanic-sedimentary suite), at the contact with Ordovician plagiogranite and granodiorite. Skarn envelopes may be present locally.

Similar auriferous massive replacements carry gold, in addition to fissure veins, at the Salsigne gold mine in southern France (Reynolds, 1965; 49.5 t Au/11 ppm, 149 t Ag/33 ppm, 149 Tt As/3%, 1,800 t Bi/0.04%). The host rocks are Cambrian to Devonian phyllites, limestones and sandstones but there is no exposed intrusive body in the vicinity.



1. $Cm_{1,2}$ hornfelsed slate, andesite,pyroclastics
2. limestone marble
3. diabase porphyry dikes
4. Or, granitic rocks

BLACK: high grade auriferous massive sulphide ore
GRID,DIAGONALLY RULED: lower grade, siliceous disseminated ore

Fig. 28-110. Olkhovskoe Au deposit, E. Sayans, Siberia, auriferous sulphide replacements. Modified after Shakhov (1972), scale and orientation added.

28.17.7. Fine, "invisible" gold disseminated in (replacing) sediments, with or without a visible association with plutonic rocks ("Carlin-type")

The "Carlin-type" gold deposits (after Carlin, Nevada) contain a fine (almost colloidal) gold typically disseminated in calcareous, little metamorphosed or unmetamorphosed sediments, usually accompanied by finely dispersed pyrite, arsenopyrite, realgar or orpiment. Such mineralizations are inconspicuous, because (1) the content of visible sulphides rarely exceeds quantities common as accessories in ordinary sediments; (2) the gold is invisible and cannot be panned and (3) the alteration is inconspicuous (particularly in the weathered outcrop), limited to light bleaching, silicification, argillization or Fe, Mn introduction. The orebodies found so far have in common a fault (often thrust) control and a low-temperature hydrothermal origin, but the hydrotherms (hot springs) could have been a consequence of contemporary volcanism, high geothermal gradient or evolving igneous intrusion in depth. The proximity of plutons, therefore, hardly constitutes a helpful guide. With increasing intensity of alteration, "Carlin-type" deposits may presumably pass into jasperoid-hosted bodies and carbonate replacements.

Deposits of this "type" have already been reviewed briefly in Sections 17.8. (Getchell); 19.7.3. (Carlin, Cortez, Mercur) and 28.21. (Stibnite-Yellow Pine).

28.18. HYDROTHERMAL IRON ORES (EXCEPT SKARNS)

28.18.1. General

Phanerozoic deposits of iron that are still considered to be hydrothermal (other than subaqueous hydrothermal-sedimentary and skarns), represent some 2.8 Bt Fe contained in the past production and reserves. Of this, about 130 Mt Fe come from veins and the remainder from carbonate replacements. The bulk of iron is contained in siderite or in products of its oxidation (goethite, hematite; Fig. 28-111) and only a fraction is found in "primary" hematite veins. Metallogenic statistics involving iron are inaccurate because of genetic uncertainty (particularly in the past) and uneven economic parameters. The genetic link between hydrothermal iron ores and "granites" is the weakest one to demonstrate, of all the metals. Some siderite deposits formerly considered to be postmagmatic, "granite"-affiliated, are now interpreted by some authors as submarine "exhalative" or even groundwater replacements.

As far as the economic factors are concerned, a vein containing 95% siderite and 5% tetrahedrite as in the Coeur d'Alene district is mined for silver and the siderite is a waste, consequently not included in production statistics. The same style of veins formerly mined in Siegerland, West Germany, has a virtually complete production record, because the veins were mined as an iron ore and the minor chalcopyrite, tetrahedrite, etc. they contained recovered as a by-product.

28.18.2. Hematite fissure veins

Fissure veins filled by massive, often fibrous aggregates of hematite are relatively common in the Erzgebirge Mountains. There, they are preferentially associated with S.W. and east-trending high-level fault zones, that indiscriminately cut across the late Paleozoic granites and also rocks of the crystalline basement. Some such zones are up to 10 km long and up to 8 m wide. The hematite filling often changes into quartz, jasper, quartz-barite, fluorite, minor chalcopyrite or uraninite. Mn-oxides (pyrolusite, manganite) are locally abundant. The wallrocks are silicified or argillized.

These veins are among the youngest members of the Erzgebirge vein association, now considered to be a product of "activation" and substantially postdating the hydrothermal phase of the granites they intersect. In the past, these veins were mined at several localities (Bludná, Pernink in N.W. Czechoslovakia; Suhl, Eisenbach, Lauterberg in Germany) as a high-grade and high-quality, but small tonnage iron ore (X0-X00 Tt ore per vein). Comparable veins were mined in the Harz Mountains (e.g. Wieda-Zorge area), West Germany.

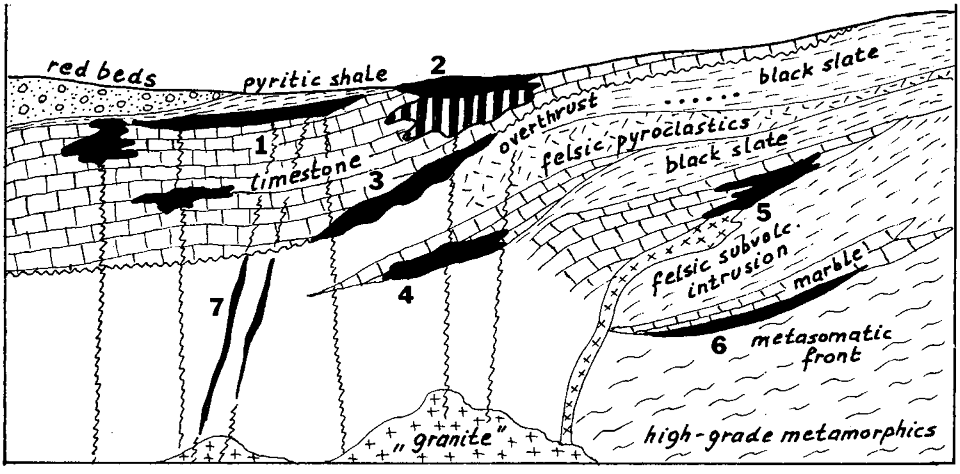


Fig. 28-111. Non-sedimentary siderite deposits: styles, settings, probable interpretations. 1=Replacements from descending waters; 2=low grade replacement siderite (ruled) topped by limonitic gossan (black); 3=hydrothermal siderite replacements along overthrusts; 4=ditto, in granite roof; 5=possibly remobilized subaqueous hydrothermal siderite; 6=possibly siderite replaced limestone in Fe metasomatic front; 7=fissure and shear veins.

28.18.3. Siderite fissure veins

Siderite veins were substantially more widespread and economically important than the hematite veins. Those in Siegerland have been the most important source of iron ore in Germany until 1885. At present, however, this style of ore is considered to be of local importance only.

In the Siegerland-Wied siderite vein district of Germany (Neumann-Redlin et al., 1976; 64.5 Mt Fe/30%, 11.4 Mt Mn/5.3%), several hundred veins occur within an area of about 3,000 km^2. The veins are hosted by a thick, monotonous sequence of Devonian shale and litharenite and there is no evidence of a proximal association with "granites". A large, probably mafic plutonic body has been detected geophysically at a depth greater than 10 km. The veins are lenticular, up to 12 km long, 2-6 m wide, and filled by coarse crystalline manganoan siderite with variable quantities of quartz, calcite and scattered chalcopyrite. Wallrock alteration consists of a slight bleaching in slates, and argillization and siderite impregnation in the host arenites.

An extensive siderite district of local importance is found in the Paleozoic core of the West Carpathians, particularly in the Spiš-Gemer region of Slovakia (Mahel' and Buday, eds., 1968; about 80 Mt Fe/30%, 5.75 Mt Mn/2.5%). This region and its siderite deposits have already been mentioned briefly in this book (Sections 10.4.1. and 11.2.). There, siderite occurrences are unusually widespread (over 2,000 known) and hosted by low-grade metavolcanics and metasediments ranging in age from Silurian to Permian. A portion of the deposits are peneconcordant lenses and sheets, interchangeable with ankerite, magnesite, dolomite and graphitic limestone. Formerly interpreted as hydrothermal replacements probably dating from the Cretaceous period and related to buried granite plutons (Bernard and Hanuš, 1961), many deposits were recently re-interpreted as being "stratiform" Paleozoic volcanic-sedimentary deposits, deformed, metamorphosed and partly remobilized during the Mesozoic alpinotype deformation (Ilavský, 1976). The remainder of the Slovak siderite deposits are bona fide structurally controlled fissure veins and, as in Siegerland, there is no granite is evidence. The veins contain high trace Ni,Cr,Co and Hg as well as accessory fuchsite, gersdorffite, Hg-tetrahedrite, chalcopyrite and cinnabar, indicating a possible genetic association with mafic-ultramafic magmatic rocks.

The largest vein deposit Rudňany (31 Mt Fe; Section 10.4.1.) could be the largest single vein siderite deposit of the world.

28.18.4. Siderite lenses and masses in (or interchangeable with) carbonates (Table 28-26)

This category of deposits used to be called "metasomatic siderites" (it still is in Zitzmann, ed., 1976), and was interpreted as limestone or dolomite replaced by siderite, by the action of hydrothermal fluids. In the past decade, however (compare Wolf, ed., 1976, 1981), there has been a tendency to re-interpret many of these orebodies (e.g. Eisenerz, Austria, the Carpathian deposits of Slovakia and Rumania) as "exhalative" and stratiform. As on other occasions in the history of geology, a sweeping global re-interpretation is harmful and it is virtually certain that subaqueous-hydrothermal, hydrothermal (solid host)-replacement and late diagenetic-replacement siderite deposits are possible and can exist side by side. An association with "granites", however, is rarely apparent.

It is beyond the purpose of this book to "bring order" into the siderite genetic problem so this will not be considered further. Siderite deposits are most common in the following lithologic associations: (1) low-grade metamorphosed mafic, felsic and bimodal volcanic-sedimentary (Chapters 10, 11, 12, respectively); (2) deeper-marine "black shale" association and its transition into carbonates (Chapter 17) and (3) shallow marine carbonate, evaporite and shale associations transitional into continental "red beds" (Chapter 19); shallow-marine platformic and "miogeoclinal" carbonate association (Chapter 20).

Zitzmann and Neumann-Redlin (1976) distinguished two "types" among the "metasomatic siderites": (a) Bilbao "type", in which the principal economic commodity is the weathering-enriched hematite-goethite zone and (b) Eisenerz "type", producing unenriched siderite or ankerite.

In the northern Spain iron ore province centred around Bilbao (Zitzmann, ed., 1976; about 216 Mt Fe), the siderite is hosted by lower Cretaceous folded and faulted limestones. The orebodies are always fault controlled and have the form of irregular replacement siderite masses to mantos that are thickest near the fault. The siderite contains, on average, 38% Fe and 0.5% Mn, but the bulk of the commercial ore was a massive, rubbly to earthy residual hematite and goethite in the oxidation zone (51-57% Fe; 0.4-0.7% Mn).

The Kremikovtsi deposit near Sofia, Bulgaria (Iovchev, 1961; 76 Mt Fe, 15.3 Mt Mn, 46 Mt barite, 1 Mt Pb; Fig. 28-112) is unusual in the variety of mineral commodities it contains. The orebody is hosted by a middle Triassic dolomitic limestone at the base of a nappe, floored by upper Jurassic marls and argillaceous siltstones. The orebody is an erosional remnant of a composite lens over 1,000 m long and up to 267 m thick, the bulk of which is now residual hematite and limonite enclosing lenses of relic barite. The "primary" ore is a massive gray siderite, laced by a second generation of siderite veinlets and it is transitional into barite and hematite. Hematite occurs in strongly brecciated zones of the original dolomitic limestone as well as the siderite, and it replaces both carbonates. Pyrite, galena, tetrahedrite, chalcopyrite and sphalerite are widespread at fractures and in remobilization veinlets within the siderite and barite bodies. The average Fe ore contains 0.4% Pb, 0.14% Cu and up to 10 ppm Ag. Additional disseminated galena occurs in Triassic dolomitized limestone on the fringe of the iron orebody.

The original, detailed description of the Kremikovtsi deposit given in the Bulgarian language by Iovchev (1961) makes a good case for the epigenetic, replacement origin of the orebody, shortly postdating the late Mesozoic thrusting. In conformity with the latest fashion, however, an "exhalational" origin has also been proposed recently.

Additional example localities of members of the former class of "metasomatic siderites" are summarized briefly in Table 28-26.

Jebel Ouenza siderite field in Algeria (Dubourdieu, 1952; Fig. 28-113) is an interesting case of replacement siderite in a lower Cretaceous carbonate unit, strongly tectonized in the Eocene period and dismembered by diapirs of Triassic sediments. Siderite replaces limestone in the core of a large N.E.-oriented anticline and is oxidized into "limonite" to a depth of 250 m.

28.19. MAGNETITE SKARN AND REPLACEMENT DEPOSITS

28.19.1. General

Magnetite skarns and replacement deposits (this category may include some subaqueous hydrothermal-sedimentary deposits subsequently modified in an intrusive aureole), represent some 6 Bt of economic iron. If the world's economic content of iron is given as 300 Bt Fe,

Table 28-26. Massive siderite deposits and districts ("metasomatic siderites"), selected examples

LOCALITY	HOST UNIT	MINERALIZATION	REFERENCES
N.Spain iron ore province (Bilbao)	Cr_1 folded and faulted limestone	irreg.to manto orebodies of siderite replacing limestone along faults (35% Fe); capped by residual hematite-goethite 51-57% direct shipping ore;216 Mt Fe	Zitzmann,ed. (1976)
Sierra Menera Fe ore region, east-central Spain	Or dolomite, pyritic shale,quartzite; Cb_3 dolomite	goethite and hemat. formed by oxidation of PZ_3 siderite and ankerite, in an up to 80 m thick ore lens replacing dolomite near fault; probably groundwater replacem. 60 Mt Fe/60%	Zitzmann,ed., (1976)
Marquesado deposit east of Granada, S. Spain	Tr limestone	irreg. siderite masses to mantos replace carbonates along tect. zones; siderite was converted into goethite and hematite to form layers and pockets in karsted carbonates; 90 Mt Fe/55%	Zitzmann, ed. (1976)
Erzberg near Eisenerz, Austria	S-quartz seric.schist (meta qtz.keratoph.); D-limest.,black phyll.	large stratabound siderite, ankerite zone with small branching veins, interpeted as syndepositional or post-Tr replacement 214 Mt Fe/33% Fe; 13.75 Mt Mn/2.5%	Holzer and Stumpfl (1980)
Ljubija, Bosnia, Yugoslavia	PZ limest.,schist, sandst.,Cb_2 metagraywacke altern.with slate Cb mafic volc.,tuff	76 struct.controlled siderite and goethite deposits, replacement lenses, veins. 500 Mt Fe/38-46.6%, 1.82-2% Mn	Čičić (1980)
Spiš-Gemer region, E.Slovakia, Czechoslovakia	S-Cb mafic and felsic metavolc., black and green phyll.,lenses of limest.,anker.,magnes., sider. Cr cryptobath.	over 2,000 sider.occurrences, both veins and conformable to irregular lenses and mantos (Železník, Nižná Slaná, Dobšiná). Interpr.at either "exhalational" or "teletherm.replac.". 50 Mt Fe/30%, 4.5 Mt Mn	Mahel' and Buday (1968) Ilavský (1976)

Rudabánya near Miskolc, northern Hungary	PZ and Tr limestone	irregular masses of siderite, ankerite, minor chalcopyrite, galena; thick goethite gossan; PZ mineralization remobilized in Tr_{2-3}	Morvai (1982)
Teliuc-Ghelar, Poiana Ruscă Mts, W. Rumania	D_3 greensch. (mafic metavolc.), black, seric., chlor., phyll., carbonate, felsic metatuff	lenses of massive to banded siderite assoc. with quartz, magnetite, stilpnomel., thuringite, pyrite, ankerite interpreted as "exhalational", partly mobilized; goethitic gossan; 22 Mt Fe	Kräutner (1977)
Ouenza Bou Khadra, N. Algeria Fe ore region	J_1, Cr, Eo limestone, dolomitized limestone	4 mineralized zones controlled by faults and diapirism. Irregular masses to mantos. Siderite, goethite in oxid. zone; minor barite, access. chalcop., chalcoc., pyr., galena; controversial origin; 135 Mt Fe/54%	Popov (1976)
Djerissa, Tunisia	Cr_1 "reef" limestone exposed in a faulted dome (diapir ?)	6 irregular to stratabound siderite orebodies oxidized to goethite and hematite; 25.12 Mt Fe/54%	Massin (1976)

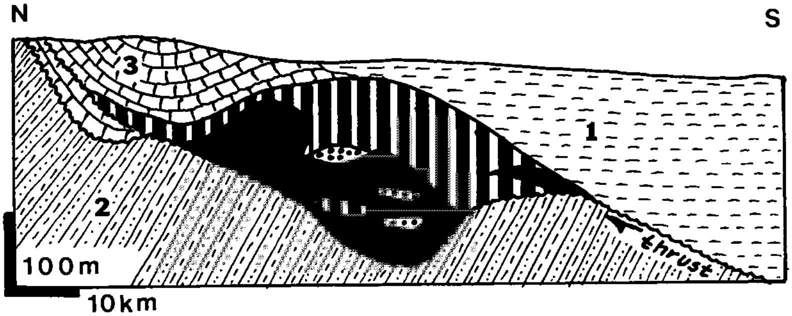
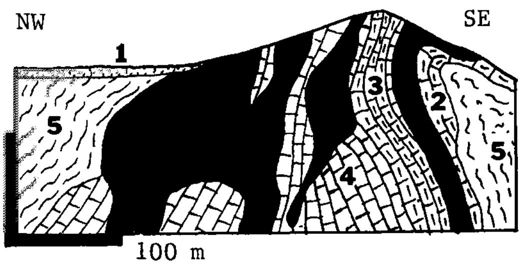


Fig. 28-112. Siderite, limonite, barite deposit Kremikovtsi, western Bulgaria. 1=T_3 sediments; 2=J flysch shale, sandstone; 3=Tr_2 sediments. Tr_2 orebodies; ruled area: dominant limonite; black area: siderite; dots: barite. Modified after Iovchev (1961).



1. Q cover sediments
2. Cr_3 marls
3. Cr_2 argillaceous limestone
4. massive limestone
5. Tr red beds / evaporite association in a diapir

BLACK: metasomatic limonite (goethite) gradational into siderite in depth

Fig. 28-113. Metasomatic limonite siderite deposit in limestone, Jebel Ouenza, Algeria. Modified after Dubourdieu (1952).

this is just about 2%. If the iron resources are considered in trillions of tons, the role of skarns fades into insignificance. Skarn magnetite deposits range in size from local showings containing several tens of tons of ore, to giant ore fields with over 2 Bt Fe (Turgai district, U.S.S.R.; Marcona field, Peru). Magnetite skarns formed in both limestones (calcic skarns) and dolomites (magnesian skarns) and several occurrences of replaced ankerite or siderite may also be present.

The bulk of skarns mined for magnetite only occur in mafic volcanic-sedimentary associations believed to have been generated in immature island arcs (Chapters 10,12,13) and containing minor lenses and interbeds of carbonates. The intrusions responsible for the skarn generation are I- ("magnetite")-type granitoids, ranging from gabbros to granodiorites. Quartz diorites are the most common. Lesser number of magnetite skarn deposits formed within former Andean-type margins. There, magnesian skarns are important, probably because dolomite is a rare rock in the previous setting. The concentrator intrusions here are more felsic and alkalic, represented by granodiorite, monzonite, syenite. Magnetite also occurs, and is recovered locally, from Cu, Pb-Zn, Sn, and other skarns. The skarns associated with gabbro or diabase intrusions in rifted continental margins (e.g. Cornwall, Pennsylvania) are reviewed in Chapter 32.

28.19.2. Calcic skarns in mafic volcanic-sedimentary association

Einaudi et al. (1981) recently reviewed the magnetite skarns, and pointed out the following basic characteristics of the "island arc calcic magnetite skarns": (1) the frequent presence of endoskarns, some of them mineralized by disseminated magnetite; (2) widespread Na-metasomatism in the endo- and exocontact (albitization, scapolitization); (3) anomalous trace concentrations of Ni and Co; cobalt is sometimes recovered as a by-product; (4) the most widespread skarn silicates are andradite, hedenbergite and epidote, but skarn zoning is poorly developed because of the large variety of rock types in the exocontact and (5) magnetite orebodies are closely associated with garnet skarns, or are hosted by limestone outside the skarn zone. The magnetite bodies are usually irregular masses close to the contact, but some magnetite orebodies are "stratabound" sheets or lenses hosted by a favourable carbonate horizon at some distance from an intrusion. The latter are difficult to distinguish from pre-skarn bedded ores.

The Gora Magnitnaya magnetite skarn deposit near Magnitogorsk, southern Urals, U.S.S.R. (280 Mt Fe/56-65%) is usually quoted as a type locality for calcic magnetite skarns (e.g. in Zitzmann, ed., 1976) and there is copious literature covering it, some of it in English translation (Magak'yan, 1968; Baklaev, 1973; Fig. 28-114). The deposit is hosted by a Devonian to lower Carboniferous sequence of marine basalt to basaltic andesite flows, tuffs and volcaniclastics with interbeds of limestone. These rocks are folded, faulted and intruded by Carboniferous quartz monzonite, granodiorite and diorite stocks. There are two peneconcordant ore sheets (1.8x2.5 km and 1.4x1.2 km in size, and, on average, 40-44 m thick). The orebodies are disrupted by a swarm of diorite dikes. Magnetite, the principal mineral with lesser pyrite, hematite, chalcopyrite and quartz, is contained in an earlier garnet, hedenbergite, magnetite skarn, and in a later epidote, calcite, magnetite, quartz skarn.

The Turgai iron ore province (Sokolov and Grigor'ev, 1974; Baklaev, 1973; 3 Bt Fe) is located in north-western Kazakhstan, in a transitional zone of the Urals into the Kazakh Block. This is a prominent polygenetic mineralized region with iron deposits in both the pre-Mesozoic basement and in the Mesozoic-Cainozoic platformic cover. The skarns in the basement are hosted by Carboniferous shallow

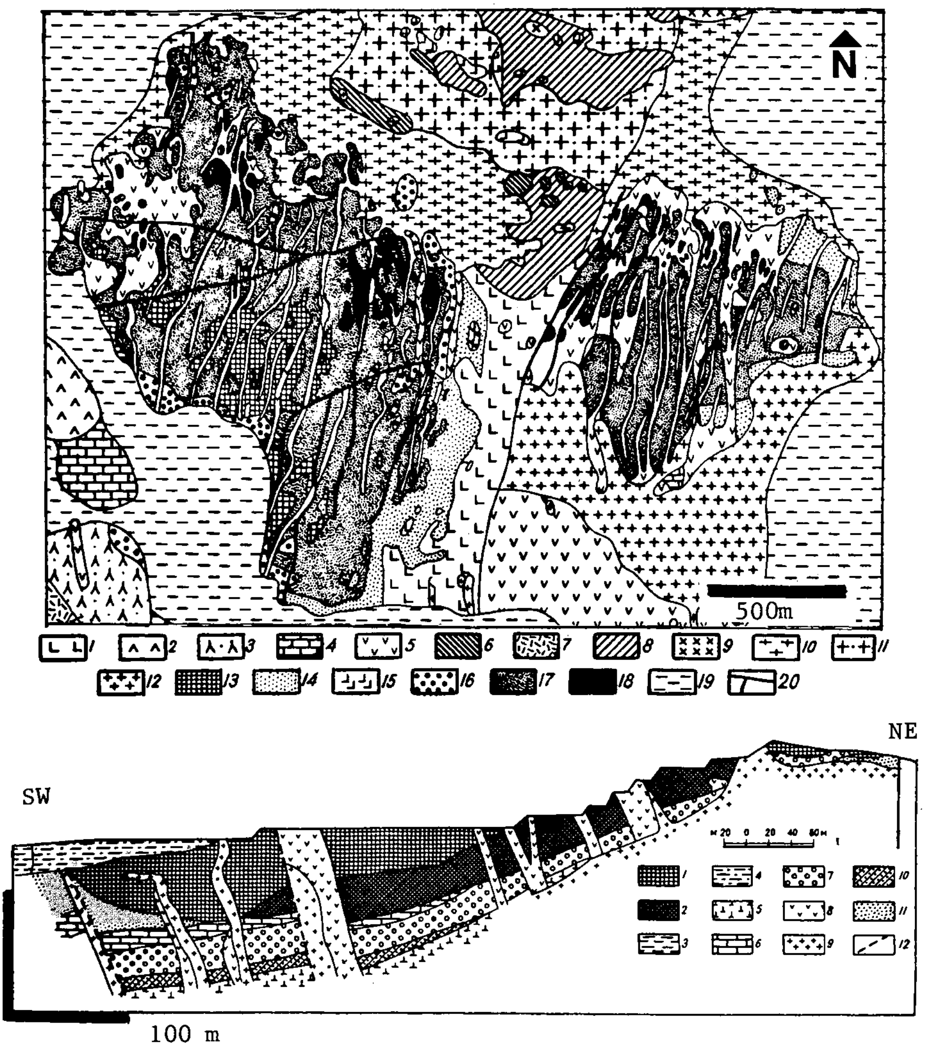


Fig. 28-114. Gora Magnitnaya magnetite skarn deposit, southern Urals, U.S.S.R. From Magak'yan (1968). MAP LEGEND: 1=D-Cb_1 basalt porphyry; 2=extrusive rhyolite porphyry; 3=rhyolite pyroclastics; 4=limestone; 5=diorite; 6=gabbrodiorite; 7=breccia with a diorite matrix; 8=granodiorite; 9=hornblende granite; 10=leucogranite; 11=low quartz granite and syenite; 12=granite porphyry, microgranite, albitophyre; 13=hornfels; 14=andalusite, sillimanite, cordierite hornfels; 15=metaporphyries; 16=garnet skarn; 17=martite; 18=magnetite; 19=talus; 20=faults. SECTION LEGEND: 1=oxidized ores; 2=primary ores; 3=barren talus; 4=ore-bearing talus; 5=porphyries; 6=limestone and marble; 7=skarns; 8=diorites; 9=granites; 10=andalusite, sillimanite, cordierite hornfels; 11=rubble ; 12=faults.

marine to continental andesites, their pyroclastics, volcaniclastics and lesser impure and bituminous limestones and minor evaporites, exposed in a N.-S.-trending anticline. The supracrustals are intruded by Carboniferous diorite porphyry, gabbrodiorite, plagiogranite and andesite porphyry. Granite and quartz-feldspar porphyries are also represented, e.g. in the Kachar deposit. The intrusives are epizonal to subvolcanic bodies, partly comagmatic with the volcanic-sedimentary suite and their emplacement has been strongly controlled by structure and lithology. Elongated plutons, dikes and sills are the most common and the intrusions overlap in time with the mineralization.

The igneous emplacement into the probably still "wet" volcanic-sedimentary pile is believed to have caused widespread sodic metasomatism and hydration (scapolite, albite, chlorite, actinolite, apatite) of the intrusive rocks, earlier hornfelsed silicate rocks and the early garnet-hedenbergite skarn along the intrusive contacts. The hydrous metasomatites were, in turn, often progressively converted to anhydrous skarn assemblage as the intrusive front advanced. Scapolite and albite metasomatism in the Turgai district is a high-level feature, rapidly diminishing with depth.

Magnetite deposits in the district are typically sheet-like, relatively persistent bodies (mantos), controlled to a considerable degree by "favourable lithology" of replaceable carbonate layers and bedded calcareous pyroclastics and volcaniclastics. In the large Kachar deposit (Sokolov and Grigor'ev, 1974; 630 Mt Fe/45%) the following petrographic types of iron ores are represented: (1) Massive, homogeneous magnetite; (2) martite after magnetite, in the oxidation zone; (3) scapolite-magnetite; (4) pyroxene, garnet, magnetite skarn; (5) albite-magnetite and (6) actinolite, chlorite, zeolites, calcite, magnetite. The above assemblages are transitional and the proportion of the silicate gangue minerals naturally controls the ore grade that ranges from under 30% Fe to 65% Fe (average about 45% Fe).

The Dashkesan magnetite deposit in Azerbaidzhan, U.S.S.R. (Smirnov, 1969) is notable for its anomalous cobalt content. Cobalt resides in accessory cobaltite and glaucodot, which, in turn, are present in a garnet, pyroxene, amphibole, magnetite, ilvaite skarn replacing late Jurassic andesitic volcaniclastics, near the contact with a Lower Cretaceous gabbro-granodiorite intrusion. Separate accumulations of massive pyrite, arsenopyrite, cobaltite and other sulphides, moreover, occur in the hangingwall of the magnetite skarn lens, enveloped by a Cl-rich (up to 7% Cl) hornfels ("dashkesanite").

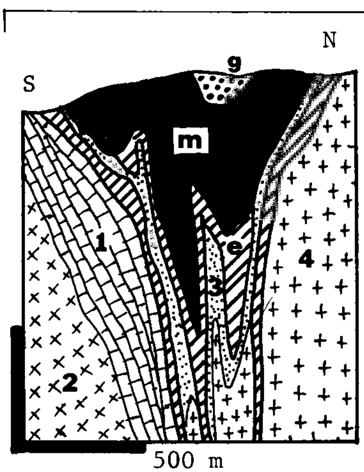
Additional examples of magnetite skarns (in British Columbia) have been reviewed briefly in Chapter 10.

28.19.3. Magnesian skarns

Einaudi et al. (1981) explained the case of magnetite formation in magnesian (dolomite-hosted) skarns by the fact that forsterite, talc and serpentine do not accept much iron in solid solution under conditions of skarn formation. Consequently, such iron accumulates in magnetite rather than in Fe-garnet or pyroxene, as at limestone contacts. The high-temperature skarns may include a diopside-spinel assemblage close to the igneous contact, and forsterite-calcite near the dolomite marble line. A garnet-pyroxene calcic skarn may form as a later-stage overprint.

The Teia (Teiskoe) iron deposit in Khakassia (S. Siberia, U.S.S.R.; Sokolov and Grigor'ev, 1974; Ivankin, ed., 1973; 48 Mt Fe/33%; Fig. 28-115), is commonly quoted as a typical producing example of magnesian magnetite skarns. There, a pipe-like body of skarn containing magnetite masses is underlain by limestone marble and topped by a dolomite marble. These rocks are a part of a Cambrian bimodal volcanic-sedimentary metamorphosed complex that also includes amphibolite, metagabbro and meta-keratophyre. The Cambrian supracrustals were intruded by Cambro-Ordovician or Devonian granosyenite, syenite, intrusive breccias and aphanitic rocks designated as felsites and keratophyres. The latter are probably metasomatic albitites. The ore zone is over 1.5 km long and up to 300 m thick. It contains 12 lens-like masses of magnetite-serpentinite; dolomite, magnetite, lesser phlogopite and magnetite-hematite composition. The magnetite is very fine grained and there are minor amounts of accessory sulphides and Ni-Co arsenides. The skarn envelope consists of forsterite, chondrodite, clinohumite, diopside and spinel skarn on the dolomite side, and garnet-pyroxene skarn on the limestone side. There is a considerable variety of late-stage metasomatites including phlogopite, scapolite, cordierite, sphene, tourmaline, etc. in the exocontact, and Na- and K-feldspathites in the intrusive breccia.

Table 28-27 gives basic data on selected localities of magnetite skarns.



1. Cm, limestone, dolomite
2. diorite, amphibolite
3. D felsite porphyry, albitophyre, albite metasomatites
4. granosyenite

SKARN ZONES:
e=zone of poor magnetite ores and serpentine-phlogopite skarn
m=zone of rich and thick magnetite ore in garnet-pyroxene skarn
g=zone of thin magnetite ore layers in epidote-chlorite metasomatite

Fig. 28-115. Teia (Teiskoe) Fe ore field, U.S.S.R., an example of a magnesian magnetite skarn. Modified after Ivankin, ed. (1973).

Table 28-27. Phanerozoic magnetite skarn and replacement deposits, selected examples

LOCALITY	SUPRACRUSTAL HOST UNIT	INTRUSION	MINERALIZATION	REFERENCES
Insular Belt of British Columbia Canada	Tr_3 basalt to andesite topped by limestone minor black slate	Tr_3-Ol qtz. diorite, granodior.	irregular, mostly small magnetite lenses, common chalcopyrite, in skarn 25 Mt Fe, 120 Tt Cu	Sutherland Brown (1968)
Tasu Sound, Queen Charlotte Islands, British Columbia (incl.above)	Tr massive metabasalt topped by limestone	J qtz.diorite,porphyry dikes	irregular sheets to masses of magnetite in skarn,thickened along faults and porphyry dikes; widespread chalcopyrite. 16 Mt Fe/37%	Sutherland Brown (1968)
Las Truchas-Ferrotepec, Michoacan, Mexico	J ? andesites Cr_2 calcareous marine sediments	T_1 granodiorite, aplite	several irreg.orebodies of magnetite in garnet,epidote skarn; 40 Mt Fe/49-55%	Min.Magaz. Oct. 1976
Marcona, southern Peru	PCm gneiss; PZ metasedim.incl.limest. and dolom.; J limestone,andesite,shale	Cr ? diorite granodiorite	numerous magnet.,pyr.,quartz actinol. up to 100 m thick bodies in a 20x8 km E.-W. zone; 2.65 Bt Fe/60%	Bellido and de Montreuil (1972)
El Pedroso,Jerez de los Caballeros,S.W. Spain	PZ limestone,marble	PZ_3 qtz.dior. granodiorite	magnetite bodies,interpr.as possibly volcanic-sediment., metamorphosed; 250 Mt Fe	Zitzmann, ed. (1976)
Elba Island, Italy	PZ andalus.schist Tr limest.,meta-keratophyre	Mi, quartz monzonite	magnetite-ilvaite masses near granite converted to goeth. gossan; interpreted as therm.modified "exhalative" ores; 35 Mt Fe	Zitzmann, ed. (1976)

Table 28-27 (continued). Phanerozoic magnetite skarn and replacement deposits, selected examples

LOCALITY	SUPRACRUSTAL HOST UNIT	INTRUSION	MINERALIZATION	REFERENCES
Sokolovka dep., Turgai distr., W. Kazakhstan, U.S.S.R.	Cb_2 andesite, tuff, limestone	Cb_3 gabbro, diorite granodior.	7.5 km long ore zone, peneconc. to discord., mass. to dissemin. magnet. in pyrox., actinolite skarn, envel. by albitization; 396 Mt Fe/41% Fe	Baklaev (1973)
Cürek and Divriği dep., E.C. Anatolia, Turkey	Eo limestone, serpentinite	Eo syenite, monzonite	2 orebodies, a contact magnet. skarn, and distal magnetite oreb. along limest.-serpentin. thrust contact; 56 Mt Fe/55%	Zitzmann, ed. (1976)
Dashkesan, Azerbaidzhan, U.S.S.R.	J_{2-3} andes., rhyol. tuff siltst., sandst., marl, slate	Cr_1 gabbro-granodior. gabbro-syen.	peneconc. magnetite skarn body up to 4 km long, garnet-pyrox., local access. cobaltite, glaucodote; 84 Mt Fe/42%, estim. 50 Tt Co	Sokolov and Grigor'yev (1974)
Teia (Teiskoe) dep., Kuznetsk Alatau, Siberia, U.S.S.R.	Pt_3-Cm_1 dolomite, basalt, andesite	Cm-Or syen., granosyen., diorite	magnesian skarn, forster., humite, spinel, diops., amphib., serpent., magnet., minor sulphides; a lens 1,500x300 m; 48 Mt Fe/33%	Sokolov and Grigor'yev (1974)
Tashtagol field, Kuznetsk Alatau Siberia, U.S.S.R.	Cm_2 greenschist, meta-andes., basalt, albitophyre, limestone	Cm-Or syenite, quartz syenite, syen. porph.	layer to lens, fault dismember. up to 1 km long, 40-70 m thick garnet, epid., magnet. skarn oreb. 152 Mt Fe/45%	Sokolov and Grigor'yev (1974)

Banat distr.(Dognacea, Ruschiţa, Ocna de Fier), Rumania	D, bimodal volc.-sed. assoc., carbonates; Cr-J limest., dolom.	Pc granod.	irreg. lenses of magnet., ilvaite, hedenb., garnet, ludwigite skarn, variable content of Cu, Zn, Pb sulph. Est. 20 Mt Fe	Ianovici and Borcoş (1982)
Gora Vysokaya near Nizhn. Tagil, Ural Mts. U.S.S.R.	S_3 limest., basalt, andes., pyroclast., volcaniclastics	D ? syenite	4 km^2 peneconc. replac. magn. oreb. in garnet-pyrox. skarn martitized, rubble zone; 31 Mt Fe/48.8%, 12 Tt Co	Baklaev (1973)
Peshchansk dep., Serov distr., central Urals, U.S.S.R.	D_1 limest., andes. and basalt volc., sedim.	D-Cb diorite	up to 60 m thick magnet., garnet, pyrox., epid. skarn; 87 Mt Fe/51%	Sokolov and Grigor'yev (1974)
Gora Blagodat, central Urals, U.S.S.R.	S, volc.-sedim. assoc. basalt, tuff, limest.	D-Cb diorite, syenite	tabular, lentic. garnet, epid., magnet. skarn; 50 Mt Fe/35% 22 Tt Co/0.022%	Sokolov and Grigor'yev (1974)
Magnitnaya Gora, Magnitogorsk, S. Ural Mts., U.S.S.R.	S_1-D_3 metabasalt, andes., phyllite, limest. over ophiolite	D-Cb gabbro to qtz. dior., granodiorite	2 peneconc. garn., pyrox., magnet. skarn lenses up to 115 m thick; 280 Mt Fe/56-65%	Baklaev (1973)
Kachar deposit, Turgai distr., W. Kazakhstan, U.S.S.R.	Cb_2 andes., andes. tuff, bituminous limest., slate	Cb_3 gabbro-dior., granodior., dior. porphyry	peneconc. magnet. bodies in scapol.-magn.; pyrox., garnet, magnet.; albite-magnet. assoc. 630 Mt to 2.23 Bt Fe/45%	Baklaev (1973)
Sarbai dep., Turgai distr., W. Kazakhstan U.S.S.R.	Cb_2 limest., andes. flows, tuffs, volcaniclastics	Cb_3 diorite porphyry	massive to dissem. conformable pyrox., scapol., albite, epid., actinol., magnetite lens up to 185 m thick, 2 km long; 684 Mt Fe/45.6%	Sokolov and Grigor'yev (1974)

28.19. MANGANESE DEPOSITS

Independent manganese deposits associated in some way with granitic plutons or forming hydrothermal orebodies are of limited importance and represent some 4 Mt Mn. In contrast, the Mn content of the siderite veins and replacements alone is at least 50 Mt Mn. Manganese mineralization styles are close equivalents of the iron deposits treated in the earlier paragraphs, and the following varieties can be recognized:

(1) Hypogene pyrolusite or manganite-filled veins in fault zones, greatly postdating the emplacement of granites which they may intersect. In the Erzgebirge, these veins are gradational into or interchangeable with the fibrous hematite-filled veins. Additional localities include the Harz Mts. and Schwarzwald in Germany; Sierra del Norte (part of Sierras Pampeñas), Argentina and others.

(2) Rhodochrosite, kutnahorite, manganocalcite or oligonite-filled veins. These are rare as independent orebodies, but common as gangue to Pb-Zn ores (e.g. at Philipsburg and Butte, Montana).

(3) Mn carbonates (the same as under 2) replacing limestone, dolomite or jasperoid. At Leadville, Pioche and other localities, Mn carbonates formed an alteration envelope around galena-sphalerite replacements.

(4) Mn-rich skarns (Mn-ilvaite, Mn-hedenbergite, rhodonite, dannemorite, etc.) are commonly associated with Pb-Zn sulphide orebodies, but there has been no substantial manganese production reported.

Most of the Mn production from "granite" aureoles was derived from psilomelane and cryptomelane accumulations in oxidation zones over Zn-Pb vein or replacement deposits with manganiferous gangue or alteration (e.g. Leadville, 550 Tt Mn; Pioche, Nevada, 330 Tt Mn; Philipsburg, Montana, 174 Tt Mn).

28.20. URANIUM DEPOSITS

28.20.1. General

Phanerozoic hydrothermal uranium vein deposits represent some 250 Tt U, and U minerals impregnations and fracture coatings in granite exocontacts acount for another 25 Tt U or so. This makes up a total of about 275 Tt U, a rather insignificant quantity compared with the 4 Mt U in currently recoverable ores, and additional tens of million tons of U in low-grade uraniferous sediments. Curiously, this style of U deposits is almost exclusively European and all but some 25 Tt U included in the 275 Tt total occur in a discontinuous belt of sialic, Proterozoic basement-floored Hercynian (=late Paleozoic) median massifs and blocks. These are intruded by Permo-Carboniferous granites and traceable, discontinuously, from Spain and Portugal through Cornwall, France and West Germany to the Bohemian Massif and Sudeten (Fig. 28-116). The bulk of the uranium came from the French

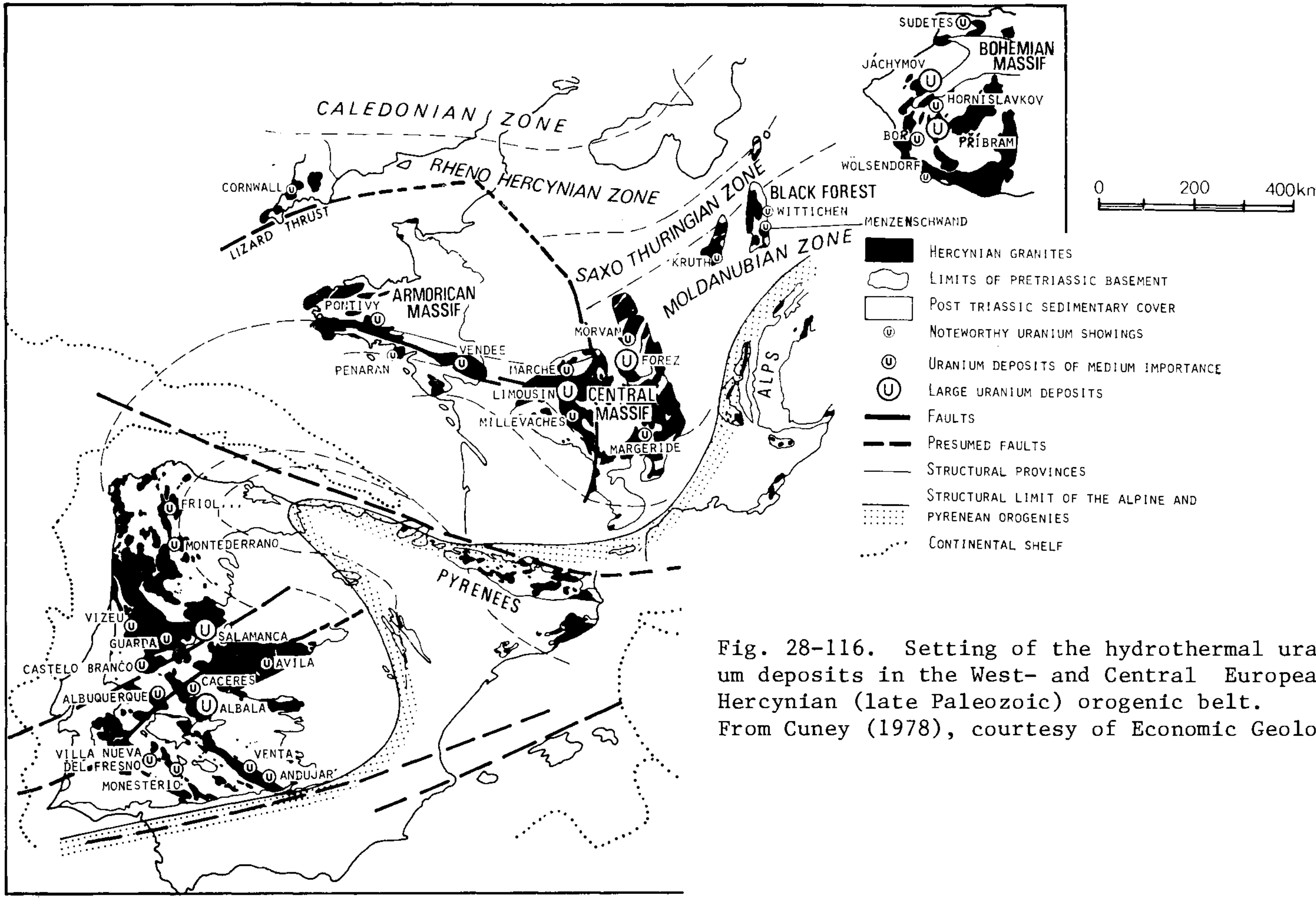


Fig. 28-116. Setting of the hydrothermal uranium deposits in the West- and Central European Hercynian (late Paleozoic) orogenic belt. From Cuney (1978), courtesy of Economic Geology.

(65 Tt U) and Czechoslovakian (estimated 150 Tt U) deposits.

Uranium deposits including those associated with granites have been reviewed recently by Nash et al. (1981) and Ruzicka (1971), and these authors distinguished three major "types" (or rather end-members) of granite-affiliated (or hydrothermal with uncertain affiliation) mineralizations: (1) mineralogically simple veins; (2) mineralogically complex veins and (3) exocontact fracture coating or disseminated ores. To this could be added (4) disseminated or stockwork U concentrations in granite endocontacts. Fig. 28-117 shows, diagrammatically, the U mineralization styles in the present setting.

28.20.2. Mineralogically simple uranium veins (Table 28-28)

These ores are contained in granite endocontacts (most of the French deposits), in metamorphics in granite exocontacts (most of the Czech deposits, Schwartzwalder mine in Colorado), or in both.

A "typical" small and simple intragranite orebody, such as the La Faye deposit near Grury, France (Roubault, 1956 and own visit, 1978; 2 Tt U/0.2%; Fig. 28-118), is hosted by an upper mesozonal, late Carboniferous coarse porphyritic biotite granite to quartz monzonite pluton. The main intrusive phase is cut by fine grained biotite microgranite, aplite and kersantite dikes. The intrusive rocks show evidence of high-level brittle fracturing with numerous thin zones of brecciation and mylonitization. Many fractures and faults have distinct and conspicuous red or pink alteration haloes, and several breccia or fracture zones have been converted into "episyenites", feldspathic (K-feldspar or albite) rocks formed by (a) dissolution and removal of quartz, sericitization of plagioclase and biotite, feldspathization of muscovite, preservation of orthoclase or (b) wholesale hydrothermal feldspathization of the wallrock. The variety of type (a) tends to be porous and reminescent of miarolitic structure. It is sometimes called "sponge rock". The (b) variety is usually hard, homogeneous and fresh-looking.

The mineralization at La Faye is represented by open space vein filling of fleshy red microcrystalline quartz, gradational into zones of silicification (jasper). The vein has numerous voids and vugs, and is about 1 m thick. The adjacent zone of brecciation and alteration is up to 10 m thick. Veinlets and nests of brown smoky quartz, dark violet fluorite and white or pink barite cut the microcrystalline quartz. Masses, veinlets, blebs of black pitchblende accompanied by pyrite and rare Ni-Co arsenides are irregularly distributed in the vein quartz and the adjacent breccia, and are accompanied by inconspicuous black sooty uraninite coatings. The oxidation zone has impregnations and fracture coatings of torbernite, autunite and kasolite.

The contrasting variety of uranium minerals apparent in this style of mineralization (the colourful, hexavalent U compounds; sooty pitchblende; massive, metacolloform pitchblende) triggered a

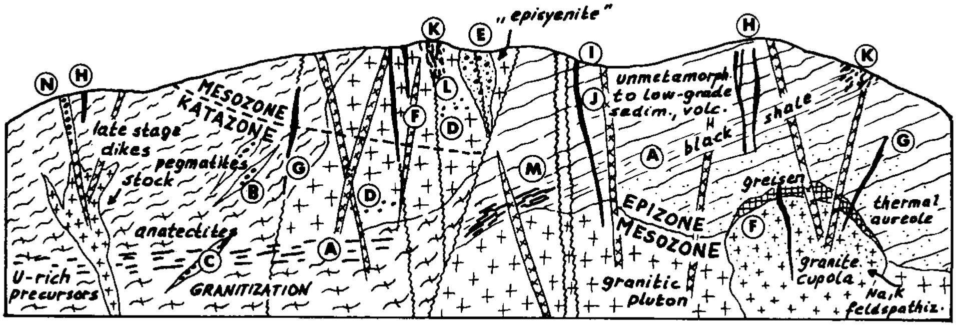
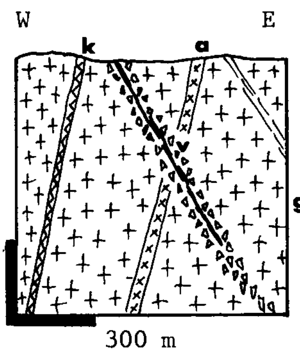


Fig. 28-117. Common styles of U mineralization spatially associated with granitic plutons (styles A-C are treated in Chapter 29). From Laznicka (1984). A=High trace U layered (foliated) supracrustal rocks (e.g. graphitic slate, schist); B=uraniferous anatectites, aplite and pegmatite veined katazonal granites (e.g. Rössing); C=discrete U pegmatites; D=minor (non-ore) accessory uraninite in mesozonal and katazonal S granites; E=disseminated "primary" and "secondary" U^{+4} oxides in "episyenite" (=desilicified and/or feldspathized granite); simple vein composition.

Discrete "main stage" quartz or carbonate, pitchblende, sulphides, etc. veins; F=wholly within granite; G=in granite and its roof; H=in the roof only. Supergene altered tops of ascending veins: I=U^{+6} oxides (torbernite, autunite, etc.) in the oxidation zone; J=U^{+4} sooty pitchblende in cementation zone. Shallow, descending infiltration veins, impregnations, stockworks of: l=U^{+6} oxides; L=sooty pitchblende. M=U^{+4} oxide stockworks, impregnations in granite-schist hornfelsed exocontacts; N=radioactive high level dikes.



k Cb-Pe kersantite dikes
a fine grained biotite leucogranite to aplite dikes
g Cb_3 coarse porphyritic biotite granite to quartz monzonite
v vein structure in brecciated and altered granite

Fig. 28-118. La Faye vein, Grury field, east-central France. Diagrammatic from LITHOTHEQUE, based on data in Roubault (1956).

Table 28-28. Phanerozoic hydrothermal uranium vein deposits, selected examples

LOCALITY	HOST UNIT	MINERALIZATION	REFERENCES
La Crouzille, Limousin, France	350-360 m.y. muscovitized, albitized two mica katazon. granite cut by lamprophyre dikes	275 m.y.,pitchbl.,pyr.,cherty hematitic quartz,musc.,fluorite in brecc.veins in granite. 33 Tt U/ 0.16%	Leroy (1978)
Bois Noirs-Limouzat, Forez, France	335 m.y. biot. granite, microgranite, 270 m.y. quartz porph.,lamprophyre	W.N.W.,N.W. vein structures, miner. porous gran.brecc.,pitchbl.,marc., pyr.,coffin.,Ol miner. 6.4 Tt U	Cuney (1978)
Grury, Morvan, France	Cb_3 porph.biot.gran. to qtz.monzon.,micrgroganite, lamprophyre	fiss.veins,brecc.+ mylonitiz.zones in silicif.,argilliz.,hemat.alter. gran. 1 m thick, red microcr.qtz., fluor.,barite,pyr.,pitchbl. 2 Tt U	Roubault (1956)
Les Pierre Plantées, Le Cellier,Margeride, France	Cb, granite massif, kersantite and lamprophyre dikes	LPP: patchy pitchbl.dissem.in min. episyenite granite; LC: pitchbl., coffinite vein in kersantite; 4 Tt U.	Geffroy (1971)
Saint-Sulpice des Feuilles, Basse-Marche, France	Cb granite, leucogranite	small qtz.,pitchbl.,coffinite, fluorite veins and masses in "episyenite"-altered granite	Geffroy (1971)
Urgeiriça, E.-C. Portugal	Cm schist, intruded by Cb granite, lamproph.dikes; N.E. faults, shears, mylon. zones	80-100 m.y. quartz,jasper,pyr., metacollof. and sooty pitchbl., gal.,sphal.,etc. veins in seric., silic.,chloritiz.,tourmaliniz. granite. 13.6 Tt U	Rich et al. (1971)
Menzenschwand, Schwarzwald, West Germany	granite gneiss, gneiss, schist, Cb granite	botryoid. and sooty pitchbl.fiss. qtz.,fluor.,barite, pitchbl., autunite veins; 60 t U.	Rein (1960)

Jáchymov-Abertamy field, N.W. Czechoslovakia	Pt_3-PZ_1 micasch.,amphibolite, calc-silic.gneiss,chl., biot.,graph.schist; Cb-Pe_1 biot.granite,gabbro	E.-W.,N.-S. veins of quartz,carbonate,pitchbl.,lesser fluor.,pyr., Ni,Co arsenides,Ag,Bi; estim. 40 Tt U	Ruzicka (1971) Mrňa and Pavlů (1967)
Johanngeorgenstadt-Potůčky, E.Germany and N.W. Czechoslovakia	Cm-S phyl.,andalus.micasch., biot.,graph.schists; Cb-Pe_1 granite, leucogranite	qtz.,dolom.,anker.,calc.,pyrite, pitchblende, Ni-Co arsenides, Ag sulphosalts veins; estim. 8 Tt U, 500 t Bi,Co	Ruzicka (1971)
Horní Slavkov, N.W. Czechoslovakia	Pt_3-S gneiss,schist,amphibolite,skarn. Cb_{2-3} biot.granite, leucogranite,greisen cupolas	multistage fissure veins in gran. exocont.,qtz.,dolom.,calc.,sider., pitchbl.,pyr.Hematitiz.wallrocks, some fluorite; N.W.,N.veins; estim. 10 Tt U	Ruzicka (1971)
Vítkov near Bor, N.W. Czechoslovakia	Pt or PZ gneiss, intrud.by Cb granodior.,aplite dikes	qtz.,carbon.,pitchbl.,pyr.impregn. in N.E. trending sericitiz.fault zone; estim. 6 Tt U	Ruzicka (1971)
Zadní Chodov,N.W. Czechoslovakia	Pt_3,PZ,biot.gneiss near contact with PZ_3 granodior., qtz. monzonite pluton	fine,sooty pitchbl. in mylonitiz., graphitiz.,carbonatized,chloritized shear; estim. 6 Tt U	Ruzicka (1971)
Bytíz-Kamenná zone, Příbram district W.Czechoslovakia	Pt_3 slate, grayw.,spilite; Cb qtz.diorite,granodior. pluton; diabase,lamprophyre dikes	25 km long N.E. fault lineament, 11 vein groups; lenses,chimneys, stockw.,calc.,dolom.,pitchbl.,pyr., gal.,sphal.,chalcop.,minor Ag, Ni-Co arsenides. Estim. 70 Tt U	Kutina (1963) Ruzicka (1971)
Rožínka-Olší zone, Centr.Czechoslovakia	Pt biot.gneiss,amphib.,marble,graph.gneiss	W.N.W.miner.shear zones,carbonate, chlor.,pitchbl.,pyr.;est.15 Tt U	Ruzicka (1971)
Schwartzwalder M., Ralston Creek,Colorado, U.S.A.	Pt_1 garnet-biot.gneiss,biot. schist,calc-silic.gneiss, amphibolite,quartzite	62 m.y.flat or horsetail pitchbl., coffin.,adular.,pyr.,hemat.veins in subsidiary faults	Young (1979)

controversy in interpretation. The genetic debate has essentially been between the proponents of descending origin and supergene U release (e.g. Barbier, 1974) and ascending origin with hypogene U sources, of the uranium deposits. Although many small occurrences can probably form by either mechanism, it appears that at sizeable and relatively deep mineralization systems (1) the massive pitchblende is the "primary" ore, most probably precipitated from ascending fluids in depth; (2) sooty pitchblende is the equivalent of the zone of secondary sulphides at base metal suphide deposits (e.g. porphyry coppers) and (3) the hexavalent U salts mark the oxidation zone. Leached capping usually marked by barren quartz, porous silicification quartz and clay fault gouge residue, is sometimes developed.

Cuney (1978) recently interpreted, in detail, the geological environment and the activity resulting in the formation of the Bois Noirs-Limouzat uranium vein system (Forez, N.E. Massif Central, France; 6.4 Tt U). The deposit is hosted by a mesozonal Carboniferous (335 m.y.) granite interpreted as anatectite, emplaced into a Proterozoic gneiss and amphibolite terrain. The early phase granite was partly deuterically altered (to quartz, microcline, albite and chlorite). Accessory uraninite associated with quartz-muscovite alteration crystallized subsequently from a residual fluid phase. The economic uranium ore consists of pinch-and-swell ore shoots composed of comb and microcrystalline quartz, pitchblende, marcasite, pyrite with minor fluorite, chalcopyrite, hematite, galena, etc., filling N.W.-trending fractures and breccia zones. The main stage mineralization is interpreted as being a product of low-temperature (300-70^{o} C; 100-70^{o} C for pitchblende) uranium mobilization througout an interval of about 65 m.y. duration following the granite crystallization. A post main-stage process modified portion of the earlier pitchblende into coffinite, and a "per descensum" remobilization during the Oligocene age produced sooty pitchblende and hexavalent U minerals.

The small deposit Les Pierre Plantées in the Margeride ore field, S. Massif Central, France (Geffroy, 1971) is an example of a mineralized "episyenite" alteration pipe in granite. The pipe contains local patches of pitchblende impregnations.

The Schwartzwalder mine near Golden, Colorado (Young, 1979; 8.5 Tt U; Fig. 28-119) is an example of a mineralogically simple uranium vein system in metamorphics, and also the largest Phanerozoic uranium vein deposit in the Americas. The host rocks are lower Proterozoic garnet-biotite gneiss, calc-silicate gneiss and metaquartzite. "Laramide" (late Cretaceous-lower Tertiary) quartz monzonite and granite porphyry dikes are known within 2 km of the deposit. The veins are structurally controlled by an intersection of a fold nose with a N.-S.-trending, steeply west dipping fault zone, and the ore is persistent vertically for over 900 m without change in grade or mineralogy. The ore shoots are both within the main fault, and in branch and feathering-away fractures. The vein filling is ankerite, pyrite, adularia, hematite, pitchblende, coffinite. The ore deposition has been dated between 52 and 73 m.y., which is broadly

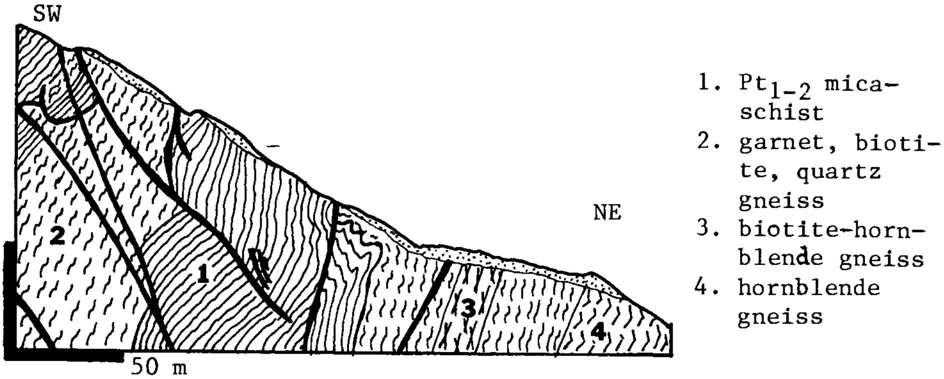


Fig. 28-119. Schwartzwalder U deposit, Ralston Creek, Colorado. After Sheridan et al. (1967).

contemporary with the Laramide phase of intrusive activity in the Colorado Front Ranges.

28.20.3. Mineralogically complex uranium veins

The hydrothermal Ni,Co,Bi,Ag,As association described in Section 28.16., frequently combines with uranium to form mineralogically complex veins. The Jáchymov-Abertamy field described earlier is the best known example which, in its 500 years of mining history, evolved from a silver-mining camp through cobalt, radium production into a post-World War II uranium boom town, before its final exhaustion in the 1960s. The geology of the field was reviewed earlier (compare Fig. 28-104). Pitchblende formed in the third mineralization stage only, accompanied by dolomite, lesser pyrite and fluorite. It is interesting to note that in all the mineralogically complex U vein deposits, the actual U-depositing stage is compositionally identical to the "simple U veins" treated earlier. The additional metals were introduced either earlier or later.

In the Eastern (uraniferous) ore zone in the Příbram district, western Czechoslovakia (Ruzicka, 1971; see also Fig. 17-8 and short description in Section 17.6.3.), a N.E.-trending fault system, 25 km long, contains eleven or more discontinuous uranium vein groups (segments). The tonnage figures have not been released, but it is estimated that the zone represents a minimum of 70 Tt U. The faults are developed in, and the ore hosted by, late Proterozoic gray to black pyritic slates and litharenites with minor tuffaceous and mafic metavolcanic horizons. It parallels the contact of the composite, mainly Carboniferous tonalite and granodiorite-dominated Central Bohemian Pluton in the east (see description of the Pluton in Section

28.2.3.). A portion of the metasediments is thermally hornfelsed and intruded by diabase, granite porphyry and lamprophyre dikes.

Ore shoots within the mineralized segment, many of them blind, have the form of short lens-like veins, chimneys, ore bunches or stockworks. They are locally crowded by, or gradational into, fault gouge and mylonite. About 12% of the vein-filled faults contain economic uranium shoots. The ore deposition took place in three stages which are as follows: (1) siderite, quartz, sphalerite, galena, dolomite, arsenopyrite, lesser Ni-Co arsenides, native silver. This phase is comparable with the vein filling in the western ("Old") Příbram Pb,Zn,Ag zone. (2) calcite, dolomite, ankerite, pitchblende, rare U-pyrobitumen, pyrite and (3) barren calcite, lesser pyrite. The carbonate-U stage took place at low temperature and alteration was slight, mainly chloritization, sericitization, hematitization and carbonate impregnation and veining of the fault gouge.

28.20.4. Exocontact fracture coating and disseminated ores (Table 28-29)

The Midnite mine, 50 km N.W. of Spokane, Washington (Nash et al., 1981; 4.6 Tt U/0.18%; Fig. 28-120), is frequently quoted as a type locality for a "contact" uranium mineralization. There, several tabular orebodies are hosted by a middle Proterozoic thermally hornfelsed siliceous pyritic phyllite and calc-silicate schist, at contact with late Cretaceous porphyritic biotite granite. Sooty pitchblende, coffinite, lesser pyrite, marcasite, arsenopyrite, chalcopyrite and sphalerite occur as disseminations along foliation and stockworks of fracture fillings in phyllite, and replacements in metacarbonate bands. Autunite and metaautunite occur in the oxidation zone. The Fé and Nisa deposits in Spain and Portugal are similar in many respects.

28.20.5. Disseminated and stockwork uranium in granite endocontacts

Under a tempting headline of "resources of the future", Armstrong (1974) popularized the concept of "porphyry uranium deposits". Unfortunately, most of the examples he used are mineralized deep-seated anatectites, katazonal granites and pegmatites far away from the mineralized "porphyries" treated earlier as hosts to Cu,Mo,Sn and other ores. The deep-seated ore systems will be reviewed in Chapter 29.

Curiously, high-level calc-alkaline intrusions (with the exception of several examples associated with continental volcanics and discussed in Chapter 26) do not seem to accumulate uranium substantially in a form comparable with the Cu,Mo or Sn stockworks or pervasive accumulations. The highly mobile uranium tends to leave the system and accumulate preferentially in the derived sediments. Exceptions occur when U (together with Th,REE,Ta,Nb, etc.) is bound in

Table 28-29. Phanerozoic "granite contact" uranium deposits

LOCALITY	HOST UNIT	GRANITIC INTRUSION	MINERALIZATION	REFERENCES
Midnite mine near Spokane, Washington U.S.A.	Pt_2 partly graphit. schist, calc-silicate hornfels, marble	Cr_3 (75 m.y.) porph. granite	380x210x50 m tabular oreb. of dissem., replac. pitchbl. and coffinite in exocontact partly // with foliation; miner. age 50-52 m.y. 4.6 Tt U/0.18%	Nash et al. (1981)
Les Bondons dep. near Mt. Lozère, Cévennes, France	Cm-Or graph. schist micasch., quartzite andalus.-biot. met.	290-280 m.y. granite locally altered to episyenite	impregn. along fract. in schists, up to 200m from gran. contact; pitchblende, coffinite, pyrite; Tr_3 supergene alteration	Eulry and Vargas (1980)
Fé deposit near Ciudad Rodrigo, Spain	Pt_3, Cm, hornfelsed meta-graywacke, shale	Cb, biot. granite	pitchbl. with pyr., chlorite in fract. veinlets in hornfelsed metased. 11.9 Tt U	O.E.C.D. (1979)
Nisa deposit, Alto Alentejo, Portugal	pre-Or schists	PZ_3 granite pluton	autunite, saleeite, bassetite phosphouranylite, impregn. along faults, fractures, foliation, breccia zones	O.E.C.D. (1979)

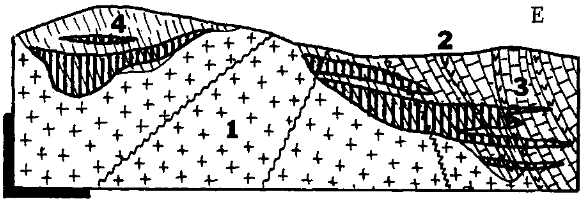


Fig. 28-120. Midnite U mine, Washington, U.S.A. Generalized after Nash et al. (1981).

accessory heavy minerals such as fergusonite, euxenite or monazite (e.g. Bugaboo, British Columbia), or is present in dispersed or cation-substituting form as in the bostonite dikes in the Central City gold field, Colorado (up to 100 ppm U in some dikes). Several stockwork and disseminated U accumulations in the alkaline association will be reviewed in Chapter 33.

28.21. ANTIMONY DEPOSITS

Antimony deposits are a very interdisciplinary group, difficult to pigeonhole. Of the total of some 6.5 Mt Sb in ores, worldwide, about 50% is in silicified carbonates (jasperoid) under a shale or schist screen (or possibly a Sb source), controlled by faults and lithology. Almost 33% of the total is contained in a single field, Hsikuangshan in China. The above low-temperature mineralizations are, in regard to granitic intrusions, distal, and their formerly automatically considered association with "granites" is no longer considered to be universal. For that reason, these deposits have been reviewed under the headings of their common host rocks, carbonates and "black" argillites (Section 17.10.4.).

Of the remainder, about 10% Sb occurs in the Precambrian deposits, reviewed in Volume 2; 6% is in subvolcanic deposits (Chapter 26) and 4% in (pene)concordant lenses in (meta)volcanics and sedimentary associations. The latter are presently largely considered to be stratiform, although often subsequently modified by tectonism (Stadt Schlaining, Austria) or by intervening later granitic intrusion (Pezinok, Pernek, Slovakia). About 30% of Sb deposits (Table 28-30) appear to be "classical" epigenetically emplaced hydrothermal bodies (veins, stockworks, replacements), some of them undisputably affiliated with "granites".

Antimony is widespread in lesser quantities in polymetallic deposits in which the main (or most valuable product) is Pb-Zn, Ag, Au, W, Hg and a few other metals. It is, however, rarely recovered in the metallic form and sold hence the presence of antimony is rarely recorded in the statistics. This class of deposits is gradational into another class of mixed ores, where the Sb content is substantial and is recovered as a by-product, together with other metals. Some example localities are listed in Table 28-31. The last, most distinct category, consists of stibnite-only (or quartz, stibnite, pyrite) orebodies. Some of these are gold-bearing.

Antimony is a cheap metal (in the region of $ 3-4 per kilogram), so only very high-grade orebodies (3% Sb plus, or around 30-40% Sb in the case of hand-cobbed concentrates) have been economic to mine until recently. Since the Sb clarke (mean crust content) is very low (0.2 ppm), the common antimony orebodies have enormous factors of concentration (150,000 times the clarke). With the exception of Hsikuangshan, most Sb deposits and fields are small to medium-sized. Low-grade "bulk" Sb deposits are little known, unless they contain other, usually more valuable commodities (e.g. gold and scheelite as in the Yellow Pine mine, Idaho).

Stibnite deposits are hosted both by "granites" and by supracrustal rocks. Stibnite in "granites" is always substantially younger than its host, and appears to be related to a later-stage hydrothermal activity frequently corresponding to an "activation" regime. Black slate to phyllite or schist, flyschoid, and marine volcanic-sedimentary associations are the most common hosts to Sb ores. Some such occurrences have been interpreted, with increasing frequency, as modified "stratiform" accumulations (e.g. Höll, 1966, 1977; Höll and Maucher, 1976), or products of lateral secretion (Roger, 1972).

The Lake George deposit, 40 km W.S.W. of Fredericton, N.B., Canada (Abbott and Watson, 1975; about 35 Tt Sb; Fig. 28-121) is an example of the simple stibnite veins, probably genetically associated with mesozonal granites. The ore is hosted by a folded, cleaved and hornfelsed Silurian slate, calcareous slate, siltstone and litharenite. Devonian porphyritic biotite quartz monzonite is anticipated in depth, and there are kersantite dikes in the mine field. Several E.-W. fracture veins filled by quartz and carbonate contain discontinuous ore bunches and lens-like ore shoots. Stibnite forms more than 90% of the ore minerals, the rest being arsenopyrite, pyrite and rare tetrahedrite. The grade ranges from 5.22 to 12.7% Sb and Au and Ag are so low and irregularly distributed that they are not recovered.

The Hillgrove field 30 km E. of Armidale, N.S.W., Australia (Harrison, 1953; own visit, 1980; over 16 Tt Sb, 15 t Au, 1.4 Tt W; Fig. 28-122), is an example of an Sb,Au,W-mineralized discrete veins. The field is underlain by cleaved, sheared and thermally metamorphosed lower Permian "flyschoid" gray slate to schist, containing thin quartzite and litharenite interbeds. This has been permissively intruded by a later Permian biotite quartz monzonite and sheared, fractured shortly after the intrusion cooling. A system of numerous N.W.-trending shears and fractures in both endo- and exocontact is filled by granodiorite porphyry dikes and steep quartz,

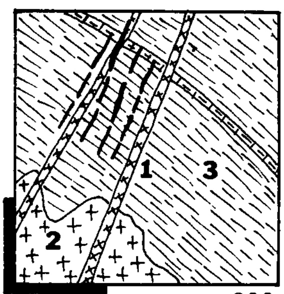
Table 28-30. Hydrothermal Sb deposits or districts hosted by or affiliated with "granites"; selected examples. NOTE: distal Sb replacements or "stratiform" deposits accompanied by jasperoid are reviewed in Table 17-6.

LOCALITY	HOST ROCKS	MINERALIZATION	REFERENCES
Lake George, N.B., Canada	S,contact hornfelsed slate, siltst.,calcar.siltst.; D,porph.biot.qtz.monzonite, kersantite dikes	several E.-W. striking quartz,stibnite,lesser arsenopyrite,pyrite fissure veins; 35 Tt Sb/3%	Abbott and Watson (1975)
Yellow Pine, Idaho, U.S.A.	J-Cr,slightly foliated biot. qtz.monzon. and aplite,intr. Or? carb.and detrit.metased. T, qtz.latite, rhyol.dikes	Large irreg.complex oreb. hosted by shattered and alterd qtz.monzon.in hangingw.of a shear. Low-grade gold bearing dissem.pyr.+arsenop.is followed by stockw.scheel.and stibnite 79 Tt Sb/0.81%,206 t Au,6,365 t W	Cooper (1951)
Tupiza region, S. Bolivia	Or,D,slate with black slate interbeds,thin arenite partings; minor qtz.monz.intr.	simple discord.qtz.,stibn.,pyrite minor ferber.veins,along shears and faults; 279 Tt Sb/8.78%	Ahlfeld and Schneider-Scherbina (1964)
Brioude-Massiac, Massif Central, France	Cm-Or biot.schist,gneiss, migmatite; Cb sandstone; Cb biot.granite,microgranite	Cb_3 veins along N.E. faults. Qtz., carbonate,stibn.,pyr.,lesser berthierite,arsenop.filling; 40 Tt Sb	Roger (1972)
La Lucette, Armoricain Massif, N. France	S-D metaquartzite, schist	Cb, quartz,stibnite,arsenop.,pyrite lesser galena,gold, fissure veins	Routhier (1963)
Dúbrava, Magurka, Nízké Tatry Mts., E. Czechoslovakia	PZ_3 cataclast.meso-to katazonal granite,granodior., quartz monzonite	E.-W. and N.-S. quartz,stibnite,pyrite,minor jameson.,berthier.,gold fissure and shear veins,impregnations in graphitic mylonite; estim. 65 Tt Sb, 3 t Au	Mahel' and Buday, eds. (1968)

Helcmanovce,Čučma, Spiš-Gemer Mts., E. Czechoslovakia	S-Cb black phyllite,chert, carbonate,bimodal metavolc. Cr granite cryptobathol.?	quartz veins with massive lenses to dissem.of stibnite, minor pyr.,ars., sphal.,gal.; estim. 35 Tt Sb	Mahel' and Buday, eds. (1968)
Krupanj-Zajača, Drina district, Yugoslavia	Cb-Tr litharenite,slate, limest.,dolom.;folded,thrusted; intr.by Mi dacite, andesite, granodiorite	peneconc.replac.bodies of stibnite with jasperoid in carbonates; breccia cementing stibnite; quartz,calcite gangue, minor galena, boulangerite; 120 Tt Sb	Janković (1982)
Sarylakh, N.E. Yakutia, U.S.S.R.	Tr$_3$ sandst.,siltst.,shale; J$_3$ qtz.diorite porphyry stocks	N.W. striking miner.crush zones, irrregular quartz,stibnite,pyrite, arsenop.veins; silicif.,sericitiz. wallrocks; estim. 20 Tt Sb	Zharikov (1974)
Bau district, Sarawak,Malaysia	J-Cr$_1$ polymictic subduction melange rich in sheared shale,grayw.,greenst.,chert, ultramaf. Cr$_3$ granitic pl.	auriferous stibnite in silicif.limest. and in veins; Au in eluvial placers; about 55 Tt Sb, 28 t Au	Kho (1976)
Hillgrove-Metz, New England, N.S.W., Australia	Pe$_1$ hornfelsed,cleaved slate to schist; Pe$_{2,3}$ quartz monzon.,sheared;granodior. dikes, diorite stocks	Pe$_3$ stibnite or qtz.-stibnite,scheel., gold shear and fissure veins, N.W. striking, in hornfels and granite; 16 Tt Sb, 1,370 t W, 15 t Au	Harrison (1953)
Costerfield,Victoria, Australia	S-D$_1$ gray to black slate, litharenite; D, biotite granite	D, quartz-stibnite simple and branching fissure veins up to 6 m thick; 22.4 Tt Sb	Hill (1975)

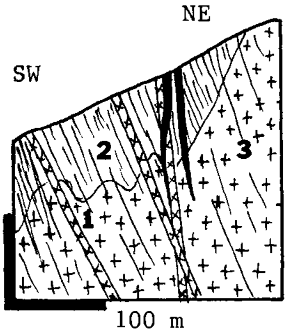
Table 28-31. Mineral associations of selected polymetallic vein deposits containing significant proportion of antimony

METAL ASSOC.	MINERALOGY	EXAMPLE LOCALITIES
Sb-Au	quartz, calcite, ankerite, stibnite, arsenopyrite, gold	Magurka, Czech.
Sb-Hg	dolomite, livingstonite, stibnite, anhydrite, native sulphur	Huitzuco, Mexico
Sb-As	quartz, stibnite, arsenopyrite, pyrite, galena, gold	La Lucette, France
Sb,As, Ni,Co,U	quartz, dolomite, stibnite, realgar, pyrite, marcasite, bravoite, pitchblende, vaesite	Lojane, Yugosl.
Sb,Ag, Pb,Zn	siderite, quartz, ankerite, galena, sphalerite, chalcopyrite, tetrahedrite	Coeur d'Alene, Idaho
Sb,Cu	siderite, tetrahedrite, quartz	Schwaz, Austria
(Ag,Hg)	siderite, quartz, tetrahedrite, pyrite	Sunshine m., Idaho
Sb,W	quartz, wolframite, pyrite, scheelite	Osanica, Yugosl.
	quartz, dolomite, calcite, pyrite, stibnite, arsenopyrite, scheelite	Yellow Pine, Idaho
	quartz, scheelite, pyrite, arsenopyrite, stibnite, calcite, gold	Hillgrove, N.S.W.
Sb,As Tl	quartz, dolomite, stibnite, realgar, orpiment, arsenopyrite, marcasite, pyrite, sulphur, lorandite, vrbaite	Alšar, Yugoslavia
Sb only	quartz, stibnite, pyrite	Zajača, Yugosl.
	quartz, stibnite, pyrite, arsenopyrite, berthierite	Brioude-Massiac, Fr.



1. D, biotite kersantite dikes
2. D, porphyritic biotite quartz monzonite
3. S slate, calcareous slate, siltstone

Fig. 28-121. Lake George Sb deposit, New Brunswick, Canada (diagrammatic). From LITHOTHEQUE.



1. Pe_3 qtz.monzonite and granodiorite porphyry dikes
2. Pe_1 gray cleaved slate to schist, minor quartzite and litharenite
3. Pe_2 medium crystalline to porphyritic protoclastic biotite quartz monzonite sheared and altered in the ore zone

Fig. 28-122. Hillgrove vein stibnite and scheelite field, N.S.W., Australia (generalized). From LITHOTHEQUE.

quartz-stibnite, quartz-gold and quartz-scheelite veins. The Sb-mineralized structures contain fine crystalline ("steely") or fibrous stibnite as bunches, lenses, fracture fillings or as disseminations in slightly bleached or unaltered hornfels, or in a slightly sericitized cataclastic quartz monzonite. Brecciated and sheared vein stibnite and stibnite-coated slickensided fractures are common.

The Stibnite (a ghost town) ore field in the Yellow Pine district, central Idaho (Cooper, 1951; 79 Tt Sb, 206 t Au, 6,365 t W, 170 t Ag; Fig. 28-123) has an interesting combination of metals and mineralization styles probably emplaced at a variety of levels along and within a N.E.-trending broad shear and fracture zone. The host rock is a mesozonal Jurassic to Cretaceous slightly foliated biotite quartz monzonite, intersected by numerous aplite dikes and emplaced into carbonates and detrital metasediments of probably Ordovician age. These rocks have been faulted and sheared probably in the early Tertiary period and the Meadow Creek Fault zone is a fault gouge-filled structure up to 50 m wide. Fracturing and shearing is intense in quartz monzonite in the hangingwall (west of) the main shear in the Yellow Pine mine field, and an irregular block 660 m long, 230 m wide and more than 130 m deep, contains the mineralization.

The ores formed in three successive hydrothermal phases probably in the middle or late Tertiary age, and broadly coincide with the emplacement of felsic (quartz latite, rhyolite porphyry) and mafic dikes. The earliest phase produced the broadest zone of sparsely disseminated auriferous pyrite and arsenopyrite. This zone contains gold values ranging from 1.4 ppm to 6.53 ppm Au and is currently mined as a large ("bulk"), low-grade gold orebody reminescent of the "Carlin-type". The gold is invisible, bound in the sulphides. The associated alteration is a broad fracture carbonatization,

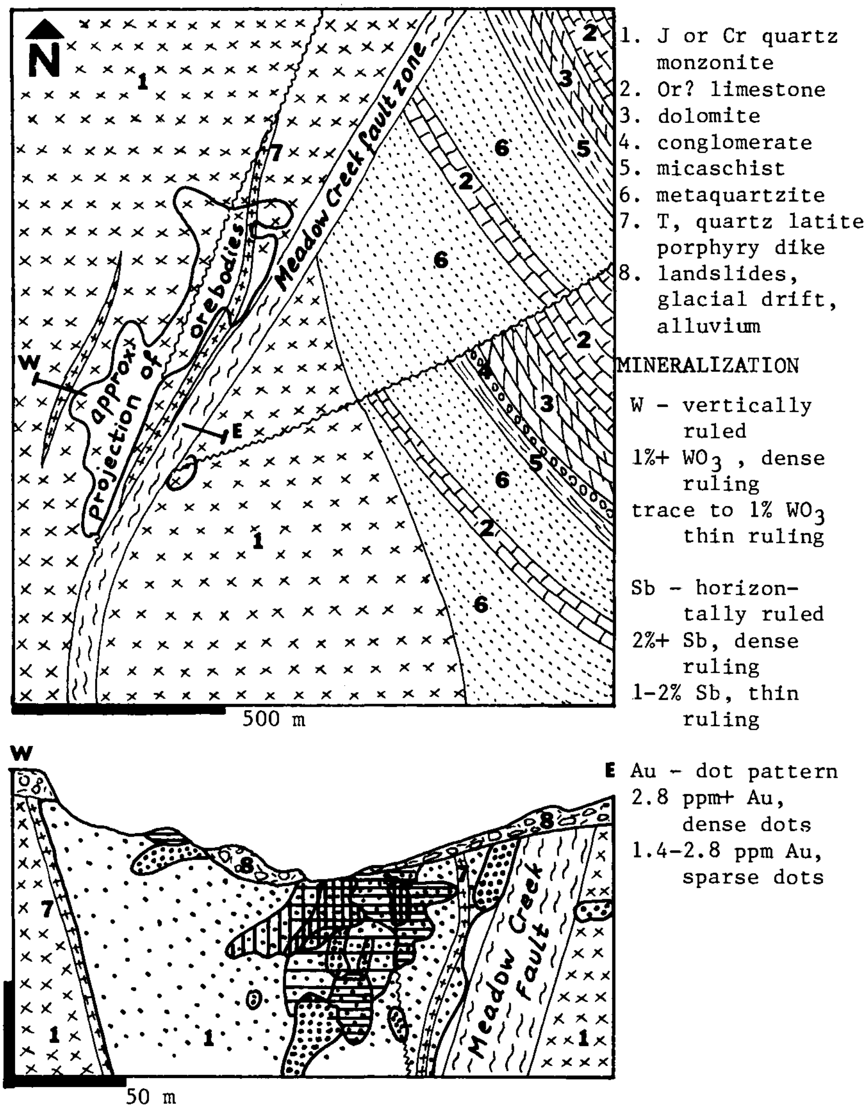


Fig. 28-123. Yellow Pine Sb-W-Au mine, Idaho, map and section. From LITHOTHEQUE, modified after Cooper (1951).

sericitization, silicification and biotite bleaching.

A relatively high-grade (1.7% W) but small scheelite orebody formed during the second phase, in the centre of the mineralized zone. Most of the scheelite is fine grained, disseminated in brecciated gold ore, or filling small veinlets and stringers. A portion of the scheelite appears to have replaced an earlier generation of calcite fracture veinlets. Stibnite orebody envelopes and overlaps the scheelite body, and consists of disseminations, thin veinlets, stockworks, massive lenses, small veins, and scattered crystals on fractures. The antimony grade in the period of wartime mining was 4% Sb, but there is still a large amount of ore with 0.81% Sb left. The stibnite is silver-bearing. Several cinnabar occurrences (the largest was Hermes mine) are known that are located within 5 km from the Yellow Pine Au,W,Sb orebody.

28.22. MERCURY DEPOSITS

In the classical model of the 1940s, cinnabar deposits were placed into the "telethermal" category in terms of their association with granitic intrusions. These days there is a tendency to dismiss the "granite"/cinnabar affiliation altogether, and attribute Hg deposition to hot springs, "exhalations", volcanism, etc. Some of the late Cainozoic low-temperature cinnabar depositing convecting spring systems such as those in the Clear Lake area, California (McLaughlin, 1981; compare Section 5.7.5. and Fig. 5-5 for discussion), however, have been interpreted as having been heated and controlled by an evolving silicic intrusion 7 km under the surface (hence a mesozonal granite according to the depth zoning as shown in Chapter 27!).

Consequently, the "granite"/cinnabar genetic affiliation cannot be dismissed altogether but, given the highly disparate depth levels of formation of both, the presence of "granite" on the surface is indeed of little assistance in exploration for Hg orebodies. Epigenetic, low-temperature hydrothermal cinnabar concentrations hosted by ophiolites, subduction mélanges, "black" sedimentary association, shallow-marine and continental sediments, have been treated in Chapters 7,8,16, 17,19,20 and 26, respectively.

Several small Hg occurrences are known which are hosted by older, genetically probably unrelated "granites". At the Yamato mine, Japan (Saito, ed., 1960), late Paleozoic biotite granite hosts irregular cinnabar mineralized fissure veins. The ore emplacement is probably Miocene or Pliocene.

At several localities in the Gordonbrook serpentinite belt, New England, Australia (Yulgilbar, Pulganabar, Lionsville; Carne, 1913), cinnabar was deposited in small quantities at sites of interaction of ultramafics and Permian "granites". In Yulgilbar, cinnabar forms disseminations and narrow siliceous replacement veins in hornblende granodiorite near the contact with diorite dikes and about 1-2 km from the edge of the serpentinite belt. Only about 2.3 t Hg were produced. At Lionsville, sparsely disseminated cinnabar is located on both sides of a contact of felsite porphyry dike in serpentinite. At Pulganabar, quartz, calcite, specularite, Hg-tetrahedrite and cinnabar veins are situated in the endo- and exocontact of granodiorite and tourmaline granite.

28.23. BISMUTH DEPOSITS

Most depositional accumulations of bismuth are associated with "granites", but usually Bi is a by-product or unrecovered companion metal in Sn-W, Pb-Zn, Au, Cu, Ni,Co,Ag, and U deposits. Orebodies mined for bimuth only are exceptional (e.g. Tasna, Bolivia). Data on minor and trace Bi distribution in ore deposits are fragmentary and often unreliable. A substantial proportion of Bi is recovered in smelters that process ores from a broad region (e.g. the La Oroya smelter, Peru, to which the single largest ore supplier is Cerro de Pasco). Of the 350 Tt Bi in major ore accumulations that could be accounted for, 275 Tt Bi are in Sn-W-Mo skarns (Xi Zhoyouang, China, 230 Tt Bi; Gejiu, China, 30 Tt Bi ?; Sandong, Korea, 9 Tt Bi; Brichmula-Ustarasai, Soviet Central Asia, no data). 8 Tt Bi is in Zn-Pb skarns (Kamioka, Japan, 6.24 Tt Bi; Baiţa Bihor, Rumania). 2 Tt Bi is in magnetite skarns (e.g. Biggenden, Queensland; Chokadam-Bulak, Uzbekistan). 28 Tt Bi is in subvolcanic and high-level plutonic W,Mo,Sn veins and stockworks (Mt. Pleasant, Canada; 24 Tt Bi; Tasna, Bolivia, min. 1.2 Tt Bi). 10 Tt Bi is in massive pyritic replacements and superimposed veins (Cerro de Pasco). 7 Tt Bi is in quartz, gold, arsenopyrite veins (Salsigne, 5 Tt Bi). About 5 Tt Bi is in Ni,Co,Bi,Ag,U veins (Schneeberg, Johanngeorgenstadt, Jáchymov). About 10 Tt Bi is in Precambrian deposits (Tenant Creek, Boliden) and 5 Tt Bi in miscellaneous hydrothermal ores. Most of the Bi-containing mineralization styles have already been described earlier, and bismuthinite with native bismuth are the two principal Bi minerals.

In the Biggenden ore field, S.E. Queensland (Clarke, 1969), Lower Permian nearshore marine to continental andesite and basalt flows, pyroclastics, volcaniclastics, argillite and limestone, are intruded by lower Triassic porphyry dikes and biotite granodiorite. In the exocontact, basic hornfels formed from the volcanics and hornblende, epidote, scapolite, magnetite, sphene skarns were generated from the impure carbonate. Bismuthinite and rare native bismuth with lesser chalcopyrite, sphalerite, tetrahedrite, cobaltite and molybdenite, are disseminated in magnetite. The total production has been about 470 t Bi and 1.28 t Au.

28.24. ARSENIC DEPOSITS

Arsenic is extremely widespread in many styles of hydrothermal-plutonic ores, but it is rarely recovered and sold due to lack of demand. Consequently, quantitative data on As accumulations are scarce. About 3 Mt As can be accounted for as having been present in Phanerozoic hydrothermal-plutonic deposits (largest accumulations for which data are available: Cerro de Pasco, 1.5 Mt As; Olympias mine, Chalkidiki, Greece, 240 Tt As/2.4%, in Pb-Zn skarn and replacement; Hedley, British Columbia, about 200 Tt As/5%, gold-bearing arsenopyrite skarn; Salsigne, France, 150 Tt As/3%, complex gold vein deposit).

Few major deposits have ever been mined for As alone. When arsenic was recovered, it was almost always a by-product, usually of gold. This applies even to the largest-known massive arsenopyrite accumulation in the Boliden deposit, Sweden (544 Tt As/6.8%; this is a Precambrian orebody treated in Volume 2). Magak'yan (1968) discussed two Soviet localities (Mosrif and Takeli, both in Tadzhik S.S.R.) as examples of As deposits, but both are complex high-As carbonate replacements containing also Pb,Zn,Cu, Au,Ag, and other metals.

Arsenic deposits have traditionally been subdivided into three broad classes: (1) high-temperature deposits developed in the proximal intrusive exocontact, such as As and complex skarns and carbonate replacements, and quartz-arsenopyrite veins. In the endocontact, arsenopyrite is significantly distributed in many greisens (e.g. Krásno, Czechoslovakia). Magak'yan (1968) mentioned a "porphyry arsenopyrite" occurrence in granodiorite from Takeli, having a grade of 2% As; (2) medium-temperature (mesothermal) deposits, in which As is partly contained in arsenopyrite, partly in enargite or tennantite (Butte, Cerro de Pasco, Morococha); in Ni-Co arsenides (Jáchymov) or in Ag-sulphoarsenides such as proustite and (3) low-temperature realgar-orpiment deposits, limited to high-level accumulations usually attributed to the activity of hot springs (Getchell, Nevada; Matra, Corsica; Tajov, Slovakia). Most styles of As-containing mineralizations have already been described.

28.25. MINOR METALS AND METALLOIDS: Se,Te,Tl, In,Ge,Ga, Cd

The above metals (except Cd) are produced in small quantities from "technological ores" such as the residues after electrolytic Cu and Zn recovery; from slimes that accumulate during sulphuric acid production from pyrite or from similar materials. The deposits from which the rare metals were derived need not demonstrate any anomalous local enrichment of such metals and need not contain their discrete minerals (e.g. Butte is credited with the total production of 107 t Te and 143 t Se; the smelter in La Oroya, Peru, produced about 50 t In, 20 t Te and 20 t Se in 1982; Eng. and Min. Journ., November 1984, derived from 6 major and about 200 small deposits in the region).

In contrast to the "technological ores", certain deposits and occurrences contain widely quoted minerals of rare metals, but in quantities so small that industrial production of the contained metals would be uneconomic. Such localities are, nevertheless, listed in the literature as "deposits" of such metals.

Selenium

The largest recorded Se accumulation in metallic ores (2.4 Tt Se/0.03%) has been reported in the Precambrian Boliden deposit, treated in Volume 2. Of the rest, Se minerals have been recorded from: (1) pitchblende vein deposits (clausthallite, berzelianite, tiemannite, e.g. in Olší, Slavkovice and others localities, Czechoslovakia); (2) Ag deposits with naumannite; (3) Au,Se,Pb occurrences, e.g. Corbach, West Germany and (4) carbonate-polymetallic veins, e.g. Tilkerode, Germany; Sierra de Umango, Argentina; etc.

Tellurium

Tellurium is most conspicuous (but rarely recovered) in Au and Ag tellurides (sylvanite, hessite, petzite, krennerite, nagyagite) and as native tellurium, in the Au-Te association. This could be either subvolcanic (e.g. Apuseni Mts., Rumania; Cripple Creek, Colorado) or plutonic (e.g. Bohuliby, Czechoslovakia; Darasun, Siberia; Jamestown, Colorado). Non-precious metals tellurides (e.g. tetradymite) are common at vein gold deposits as well as in some polymetallic deposits.

Thallium

Thallium is enriched in some "Carlin-type" deposits of "invisible" dispersed gold replacements in carbonaceous sediments (e.g. Mercur, Utah; 1.8 Tt Tl) and in some probably subvolcanic As-Sb deposits (e.g. Alšar, Macedonia, Yugoslavia; probably 2 Tt Tl).

Indium, germanium, gallium

These metals form rare minerals of their own. Indium forms indite, germanium forms germanite and argyrodite and gallium forms gallite, respectively. Among the common sulphides, the highest enrichment of these metals is in sphalerite.

Cadmium

Cadmium is different from the above metals, because it is produced in relatively large quantities and its recoverable economic metal content is measured in millions of tons. Except for a few interesting but uneconomic small Cd-dominated occurrences (e.g. Berenguela, Bolivia), Cd is always present in sphalerite, substituting for Zn. The light-coloured (yellow, light brown) sphalerites are usually richest in Cd (up to 1.5% Cd) and the high-Fe black marmatites poorest (up to 0.05% Cd). Cadmium is not confined to hydrothermal-plutonic sphalerite deposits only, and is equally widespread in the MVT, APT, volcanic-sedimentary and other deposits.

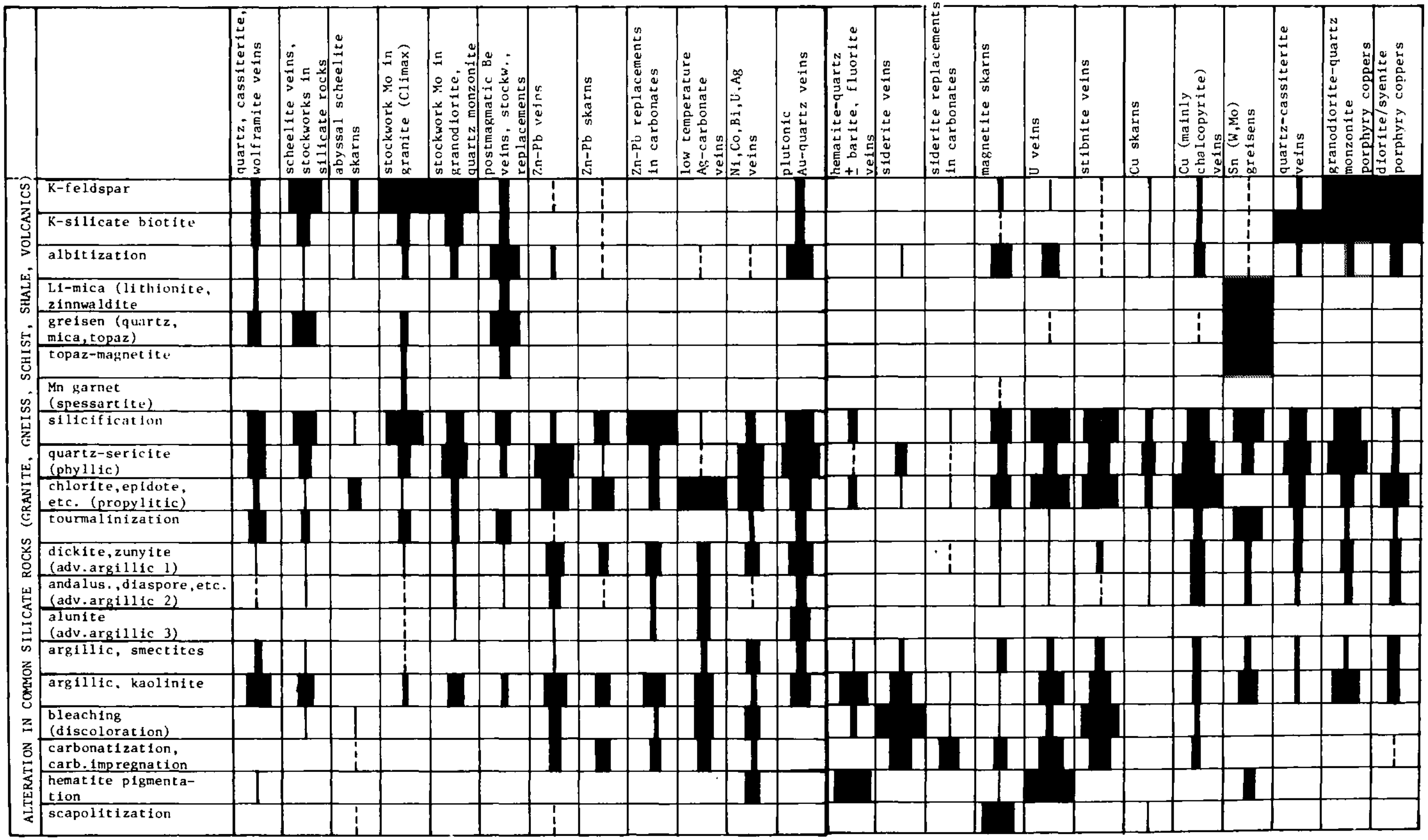
There does not seem to be a systematic difference in Cd contents in sphalerites of different origin. Sphalerites from thirteen North American deposits or regions listed by Wedow (1973) contained from 0.11 to 1.34% Cd (MVT localities: Pine Point, 0.11%; Joplin, 0.358%; APT localities: E. Tennessee, 0.32% Cd; S.E. United States, 0.52% Cd; hydrothermal veins and replacements: Illinois-Kentucky, 0.69%;

Central Kentucky, 1.34%; Colorado Rocky Mts., 0.28%; Butte, 0.58%; Coeur d'Alene, 0.4%). Wedow (1973) also calculated the world's average Cd content in 55% Zn concentrates, which is 0.24% Cd. This corresponds to 4.36 kg Cd per ton of zinc. Using this ratio, the Zn(Pb) deposits in "granite" aureole represent some 305 Tt Cd.

The Berenguela field in S.W. Bolivia (Ahlfeld and Schneider-Scherbina, 1964) contains unique mineralization dominated by cadmium. There, probably subvolcanic or hot-spring impregnations, veins and replacements of rhythmic greenockite, "Schallenblende" (metacolloform sphalerite), freieslebenite and other minerals containing up to 11% Cd, are hosted by Meso-Cainozoic arenites and quartzites and late Tertiary andesite pyroclastics.

28.26. SUMMARY GRAPHS OF ORE DISTRIBUTION PATTERNS

This chapter reviewing the granite-diorite (gabbro) association and associated metallic mineralization is concluded with a set of graphs, showing semiquantitatively: (1) the preferential association of the various ores with the different host rock assemblages and with the compositional variety of their concentrator intrusions (Fig. 28-124); (2) the preferred mineralization and alteration combinations (Fig. 28-125) and (3) the frequent evolutionary and timing pattern of intrusions, host rocks and mineralizations (Fig. 28-126).


ALTERATION IN COMMON SILICATE ROCKS (GRANITE, GNEISS, SCHIST, SHALE, VOLCANICS)
quartz, cassiterite, wolframite veins
scheelite veins, stockworks in silicate rocks
abyssal scheelite skarns
stockwork Mo in granite (Climax)
stockwork Mo in granodiorite, quartz monzonite
postmagmatic Be veins, stockw., replacements
Zn-Pb veins
Zn-Pb skarns
Zn-Pb replacements in carbonates
low temperature Ag-carbonate veins
Ni,Co,Bi,U,Ag veins
plutonic Au-quartz veins
hematite-quartz ± barite, fluorite veins
siderite veins
siderite replacements in carbonates
magnetite skarns
U veins
stibnite veins
Cu skarns
Cu (mainly chalcopyrite) veins
Sn (W,Mo) greisens
quartz-cassiterite veins
granodiorite-quartz monzonite porphyry coppers
diorite/syenite porphyry coppers
K-feldspar
K-silicate biotite
albitization
Li-mica (lithionite, zinnwaldite
greisen (quartz, mica, topaz)
topaz-magnetite
Mn garnet (spessartite)
silicification
quartz-sericite (phyllic)
chlorite, epidote, etc. (propylitic)
tourmalinization
dickite, zunyite (adv. argillic 1)
andalus., diaspore, etc. (adv. argillic 2)
alunite (adv. argillic 3)
argillic, smectites
argillic, kaolinite
bleaching (discoloration)
carbonatization, carb. impregnation
hematite pigmentation
scapolitization

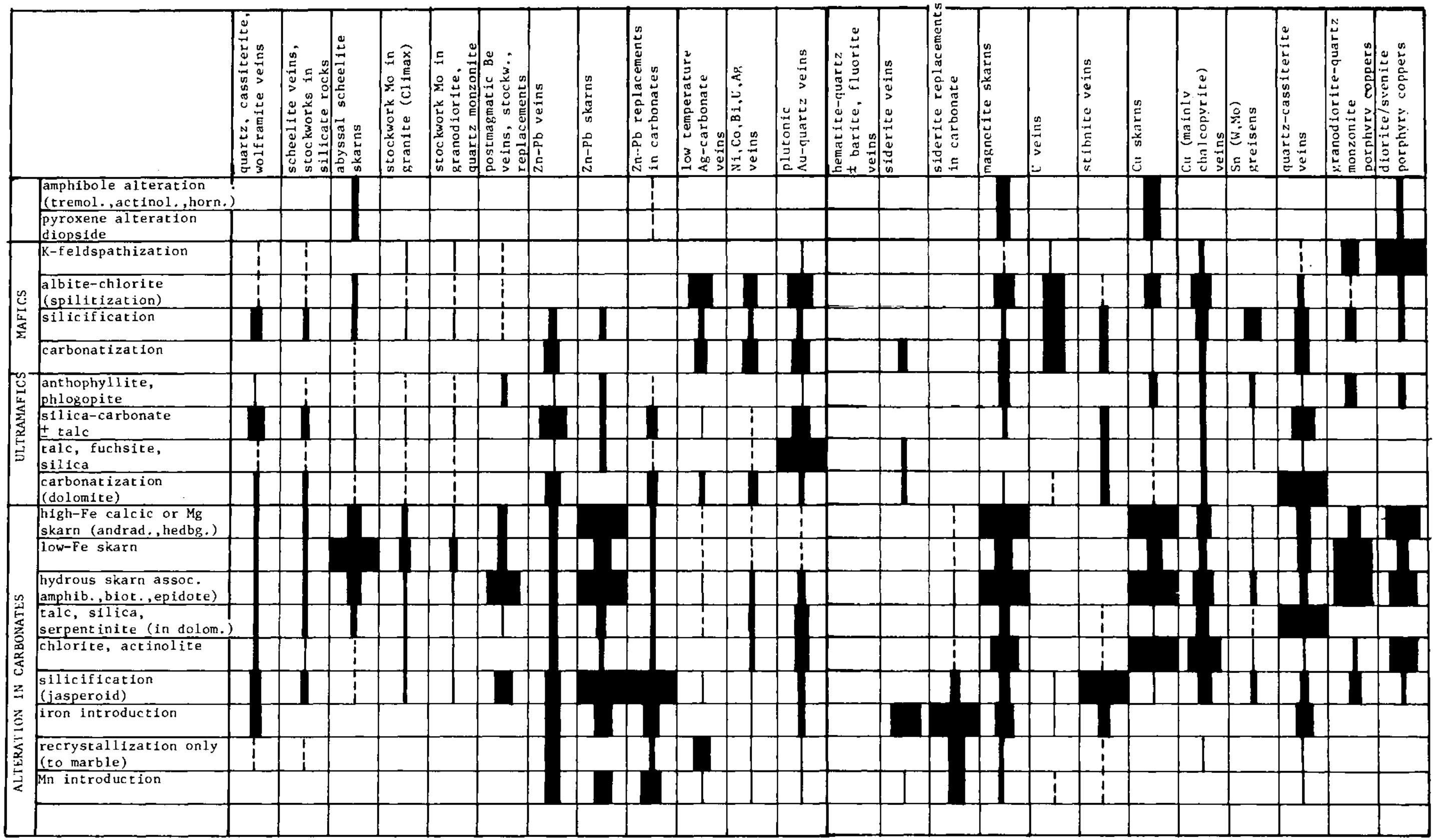


Fig. 28-124. "Granite"-associated (hydrothermal, epigenetic, postmagmatic) metallic ores as related to wallrock alterations. From Laznicka (1984).

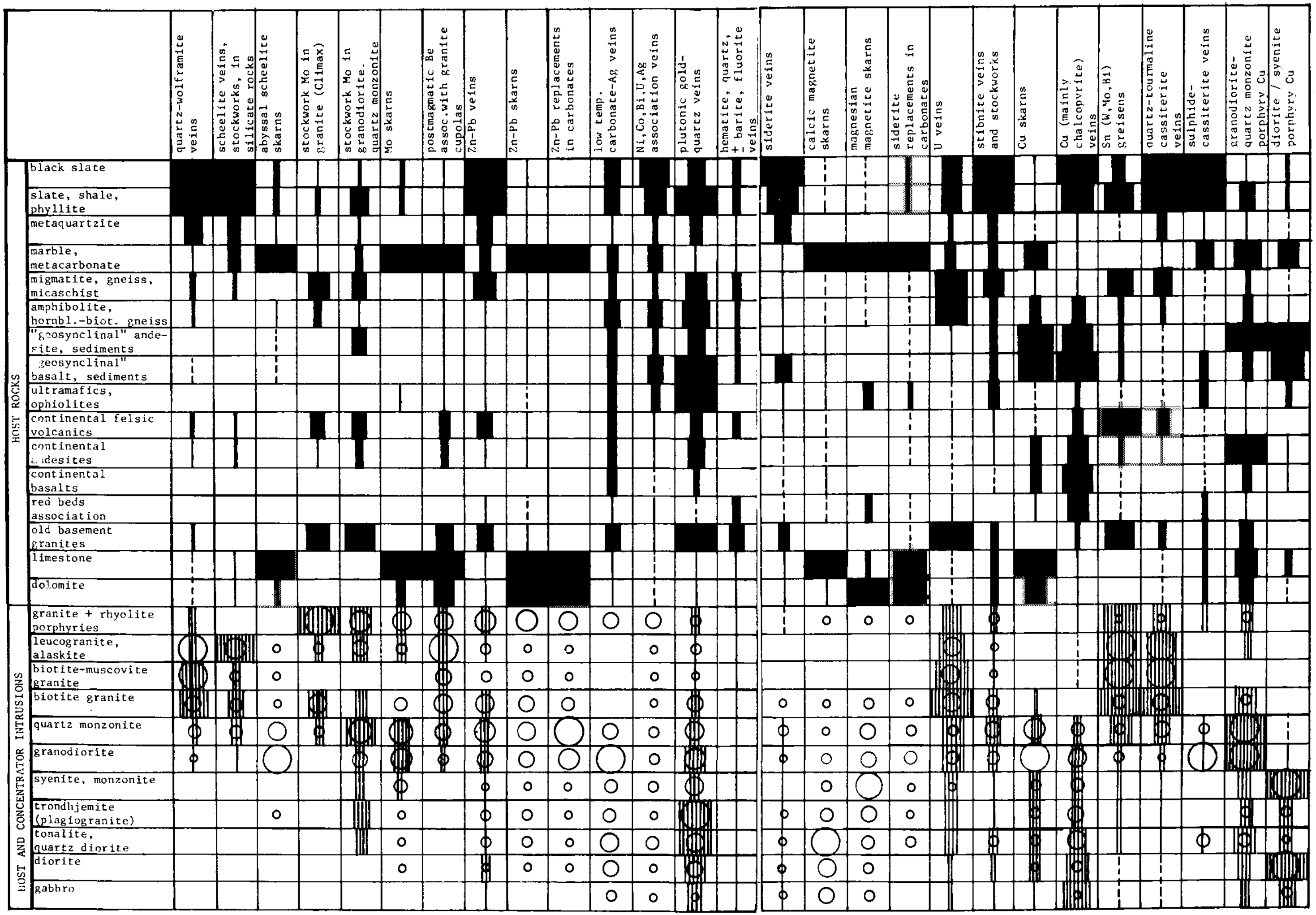

quartz-wolframite veins
scheelite veins, stockworks, in silicate rocks
abyssal scheelite skarns
stockwork Mo in granite (Climax)
stockwork Mo in granodiorite. quartz monzonite
Mo skarns
postmagmatic Be assoc. with granite cupolas
Zn-Pb veins
Zn-Pb skarns
Zn-Pb replacements in carbonates
low temp. carbonate-Ag veins
Ni,Co,Bi,U,Ag association veins
plutonic gold-quartz veins
hematite, quartz, ± barite, fluorite veins
siderite veins
calcic magnetite skarns
magnesian magnetite skarns
siderite replacements in carbonates
U veins
stibnite veins and stockworks
Cu skarns
Cu (mainly chalcopyrite) veins
Sn (W,Mo,Bi) greisens
quartz-tourmaline cassiterite veins
sulphide-cassiterite veins
granodiorite-quartz monzonite porphyry Cu
diorite / syenite porphyry Cu
HOST ROCKS
black slate
slate, shale, phyllite
metaquartzite
marble, metacarbonate
migmatite, gneiss, micaschist
amphibolite, hornbl.-biot. gneiss
"geosynclinal" andesite, sediments
"geosynclinal" basalt, sediments
ultramafics, ophiolites
continental felsic volcanics
continental andesites
continental basalts
red beds association
old basement granites
limestone
dolomite
HOST AND CONCENTRATOR INTRUSIONS
granite + rhyolite porphyries
leucogranite, alaskite
biotite-muscovite granite
biotite granite
quartz monzonite
granodiorite
syenite, monzonite
trondhjemite (plagiogranite)
tonalite, quartz diorite
diorite
gabbro

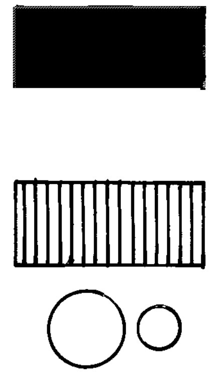
Fig. 28-125. "Granite"-associated (hydrothermal, epigenetic, postmagmatic) metallic mineralizations indicating, semiquantitatively, the frequency of their host rock and concentrator intrusion compositions. From Laznicka (1984).

HOSTS TO ORES:

"Passive" host rock units (those genetically unrelated to the magmatic and postmagmatic heat sources and processes, driving the hydrothermal systems; mostly (meta)sediments and (meta)volcanics)

Intrusive units acting as "passive" hosts to ores (some may be, however, sequentially earlier members of complexes that include "concentrator" intrusion coeval with the ores)

"Concentrator" intrusions (those driving the hydrothermal systems)



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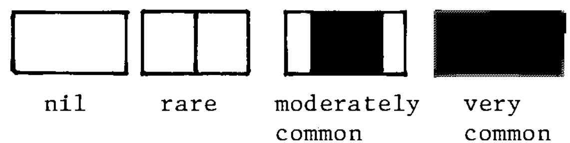


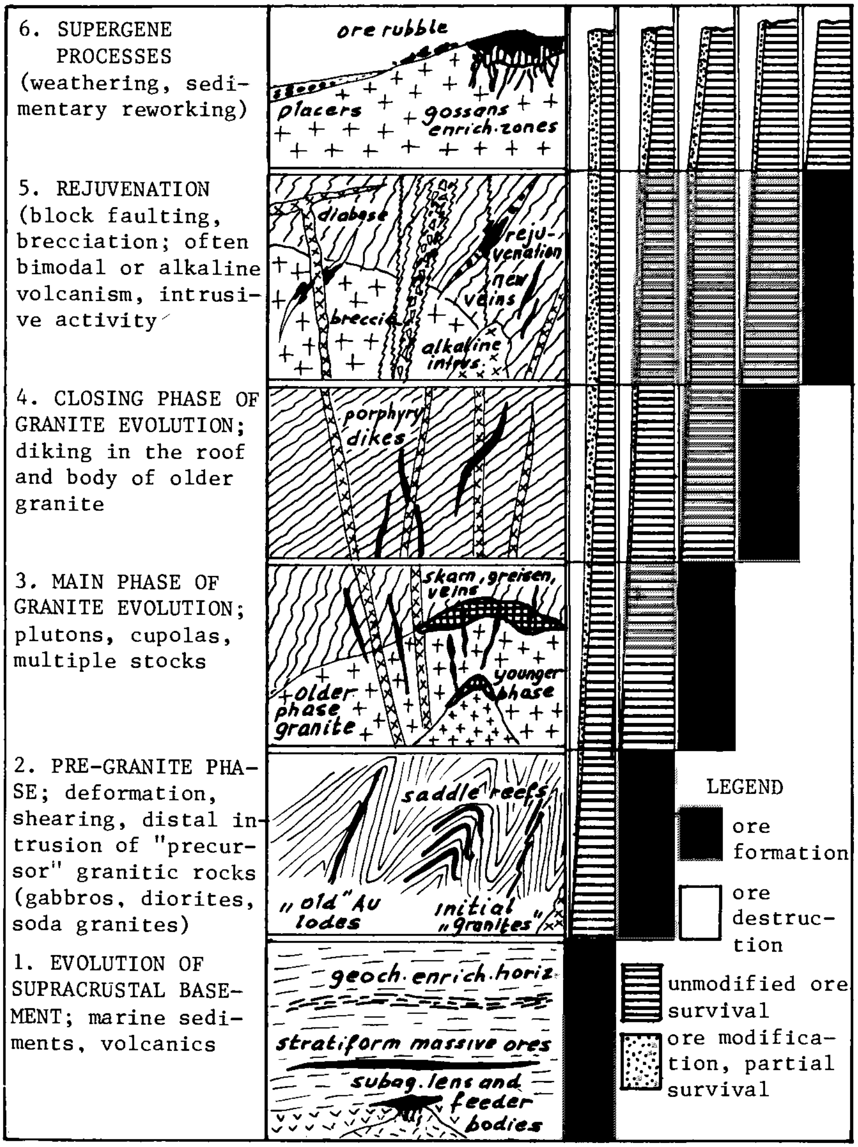


Fig. 28-126. The usual evolutionary phases in a multiphase polygenetic mineralized region, showing a real as well as an apparent genetic association with granitic intrusions. From Laznicka (1984).

"I believe that it will be discovered that a great number, if not the majority, of ore deposits, are not the result of a single segregation, but are the accumulated fruits of a great interrupted process of segregation, a part of the metals for the deposits having been worked over many times by the metamorphic process".
C. R. Van Hise in Treatise on Metamorphism, 1904.

CHAPTER 29

High- to Medium-Grade Metamorphosed Terrains, Katazonal Granites, Pegmatites

29.1. INTRODUCTION

Metamorphism starts gradually as a process superimposed on preexisting rocks. Initial, mild metamorphic effects (e.g. of zeolite facies) are barely recognizable megascopically during the general fieldwork, and rarely emphasized on geological maps and in field reports. With increasing metamorphism, the appearance and mineralogical composition of rocks keeps changing, until a point is reached beyond which the metamorphism-generated features far exceed the relic features of the original rock. The original rocks become no more directly recognizable megascopically and have to be interpreted. The interpretation of many metamorphic rocks is still in its infancy. Finally, ultrametamorphism that involves partial or total melting of older rocks or metasomatic crystalloblastesis, produces completely "new" rocks some of which remain "in situ", while others are found in new locations into which they moved in the form of plastic or fluid magma or migma.

There is a tendency amongst field and exploration geologists to disregard the effects of metamorphism (or dismiss them as a nuisance modification only), as long as the original rock type and depositional style can be easily recognized and interpreted. In the Canadian Shield, amphibolites composed of an entirely metamorphic assemblage, but still showing well-preserved pillow structures in outcrop, are designated as "basalts". Quartz-sericite schists are "rhyolites", and a variety of schists are "graywackes" or "shales". Although petrographers have serious reservations about the above practice (I require my students at least to use the prefix meta- in naming such rocks; e.g. meta-basalt, meta-shale), it is undeniable that metallogenic analysis of low- to moderately-metamorphosed associations appears to be more convenient and faster when done in the pre-metamorphic framework. This, however, requires an assumption (which most geologists accept as an established fact) that most orebodies in low-grade metamorphic terrains formed before the metamorphism which they survived as easily recognizable relics (e.g. of volcanics-hosted massive sulphides). Alternatively, ores were generated by epigenetic introduction during or after metamorphism (e.g. granite-affiliated postmagmatic hydrothermal deposits), usually at higher crustal levels than those in which the metamorphism took place. Metamorphism as a new ore-forming process had not been seriously considered, until very recently.

In this book, so far, the ore-hosting lithologic associations and their ores have been arranged according to their pre-metamorphic state, and although the modifications due to metamorphism have been noted and recorded, the intensity of metamorphism was not applied to draw first-order division between the categories. The time has now come to do so.

In this chapter, the emphasis is on high-grade metamorphic and ultrametamorphic (=granitization) terrains regardless of their pre-metamorphic composition, and on their metallogeny. Katazonal granites and pegmatites are generally present at the same level and overlapping, so they are also considered. As for the other lithologic associations, this category has gradational boundaries and overlaps with the subjects treated in Chapters 7-17, 19, 20-22, 24, 26, 28, 32-36. The overwhelming majority of high-grade metamorphic terrains are of Precambrian age and reside in Precambrian shields, in the basement of platforms and in large (e.g. median) massifs within orogenic belts. These are treated in Volume 2. A substantially smaller proportion of high-grade metamorphics are exposed in cores of Phanerozoic orogenic belts. Although many of these rocks are of Precambrian age anyway, Phanerozoic units are usually also involved. Post-Precambrian metamorphism, ultrametamorphism and interaction with Phanerozoic surroundings and roof assemblages, justifies treatment of such terrains in this chapter.

29.2. PETROGRAPHY, ORIGIN AND SETTING OF HIGH-GRADE METAMORPHIC TERRAINS

There is not sufficient space in this book to provide an adequate introduction into the metamorphic petrology and petrography, and the reader is urged to consult some of the recently published text and reference books (e.g. Winkler, 1974; Turner, 1980). The excellent book by Suk (1983) is particularly suitable for use as a basis for metallogenic interpretation of metamorphic terrains. Table 29-1 summarizes briefly some of the classifications, aspects, contrasts, etc. of metamorphism and its products of the greatest practical importance, largely abstracted from Suk (1983) and Turner (1980).

The heterogeneous nature of metamorphics and the numerous directions from which they can be studied, makes their elegant organization virtually impossible. Even the theoretically-minded textbooks (e.g. Turner, 1980) had to devote considerable space to brief descriptions of numerous local areas to cover the field adequately, and this book is no exception. High-grade metamorphism overlaps with "granitic" magmatism, so it is advantageous to borrow some of the recent concepts bearing on the petrochemistry and setting of "granites" (reviewed in Chapter 28) for the purpose of organization of the present subject.

All Phanerozoic progressive high-grade metamorphics occur in orogenic belts. There, the micaschist, gneiss, migmatite, granite assemblage is most common, and it occurs in thermal domes, ridges and anticlinal belts. Two end-member varieties of the above terrains can be distinguished: (1) the more internal (i.e., near-oceanic) ones, characterized by associated I ("magnetite")-type granitic rocks and evolutionarily less mature (e.g. the Coast Range metamorphic complex, British Columbia) and (2) the more external (i.e., near-continental) ones, marked by S ("ilmenite")-type granites and a long period of residence within or at a margin of a thick sialic craton (e.g. the Shuswap Complex, British Columbia).

Suk (1983) pointed out that metamorphic equivalents of all rocks are known. This is summarized briefly in Table 29-2.

29.3. TRACE METAL GEOCHEMISTRY AND ORE GENESIS

Trace metal geochemistry of high-grade metamorphics is a function of the pre-metamorphic heritage combined with the metamorphic differentiation. In relatively open systems that permit upward migration of metamorphically displaced mobile elements, trace-metal migration starts and, in fact, is probably most intensive, under the conditions of low-grade metamorphism (particularly along the intervals of accelerated dehydration, such as chlorite→amphibole and illite→muscovite). Quantitative evidence for syn-metamorphic metal migration is, however, difficult to obtain because it is impossible to sample a lithologically and geochemically uniform rock sequence over a considerable vertical span. Trace-metal contents of originally similar rock associations affected by prograde metamorphism to form zones of increasing metamorphic intensity, indicate gradual depletion in trace Cu,Au,Zn, U,Ni,Cr,V and enrichment in Ba,Sr,Zr, Ce and La, with the increasing metamorphic grade (e.g. Belevtsev, 1976, 1979). The majority of studies have been performed in the Precambrian shields, and their results are further treated in greater detail in Volume 2.

Boyle (1979; p. 116, 117) stated the case for gold deposits as follows: "Nearly all types of epigenetic gold deposits are restricted to rocks that exhibit a low to moderate degree of metamorphism (greenschist and amphibolite facies). One does not find epigenetic gold deposits in rocks that do show the effects of considerable recrystallization and alteration such as regional propylitization. From this fact the logical conclusion seems to follow that epigenetic gold deposits are more closely related to metamorphism than to magmatic phenomena. In the grand scheme of orogenesis the occurrence of epigenetic gold deposits in the vicinity of intrusive granitic rocks is not fortuitous. The reason for this, however, may not be that the granitic bodies provided the gold, but that these bodies are simply one in the series of products of intensive metamorphism. These

Table 29-1. Selection of practically important classifications, definitions and concepts bearing on metamorphism and its products. Summarized and slightly modified from Suk (1983) and Turner (1980)

VARIETIES OF METAMORPHISM BY SCALE, SETTING AND PROCESS

Regional metamorphism (RM; generates metamorphic rocks over extensive areas); varieties:

- RM of continental (Precambrian) shields
- RM of central parts of thermal domes
- RM of orogenic areas
- RM in the zone along lithospheric plate edges
- RM of ocean floor

Local metamorphism

- contact metamorphism
- dislocation metamorphism
- shock metamorphism
- combustion metamorphism (surficial or shallow subsurficial coal or bitumen burning)

VARIETIES OF METAMORPHISM BY PRESSURE/TEMPERATURE RELATIONSHIP

(1) high temperature, almost no pressure (e.g. baking, hornfelsing at surficial volcanics and sediments contacts

(2) high temperature, moderate pressure ("normal" metamorphism as e.g. in orogenic belts)

(3) high pressure, moderate temperature ("blueschist-type")

(4) high pressure, almost ordinary temperature (e.g. cataclasis and mylonitization along shallow faults)

SUBDIVISION OF THE "NORMAL" METAMORPHISM BY THE DEGREE OF INVOLVEMENT OF INTRUSIVE PLUTONS

(1) Enorogenic (Barrovian, Dalradian, "typical regional", kyanite-sillimanite) metamorphism, predominantly pressure activated

(2) Periplutonic (Buchan, Abukuma, andalusite-sillimanite) metamorphism; heat activated in the proximity of intrusive plutons

VARIETIES OF METAMORPHISM BY ITS CHEMICAL CHARACTER

(1) Chemically conservative metamorphism (isochemical); no elements added or removed

(2) Metasomatism (metasomatic, allochemical, etc. metamorphism); element exchange along rock contacts (bimetasomatism, reaction metasomatism), or element addition and removal to and from the site under consideration

(3) Ultrametamorphism; rock transformations under conditions near to the melting of the rock system involved (migmatitization, formation of anatectites)

METAMORPHIC DIFFERENTIATION: a process that brings about mineral heterogeneity in an originally homogenous rock, by migration of substances within the rock (e.g. quartz or pegmatite secretions, concretions, boudins, etc.)

METAMORPHIC HOMOGENIZATION: the opposite, largely a consequence of equilibration of the chemistry of the fluid phase

METAMORPHIC FACIES AND FACIES GROUPS

"A metamorphic facies is a set of metamorphic mineral assemblages repeatedly associated in space and time, such that there is a constant and therefore predictable relation between mineral composition and chemical composition" (Turner, 1980, p.54). Den Tex (1971) distinguished four facies groups of regional metamorphism:

(1) Very low grade metamorphism. Zeolite, prehnite-pumpellyite, laumontite-albite, portion of lawsonite-glaucophane
(2) Low-grade metamorphism. Greenschist facies, albite epidote amphibolite facies
(3) Medium grade metamorphism, amphibolite facies
(4) High-grade metamorphism, granulite facies

PROGRESSIVE AND RETROGRESSIVE METAMORPHISM

Progressive metamorphism is recorded in a sequence of rocks showing a rising grade of metamorphism out of previously unmetamorphosed rocks. Retrogressive metamorphism produces a metamorphic facies equivalent lower in the sequence than the modified precursor rock, and it is accomplished mostly by localized tectonic deformation and action of hydrothermal fluids

METAMORPHIC CONVERGENCE AND DIVERGENCE

Convergence: formation of identical metamorphics out of a variety of precursors (e.g. biotite gneiss out of granite, arkose, litharenite, shale)

Divergence: formation of different metamorphics out of a single precursor as a consequence of a different metamorphic grade or style (e.g. phyllite, micaschist, gneiss out of shale)

bodies also include the gold deposits, the gold being derived from piles of sedimentary and volcanic rocks and concentrated as a result of granitization and later metamorphic processes that continued long after the emplacement, crystallization and consolidation of batholiths, stocks and dikes of granite".

Overstreet (1967) in his exhaustive review of the world monazite occurrences, argued that most monazite accumulations in high-grade metamorphic terrains and in associated magmatic rocks (pegmatites, granites, charnockites) are metamorphogenic, rather than a detrital relic. The global distribution of bedrock monazite and proximal monazite placers, supports this thesis beautifully. Moreover, the chemical composition of monazite, particularly its Th/REE ratio, appears to increase with the metamorphic grade and the Sri Lanka monazite with 10% ThO_2 derived from charnockite association, is among the highest Th monazites commercially produced. Although scattered monazite in high-grade metamorphics (granites, charnockites) may

Table 29-2. High-grade metamorphic equivalents of pre-metamorphic rocks, a brief summary.

HIGH TO MEDIUM GRADE METAMORPHIC	PROTOLITH
muscovite, biotite, staurolite, kyanite, garnet, sillimanite, etc. schist and gneiss; partly granulite	shale, siltstone, graywacke, arkose, conglomerate
graphitic schist, marble, quartzite	bituminous or coaly pelite, carbonate, chert
graphite (amorphous)	humitic coal, rarely sapropelite
metaquartzite	quartz arenite, chert
hornblende-biotite schist, gneiss	intermediate to mafic tuffs, volcaniclastics
amphibolite (schistose)	basalt, andesite flows, pyroclastics, volcaniclastics, marls
gabbro-amphibolite (massive)	diabase, gabbro
limestone or dolomitic marble	sedimentary carbonates; rarely igneous carbonatite
calc-silicate gneiss, hornfels	impure sedimentary carbonate, marl
magnetite-quartz rock	ironstone or iron formation
corundum and corundum-magnetite	bauxite and laterite
tourmaline schist (some)	sedimentary borates
albitites (some)	halite with clay layers
apatite-rich metamorphics	sedimentary phosphorite
scapolite metamorphics	sedim. gypsum, anhydrite, halite
meta-anhydrite	sedimentary gypsum, anhydrite
leucocratic orthogneiss, leptynite, partly granulite	rhyolite and felsic pyroclastics, granite
nepheline gneiss (partly)	nepheline syenite, phonolite
prasinite (chromian barroisite hornblendite)	high-Mg basalts, picrites

glaucophanite (blueschist)	spilite or any metabasalt of graywacke metam. under high P/low T metamorphic conditions
eclogite	gabbro, basalt, troctolite, spilite
concordant olivinite	ultramafics (peridotite, serpentine)
gedrite, anthophyllite, actinolite schists	ditto
skarnoids	pelosiderite, peloankerite, ironstone, iron formation

represent a case of metamorphogenic mineralization, the bedrocks (even regoliths !) never approach an economic grade and the monazite can be profitably recovered only when reworked into placers.

It appears that the bulk of significant metamorphogenic and metamorphics-hosted (other than relic) deposits formed by precipitation from a mobile phase (magmatic, hydrothermal) displaced during ultrametamorphism or during metamorphogenic hydration or dehydration. Such ores and their host rocks fill dilations or replace earlier rocks usually above (rarely within) the metal source regions and often merge with the "granite"-affiliated ores. In the recent classification of metamorphogenic ore deposits by Belevtsev (1976, 1979; Table 29-3), the former (in situ) deposits are designated as autochthonous, the latter (transported) as allochthonous.

29.4. MINERALIZATION STYLES IN METAMORPHOSED NON-CARBONATE SUPRACRUSTALS (SCHISTS, GNEISSES; Fig. 29-1)

29.4.1. "Metalliferous schists", containing dispersed to disseminated metals conformable with foliation (Fig. 29-1a)

These are thin, short lenses to extensive horizons of fine-grained schistose metamorphics usually differing compositionally from their environment and anomalously enriched in trace metals. "Black" (graphitic) metasediments are most common, combined with (or followed by) pyritic metasediments, impure metacarbonates, amphibolites, etc. The best-known examples are the Proterozoic "Fahlbånds" of Norway (Volume 2), which are closely comparable with some of the graphitic and pyritic siliceous schists in the late Proterozoic and Paleozoic of the Erzgebirge Mountains (e.g. in the Jáchymov area).

The "metalliferous schists" are rarely economic in themselves, but they often appear to have been the source rocks of metalliferous fissure veins or stockworks, such as veins with Ni,Co,Bi,U,Ag

Table 29-3. Classification of metamorphogenic ore deposits of Belevtsev (1976, 1979)

		TEMPERATURE OF METAMORPHISM		
		LOW	MEDIUM	HIGH
METAMORPHOSED DEPOSITS (pre-metamorphic, later metamorph.)	META-SEDIMENTARY	chlorite-magnetite b.i.f., U-conglomerates (Elliot Lake)	amphibole-magnetite b.i.f.	pyroxene-magnetite b.i.f.
	META-VOLCANIC	volcanogenic massive sulphides; Cu in metabasalts (Michigan)	volcanogenic massive sulphides; Mn gondites	PCm iron quartzites; Mn khondurites (India)
	META-MAGMATOGENE	Ni-Cu sulphides in mafic magmatites (Pechenga)	Ni-Cu sulphides (Voronezh Massif)	ilmenite-rutile ores, the Urals
METAMORPHIC DEPOSITS (formed during regional metamorphism)	AUTOCHTHONOUS (generated in situ by concentration of ore matter present in the hosts)	rich hematite-magnetite ores of the PCm b.i.f.; massive sulphides in the Urals; Pb-Zn deposits Zhairem, Mt. Isa	rich amphibole-magnetite b.i.f.; "Alpine-type" veins	rich magnetite-pyroxene ores (Azov Sea); Mary Kathleen U-REE skarns
	ALLOCHTHONOUS (generated from transported components released during metamorphism)	Cu-Ni sulphides in schists (Baltic Shield); pyrite-polymetallic deposits, Lake Baikal region	Fe metasomatites, Gora Vysokaya, Blagodat', the Urals	corundum, phlogopite, saphirine, wollastonite materials

ULTRAMETAMORPHIC DEPOSITS (formed under the influence of ore-bearing fluids, released in zones of polygenetic and metasomatic granitization)	PALINGENETIC-METASOMATIC resulted from metasomatic granitization; also affiliated with rheomorphic granites and pegmatites		ore-bearing granites rare elements pegmatites and metasomatites	Sn-W muscovite pegmatites Sn-Nb granites (in Nigeria)
	POST-GRANITIZATION DEPOSITS formed in waning stage of ultrametamorphism at the same structural level by precipitation of metals migrating from depth along faults	U,Au,Hg,etc. mineralized albitites, berezites, listvenites	rare elements albitites; U vein deposits (Beaverlodge); Cu, Singbhum	rare elements metasomatites (Siberia)

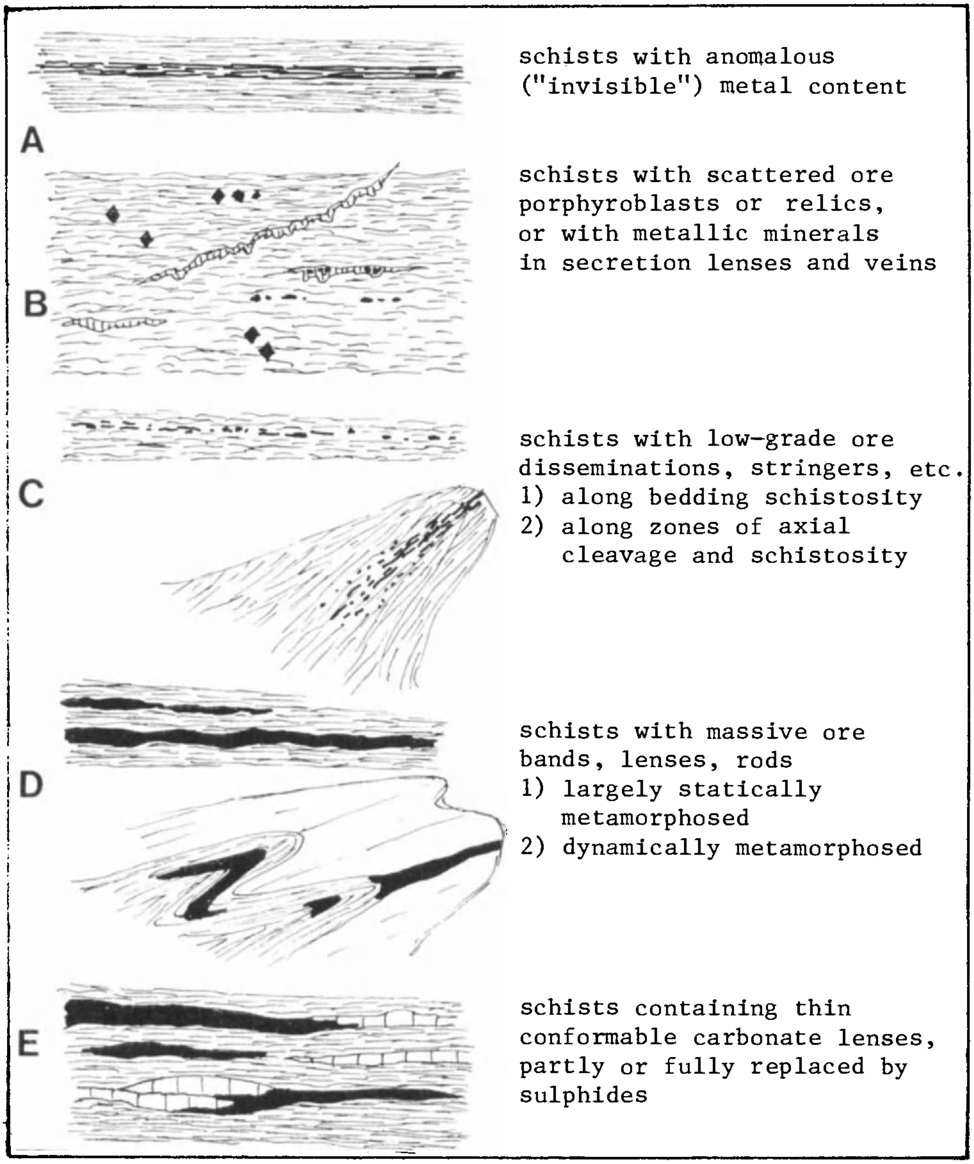


Fig. 29-1. Diagrammatic representation of mineralization styles in non-carbonate, progressively metamorphosed supracrustal schists. From Laznicka (1984).

association. The most commonly expected enriched metals are U,Ag,Au, Ni,Co,Bi, Mo,V,Hg,Sb, or their combinations. Visible ore minerals in schists occasionally appear as scattered porphyroblasts (most common are pyrite or arsenopyrite), or as components of secretion quartz, carbonate or silicate lenses; fillings of gash veinlets; etc.

The economically important Rönneburg uranium field, East Germany (Ruzicka, 1971) is situated in black schists that are metamorphosed equivalents of lower Paleozoic graptolithic shales. Visible U minerals (pitchblende) appear sporadically in secretion veins. The mineable ore comes in irregular lenses grading between 0.07 and 0.14% U.

29.4.2. Schists with scattered ore mineral porphyroblasts or relics (Fig. 29-1b)

This style is a close equivalent of the volcanic flows with ore phenocrysts, paleoplacer beds or sedimentary beds with ore nodules. Lenses and intervals of a variety of so mineralized metamorphics are conformable with schistosity and usually also with bedding. The ore mineral particles may be haphazardly scattered throughout the entire thickness of the ore horizon (the thickness usually ranges from several centimetres to several metres). Alternatively they may be arranged into trains parallel with schistosity. Genetically, the ore particles are either metamorphically modified relics (e.g. heavy mineral grains in metasediments), or porphyroblasts produced by metamorphic growth. Sometimes, their origin is uncertain. A variety of inhomogeneities superimposed on the ordinary mineralized horizon such as secretion quartz or quartz, feldspar, mica, etc. lenses, carry the same minerals in the form of larger, more conspicuous grains. Currently economic ore deposits of this style are rare, but the ore particles can be reworked into placers.

RUTILE OR ILMENITE-BEARING SCHISTS

At Shooting Creek, North Carolina (Williams, 1964; 37 Tt Ti), rutile and minor ilmenite are associated with sugary white quartz secretions in a Proterozoic garnet mica schist, discontinuously along a 16 km long belt. The mineralization is interpreted as being metamorphogenic, and small quantities of concentrate have been produced from regolith and small placers.

In the Yadkin Valley Ti deposit near Richlands, North Carolina (Bryant and Reed, 1966; 66 Tt Ti), ilmenite with magnetite are disseminated in a talcose layer conformable with enclosing cataclastic micaschist, quartzite and gneiss. The orebody consists of a series of closely spaced mineralized lenses, 110 m long and 6-17 m thick, conformable with foliation. Most of the production came from saprolite.

MONAZITE, XENOTIME, ETC.-BEARING SCHISTS

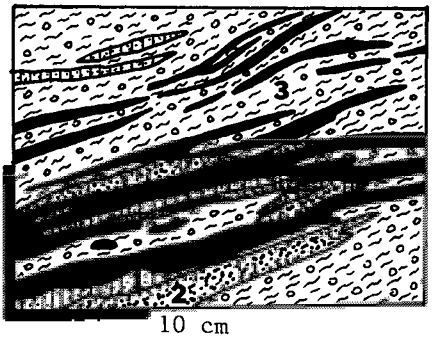
Lower Proterozoic biotite schists and gneisses that are part of the early Tertiary Colorado Rocky Mountains uplift, contain localized intervals enriched in monazite and xenotime. These minerals are megascopically invisible or inconspicuous, and have been discovered by a chance microscopic examination or by increased radioactivity. In the Central City district (Young and Sims, 1961), lenses up to 1.6 m thick and several tens of metres long, contain up to 5% by volume of xenotime and monazite. The authors favour the concept of metamorphogenic origin of the heavy minerals, over that of paleoplacers.

TIN-BEARING SCHISTS

The frequently mentioned Gierczyn (Göhren), Przecznica, Nové Město pod Smrkem stanniferous zone (Polish and Czech Sudeten; Jaskołski, 1960; Chrt and Bolduan, 1966) has been listed several times under the heading "Tin paleoplacer". This is an E.-W.-trending band, about 20 km long, of sericite, chlorite, garnet micaschist of late Proterozoic or Cambro-Silurian age, interfoliated with amphibolites, and periplutonically metamorphosed in the mantle of a late Paleozoic granite gneiss core. The tin is contained in inconspicuous, light-coloured small scattered grains of cassiterite, accompanied by scheelite, pyrrhotite, sphalerite, chalcopyrite, bismuthinite, niccolite and cobaltite. The ore minerals accumulated locally in lenses, 1-8 m thick and 15-100 m long, rich in two varieties ("white" and "blue") of "secretion" quartz, peneconcordant with schistosity (Fig. 29-2). The tin values are very irregularly distributed and range from 0.02 to 5% Sn. The paleoplacer origin has not been demonstrated convincingly and an alternative explanation assumes a (re)mobilized "fahlbånd-style" metalliferous horizon, with a portion of the Sn possibly being supplied from the "granite".

29.4.3. Schists with low-grade disseminations, stringers, veinlets, etc. of sulphides, gold, scheelite and other metallic minerals (Fig. 29-1c)

This style is transitional into the previous one. The ore minerals are distributed as disseminated flat grains, coatings, stringers, fracture veinlets, bunches, etc. in a schist, and there appear to be two fundamental end-member ore arrangements: (1) along bedding schistosity, where the orebodies are usually flat, stratigraphically controlled (meta-stratabound) lenses or (2) along zones of axial cleavage and schistosity, in which the orebodies usually cut across the original bedding. Type (1) cases are usually interpreted as metamorphosed sulphidic sediments or volcanics and tend to be of lower grade but greater persistence. Several examples have been reviewed in



1. milky (secretion ?) quartz lenses
2. gray,transparent quartz
3. Pt_3-PZ_1 garnet-chlorite schist

BLACK: magnetite and sulphide lenses,scattered masses, grains, stringers,hosted by the gray quartz; contain microscopic cassiterite

Fig. 29-2. Detailed section of the cassiterite, sulphide, magnetite mineralization near Gierczyn, S.W. Poland. Modified after Jaskolski (1960).

Chapters 10-17. Type (2) cases are clearly metamorphogenic or metamorphically (re)mobilized orebodies.

KANMANTOO COPPER DEPOSIT, SOUTH AUSTRALIA

This locality (Verwoerd and Cleghorn, 1975; 122.5 Tt Cu/1%; Fig. 29-3) is an example of (2). There, the orebody is a system of flat ore lenses parallel with the axial plane schistosity, which has an overall shape of a 80^{o} N-plunging elongated pipe. The host rock is a lower-middle Cambrian coarse grained porphyroblastic garnet-chlorite schist, enveloped by garnet-andalusite and quartz-mica schist. Pyrite, chalcopyrite and minor arsenopyrite with or without quartz,form parallel veinlets, stringers and flat grains along the schistosity, fine-grained disseminations and local massive pockets and bands. The final act of ore emplacement was contemporary with the last, third phase of deformation which dates from the early Ordovician period.

COPPER DEPOSITS IN THE CABO ORTEGAL COMPLEX, N.W. SPAIN

A group of copper deposits in high-grade metamorphosed lower Paleozoic rocks interpreted as original ophiolites near Santiago de Compostela (200 Tt Cu/0.6-0.6% Cu), has recently been studied by Badham and Williams (1981). The mafic complex is composed of granulite, meta-ultramafics, eclogites and amphibolites, and is situated in thrust-fault contact with a Silurian mélange. Disseminated, stringer, veinlet and occasionally massive pyrite, pyrrhotite and chalcopyrite form lenses, up to 10 m thick, in a

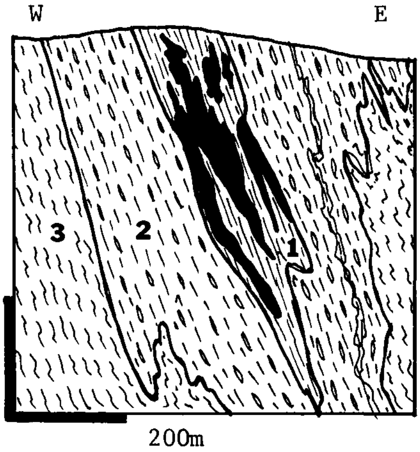


Fig. 29-3. Kanmantoo sulphide orebody, South Australia. From LITHOTHEQUE, modified after Verwoerd and Cleghorn (1975).

distinct stratigraphic horizon of quartz, pink garnet, gedrite and cummingtonite containing amphibolite, enclosed in a fine garnet amphibolite. The ores are also structurally controlled and confined to masses of isoclinal folds. Two medium-sized deposits (Arinteiro, 11 Mt ore with 0.67% Cu and Bama, 20 Mt ore with 0.5-0.6% Cu) have been mined, and additional small deposits and prospects are known in the area.

THE SCHEELITE DEPOSIT, FELBERTAL, AUSTRIA

The interesting scheelite deposit Felbertal near Mittersil in northern Austria which is hosted by a lower Paleozoic metamorphosed bimodal volcanic-sedimentary association, has already been discussed briefly earlier (Chapter 12). There, scheelite is scattered in metaquartzite bodies, confined to a "prasinite" (=chromian hornblendite interpreted as being a metamorphosed high-Mg basalt or picrite), amphibolite, albite gneiss and porphyroid gneiss unit. Höll (1977) emphasized the stratabound nature of the scheelite orebodies, confined to a 400 m thick sequence traceable for several kilometres, and to a prevalent concordancy of the "primary" (fine crystalline, metamorphosed) disseminated scheelite with the relic pre-metamorphic fabrics of its hosts, implying common and contemporary origin (by "exhalation").

"Secondary" (metamorphogenic) scheelite occurs as large scheelite-powellite porphyroblasts with dimensions of up to 1 cm accompanied by pyrrhotite, chalcopyrite, molybdenite, galenobismuthite, etc. in quartz stockworks. The Felbertal deposit is in the mantling complex of the Hohe Tauern ultrametamorphic core, deformed and metamorphosed in the Oligocene. No allochthonous granites are known so far, but the scheelite-bearing sequence is situated in such a way that it may have acted as a confining screen to metasomatic fronts. The main scheelite carrier, metaquartzite, occurs as peneconcordant intercalations, but also as crosscutting bodies. Holzer and Stumpfl (1980) pointed out the probable genetic association of quartz and ore. The considerable thickness and variety of the scheelite-bearing rocks (readily apparent in the paper of Höll, 1977, Fig. 2) can be attributed equally well or possibly better to metamorphic (re)distribution, as to an isochemical metamorphism of a syndepositional mineralization.

29.4.4. Schists with massive ore bands, lenses and rods (Fig. 29-1d)

GENERAL

Massive Fe and Mn oxide or silicate ores, massive sulphides and other commodities are commonly located in strongly schistose silicate metamorphics. There, they have the form of thin, persistent bands or laminae alternating with a barren rock, or of more localized, thin to thick massive ore lenses. As in the previous section, two end-members can be distinguished. They are as follows: (1) largely statically metamorphosed but little deformed orebodies, in which the ore bands are obviously relics inherited from the time of supracrustal deposition. Although complete or partial metamorphic recrystallization and corresponding mineralogical changes of the ore bands took place, the overall pre-metamorphic ore distribution pattern has been well preserved; and (2) penetratively (dynamically) metamorphosed orebodies, usually massive ore lenses, preferentially accumulated along shears, zones of axial cleavage, pressure shades, etc. These orebodies are concordant to peneconcordant with schistosity, but concordant to discordant with the original bedding. Although the ore can be banded, the banding is not necessarily a relic of a depositional structure. More commonly, it is a metamorphically formed banding.

The orebodies, in addition to having undergone the mineralogical and textural changes due to metamorphism, could have been reshaped, plastically moved into a new location, cataclastically comminuted and subsequently recrystallized to form ore blastomylonites, remobilized through a fluid phase, etc. In many cases, the orebodies need not have been present before the deformation and metamorphism at all, and are truly metamorphogenic: that is, precipitated from metamorphic-hydrothermal fluids during, or shortly after, the metamorphism.

The origin of similar orebodies has to be interpreted painstakingly. It is not apparent on first sight, and even less amenable to an armchair re-interpretation by a distant reader. It is becoming increasingly apparent that many of the "stratiform" massive sulphide orebodies in metamorphics were not in their present position at the onset of deformation and metamorphism, so they are metamorphogenic. This matter is further discussed later in this chapter. It is also discussed in Volume 2, and it has been reviewed recently in Laznicka (1985b).

Many of the massive ore deposits in metamorphics have already been reviewed earlier, in the lithologic framework of the pre-metamorphic host associations. The earlier descriptions will not be repeated and the emphasis in this section is on the particularly highly modified deposits not treated before.

Statically metamorphosed iron ores (limited mobilization)

The most common statically metamorphosed iron ores are the Precambrian iron formations, treated in Volume 2. Examples in Phanerozoic orogenic belts are much rarer. In the Desná Gneiss Dome, Jeseník Mts., N.C. Czechoslovakia (Gruczczyk and Pouba, 1968; Svoboda, ed., 1966; Fig. 29-4), delicately banded quartz-magnetite horizons in late Proterozoic gneisses are traceable for over 100 km. The dynamometamorphic overprint is apparent mainly on a local scale (boudinage, interruption of bands, thinning and swelling).

Statically metamorphosed manganese ores

In the eastern Carpathians, Rumania (Sebeş and Semenic Mts.; Ianovici and Borcoş, 1982), the Proterozoic basement contains numerous lenses and bedding schistosity-concordant Mn orebodies. The host rocks are metaquartzite, gneiss and amphibolite, and the Mn ores are composed of spessartite, rhodonite, pyroxmangite, dannemorite, knebelite, rhodochrosite, piemontite, and jacobsite. The Delinesti field has produced about 100 Tt Mn.

Statically metamorphosed bedded sulphide ores

Probably the best-known examples are the "vasskis" (or Leksdal-"type" orebodies) of the Norwegian Caledonides, described in numerous publications (e.g. Holtedahl et al., 1960; Vokes, 1976, 1978). These are persistent, regular, horizons of pyrite and pyrrhotite-impregnated schist, metaquartzite or oxide-silicate iron formation 1-2 m thick, grading to massive sulphide lenses. The sulphides are most frequently hosted by amphibolite (greenstone), black schist, or occur at lithological contacts such as between an ultramafic body and graphitic schist. Their lithofacies, relic structures and geochemistry indicate, quite convincingly, the pre-metamorphic origin of these ores. Although at several Scandinavian localities the "vasskis" are spatially associated with Fe,Zn,Cu massive sulphide bodies, both styles may occur independently.

Skarnoids and skarn enveloped by non-carbonate rocks (Fig. 29-1e)

Skarnoids are metamorphosed rocks composed of "skarn mineralogical assemblage" (essentially Ca-garnet and diopside-hedenbergite; compare Chapter 28), formed by metamorphism of rocks of appropriate composition (marls, mafic tuffs, sedimentary iron ores, some

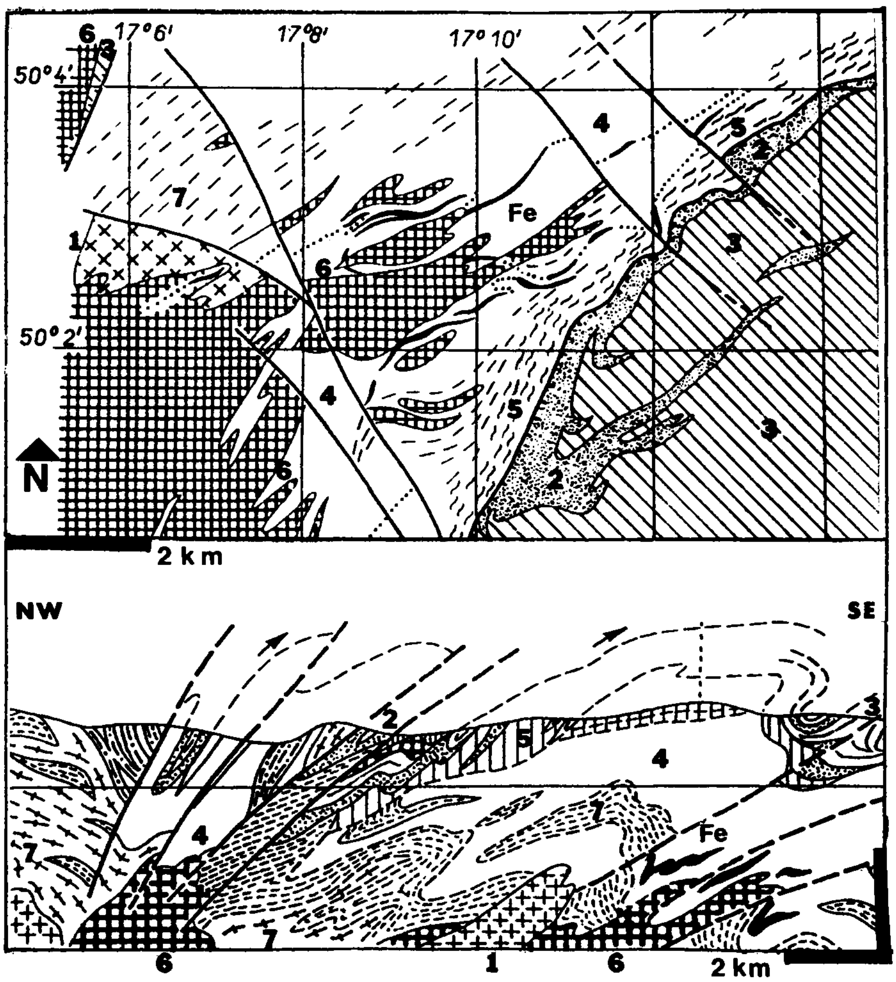


Fig. 29-4. Banded siliceous magnetite ores considered of "Sydvaranger type" in late Proterozoic or Devonian amphibolites in the core of the Desná (thermal, gneiss) Dome (Jeseník Mts., N.C. Czechoslovakia). After Pouba and Mísař from Svoboda, ed.(1966), courtesy of the Ústřední Ústav Geologický, Praha. The magnetite bands shown on the map are in correct position; those in the section are diagrammatic projection only, in the correct stratigraphic position. 1=PZ_3 granitic plutons; 2=D quartzite; 3=D phyllite; 4=D and/or Pt_3 biotite paragneiss; 5=chloritized biotite gneiss; 6=amphibolite; 7=Pt_3 migmatite to orthogneiss; Fe=banded magnetite ore.

metamorphics, some regoliths; Suk, 1983). In high grade metamorphic and ultrametamorphic terrains the skarnoids are difficult to distinguish from metasomatically completely skarnized limestone lenses sandwiched between silicate wallrocks, and also regionally metamorphosed earlier periplutonic metasomatic skarns. Suk (1983) coined the term "metaferrolite" which is applicable to the magnetite skarnoids formed by metamorphism of bedded iron ores.

Numerous small lenses of polymetamorphic skarns or skarnoids, some containing magnetite and many mined on a small scale in the past (e.g. Vlastějovice, Budeč, Županovice), occur in the Moldanubian metamorphic terrain of central Czechoslovakia. Their origin is uncertain. Elsewhere, skarns or skarnoids in high-grade metamorphics carry rare or base metal minerals. This could be the case of the stanniferous "Felsite Horizon" on the N.W. rim of the Freiberg Dome (near Halsbrücke and Bräunsdorf, Erzgebirge; Baumann, 1970). This is a 600 m thick, N.E.-trending metamorphic unit of interbedded gneiss, micaschist, amphibolite, dolomitic limestone and "metarhyolite", containing irregularly disseminated cassiterite with minor chalcopyrite. These minerals are confined to a magnetite and hematite-bearing, retrogressive chlorite schist and "skarn". Four mineralized horizons have been proven so far.

Dynamically metamorphosed iron ores

Probably the most extensive horizon of Phanerozoic (possibly Cambro-Silurian) industrial-grade metamorphosed ironstones is situated in the Dunderland Group of northern Norway, traceable for over 550 km strike length (Bugge, 1978). In the Mo-i-Rana region (Dunderlandsdalen iron field; 170 Mt Fe/34%; Fig. 29-5), the ore-bearing sequence contains interbedded dolomite and calcite marble, quartz-mica schist, and calcareous micaschist. Two iron ore horizons have developed. The upper horizon hosted by the quartz-mica schist, consists of specularite, granular hematite and magnetite in quartz, calcite, epidote, biotite gangue. The lower horizon in calcareous micaschist has magnetite and minor apatite in quartz, calcite, biotite, hornblende and grünerite gangue. The orebodies are penetratively deformed, 20-50 m thick and swelling in the axial zones up to a combined thickness of 70 m. The ores are interpreted as being metamorphosed chemical sediments. Metavolcanics are rare in the host sequence.

The Fosdalen deposit N.E. of Trondheim, central Norway (Bugge, 1978; 10.5 Mt Fe/35%) occurs along a E.N.E.-trending stratigraphic horizon 150 km long, located in Cambro-Ordovician metavolcanics and metasediments (schists, marbles, quartzite, amphibolite), interpreted as being a bimodal spilite-keratophyre suite. The orebodies are steeply dipping, ruler-shaped and composed of magnetite with accessory quantities of pyrite and chalcopyrite and hornblende, biotite, epidote, calcite and quartz gangue. They are interpreted as being former subaqueous-hydrothermal (Lahn-Dill "type") deposits.

At Kowary, S.W. Poland (formerly Schmiedeberg; Banaś and Mochnacka, 1974), a metamorphosed and repeatedly deformed lens of magnetite hosted by late Proterozoic gneiss, metacarbonate and amphibolite, is interpreted as being a pre-metamorphic orebody. Over it is superimposed a late Paleozoic periplutonic skarnization of the metacarbonate, and still later ("activation") emplacement of pitchblende, and Ni,Co,Bi, Cu,As,Hg,Se minerals veins and stockworks.

Dynamically metamorphosed manganese ores

The most common representatives are the Precambrian "gondites" treated in Volume 2. Phanerozoic examples are few, low-grade, and economically of little importance. Example localities include Mn-silicate horizons in Cambro-Silurian schists in the Mo-i-Rana area, Norway (Bugge, 1978). The most important horizon located stratigraphically above the Dunderlandsdal iron ore unit is fine grained, several metres thick and composed of quartz, Mn-almandine, accessory spessartite and dannemorite. The rock has a brownish-red colour and an average content of about 3.5-7% Mn (max. 14% Mn).

Dynamically metamorphosed massive sulphides

Large-scale physical transformations of ores are the result of differences in the physicochemical properties of orebodies, as compared with their host rocks. Stretching and flattening of sulphide lenses is most common, followed by boudinage and dismemberement. Brecciation and "Durchbewegung" (i.e., kneading; thorough deformation caused by inhomogeneous rotational strain) are also common. In many massive sulphide bodies mechanically more resistant fragments (of pyrite, arsenopyrite, garnet, quartz, feldspar) rotate, and are surrounded by a flow-banded matrix of pyrrhotite, chalcopyrite, galena, sphalerite and other minerals.

At most massive sulphide localities, the ore had lower strength than the wallrocks, so it was more mobile and flowed plastically. This is expressed almost universally in a variable thickness of the originally

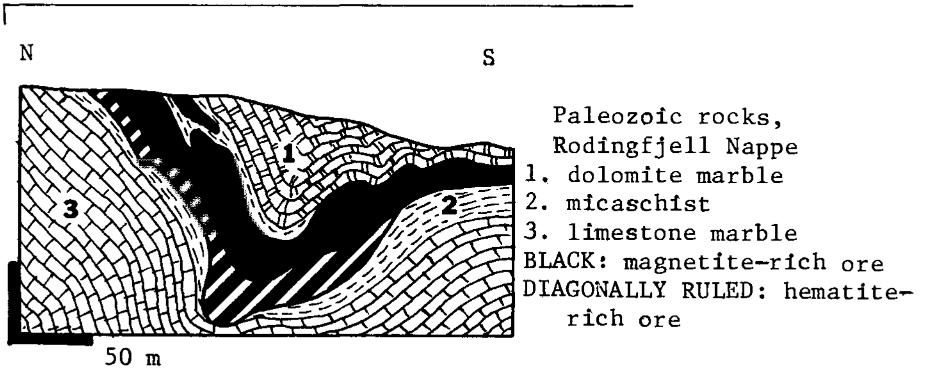


Fig. 29-5. Dunderlandsdal iron district, N. Norway; Ørtvann pit. From LITHOTHEQUE, after Mining Magazine, November 1980.

uniform ore beds and lenses, thickening in fold hinges and thinning along limbs. Many sulphide lenses in metamorphics which have been traditionally interpreted as "stratiform" have recently been re-interpreted as being structurally composite products of intrafolial folding (e.g. the Caribou deposit, New Brunswick; Davis, 1972). Rod and ruler-shaped orebodies, strongly elongated parallel to fold hinges of intensively compressed fold structures, constitute another extreme example of the dynamometamorphic control of orebodies. An ore rod can form by (1) multiple refolding of an earlier concordant sheet, or (2) replacement or dilation-filling in the axial area of folds, by fluid-transported regionally mobilized metals. Several deposits in the Scandinavian Caledonides (e.g. Killingdal; Rui, 1973) and the Sanbagawa metamorphic terrain in Japan (Chichara and Shingu mines; Kanehira and Tatsumi, 1970), contain rod-shaped orebodies.

Dynamometamorphism interferes with the banding or lamination in massive sulphides, which can either be destroyed, or newly created. The former case is a common result of metamorphic homogenization, in which originally heterogeneously banded sulphides revert partly or wholly to a massive, non-banded, monosulphide solution. The latter case results from metamorphic differentiation. The banding is oriented in regard to the stress vector, and need not be parallel to the wallrocks.

The last effect of dynamometamorphism on massive sulphide bodies that will be mentioned, is that of remobilization through a fluid phase. Stringers, veinlets, fracture networks, schlieren, disseminations of paragenetically younger minerals (in particular chalcopyrite) overprinting a usually pyritic main ore lens and also injected into the wallrocks, are commonplace.

Mineralogical and chemical compositions of dynamometamorphosed massive sulphide deposits in high-grade metamorphic terrains are almost identical with those in the lightly metamorphosed terrains, except for the greater representation of pyrrhotite at the expense of pyrite. The principal base metals ratios (Zn,Cu,Pb) also correspond to the latter, thus giving some indication as to the environmental and geotectonic setting. As expected, Cu-dominated orebodies are in amphibolite (mafic metavolcanic) terrains, e.g. Fornas, Cabo Ortegal Complex, Spain; Sulitjelma, Norway; Cajla, S.W. Slovakia (Table 29-4).

Zn-Cu orebodies are contained in mafic and felsic metavolcanics and associated metasediments, apparently corresponding to bimodal mafic-felsic volcanic-sedimentary terrains (e.g. Ducktown, Ore Knob, Gossan Lead and other deposits in the southern Appalachians; Tezuitlan, Mexico; Table 29-5). Zn-Pb orebodies are situated in metasedimentary (typically graphitic); metasedimentary-mafic metavolcanic (taphrogenic) and sequentially differentiated metavolcanic-metasedimentary terrains (e.g. Bleikvassli, Shuswap Complex, Pflersch, Achik-Tash; Table 29-6).

Nickel and Ni-Cu sulphides spatially associated with the metamorphosed ultramafics are common and economically important in the Precambrian terrains (e.g. Thompson, Manitoba; Selebi-Phikwe,

Table 29-4. Massive to disseminated, Cu-dominated schistosity-peneconcordant sulphide bodies in high-grade metamorphic terrains (mostly amphibolites)

LOCALITY	HOST UNIT	MINERALIZATION	REFERENCES
Sulitjelma, N. Norway	S, amphibolite, retrograde chlorite schist, meta-keratophyre, minor ultramafics; in allochthon	up to 1.5 km x 400 x 8 m oreb. at several stratigr. horizons near or within amphibolite; massive to disseminated pyrite, pyrrhot.,chalcop.,minor sphalerite, cubanite, valeriite; 370 Tt Cu	Bugge (1978)
Arinteiro and Bama deposits, Galicia, Spain	S ? garnet amphibolite (meta-ophiolite ?), granulite, gneiss	chalcop.,pyrrhot.,pyrite dissem., veins and veinlets assoc. with garnet porphyroblasts in amphibolite; elongated ore lenses in noses of isoclinal folds, up to 10m thick; 200 Tt Cu/0.5-0.67%	Badham and Williams (1981)
Cajla, Male Karpaty Mts.,Czechoslovakia	S ? micasch., graph.schist, amphibolite, intr. by late to post-orogenic Cb granite	pyrrhot.,pyrite, minor chalcopyr., dissem. to locally massive in amphibolite	Mahel' and Buday, eds.(1968)

Table 29-5. Massive to disseminated, Zn-Cu dominated schistosity-peneconcordant sulphide bodies in high-grade metamorphic terrains

LOCALITY	HOST UNIT	MINERALIZATION	REFERENCES
Ducktown, Blue Ridge, S.E. Tennessee, U.S.A.	Pt_3 chlorite-garnet gneiss, seric.-biot.schist, biot. quartzite, amphibolite	string of massive pyrrh.,pyr.,mag., chalcop.,sphal.,in calcite,dolom., qtz.,tremol.,chlor.,biot.gangue in schists, peneconc.with foliation; 8 tabular oreb., 9 km length 500 Tt Cu/0.7-1.6%, 18 Tt Co	Magee (1968)
Ore Knob, North Carolina, U.S.A.	Pt_3 biot.-sillimanite gneiss, amphibolite	pyrrhot., pyr.,chalcop.,quartz, biot.,amphibole peneconc.massive to dissem.bodies, 1.3 km long zone 31.5 Tt Cu/2.22%; 4.1 t Ag	Kinkel (1967)
Gossan Lead, Blue Ridge, Virginia, U.S.A.	Pt_3 gneiss, quartz-mica schist, minor amphibolite	N.E.-trending zone of discontin. massive pyrrhot.,lesser sphal., chalcop.,galena, 28 km long, en-echelon lenses. 100 Mt pyrrhot., estim. 2 Mt Zn/2%	Kinkel (1967)
Mofjell, Northern Norway	Cm-S, feldspar gneiss	sphalerite,galena,chalcopyrite in 3 ruler-shaped orebodies, plunging 8^{o} east; 147 Tt Zn/3.5%; 35.7 Tt Pb/ 0.85%; 11.8 Tt Cu/0.28%	Bugge (1978)
Goldstream deposit Shuswap Complex, Brit. Columbia	Pt_3-PZ_1 graphit.schist, calc-schist,marble,amphibolite (metabasalt, metatuff)	massive pyrrhot.,sphal.,chalcop., 3-4 m thick, 1.2 km long lens in quartz-rich schist interb.with garn.-chlor. and graph. schist. 160 Tt Cu/3.7%; 117 Tt Zn/2.2% 69 t Ag/16 ppm	Höy (1979)

Table 29-6. Massive to disseminated, Zn-Pb schistosity-peneconcordant sulphide bodies in high-grade metamorphosed schist, gneiss, and/or minor intercalated carbonate horizons

LOCALITY	HOST UNIT	MINERALIZATION	REFERENCES
Mt.Copeland, Shuswap Complex, British Columbia	Pt_3 or PZ sillim.-biot.gneiss, micasch., metaquartzite, calc.-silic. gneiss, amphib.	up to 3m thick fine sphal., gal., pyr., pyrrhot. massive repl. in a thin marble horiz.; min.161 Tt Zn/6.2%, 146 Tt Pb/5.6%; 88 t Ag	Fyles (1970)
Ruddock Creek, Shuswap Complex, Brit. Columbia	micasch., calc-silic.gneiss, marble, veined by pegmatite and katazonal granite	lenses of mass. sphal., pyrrhot., gal., pyr., barite, fluorite up to 1.6 m thick; discontin. deformed horizons. Estim.min. 400 Tt Zn	COMINCO Staff oral commun. (1976)
Groundhog Basin, S.E. Alaska U.S.A.	PZ? schist, gneiss, calc-silicate gneiss, minor marble	massive pyrrhot., sphaler., lesser pyrite, galena; tabular oreb. max. 3m thick, 1,070 m long; 20 Tt Zn	Buddington and Chapin (1929)
Tracy Arm and Sumdum, S.E. Alaska U.S.A.	PZ? muscovite schist with a marble band	mass. to dissem. pyrrh., chalcop., sphalerite, lesser galena; 144 Tt Cu/0.6%, 96 Tt Zn/0.4%	as above
Bayindir, Menderes Massif, Turkey	Or-S, garnet-chlorite schist, calc-silic.gneiss, graphite schist, marble, metaquartzite	3 up to 3 km long gal., sphal., pyr., dissem. to massive ore layers	Dora (1977)
Bleikvassli, N. Norway	Pt_3 or Cm-S gneiss, schist, metaquartzite, graph.quartz., garnet schist, marble	series of interconn. and branching mass. and dissem. pyr., sphal., galena, pyrrhot., chalcopyr. lenses 163 Tt Zn/6.81%; 88 Tt Pb/3.67% 10 Tt Cu/0.42%	Vokes (1963)

Botswana; Western Australia; Volume 2), but insignificant in the Phanerozoic terrains.

The Zn-Pb dominated massive sulphide deposits in high-grade metamorphics (sometimes designated as Broken Hill-"type") are a special class of orebodies showing some links with carbonate hosts and with migmatite terrains, so they are reviewed in an independent section. Deformation and metamorphism of massive sulphide deposits not only produced the profound textural and structural changes discussed earlier, but also obliterated, to a considerable extent, traces of the pre-metamorphic depositional systems and environments (provided the orebodies are indeed pre-metamorphic), such as the characteristic "stratiform" lens and discordant footwall-feeder configuration (compare Chapter 6).

Sundblad (1980) convincingly demonstrated the disappearance of the anticipated feeder stockwork, following a twelve-fold flattening of an originally rooted massive sulphide lens along a shear, in Ankarvattnet, Sweden. The original vertical zoning common in massive sulphide deposits, moreover, had been tectonically transposed so, at present, it shows a lateral gradient.

Ducktown ore field, Tennessee, is one of the best-studied examples of Zn-Cu bearing massive sulphides in medium-grade metamorphics (Magee, 1968; Addy and Ypma, 1977; over 500 Tt Cu, 700 Tt Zn, 18 Tt Co; Fig. 29-6). There, eight folded and penetratively deformed, originally tabular orebodies exist with a composition: 60% pyrrhotite, 30% pyrite, 4% chalcopyrite, 4% sphalerite and 2% magnetite. They occupy a system of subparallel N.E.-trending shear zones in late Paleozoic staurolite, chlorite, garnet schists and biotite-rich metamorphics. These rocks are interpreted as being partly retrogressively metamorphosed metagraywackes, shales and conglomerates, cut by gabbro dikes. The orebodies appear to be at least partly conformable with the original bedding, and are interpreted as being the result of polystage mineralization. This involved syn-sedimentary hydrothermal seafloor precipitation, followed by shearing, partial metamorphogenic remobilization, accretion of additional sulphides, and retrogressive sericitization and chloritization.

In the early days of mining at Ducktown, 11 Tt Cu were produced from a chalcocite secondary enrichment blanket, and about 1 Mt Fe came from a thick limonitic gossan.

Ore Knob, North Carolina (Kinkel, 1967; 31.5 Tt Cu/2.22%; Fig. 29-7), is a much smaller massive pyrrhotite, pyrite, chalcopyrite, quartz, biotite and amphibole deposit vein-like to lenticular in shape, hosted by a late Proterozoic gneiss. As in Ducktown, the ore zone is contained in a narrow shear to breccia zone and is peneconcordant to foliation, slightly crossing the gneissic banding. The ore shoot is at least 1,300 m long and aligned along the plunge of lineation. The ore is polygenetic and surrounded by a fringe of retrogressive alteration that is up to 1.6 m thick. Most of the remaining deposits of this style are variations on a theme.

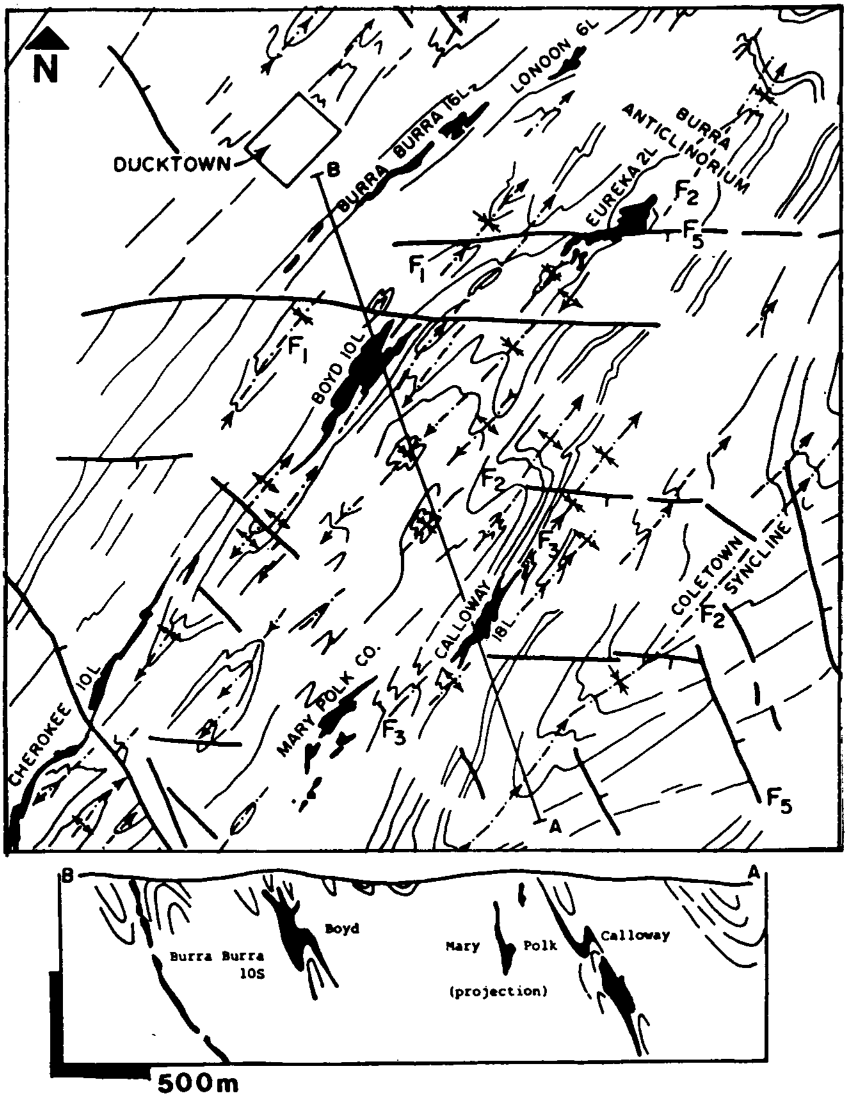


Fig. 29-6. A portion of a structural map of the Ducktown field, Tennessee, sulphide orebodies conformable with foliation in the host metamorphics. From Addy and Ypma (1977), courtesy of Economic Geology.

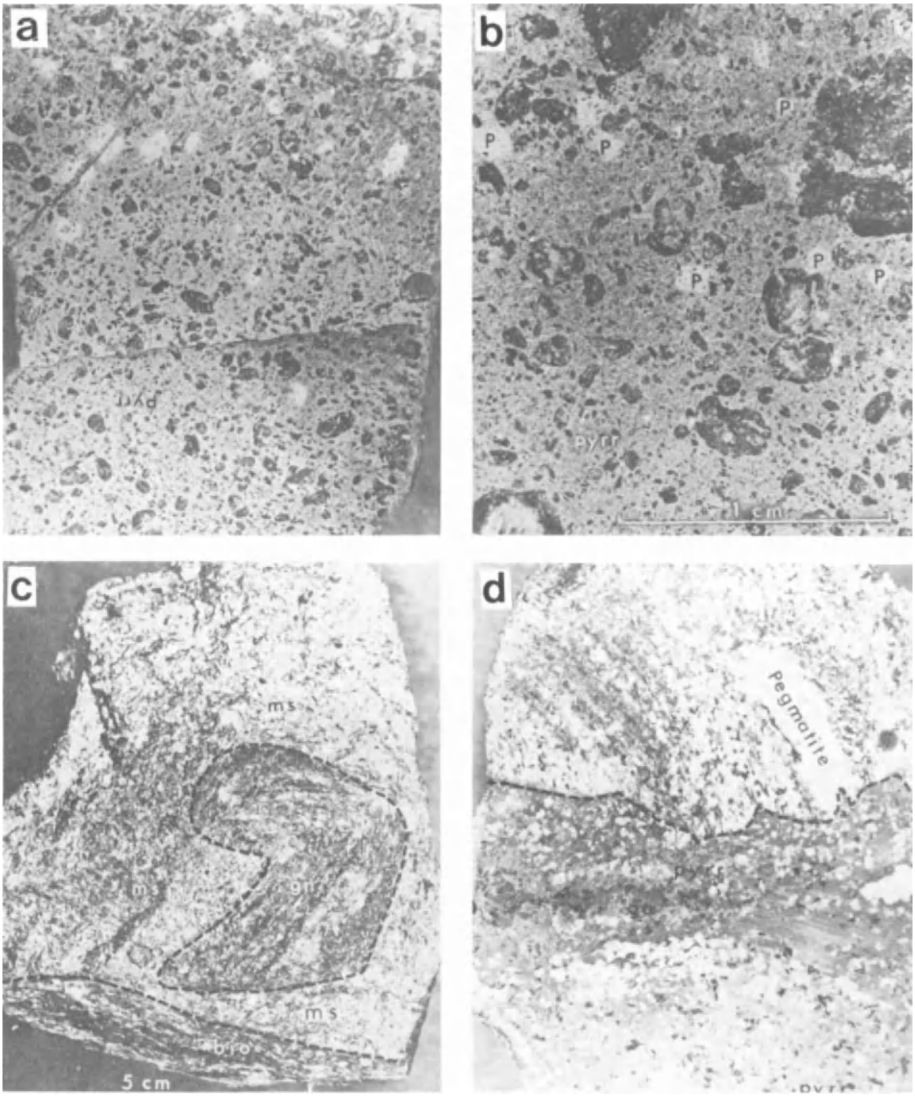
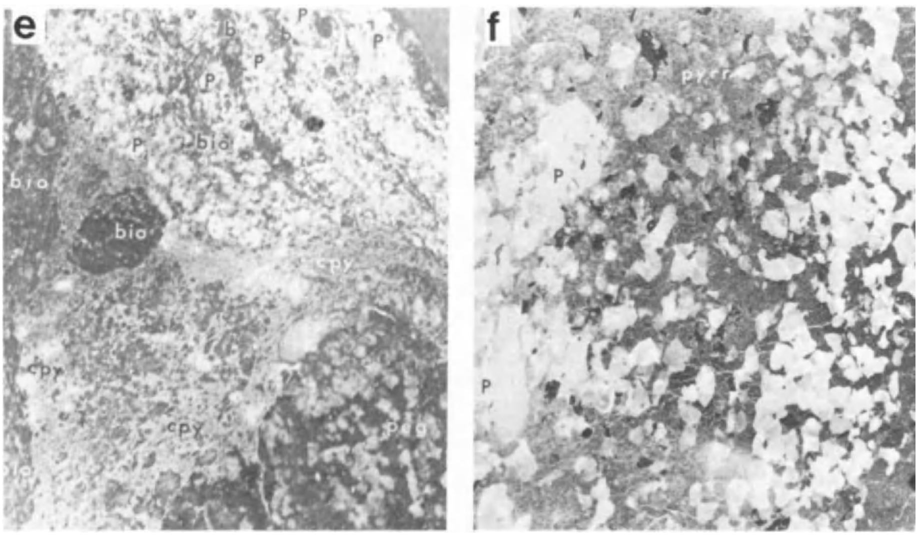


Fig. 29-7. Fabrics of high-grade metamorphosed massive sulphides and their host rocks in the Ore Knob deposit, North Carolina. From Kinkel (1967). (a) Rounded rock and mineral fragments (black) in massive, fine grained pyrrhotite (pyrr). White areas are pyrite porphyroblasts. The sharp contact between ore and sheared gneiss (gn) is a common feature. (b) Rounded rock and mineral fragments in massive sulphide ore. Silicate and quartz fragments have partial or complete biotite rims. The gray matrix (pyrr) is massive pyrrhotite. The small black minerals are biotite and hornblende crystals;

29.4.5. Disseminated to massive Zn-Pb sulphide deposits in high-grade metamorphics, peneconcordant with schistosity: the Broken Hill "type"

Broken Hill, N.S.W., Australia, is a composite ore zone, made up of six rich orebodies of coarse crystalline galena, sphalerite, pyrrhotite, bustamite and other minerals. The zone is conformable with the regional schistosity in a high-grade metamorphosed assemblage of gneiss, amphibolite, iron formation, carbonate and synorogenic granite. Broken Hill is lower Proterozoic in age and situated in the Willyama Precambrian block. It is therefore described in Volume 2. Zn-Pb deposits showing many (but not all !) Broken Hill characteristics, however, are known in many Phanerozoic orogens and these are reviewed briefly here.



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P=pyrite. (c) Twisted partly recrystallized fragments of gneiss (gn) in massive sulphide (ms). Coarse-grained black biotite (bio) at bottom of specimen is aligned parallel to vein wall. (d) Massive pyrrhotite ore (pyrr) cutting gneissic banding in wallrock. The vein contains much coarse granular white calcite and garnet; the wallrock contains no calcite or garnet. The black crystals in pyrrhotite are biotite and hornblende. (e) Pyrite bands (P) in gneiss that has been altered to biotite but retains planar structure. Banded biotite gneiss (bio) bends around a large fragment of unoriented, recrystallized pegmatitelike gneiss (peg), which is altered to coarse grained biotite, quartz and plagioclase. Chalcopyrite (cpy) enclosing quartz and rock fragments was formed in the pressure shadow and as rims on rounded pyrite grains. (f) Coarse calcite grains in massive pyrrhotite (pyrr) and minor pyrite (P).

The Mount Copeland Zn-Pb orebody (also known as River Jordan, True Fissure; Fyles, 1970; Riley, 1961; Fig. 29-8), is situated in the Shuswap Metamorphic Complex of British Columbia. There, a remobilized granite core is enveloped by late Proterozoic or Paleozoic mantling assemblage of a gray gneiss, biotite-sillimanite and biotite gneiss, quartz-mica schist, quartzite, amphibolite, marble and calc-silicate gneiss. The age of metamorphism is Jurassic or Cretaceous. The Zn-Pb mineralization is confined to a discrete, stratigraphically-controlled (stratabound) horizon of a calc-silicate gneiss to marble, less than 10 m thick, which is folded and traceable with interruptions for several kilometres. The ore reserve available in a single outcropping segment of the ore zone is 2.6 Mt with 6.2% Zn, 5.6% Pb and 34 ppm Ag, but it is estimated that the entire zone, prior to erosion, contained at least 60 Mt ore.

The orebody itself is up to 3 m thick, and consists of fine grained pyrrhotite, sphalerite, galena, pyrite, containing "eyes" and bunches of quartz and pegmatitic feldspar. When the ore is located at the contact with the footwall sillimanite, biotite, garnet schist or gneiss or the hangingwall light-gray quartzitic micaschist, its boundary is sharp. When the entire width of the host horizon is represented by sulphide, the orebody has the form of sharply outlined, concordant band enveloped by the silicate metamorphics. When the ore minerals constitute less than 100% of the ore horizon, the carbonate background shows up. The ore then displays the character of replacement pockets, blebs, veinlets and disseminations in the metacarbonate, often along contacts with short, impersistent lenses and veins of pegmatite. Although the ore appears to be metamorphosed in a grade identical to that of the wallrocks, it is by no means certain that this was originally a seafloor-deposited sedimentary ore layer as is popularly believed.

The remaining schistosity-peneconcordant Zn-Pb zones in the Shuswap Complex (Big Ledge, Ruddock Creek; Fig. 29-9; Wigwam, Cottonwood; Table 29-6), are all immediately hosted by a thin, often boudinaged or completely sulphide-replaced horizon of metacarbonate, sandwiched between gneiss or schist, so that they correspond closely to the situation at Mount Copeland. Even at Broken Hill, N.S.W., calcite, Mn carbonates and Ca or Mn silicates probably produced by contact metasomatism are widespread in the ore zone and although there are no conspicuous relics of unreplaced marble, a complete pseudomorphic replacement of an earlier carbonate body is one of the possible alternatives of the Broken Hill origin.

In the Shuswap Complex, graphitic metasediments are neither widespread nor typical, but elsewhere they may be abundant and prominently associated with metamorphosed Zn-Pb sulphide masses. The Bleikvassli deposit in the northern part of the Norwegian Caledonides (Vokes, 1963; 163 Tt Zn/6.81%, 88 Tt Pb/3.67%, 10 Tt Cu/0.42%; Fig. 29-10) is in Proterozoic or Cambro-Silurian micaschist and gneiss at or near contact with a unit of graphitic and muscovitic quartzite and schist. A series of interconnected and branching, schistosity-concordant lenses of massive and disseminated pyrite,

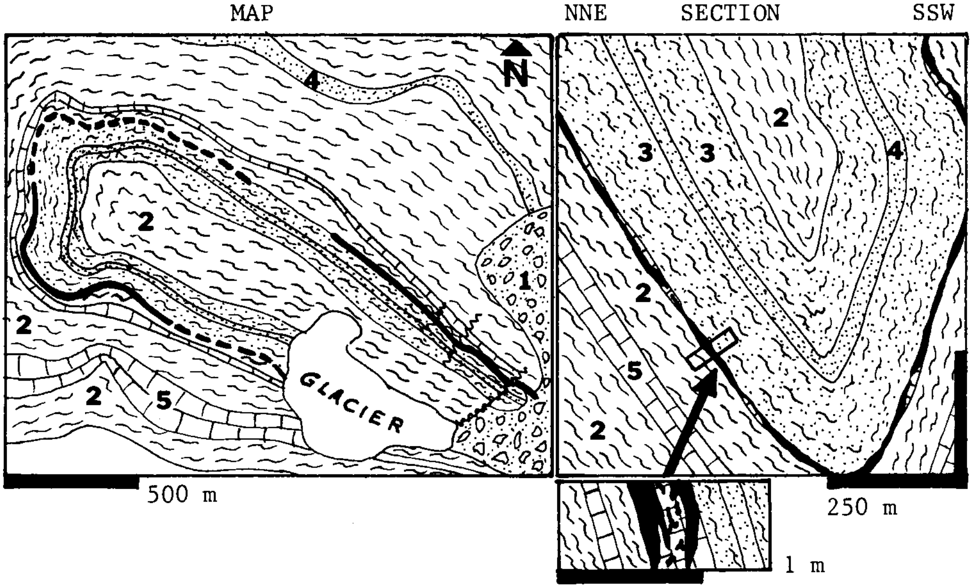


Fig. 29-8. Mount Copeland near Revelstoke, British Columbia, a schistosity-concordant Zn-Pb massive orebody in amphibolite grade metamorphics. 1=Q glacial sediments; 2=Pt_3 or PZ mantling assemblage of the Shuswap Complex (J metamorphism), biotite or biotite sillimanite gneiss and schist; 3=mica quartzite to quartz-mica schist; 4=metaquartzite; 5=calc-silicate gneiss to marble; black: Zn-Pb ore horizon. From LITHOTHEQUE, after Fyles (1970), Riley (1961) and own fieldwork.

sphalerite, galena, pyrrhotite, lesser chalcopyrite, stannite and cassiterite, show typical metamorphic ore textures and has the same metamorphic grade as the enclosing rocks, so it is pre-metamorphic. Although there are no traces of carbonate in the orebody itself, lenses of marble do occur in the host series, an allochthonous unit. The associated metamorphics suggest that Bleikvassli could have been a member of the "black slate" lithologic association which was reviewed, in its pre-metamorphic state, in Section 17.5.

29.4.6. Granulite, charnockite, eclogite

Granulite facies consists of completely dehydrated rocks, such as ordinary (quartz, feldspar or garnet) granulite, hypersthene granulite and charnockite. Eclogites are composed of omphacite pyroxene and garnet. In the recent literature (see review in Suk, 1983, p.213), two varieties of granulite terrains have usually been distinguished:

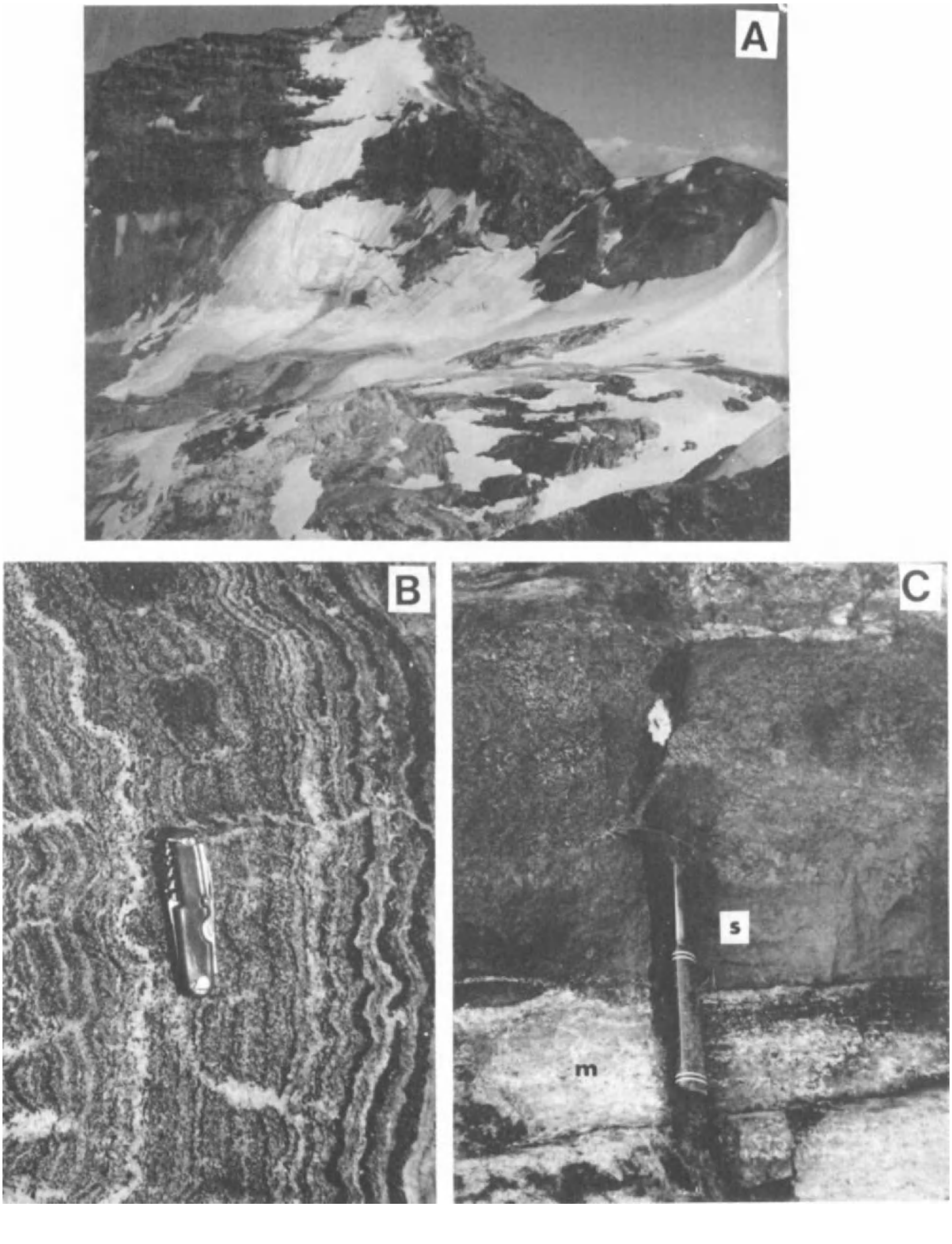
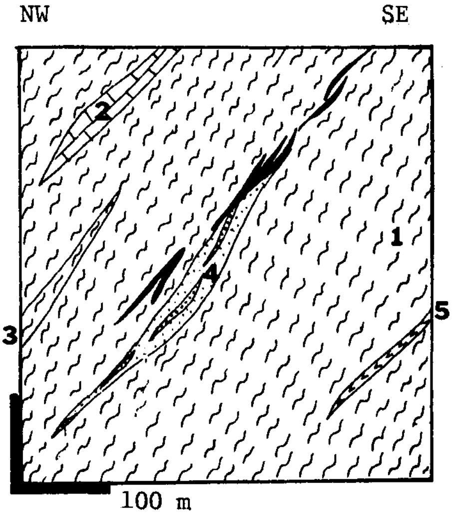


Fig. 29-9. Ruddock Creek massive Zn-Pb sulphide zone, British Columbia. (A) General view. (B) Gneiss of the host sequence, showing initial partial melting and metasome segregation. (C) Contact of massive sphalerite, galena, pyrrhotite band (s) and marble (m).



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1. gray microcline, quartz, biotite gneiss
2. marble
3. garnet micaschist
4. muscovite and graphite metaquartzite and schist
5. amphibolite

Fig. 29-10. Bleikvassli, N. Norway, Zn-Pb massive sulphide deposit. From LITHOTHEQUE, based on data in Vokes (1963).

(1) those in Precambrian shields, Vol. 2, considered "typical" granulite facies metamorphics and (2) those in Phanerozoic orogenes, often interpreted as originally anhydrous rocks of suitable composition such as continental rhyolite or andesite, that achieved their granulitic character under conditions of lower, amphibolite facies metamorphism. Those of type (2) are relatively uncommon, although nine areas of distribution are known from the Bohemian Massif alone. No metallic occurrences in the granulites proper are known, with the exception of small quantities of accessory pyrite in some of the hypersthene varieties.

The category of the "deepest-seated" pegmatites of Ginsburg et al. (1979) is spatially associated with granulites, being gradational into pegmatites in migmatite terrains or a product of retrogression. Monazite and/or allanite have been reported in mineralogical quantities from some of the "deepest-seated" pegmatites, and Be (taafeite) and complex Th-U minerals have been found in exceptional cases. Small amounts of monazite recovered from terrace and channel sands of some of the rivers draining the southern Bohemian granulites (Blanice, upper Vltava), may have been derived from such pegmatites.

Eclogites had probably formed under similar conditions of pressure and temperature as granulites, although from different precursors (spilites, gabbros, basalts). They occur in association with amphibolites and ultramafics in Barrovian metamorphic belts, as well as in high-pressure blueschist associations. No metallic deposits are known from the former. A rutile deposit hosted by the high-pressure eclogites in the Urals, has been described briefly in Chapter 8.

29.5. MINERALIZATION STYLES IN METACARBONATES

29.5.1. Meta-bauxites

Meta-bauxites associated with metacarbonates (former "Mediterranean-type" or "karst" bauxites; Chapter 20) are the least controversial example of metamorphosed relic mineralization in carbonates. Unfortunately, thoroughly studied meta-bauxite occurrences are extremely rare, and the best examples can be found on the Greek Cyclade Islands, particularly on Naxos. There (Jansen and Schuiling, 1976; Fig. 29-10), a migmatitic gneiss dome having an Oligocene age of metamorphism, is enveloped by metasediments (marble, micaschist) and mafic-ultramafic members of ophiolites (amphibolite, serpentinite) with concentrically decreasing metamorphic grade (away from the central dome). A Miocene high-level granodiorite intrusion is to be found in the western part of the island.

The dominant rock, the metacarbonate, contains numerous lenses and pockets of meta-bauxite. The close proximity of the mafic-ultramafic rocks to the meta-bauxite, its highly ferruginous nature and the presence of unusual minerals (e.g. Ni-fuchsite) suggest that the ophiolites could have been the source of the Fe and Al-oxides rich residuum, washed into the carbonate karst. The meta-bauxites are present in a wide range of metamorphic zones and change their mineralogical composition accordingly. In the lowest metamorphic zone (greenschist facies), the meta-bauxite has an assemblage of diaspore, chloritoid and hematite. With increasing metamorphism, dehydration resulted in the formation of corundum and magnetite, and emery deposits formed. In the biotite-chloritoid zone, the meta-bauxites contain corundum, chloritoid, kyanite, magnetite assemblage in the centre, and corundum, calcite, margarite, chloritoid along the contact. In the kyanite zone, the emery consists of kyanite, corundum, staurolite, magnetite, grading into a marginal margarite, anorthite, corundum assemblage. In the sillimanite zone, the emery is composed of corundum, staurolite and magnetite.

29.5.2. Skarns

In the previous section, the peculiarity of skarns and skarnoids in the predominantly non-carbonate high-grade metamorphic terrains were discussed briefly. This section is concerned with skarns hosted by high-grade metamorphosed, widespread carbonates (marbles). There, the skarn bodies could have formed in several ways. These are as follows: (1) by isochemical metamorphism of a pre-metamorphic compositionally suitable assemblage (pelosiderite, marl, ankerite); (2) by bimetasomatism or local infiltration metasomatism at a marble-contrasting rock (e.g. mafic or ultramafic body, ironstone) contact, in the metamorphic or ultrametamorphic environment; (3) by pre-metamorphic infiltration metasomatism at the marble-"granite" contact and subsequent regional metamorphism that generated a

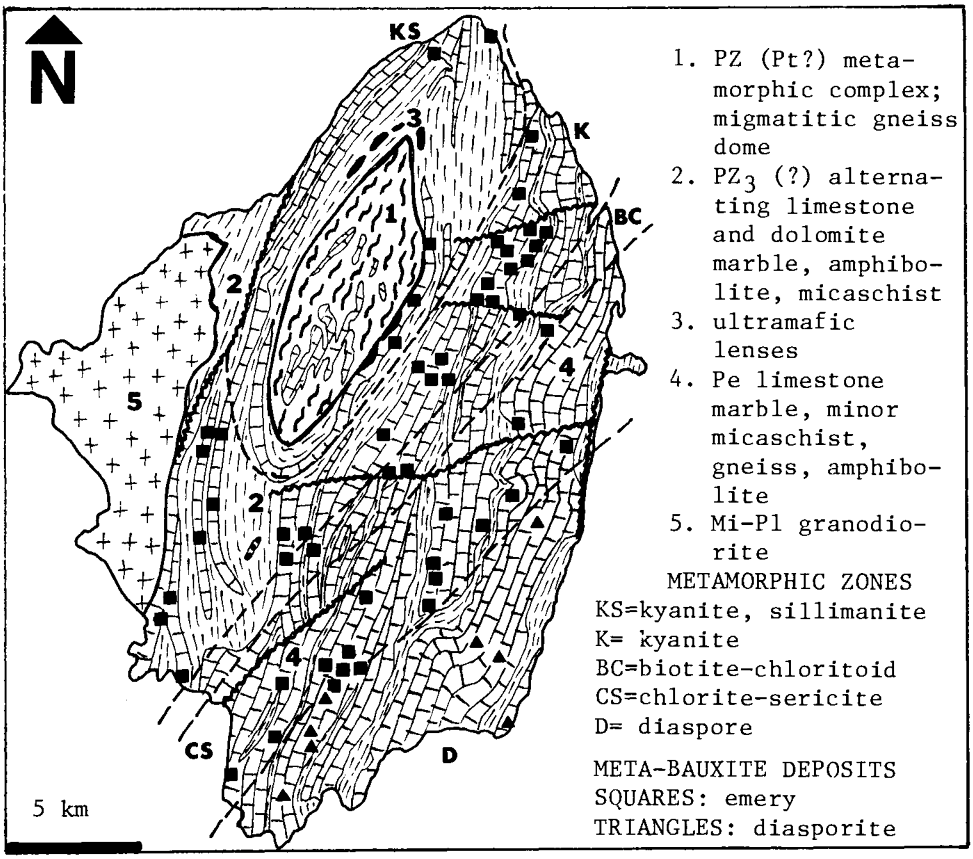


Fig. 29-11. Setting of meta-bauxite occurrences on Naxos Island, Greece. Slightly simplified after Jansen and Schuiling (1976). Redrawn with permission from the American Journal of Science and the authors.

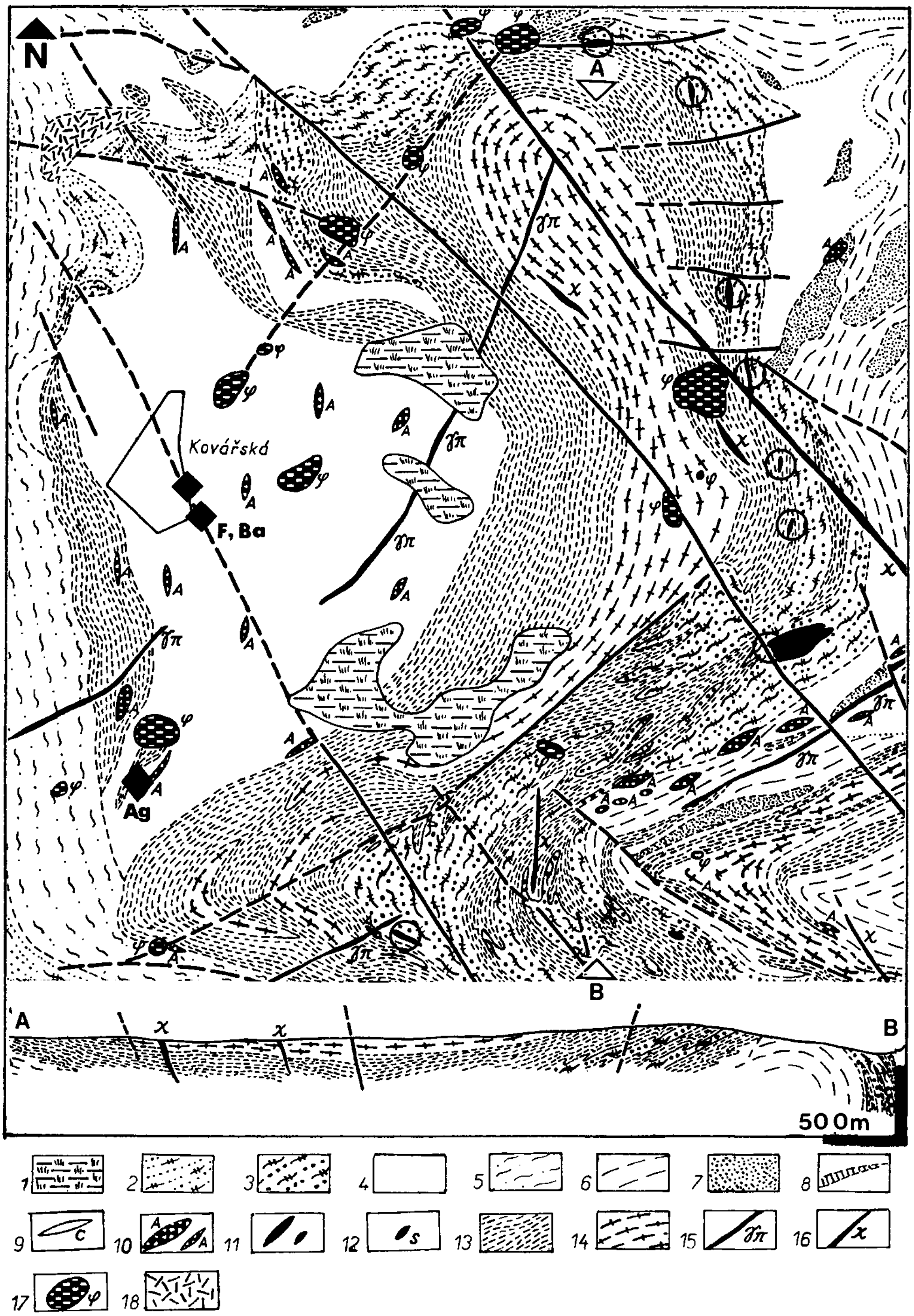
meta-skarn and converted the granite into an orthogneiss or (4) by post-metamorphic infiltration metasomatism at marble-"granite" contact. The latter possibility was treated in Chapter 28 and will not be considered further here. Categories (1-3) are virtually indistinguishable in the field and the literature interpretations are usually the consequence of the interpreter's bias.

In the Erzgebirge Mountains (East Germany and Czechoslovakia; Svoboda, ed., 1966; Chrt and Bolduan, 1966; Fig. 29-12), skarns which are interpreted as belonging to categories (3) and (4) are widespread and locally of economic importance. The (3) skarns are hosted by minor late Proterozoic carbonate lenses in a complex gneiss, micaschist, amphibolite, metacarbonate and ultramafics sequence, have the form of lenses concordant with schistosity, and the skarnization is attributed to synorogenic early Paleozoic "granites" (now a "red orthogneiss"). Magnetite is the main commodity produced from these skarns (e.g. at Měděnec) and Cu,Pb,Zn sulphides are minor. The average Fe content is 37% Fe. The Měděnec skarn deposit is a lens, over 100 m thick and 500 m long consisting of hedenbergite-andradite skarn with local portions of amphibole, epidote, idocrase and biotite skarn, enveloped by garnet-muscovite micaschist. A medium- to fine-grained muscovite or two-mica orthogneiss is located in the vicinity. Banded magnetite-rich lenses up to 60 m thick with minor and irregularly distributed pyrite, pyrrhotite and chalcopyrite are being mined.

The type (4) skarns in the Erzgebirge are more variable in composition, and formed by replacement of Proterozoic and lower Paleozoic carbonates, mafic calcic tuffs and partly carbonatic metabasalts in the contact aureole of the post-orogenic Permo-Carboniferous "granites". Polymetallic skarns (Zn,Pb,Cu), some with superimposed fracture filling cassiterite (Zlatý Kopec, Breitenbrunn), are common.

Fig. 29-12. Geological map and section of a polymetamorphic terrain in the Erzgebirge Mountains near Kovářská, N.W. Czechoslovakia, showing ore occurrences.

1=Q peat bogs; 2=quartzitic micaschist and metaquartzite; 3=garnet micaschist; 4=two mica gneiss; 5=gneiss with feldspar porphyroblasts; 6=two mica gneiss and paragneiss; 7=massive graywacke gneiss; 8=two mica gneiss with layers of graywacke gneiss; 9=marble; 10=amphibolite; 11=skarn; 12=serpentinite; 13=migmatitic orthogneiss; 14=coarse augengneiss; 15=granite porphyry; 16=lamprophyre; 17=T volcanics; 18=tuffs. ORES: Fe=magnetite skarns (circled); Ag=Ag,Co,Ni,As,Pb veins; F,Ba=T? fluorite and barite veins along faults. After Šattran and Škvor in Svoboda, ed. (1966); courtesy of the Ústřední Ústav Geologický, Praha. Ore occurrences added.


N
A
Kovářská
F, Ba
Ag
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500m
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29.5.3. Manganese ores

Phanerozoic equivalents of the Precambrian "queluzite" (i.e., rhodochrosite marble and rhodonite hornfels) acting as a protore to rich residual Mn-oxide deposits (e.g. Cons. Lafaiete and Serra do Navio, Brazil; Section 23.3.5. and Fig. 23-10), are rare. One example is the Takhta-Karacha zone in the Zeravshan Range, Soviet Central Asia, where a Mn-member in a Silurian metacarbonate sequence is traceable for over 250 km (Varentsov and Rakhmanov, 1974). The Mn-member is a dark gray to black finely banded to massive limestone marble, interbedded with minor amphibolite. Two seams of rhodochrosite and manganocalcite with minor "floating" crystals of spessartite, 6-8 m thick, crop out in numerous small deposits, some of which contain secondary vernadite, psilomelane and pyrolusite in the oxidation zone.

In the small James River-Roanoke River Mn field in Virginia (Espenshade, 1954; 16 Tt Mn/43.3%), lumps and masses of hard psilomelane occur in residual clay, formed over late Proterozoic to lower Cambrian white marbles that carry a mere 0.11 to 0.85% MnO. The marble is interbedded with schist and meta-quartzite. Some Mn deposits in the lower Cambrian Tulgheş Series, N.E. Rumanian Carpathians (Ianovici and Borcoş, 1982), are hosted by marbles.

29.5.4. Zn-Pb ores

Metamorphosed galena-sphalerite bodies hosted by widespread marbles are usually designated Balmat "type" in the literature, and are common in several Precambrian metamorphic terrains (e.g. Balmat, New York; Marmorilik, Greenland; Vol.2). Only a few minor occurrences are known dating from the Phanerozoic time.

In the Rodna Mountains (northern Rumanian Carpathians; Ianovici and Borcoş, 1982), late Proterozoic marbles interbedded with micaschists in a thrust, contain tabular peneconcordant metamorphosed bodies of shpalerite, galena and barite. These are interpreted as being partly remobilized, metamorphosed Mississippi Valley-"type" deposits.

29.6. MINERALIZATION STYLES IN AND RELATED TO THE ZONE OF ULTRAMETAMORPHISM AND GRANITIZATION

29.6.1. General

Ultrametamorphism causes transformations of rocks under conditions near to the melting point of the rock system involved (Suk, 1983). This can take place in regions of high-grade regional metamorphism, but also at intrusive contacts. It has been demonstrated that ultrametamorphism is sometimes independent of isometamorphic zones, but requires a high water pressure. Ultrametamorphism starts with partial melting of rocks. That triggers a chain reaction: melting→ metamorphic differentiation→ metasomatism by the mobile substance and cation exchange→ formation of magmatic melts and their local injection, or rise into the higher crust in the form of granitic magma (Mehnert, 1968).

The most common rocks in the zone of ultrametamorphism are migmatites, rocks composed of the usually darker immobile residue of the partially melted material (paleosome, melanosome, substrate, restite), and the lighter mobile melt (neosome, leucosome, metatect, mobilizate). Granite gneiss is "a gneiss derived from a sedimentary or igneous rock and having a granite mineralogy" (A.G.I. Glossary of Geology) and is either an evolutionarily more advanced product of granitization that also generated migmatites (a product of metamorphic homogenization rather than differentiation like the migmatite), or an equivalent of migmatite in a suitable environment.

The structural varieties of migmatites and granite gneisses are treated in most textbooks and will not be considered here. Compositionally, the bulk of migmatites have a substrate of biotite, feldspar, quartz, lesser sillimanite, garnet gneiss, and a quartz-feldspar metatect. The second most common variety are the migmatites with a green amphibole-rich (amphibolitic) metatect. The remainder of high-grade metamorphics rarely form regularly banded migmatites and the metatect tends to form fracture or bedding veins, replacements, breccia matrix, etc., as well as a variety of reaction and infiltration metasomatites.

For the purposes of metallogenic interpretation and description (Fig. 29-13), it is advantageous to treat separately (I) the zone of actual granitization (migmatite and granite-gneiss terrain); (II) the high- to medium-grade metamorphosed mantle; (III) the katazonal granites, and (IV) pegmatites.

29.6.2. Migmatite and granite-gneiss terrains

These are among the least attractive terrains to a prospector, except in cases where the deep-generated migmatite terrains were uplifted and subsequently intruded by high level "granitic" (e.g. the Colorado Mineral Belt) or other, e.g. alkaline, intrusions. In the latter case, however, there is a substantial time difference between the ultrametamorphism and high-level intrusion. The granitization processes have a highly negative metallogenetic balance, that is, more earlier orebodies are destroyed than are newly created.

Although reliable analytical data are scarce, there is an abundant circumstantial evidence that in a reasonably open system (having avenues of communication with the shallower zones of the crust via ascending granitic magmas, chains of metasomatic fronts, deep lineaments, etc.), a considerable proportion of the transition metals leave the system and move upward. There is no clear evidence that any metals accumulated residually in the granitized rocks. The rarely encountered mineralizations in this zone correspond to four styles:

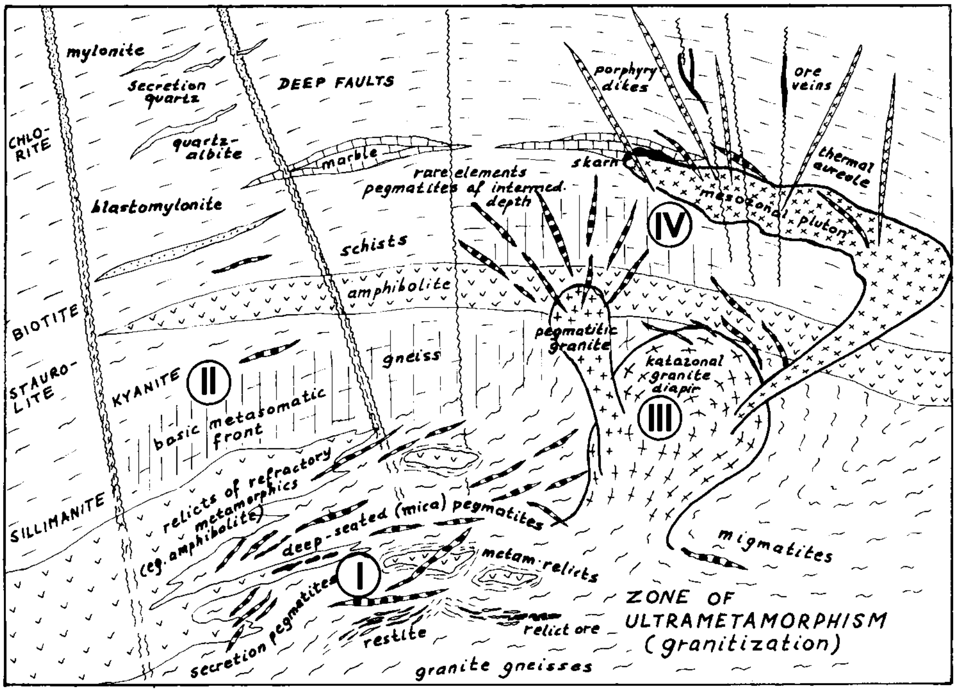


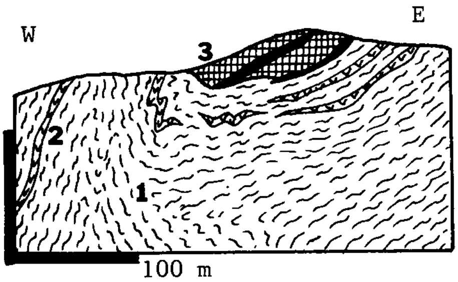
Fig. 29-13. The zone of ultrametamorphism and adjacent zones. Diagrammatic only, dimensions distorted and telescoped. Roman numerals: zones of metallogenic interest as described in the text: I=core zone of granitization; II=metamorphism in mantling assemblage; III=katazonal granites; IV=metalliferous pegmatites of intermediate depth. From Laznicka (1984).

(1) resisters (relics); (2) semi-resisters; (3) metal accumulations in secretions within the granitization zone and (4) metals intercepted during their upward escape and forced to precipitate at or under physical or chemical screens.

(1) RESISTER (RELIC) ORES

Relic mineralizations occur either hosted by refractory rocks preserved as rafts, inclusions or non-granitized segments of earlier rocks, surrounded by or in contact with migmatites, or as "denuded" bodies in the migmatites themselves. The former category includes small magnetite skarns enveloped by migmatites. Several examples (Budeč, Županovice, Vlastějovice) are known from the Moldanubian terrains of the Bohemian Massif.

The Vlastějovice deposit (Koutek, 1963; Fig. 29-14) is confined to



Pt, Moldanubicum Complex metamorphics

1. biotite gneiss to migmatite
2. amphibolite
3. garnet-pyroxene polymetamorphosed skarn with two lenses of magnetite

Fig. 29-14. Polymetamorphosed magnetite skarn in Vlastějovice, central Czechoslovakia. Modified after Koutek (1963).

two isolated synclinal lenses of andradite-hedenbergite and hedenbergite-amphibole skarn, surrounded by Proterozoic migmatites. The skarn is intersected by numerous hybrid pegmatite veins. The magnetite-rich skarn occurs in several lenses up to 10 m thick, and several million tons of iron ore have been produced.

Bands, schlieren, disseminations and small lenses of magnetite are common in rafts and blocks of amphibolite resisters in migmatites and granitic gneisses. There are few significant Phanerozoic examples, and Precambrian localities (e.g. Dover, New Jersey; Labrador Iron Belt) are reviewed in Volume 2 as well as in Laznicka (1985b).

"Denuded orebodies" in terrains of granitization (Fig. 29-15) are represented by several examples of massive Zn,Pb(Cu) orebodies in the Proterozoic Moldanubian Complex in Bavaria and western Czechoslovakia, granitized in the late Paleozoic. The historical Bodenmais deposit in the Bavarian Forest (Teuscher, 1982) is the largest sulphide orebody along a 30 km long W.N.W.-trending mineralized zone, running parallel with the remnants of schistosity in migmatites. The orebody, nearly 1,000 m long and 150 m deep, is a system of boudins over 10 m thick, thinning to about 1 m in the connecting necks. The ore is coarse grained and composed of pyrrhotite, pyrite, sphalerite, chalcopyrite , magnetite and additional ore minerals. The immediate host rock is a garnet, cordierite, sillimanite restite, and pegmatitic mobilizate, pegmatite. Monazite is anomalously concentrated in the migmatite in a separate layer adjacent to the sulphide orebody. The Pohled deposit in central Czechoslovakia is very similar.

(2) SEMI-RESISTER OREBODIES

Semi-resisters, an informal term, is applied here to former metal concentrations modified by granitization often beyond recognition, and to a large degree digested (dissipated) so that only minor remnants of the former orebody remain (Fig. 29-15). Of particular interest are

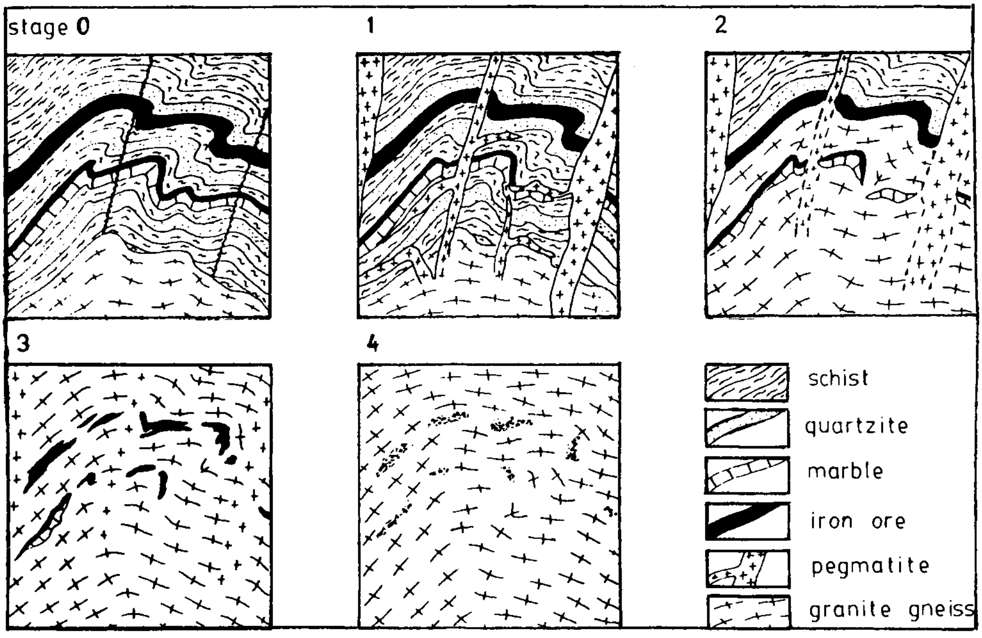


Fig. 29-15. Development of "denuded" resister and semi-resister orebodies in terrains of granitization. From Laznicka (1985b).

the cases of digestion of metalliferous horizons in which the base metals (or gangue elements such as Ba), were accomodated as inconspicuous silicates or oxides. Zinc frequently accumulates in dark green crystals of gahnite (Zn spinel), Pb in the green (amazonite) microcline, Ba in barian feldspars, Co in amphibole, Sn in sphene, staurolite, garnet, etc. Most examples are located in the Precambrian shields (e.g. in the Broken Hill lode zone, gahnite and hyalophane).

Höll and Maucher (1976) described occurrences of scheelite semi-resisters in the Central Gneiss (a migmatite) in the Hohe Tauern Range of Austria. They interpreted the scheelite as being a product of palingenetic regeneration and partly anatectic granitization of the Paleozoic scheelite-bearing strata, during the Variscan orogeny.

The observation made about metallogenically negative processes earlier (e.g. about glaciation) that even when a previously metal-enriched environment is subject to destruction transitional mineralization may appear before such destruction is complete, is applicable here as well. As an example one may quote semi-resister style local uranium enrichments in granitized terrains, formed at the site of uraniferous black sediments.

(3) METAL ACCUMULATIONS IN SECRETIONS AND CONCRETIONS WITHIN THE GRANITIZATION ZONE

Secretions and concretions are nest, lens, vein-like inhomogeneities composed by the most mobile minerals (usually pegmatitic, or of quartz, tourmaline, etc.). They frequently contain porphyroblasts of metalliferous minerals such as spessartite, monazite, allanite and others, but only in mineralogical quantities. Deeply weathered ultrametamorphic terrains may supply these minerals into placers, but only monazite is sufficiently resistant chemically to be able to persist.

(4) METALS INTERCEPTED AND PRECIPITATED DURING THEIR UPWARD MIGRATION

Granitization and anatexis of slightly to strongly uraniferous sediments causes U mobilization and ultimate removal, unless a portion of the U on the move is trapped. The most popular and economically important example of this is the Rössing U deposit in Namibia (and Charlebois Lake, partly Bancroft, Canada; Crocker's Well, South Australia). At Rössing (Berning et al., 1976), uranium concentrated in residual melt of alaskitic composition during syntexis formed low-grade U-oxide disseminations now occurring in a wide variety of rocks including pegmatite, aplite, migmatite, gneiss, and several types of resisters. All the above deposits, often incorrectly designated as "porphyry uraniums", are Precambrian, thus treated in Volume 2. The known Phanerozoic examples, so far, have been insignificant. Recently, Rogers et al. (1978) reviewed this style of mineralization, and offered a prognosis of its possible occurrences in the eastern United States.

29.6.3. Granite-gneiss domes, the core and the mantling complex

GENERAL

This subject overlaps with the subject matter treated earlier in Sections 29.4. and 29.5. The rock types involved are the same, but the emphasis, at present, is on the mutual relation of the metamorphic mantle assemblage and the ultrametamorphic core. In this context, the fundamental metallogenic function of the mantle to be considered is its likely ability to provide a reservoir for the entrapment of metalliferous volatiles (melts, fluids, gasses), supposedly moving upward from the core. This emphasis is different from the emphasis placed on pre-metamorphic relic ores earlier. In many respects the present exercise involves processes and conditions parallel with those taking place during the interaction of medium to high-level "granitic" plutons with their roof, treated in Chapter 28.

The mantled gneiss (thermal) domes recognized by Eskola and studied later by Wegmann, de Sitter, Zwart and other investigators (compare

Suk, 1983, for review), are a characteristic fixture of Precambrian shield as well as Phanerozoic orogenic belt geology. In some geologically young domes, such as in the Shuswap Complex, British Columbia (Jurassic to Cretaceous metamorphism), the geologically younger mantle (late Proterozoic to Paleoozic) formerly resting unconformably on the early Proterozoic basement, is now largely converted into granite gneiss. The contrast in style and degree of metamorphism between the core and the mantle is substantial. In older, deeper eroded domes, such as the late Paleozoic Central Moldanubian Dome in central Czechoslovakia (Fig. 29-16), migmatites are widespread and dominant and the core/mantle relationship less distinct. In both the above-mentioned, as well as other domes, katazonal to mesozonal granites appear near the thermal centres.

Ever since Reid and Reynolds, the idea of metasomatic fronts (acid, basic, alkalic) initially triggered by granitization and gradually propagating upward, has from time to time been discussed or applied, so far with inconclusive general results (e.g. Hietanen, 1962; Velikoslavinsky et al., 1968; see also review in Suk, 1983). The "basic front" supposed immediately to top the ultrametamorphic or periplutonic dome, could be of interest in metallogeny. The alkalic fronts, interchangeably K or Na specialized, appear, in many respects, to be larger scale and substantially more heterogeneous counterparts of the system that produced the apogranite alteration assemblages (Chapter 28). Regional metasomatic fronts have occasionally been suspected in the generation of the regionally distributed ankerite, siderite and magnesite deposits in the Alps and Carpathians, and possibly as a cause of several major gold-mineralized provinces.

GEOLOGY

The characteristic anatomy of a multiphase mantled granite-gneiss dome is shown in Fig. 29-17. The bulk of the core consists of migmatite (A) and synorogenic katazonal granite (B). The granite has numerous subvarieties, such as anatectite formed by a complete in-situ remelting and homogenization of the original rock; anatectite transported for short distances, during which it could have acquired a different character due to assimilation of various host rocks. Alternatively, metasomatic granite formed by feldspathization and feldspar porphyroblastesis of paragneisses (C). The latter is, for example, represented by the "durbachitic" granodiorite, syenodiorite and syenite with large, tabular, feldspar porphyroblasts resting in a foliated dark biotite-rich groundmass, described from the Schwarzwald Range (Germany) and Central Bohemian Pluton border (Czechoslovakia; Svoboda, ed., 1966). Numerous but minor, non-persistent bodies of compositionally simple (quartz, feldspar, mica) pegmatites and aplites are abundant (D).

Emplacement of sub-autochthonous to allochthonous leucocratic plutons formed from palingenetic magmas (E) took place during the closing stages of synkinematic granitization and shortly afterwards.

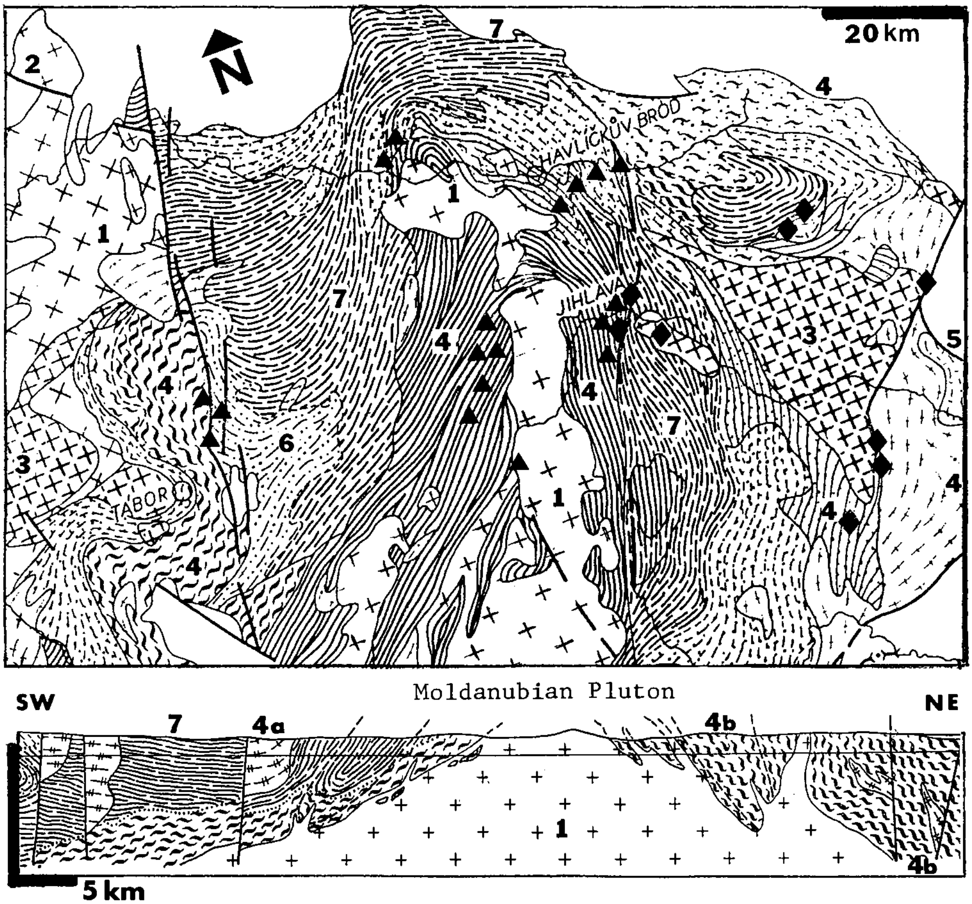
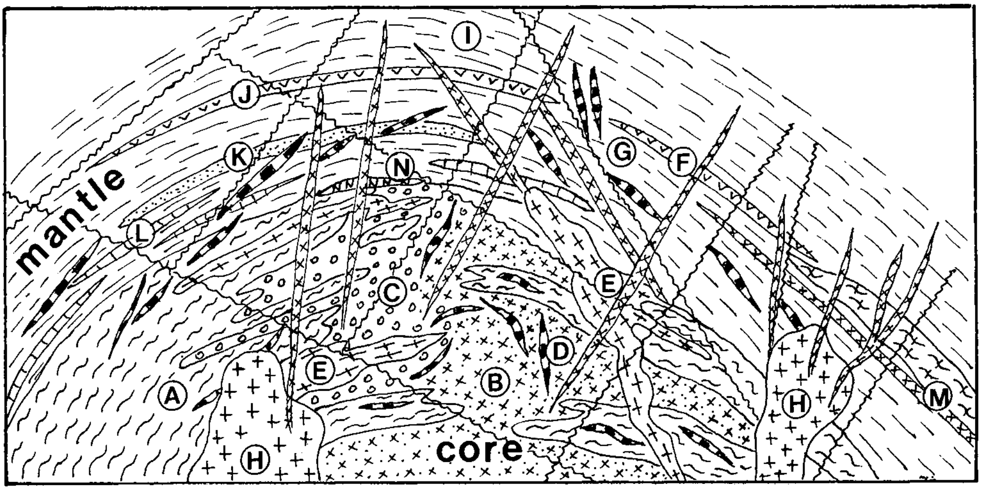


Fig. 29-15. The axial portion of the Moldanubian Complex, Bohemian Massif, intruded by a mesozonal Moldanubian Pluton. After Kodym and Suk from Svoboda, ed. (1966), courtesy of the Ústřední Ústav Geologický, Praha. 1=PZ_3 biotite granite and quartz monzonite; 2=granodiorite, diorite, gabbro; 3=melanocratic granite, syenite, syenodiorite. Pt metasediments metamorphosed in PZ_3. 4=orthogneiss (a) and migmatite (b); 5=granulite; 6=micaschist, two mica gneiss; 7=paragneiss. Triangles: Pb-Zn veins; diamonds: Li pegmatites.

These granites reached some way into the sillimanite or at most kyanite zones in the mantling complex. Andalusite and locally cordierite-anthophyllite assemblages occur frequently in the exocontact and sometimes, in lesser quantities, in the granite endocontact as well. The plutons exhibit both gradational and sharp contacts and many appear to narrow downward and to be rooted in the core granite gneiss. Lamprophyre (minette, kersantite) (F) and more evolved, more persistent aplite and pegmatite dikes and sills (G) are

LITHOLOGIC ASSOCIATIONS



ORES

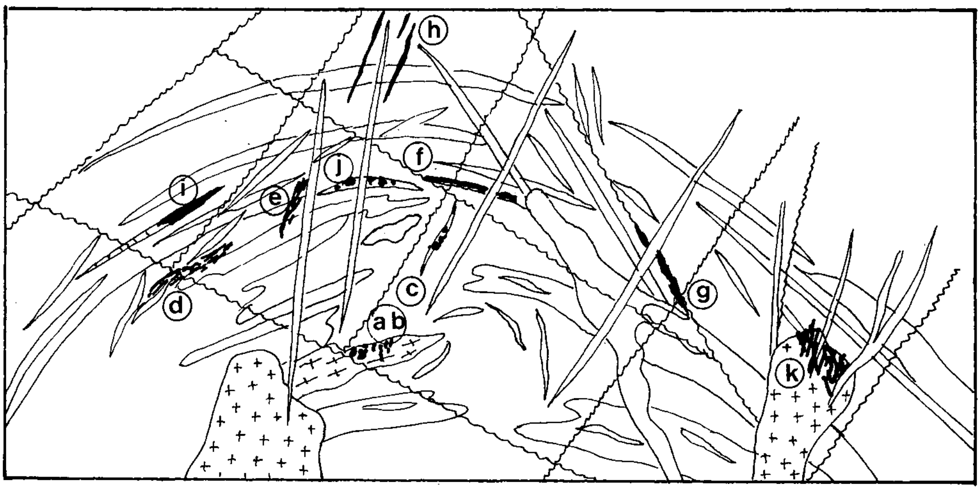


Fig. 29-17. Multiphase mantled granite gneiss domes and their mineralization styles.

TOP: rock types. A=migmatite; B=synorogenic katazonal granite; C=metasomatic (porphyroblastic) granite; D=simple (mica) pegmatite; E=late synorogenic, early postorogenic kata- to mesozonal plutons; F=lamprophyre dikes; G=evolved pegmatite dikes, sills; H=high-level postorogenic intrusive stocks; I=micaschist, biotite gneiss; J=amphibolite; K=metaquartzite; L=marble, calc-silicate gneiss; M=orthogneiss; N=nepheline syenite gneiss. (continues on right)

contemporary with or shortly postdate the leucocratic plutons.

High-level granodiorite, monzonite or leucogranite stocks (H) may have formed during a period of tectonomagmatic activation following an uplift of the dome into the shallow crustal region, coupled with considerable erosion (e.g. in the Coast Range Complex of British Columbia or the Colorado Rocky Mountains).

The metasedimentary and metavolcanic mantle is dominated by biotite (sillimanite) paragneiss grading to micaschists at most locations (I). It commonly contains units of amphibolite (J), metaquartzite (K), marble or calc-silicate gneiss (L) and sometimes an "orthogneiss" (M) that could have formed from felsic metavolcanics, arkoses, granitic plutons, etc. Less common rocks include graphitic schists or gneisses, meta-ultramafics, eclogite, nepheline syenite gneiss (N), meta-anhydrite, etc.

The nepheline syenite gneiss in the Shuswap Complex, British Columbia (McMillan and Moore, 1974) is a controversial peneconcordant body, enveloped by a calc-silicate gneiss and marble. Its interpretation ranges from a synkinematic alkaline metasomatite to pre-metamorphic alkaline intrusion. The Ditrău alkaline massif in the crystalline core of the East Carpathians in Rumania (Ianovici and Borcoş, 1982) is similar in some respects, but the recent interpretation is that it is a postkinematic, superimposed intrusion fringed by an aureole of gneissic fenite.

MINERALIZATION STYLES

Late synorogenic to postorogenic plutons (E on Fig. 29-17)

These plutons can, under favourable conditions, reach up to the lower mesozone level so that they merge and overlap with the plutons discussed in Chapter 28. The "typical" deep-seated plutons are rarely mineralized. Near their roof, they contain numerous inhomogeneities in the form of semi-digested xenoliths or rafts (most commonly of biotite migmatite composition or amphibole-rich), or aplite-pegmatite secretions. Endocontact mineralization is rare. Scattered black allanite is relatively common in the pegmatite or aplite schlieren, or in deuterically altered granite (e.g. Red Rock, Nevada, in aplite pods in quartz diorite; Elberton, Georgia). Some granites emplaced into a

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BOTTOM: mineralization styles. (a) Minerals scattered in endocontact inhomogenities (e.g. allanite, uraninite); (b) redistributed secondary U minerals on fractures of slightly uraniferous granites; (c) "simple" pegmatites, rare Th,U,Ti complex minerals; (d) remobilized massive sulphide orebodies in granite aureole; (e) sulphide and quartz sulphide veins, probably remobilized from pre-metamorphic ore accumulations; (f) bedding lodes; (g) shear lodes; (h) high level fissure veins; (i) carbonate replacements; (j) molybdenite in nepheline syenite gneiss; (k) apical stockworks. From Laznicka (1984).

uranium-rich environment contain minor accessory uraninite. So far, this does not constitute an ore in itself, but it provides an easily leacheable source of uranium for a later hydrothermal or groundwater deposition.

The Precambrian katazonal granites in the Darwin region of Australia (Vol.2) provided at least some of the U to the significant "unconformity uranium" deposits there. Some Archean granites in the Wyoming crystalline basement supplied U to the Cainozoic "sandstone uraniums" (Chapter 25), and the older phases of the French Hercynian granites lightly enriched in uraninite supplied U to the later generation of "episyenites" and veins (Chapter 28). In the oxidation zone, the sub-economic and usually haphazard uraninite occurrences produce often conspicuous autunite, torbernite, uranophane, etc. fracture infiltrations. Many such occurrences were investigated in the Massif Central of France and the Central Moldanubian Massif of Czechoslovakia.

Zn-Pb or Cu sulphides in cordierite or cordierite-anthophyllite gneisses

This is a quite distinct ore style most common in the Precambrian shields (e.g. Manitouwadge, Sherridon, etc. in Canada), and known also in the Phanerozoic orogens. The small but interesting Gull Pond (Gullbridge) deposit in N.W. Newfoundland was recently studied by Bachinski (1978). There, pyrrhotite is intergrown with pyrite and chalcopyrite in a lens-like massive to disseminated sulphide orebody, situated along a shear zone in cordierite-anthophyllite and andalusite schist probably dating from the Ordovician period. These schists grade into metabasalt, siliceous iron formation, metarhyolite (porphyroid) and quartz-sericite phyllite. The mineralization is interpreted as being an Ordovician synvolcanic subaqueous-hydrothermal stratabound orebody, remobilized in the thermal aureole of Devonian kata- to mesozonal granite.

In the Jihlava and Havlíčkův Brod districts located in the aureole of the late Paleozoic Central Moldanubian Pluton (Svoboda, ed., 1966), Pb,Zn,Ag association is most common. At the Pohled and Bartoušov deposits (Němec, 1965), massive pyrrhotite, marmatite, galena and pyrite grading to quartz-sulphide veins, are to be found along shears and fractures in migmatite, cordierite gneiss and lamprophyre near "granite" contact. The ores are clearly epigenetic, post-granite and post-lamprophyre, and remobilization of an earlier orebody is a possibility.

In the Hitachi massive sulphide deposit, Japan, cordierite, anthophyllite and andalusite form wallrock to the Permo-Carboniferous pre-metamorphic massive sulphides, where these were intruded by a Mesozoic "granite".

Scheelite skarns

Scheelite skarns have been reported from several mantling complexes where they occur at or near contact with the core. In the Fairbanks district, Alaska (e.g. Stepovich mine; Byers, 1957) thin, boudinaged marble horizons interbedded with a Proterozoic micaschist, quartzite and amphibolite envelope a gentle thermal dome intruded by Mesozoic synorogenic porphyritic biotite granite, and Tertiary post-orogenic granodiorite. Scheelite occurs in skarn-replaced marble and the richest ore shoots are located at intersections of skarn with pegmatite. In the Pedro Dome area, scheelite exists in quartz veins along shears.

"Katathermal" gold-quartz lodes

In the Fairbanks area, Alaska (Byers, 1957) numerous but impersistent bedding, shear and fracture gold-quartz lodes are located in the metamorphics of the mantling complex, close to granite contact. In the Liberty Bell mine, a nearly horizontal lode, 2-10 m thick, contains arsenopyrite, lesser chalcopyrite, pyrite, löllingite, bismuthinite and gold with or without quartz. It consists of small ore lenses and stringers parallel with foliation. Most of the gold in the Fairbanks district (220 t Au) came from placers.

In the gold region of southern Piedmont, U.S.A. (Pardee and Park, 1948), several gold deposits are situated along or near the contact of granite gneiss and a mantling gneiss and schist complex. In the Barlow mine S.E. of Dahlonega, the country rock is hornblende gneiss intruded by irregular masses of granitoid gneiss. Gold occurs in many quartz stringers and lenses most of which are conformable with foliation, but some are crosscutting. In the quartz, gold occurs as free metal as well as in the minerals pyrite and arsenopyrite, but its distribution is, to a considerable degree, masked by deep weathering. At the Barlow mine, small quantities of gold are widespread in the metamorphics.

Molybdenite in nepheline syenite gneiss, Mt. Copeland, British Columbia

At Mt. Copeland near Revelstoke (McMillan and Moore, 1974; 2,075 t Mo/1.1%; Fig. 29-18), nepheline syenite gneiss occurs as a thick lens along a stratigraphic horizon of a calc-silicate gneiss. The latter is member of the mantling complex, close to the migmatite and granite gneiss core of the Frenchman's Cap mantled gneiss dome, Shuswap Complex. The emplacement age of the nepheline syenite and associated minor carbonatites is not known, but the rocks suffered multiple deformation and partial anatectic melting. The melting produced aplitic, syenitic and pegmatitic schlieren and dikes. Scattered molybdenite in small quantities occurs as an accesory mineral in the main body of the nepheline syenite gneiss, but the commercial orebodies were located along its northern contact with the calc-silicate gneiss, hosted by aplite-pegmatite bodies. Most such bodies lie parallel with the foliation and are up to 3 m thick. They are composed of K-feldspar with exsolved albite. Molybdenite with some pyrite, pyrrhotite and minor chalcopyrite fills thin fractures. There is a light kaolinite, sericite, calcite alteration and the mineralization has been dated 44 m.y., contemporary with the emplacement of lamprophyre dikes. Molybdenite also occurs in veins in

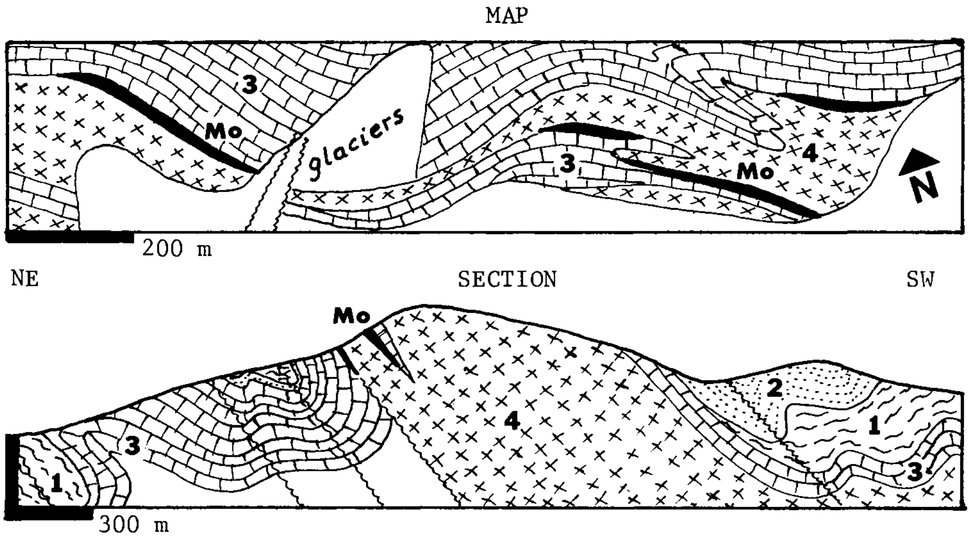


Fig. 29-18. Mount Copeland molybdenite deposit in nepheline syenite and calc-silicate gneiss, British Columbia. Pt_3 or PZ Shuswap Complex (J metamorphism). 1=biotite gneiss and schist; 2=quartzite; 3=calc-silicate gneiss and marble; 4=nepheline syenite gneiss. From LITHOTHEQUE, after Fyles (1970).

alkaline diorites along the northern margin of the Ditrău alkaline complex (Rumania; Ianovici and Borcoş, 1982). Monazite, orthite, yttrocalcite, calcite, siderite, etc. veins are hosted by albite metasomatites.

Monazite, allanite, etc. in marble, Mineral Hill district

In the Mineral Hill district, N.E. Idaho and W. Montana (Anderson, 1958), monazite, allanite, ilmenorutile and apatite occur in thin marble lenses within a belt of occurrences 40 km long and 4 km wide, in the schist, amphibolite, pegmatite, etc. association mantling the Idaho Batholith. This could be a true metasedimentary marble possibly mineralized within the reach of a "metasomatic front", or alternatively a series of meta-carbonatite sills.

Postmagmatic hydrothermal fissure veins, stockworks, etc. in granite-gneiss domes and their roofs

Fissure veins bearing a variety of metals (Pb,Zn,Ag, Au,Cu, etc.) located in granite-gneiss domes, but emplaced later at relatively shallow levels following the dome uplift, are common mostly because of the favourable conjugate or grid-like fracture patterns. The veins or stockworks are genetically related to high-level intrusive stocks either visibly affiliated (e.g. Climax-Mo, Colorado), or postulated to exist in depth (e.g. Freiberg Pb,Zn,Ag, East Germany).

Examples of mineralized Phanerozoic gneissic domes are listed in Table 29-7.

29.7. GRANITIC PEGMATITES

29.7.1. General

The occurrence of the bulk of pegmatites (excluding the high-level miarolitic pegmatites and those associated with tin granite cupolas, Chapter 28) are restricted to zones of medium to high-grade metamorphism. In enorogenic metamorphic terrains pegmatites usually correlate with the kyanite to sillimanite assemblage (almandine amphibolite facies) of their host rocks. In periplutonic terrains, pegmatites are most common in the metamorphics of the andalusite, cordierite, muscovite zone. In the classification of pegmatites drawn up by Ginsburg et al. (1979) according to their depth of formation and occurrence, the former (enorogenic) terrains host the "pegmatites of great depths", the latter (periplutonic) terrains host the "pegmatites of intermediate depths". Both seem to have a slightly different derivation and different setting, although both pegmatite varieties appear to be members of the "S granite" suite. It is quite remarkable that the large masses of "I granites" and associated metamorphics generated along the former Pacific- and Andean-type continental margins, are virtually devoid of pegmatites.

Pegmatites have an extensive literature and a large following of investigators. Numerous and comprehensive reviews are available in several languages (Fersman, 1960; Jahns, 1955; Schneiderhöhn, 1961; Ginsburg et al., 1979; Černý, ed., 1982). This is because of the mineralogical uniqueness of these rocks, rather than their economic importance. Pegmatites are not impressive as a source of metals, having accounted for less than 0.05% of the metals production value in the 1980s, in the entire world (they are more important as a source of nonmetallic commodities). Even so, the majority of metalliferous pegmatites are Precambrian and so treated in Volume 2. The Phanerozoic pegmatites are estimated to represent some 20 Tt Be, 20 Tt Sn, 5 Tt Ta and 5 Tt Nb. The figures quoted above include minerals accumulated in placers demonstrably and proximally derived from pegmatites. Some components of placers of mixed provenance or "distal placers" (such as monazite, zircon), may have come partly from pegmatites.

29.7.2. Pegmatites as metallic ores

When a large volume of literature is reviewed, it becomes obvious that virtually all metals have been found, at least once, in some sort of affiliation with pegmatites, and variable but mostly small quantities of Be,Sn,Ta, Nb,U,Th, Au,Mo,W, Bi,Cu,Sb, Pb,Zn,Ag, As,Ni,Co have actually been produced from this setting. The above list of

Table 29-7. Selected examples of mineralized gneiss domes in Phanerozoic orogenic belts

GNEISS DOME	AGE OF METAM.	GEOLOGY	MINERALIZATION	REFERENCES
Central Gneiss Complex, Coast Plutonic Belt, N.W. Canada and S.E. Alaska	MZ	C: migmatite to gran. gneiss; M: PZ to J gneiss, schist, amphibolite; I: J-Cr diorite to quartz monzonite	Ecstall, mass. py, po, in marble; Surf Inlet, Au, qtz.-pyr. vein in diorite; Britannia, massive Cu-Zn sulph., relict in mantle	Douglas, ed. (1970)
Fairbanks area, Alaska, several domes	MZ	C: PCm? migmatite, granitic gneiss; M: PCm? micaschist, gneiss, lesser amphibolite, marble; I: MZ porph. granite, T_1 post-orog. granodiorite	Au, qtz. veins in mantle along foliation, shears, fissures; scheelite skarn in mantle; Au placers	Byers (1957)
Shuswap Complex, Brit. Columbia, several domes	J	C: 1.7 b.y. anatectic granite, migmatite; M: Pt_3-PZ gneiss, amphibolite, quartz., calc-sil. gneiss, marble, neph. syen. gn. I: MZ-T_1 granite, qtz. dior., granodiorite	massive Zn-Pb sulphides conform. with foliation; dissem. molybd. in neph. syen. assoc.; Pb-Zn veins, replac.	Fyles (1970) Douglas, ed. (1970)
Hohe Tauern Mts., Austria	MZ	C: PZ_1 gran. gneiss, migmatite; M: PZ_1 gneiss, schist, marble, amphibolite, prasinite, quartzite; I: not known	scheelite dispersed in core migmatite; Felbertal scheelite in mantling metamorphics	Höll and Maucher (1976)
Menderes Massif, W. Anatolia, Turkey	PZ-J	C: PCm augen gneiss; M: Or-S qtz.-musc. schist, amphibolite, calc-silic. gneiss, graphitic schist, metaquartzite; I: MZ ophiolites, T contin. volc.	Pb-Zn Bayindir, mass. sulph. peneconc. with schistosity; Hg, in retrogress. fault zone, Haliköy	Dora (1977)

metals can be subdivided into those that are systematically associated with the deep and moderately deep-seated pegmatites treated in this chapter (Be,Ta,Nb, partly Sn, REE, Th, U) and those due to one-of-a-kind, chance associations usually involving higher-level pegmatites interacting with unique environments (the rest). The latter will not be treated here. The systematically associated metals have the following distribution in pegmatite bodies and their contacts (in nature, usually two or more distribution styles combine):

(1) Lump (blocky) ore. Discrete, large to small crystals (e.g. of beryl) are irregularly scattered in pegmatite, often confined to a particular compositional and textural zone. It is virtually impossible to estimate the average grade and tonnage of the metallic mineral in such bodies. A single orebody (pegmatite lens) having a tonnage of several tens to hundred thousands tons of pegmatite, may contain several tons or tens of tons of beryl (beryl itself contains only 3.85% Be). Few such deposits have ever been mined for the rare metal content itself, but a minor (X0-X00 t of beryl) cumulative production has often been achieved over a period of several years or decades by handpicking and stockpiling the beryl as a by-product of mining of a bulkier nonmetallic commodity, such as feldspar, mica or quartz. Few other minerals occur in lumps amenable for handpicking. Those that occasionally do are usually rapidly carted away by the collectors.

(1a) In humid tropics, handpicking of beryl and other ore lumps from deeply tropically weathered pegmatites has occasionally been carried out, sometimes with the aid of hydraulicing. Most such occurrences (in Africa, India) date from the Precambrian age.

(2) Scattered (disseminated) ore. The ore minerals in small (0.1-10 mm) but physically separable and recoverable crystals are usually haphazardly scattered throughout the pegmatite mass, usually confined to a specific compositional and textural zone. In the past, production was achieved by complete or selective mining and milling of the pegmatite and the metallic component (beryl, cassiterite, columbite-tantalite, etc.) were the only products obtained. At present, complex recovery (several products including feldspar, quartz, spodumene, muscovite, lepidolite) is more common.

(2a) Deeply weathered pegmatites, and

(2b) proximal colluvial or alluvial placers, are economically more profitable varieties of (2).

(3) Metals present as invisible and physically unrecoverable trace elements in the bulk of a pegmatite, or more commonly in particular mineral carriers. The range of trace metal contents is considerable even within single pegmatite bodies. Kuzmenko, ed. (1976) gave the following ranges for the Soviet pegmatites: BeO, 9-4,700 ppm; Ta_2O_5, 2-5,000 ppm; Nb_2O_5, 10-1,400 ppm; SnO_2, 13-35,500 ppm. The usual background values of most medium-level Li pegmatites are in the region of 10-20 ppm Ta_2O_5; 20-60 ppm Nb_2O_5.

(4) Metals accumulated in the wallrocks and in the sahlbands of pegmatites. Although interesting Li (in holmquistite) and Cs (in caesian biotite) contents are known in several pegmatite exocontacts,

no significant accumulations of Ta,Nb,Sn and other rare metals have been reported.

Pegmatites (including the Precambrian ones), contain about 20% of Be (around 40-60 Tt Be); 7.7% of Ta (about 20 Tt Ta); about 3-4% of Sn and less than 0.1% of the Nb present in economic ores, worldwide. 75% of the Ta share and about 66% of the Be share is said to be present in Precambrian pegmatites. Table 29-8 gives the usual grade and expected tonnage of Be,Ta and Nb in the five most common systematically mineralized compositional varieties of pegmatites. Even though the magnitude ranges appear excessive (up to 100 Tt Ta_2O_5 is in the "subalcalic" lithian pegmatite. The largest Ta accumulation of the world for which published data are available, the Abu Dhabbab in Egypt, is credited with 131.5 Tt Ta, and it is probably a late Proterozoic apogranite), the relative importance of the pegmatite varieties is well recognized in the table.

Pegmatites in the higher crustal levels are often transitional into quartz, feldspar, cassiterite, wolframite, scheelite, molybdenite, beryl, etc. veins and into mineralized greisens. These are treated in Chapter 28.

29.7.3. Internal features of pegmatite bodies

Most small pegmatite bodies are simple, rather homogeneous aggregates of feldspar, quartz, mica and other minerals, lacking any systematic internal variation. Larger pegmatites usually show some internal variations and these have been subdivided by members of the wartime U.S. Geological Survey pegmatite evaluation project (e.g. Cameron et al., 1949; Jahns et al., 1952) into three fundamental categories: (1) zones; (2) replacement bodies an (3) fracture fillings. Although minor changes have been suggested in the past 30 years (compare Černý, ed., 1982), the U.S.G.S. subdivision has proven to be a remarkably suitable one for fieldwork.

(1) Pegmatite zones represent textural and compositional variations within a pegmatite body, established at the time of the primary (main stage) crystallization. They form concentric to irregular, complete to incomplete successive shells between the wallrock and the core. Four zones can be recognized in many pegmatites, and the examples of zones offered here are based on those recognised by Jahns et al.(1952) in the S.E. Piedmont pegmatite belt (Fig. 29-19):

(a) Border zone (the outermost one) is a fine grained selvedge, 5-7 cm thick, that separates the pegmatite from its wallrock. In the Piedmont pegmatites, the zone consists of quartz-rich, sugary or granitoid rock with sharp or gradational contacts against the host rock.

(b) Wall zone, the successively inner zone, is coarser grained and thicker (up to 11 m). The most widespread constituent is sodic plagioclase with lesser amounts of quartz, muscovite, occasional biotite, perthite, garnet, apatite and beryl. Wall zones most commonly form complete envelopes along the inner units.

Table 29-8. Usual grade and tonnage range in five compositional varieties of Be,Ta and Nb-mineralized pegmatites (all ages). After Rundkvist, ed. (1978)

PEGMATITE VARIETY	USUAL RANGE OF GRADE	USUAL RANGE OF TONNAGE OF ORE
"Standard pegmatite" (mica, ceramic); microcline, beryl, columbite	BeO 50-100 ppm Ta_2O_5 30-70 ppm Nb_2O_5 70-100 ppm	1-100 t 1-10 t 1-10 t
microcline-albite with tantalite, wodginite, beryl	BeO 400-500 ppm Ta_2O_5 130-250 ppm Nb_2O_5 100-150 ppm	100-1,000 t 100-10 Tt 100-10 Tt
subalcaline lithian pegmatite; spodumene, microcline, albite, lepidolite, pollucite, tantalite, beryl	BeO 400-600 ppm Ta_2O_5 150-300 ppm Nb_2O_5 70-150 ppm	100-10 Tt 1 Tt-100 Tt 1 Tt-100 Tt
albite, tantalite, beryl, $\pm$ spodumene	BeO 800-1,500 ppm Ta_2O_5 150-250 ppm Nb_2O_5 100-150 ppm	1-50 Tt 100-1 Tt 100-1 Tt
albite-spodumene $\pm$ beryl, columbite, fergusonite	BeO 300-500 ppm Ta_2O_5 40-100 ppm Nb_2O_5 60-120 ppm	2-10 Tt 1-10 Tt 1-10 Tt

(c) Intermediate zones are the least regular and discontinuous of all the pegmatite zones. More than one such zone may be present, each possessing a slightly different mineral assemblage. The composition is highly variable. Coarse to almost massive perthite is most common, followed by quartz, plagioclase, coarse muscovite and spodumene in lithian pegmatites.

(d) Core zones tend to be irregular, ranging from thin ribs to cigar-shaped and ellipsoidal masses. The most common mineral is massive quartz, or quartz with scattered perthite or plagioclase crystals. An alternative filling is a coarse, blocky feldspar.

(2) Replacement bodies postdate the primary crystallization and can be superimposed over any (rarely all) of the pegmatite zones, although the internal zones (core, intermediate) are most often replaced. The replacement bodies are fracture-controlled stockworks and veinlets, dikelets and schlieren, irregular masses, sheets along pegmatite and wallrock contacts or along zone boundaries, etc. The replacement can be complete or partial, and a sugary or bladed ("cleavelandite") albite is by far the most characteristic mineral.

In geochemically complex pegmatites (lithian, rare earths, Ta-Nb, etc.) the bulk of the rare element minerals have been introduced with the metasomatic albite and sometimes K-feldspar (often green microcline, amazonite). There is a considerable degree of

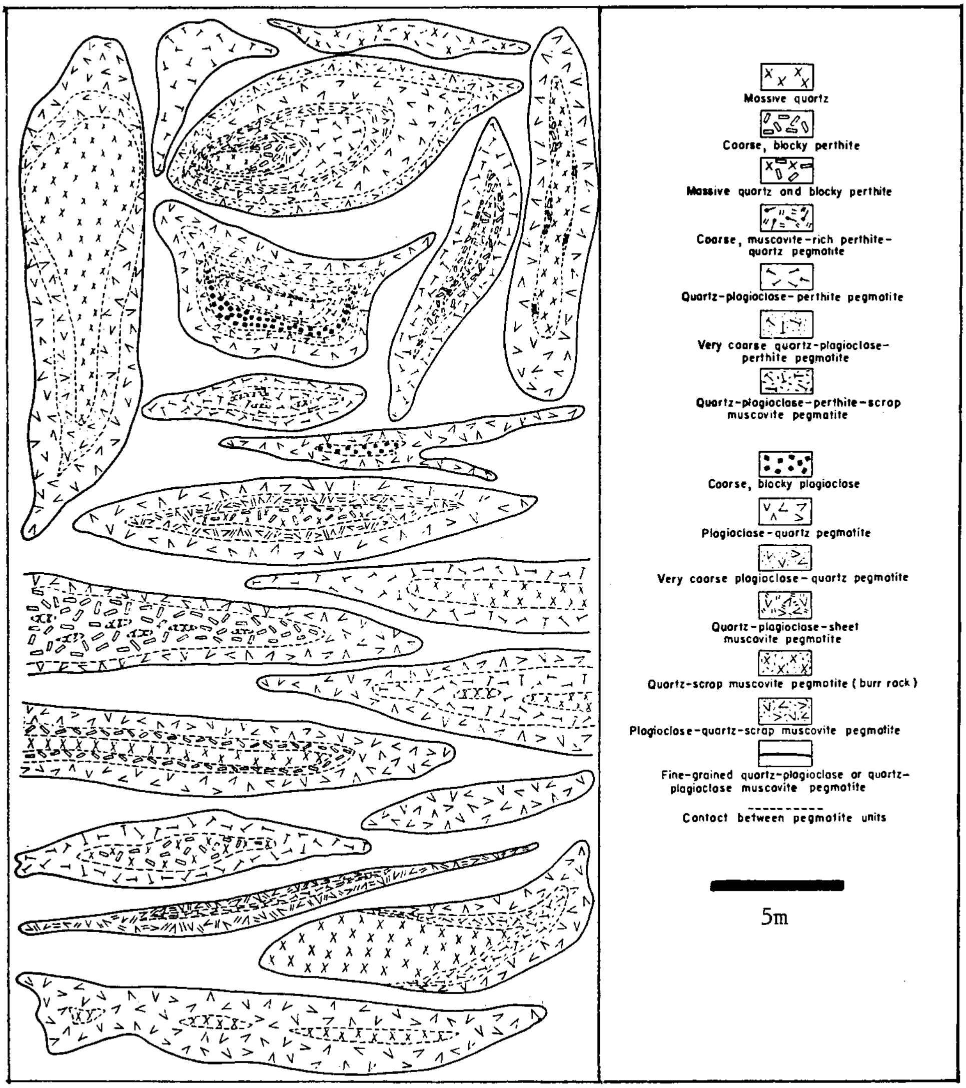


Fig. 29-19. Idealized maps, showing pegmatite zoning in the S.E. Piedmont mica pegmatite region, U.S.A. From Jahns et al. (1952).

compositional, although not necessarily textural, similarity between the Na and K metasomatites and apogranites, described in Chapter 28. Apogranites are thus most probably epizonal equivalents of the mesozonal to katazonal replacement pegmatite bodies.

(3) Fracture fillings may postdate the "primary" or the replacement pegmatite, or they may be equivalent in time to the replacement pegmatite. They have the form of veins, veinlets, stringers, and may

be composed of a great variety of hydrothermal minerals. Quartz, carbonates and sulphides are particularly characteristic.

"Pocket pegmatite" (Fig. 29-20) is an additional, minor feature of some pegmatites. It has the form of porous or clay-filled patches, marked by an euhedral form of constituent minerals or by terminated crystals extending into a cavity. Fersman described "walk-in" pockets located in the Murzinka pegmatite field, southern Urals. Quartz (often smoky quartz or amethyst), K-feldspar, albite, muscovite are most common in pocket pegmatites, augmented by a variety of rare minerals. Their origin is attributed to a late stage hydrothermal leaching and precipitation.

29.7.4. Pegmatites of "great depths" in migmatite and sillimanite- or kyanite-grade metamorphic terrains

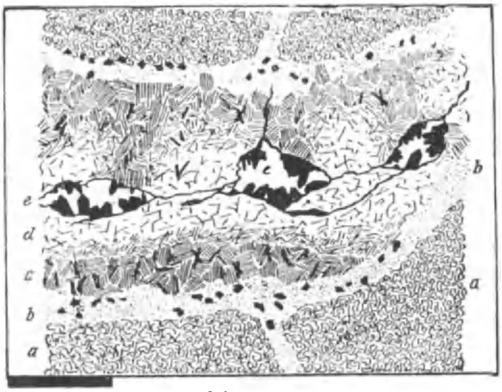
Pegmatites of "great depths" are closely associated with granite-gneiss and migmatite domes and ridges, and with biotite-sillimanite schists in the immediate vicinity. In terms of their body shape and setting, two end-members can be distinguished (Fig. 29-21): (a) tabular, lens-like, trough-shaped, bulbous, pinching and swelling bodies that are peneconcordant with foliation of the metamorphics, or schlieren subparallel with foliation in granite gneiss and (b) dikes cutting across the structural grain.

The (a) variety has a very proximal ultrametamorphic origin, corresponding to local accumulations of the leucosome in migmatites. The pegmatites bear no clear relationship to granite masses when they are present in the area, and occur in the form of broadly subparallel bodies together making up pegmatite fields and belts. Their thickness ranges from centimetres to several metres and the length of individual pegmatites is rarely over 20 m.

The pegmatite dikes corresponding to type (b) are more persistent (often for several hundred metres). They are tabular crosscutting bodies usually with sharp boundaries. They may be younger than the (a) bodies which they often intersect, and are most common within and in the proximity of katazonal granites.

Pegmatites in enorogenic terrains tend to be simple in composition. They usually comprise feldspar, quartz, muscovite or biotite, occasionally tourmaline, garnet, hornblende, although they could still be zoned. Most have been mined for mica, some for blocky feldspar and quartz. Accessory metallic minerals are rare and dominated by beryl. Monazite, although rare in a megascopically visible form, is probably present and it accumulates in proximal placers where the pegmatites have been tropically weathered.

The pegmatite belt of southern Blue Ridge and Piedmont (Appalachian Mts.), described in considerable detail in the U.S. Geological Survey Professional Paper 248 (Jahns et al., 1952, and following papers; Fig. 29-22), is a classical region of Phanerozoic "mica pegmatites". Over 1,600 mica deposits have been mined within a N.E.-trending belt, some 1,000 km long. The pegmatites in the western portion of the belt



about 20 cm

a granite
b aplite zone
c dense graphic pegmatite with scattered mica
d blocky quartz-feldspar pegmatite
e crystal-lined cavities

Fig. 29-20. "Pocket pegmatite" from Murzinka, the Urals. a=Granite; b=aplite zone; c=dense graphic pegmatite with mica flakes; d=blocky quartz, K-feldspar; e=crystal lined cavities. From Fersman (1960).

are hosted by late Proterozoic to lower Paleozoic mica, sillimanite and hornblende schists, gneisses and migmatites with numerous bodies of late Paleozoic synorogenic anatectic granites. Small quantities of accessory beryl are present throughout the area, but most pegmatites contain less than 0.3% beryl (that is, under 0.01% Be). Monazite is a widespread accessory in some pegmatites in the north (South Carolina border region), where it was reworked into placers mined in the past and still containing significant reserves (e.g. Catawba River area; Chapter 24).

Within the Piedmont pegmatite belt, the metamorphic grade decreases generally eastwards and patches of periplutonic (Buchan, Abukuma) metamorphics surround the late Paleozoic still deep-seated, but at least partly allochthonous granites in places along the eastern boundary of the belt. There, "medium depth" pegmatites with a granite affiliation (e.g. in the Carolinas "Tin-Spodumene Belt"; near Coosa, Alabama) and having a very limited area of distribution, account for the entire production and reserves of Li minerals, cassiterite (about 500 t Sn) and Ta-Nb (about 50 t). These are treated in the next section.

The "great depth" pegmatites are the most widespread (probably over 80% of pegmatites) but least interesting pegmatite variety to a metalliferous geologist. They are present in all the ultrametamorphic terrains worldwide, and no additional localities need to be reviewed.

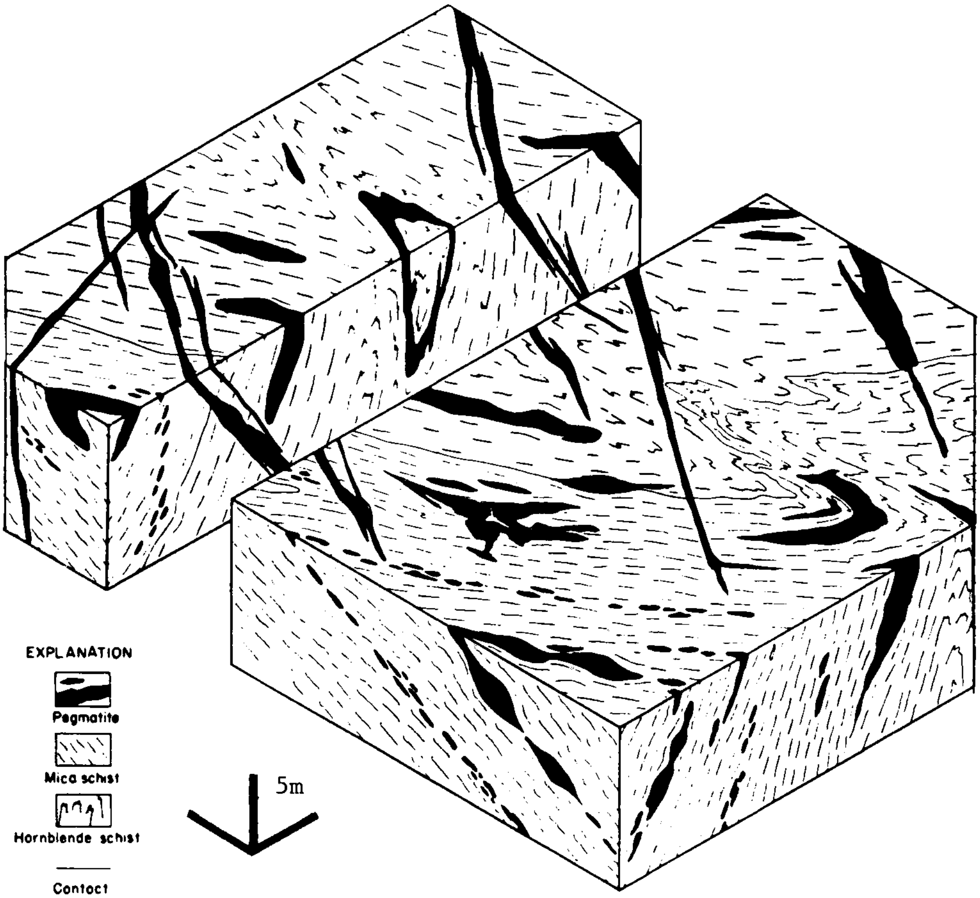


Fig. 29-21. Forms of mica pegmatite bodies and their relations to wallrock metamorphics, S.E. Piedmont, U.S.A. From Jahns et al. (1952).

29.7.5. Pegmatites of "intermediate depths" in periplutonic andalusite, cordierite, muscovite or staurolite schist metamorphic terrains

This category of pegmatites is substantially more evolved than the earlier one. Much of the pegmatite bodies are identical in shape to those already described, but extremely persistent dikes (up to 4 km long in Nuristan, Afghanistan) and thick lenses (spodumene pegmatite up to 100 m thick at Long Creek, North Carolina) are a specialty. Probably the most characteristic feature is the well-documented association with late orogenic to early post-orogenic, katazonal to lower mesozonal granites. Most of the Li and rare metal-bearing pegmatites occur in exocontact metamorphics typically 1 to 3 km from

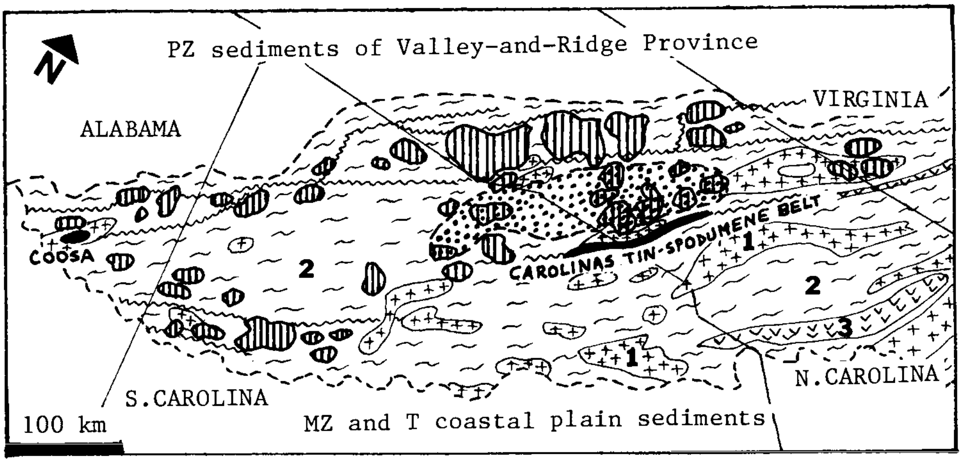


Fig. 29-22. Southern Appalachian pegmatite province, showing the fields of mica pegmatite (vertically ruled); spodumene cassiterite pegmatite (black) and detrital monazite placers (dots). 1=PZ_3 granite; 2=Pt_3-PZ high grade gneiss, schist and greenstone; 3=Tr basalt and sediments in grabens. From LITHOTHEQUE.

the contact, but endocontact pegmatites are also known. Persistent pegmatite bodies initiated in the granite and continuous into its roof have been described from the Nilau-Kulam and Alingar pegmatite fields, Nuristan, Afghanistan (Rossovskiy and Chmyrev, 1976); from the Aksu-Pushtiru field in the Soviet Central Asia (Beus, 1956) and from elsewhere.

The parent granite is most often a leucocratic biotite-muscovite coarse-grained pegmatitic "S" variety. It is usually a sequentially young (or the youngest) phase of the local orogenic magmatism (third phase in Nuristan). Partly digested sillimanite gneiss inclusions or rafts, or accessory andalusite, are common. The pegmatite bodies are zoned to unzoned, and it is interesting that many of the largest Li and Sn, Ta-Nb, Be orebodies such as those in the Carolina Tin-Spodumene Belt and some in Nuristan, are unzoned. The mineralogical composition is highly variable, but the presence of metasomatic albite and usually also of Li-minerals (spodumene, lepidolite, amblygonite, petalite) is an essential prerequisite of the rare metal (Be,Sn,Ta-Nb) mineralization. In some pegmatite fields, rare metal and mineralogical zoning is apparent (from the granite outward: barren zone → beryl → Be,Ta,Nb → Li,Be,Ta-Nb → Li,Cs,Be, Ta-Nb, Sn,U).

Rundkvist, ed.(1978) pointed out that 89% of the rare metals producing pegmatites are of Precambrian age and of the remainder 10% are Paleozoic. The pegmatite province of Eastern Afghanistan of Lower Tertiary age is exceptional and exposed only as a result of an unusually rapid uplift and erosion.

In the Nuristan pegmatite belt, E.Afghanistan (Rossovskiy and Chmyrev, 1976), late Triassic graphitic micaschists and quartz, biotite, garnet, staurolite schists with minor amphibolites and marbles, mantle upper Paleozoic sillimanite-garnet biotite gneiss and migmatite basement. Both sequences are intruded by multiphase katazonal to lower mesozonal batholiths dating from the Cretaceous to lower Tertiary age that include early granodiorite, norite and quartz diorite followed by granodiorite, biotite-hornblende quartz monzonite and a two-mica granite. The youngest biotite-muscovite granites form large elongated massifs on the fringe or in places within the composite batholith. The granites are foliated, elongated layer- or lens-like bodies peneconcordant with the surrounding metamorphics or arranged along major N.E. faults. They are nearly equivalent compositionally to the Proterozoic ultrametamorphics from which they formed by anatexis, and they range from fine and medium grained to pegmatoid varieties. Garnet and sillimanite are typical minor minerals and there are accessory zircon, monazite, allanite, cassiterite and beryl.

The rare-metal pegmatites are peneconcordant sheets, swelling veins, dikes and lenses, ranging in thickness from 1 to 60 m and in length from several tens of metres to 5 km. The bulk of them are hosted by schists exposed in "graben synclinoriums", and most pegmatites congregate in swarms (pegmatite fields) that range in area from 10 to 1,500 km^2. Internally, the pegmatites are massive, banded or indistinctly zoned. The following mineralogical assemblages have been recognized in the Afghan pegmatites: (1) oligoclase-microcline and biotite-muscovite, with both tourmaline and rare beryl; (2) albitized microcline, black tourmaline, muscovite, beryl; (3) albitized microcline (nests of blue cleavelandite), lepidolite, spodumene, Li-tourmaline; (4) albite with nests of lepidolite, spodumene, pollucite and tantalite; (5) spodumene, microcline, albite and apodumene, albite and (6) lepidolite, spodumene, albite, Li-tourmaline, pollucite, tantalite. The pegmatites with an assemblage of type (2) are the most important source of coarse (hand-cobbed) beryl. Pegmatites with assemblages of type (4) or (6) produce tantalum (e.g. the Nilau deposit).

The Tin-Spodumene Belt of the Carolinas (Kesler, 1942) is a 40x3 km N.E.-trending zone of many discontinuous pegmatite occurrences hosted by Proterozoic and lower Paleozoic gneiss, schist, minor marble, quartz schist, intruded by kata- to mesozonal granitic plutons. Cassiterite was detected in several hundred small pegmatite occurrences that form tabular, lenticular to irregular bodies having a maximum length of 90 m and a thickness of around 30 cm. Cassiterite has the form of sparsely scattered, small dark brown crystals hosted by fine albite-quartz unzoned pegmatite. The Ross mine near Gaffney accounted for over 50% of the recorded tin and contained material with a highest grade of 2% Sn. At about 92 localities, cassiterite also occurs in a quartz-muscovite transitional rock between pegmatite and feldspar. The sum of the known and estimated Sn potential of the belt (including placers) hardly exceeds 500 t Sn.

Economically the most important pegmatites in the belt are near Kings Mountain, where eight bodies of spodumene, quartz, muscovite, albite and microcline pegmatite are mined primarily for lithium (30 Mt material with 1.47% Li_2O). Beryl, columbite-tantalite and other rare minerals occur in small quantities and are not recovered.

Additional regions of Phanerozoic rare metal pegmatites are summarized in Table 29-9. Table 29-10 contains a brief list of metallic commodities present in pegmatites.

29.7.6. Hybrid pegmatites

Hybrid pegmatites are contaminated as a consequence of exchange of elements with their wallrocks. Exchange between pegmatite and biotite, cordierite, kyanite or staurolite schists generates large crystals or masses of these minerals in the pegmatite (e.g. giant cordierite or sekaninaite in the Dolní Bory pegmatite, Czechoslovakia). Exchange with mafic and ultramafic rocks (amphibolite, gabbro, serpentinite) causes desilicification of the pegmatite, and the appearance of accessory hornblende, diopside, sphene, corundum, etc. Distinct anthophyllite or anthophyllite-biotite rims form along exocontacts of pegmatite bodies in the ultramafics. In carbonates, pegmatites commonly contain scapolite, wollastonite, tremolite, diopside, phlogopite, graphite, etc. and may have skarn envelopes.

Beryllian hybrid pegmatites in ultramafics are rare but economically important as a source of gem emerald and chrysoberyl, as well as metallic Be. Their usual composition is oligoclase, albite, phlogopite, margarite and the Be minerals are represented by beryl, chrysoberyl, phenacite, bavenite, bertrandite, etc. A characteristic feature of these pegmatites is their tendency to split into systems of subparallel or branching dikes or veins of considerable persistency.

The Izumrudnye Kopy field 80 km N.E. of Sverdlovsk in the Urals, U.S.S.R. (Fig. 29-23) is a former gem emerald and alexandrite locality and more recently one of the important Soviet Be deposits described, without being named, in Beus (1956) and Zabolotnaya (1974). There, the country rock is a strongly schistose Devonian-Carboniferous metamorphosed mafic-ultramafic complex (amphibolite, serpentinite and talc schist), intruded by hornblende diorite and dunite-pyroxenite massifs. This was further intruded by a deep-seated Carboniferous granitic batholith, the muscovite-biotite granite phase of which is associated with the pegmatite dike swarm. The Be pegmatites occur in a N.N.W. trending, S.W. dipping band of numerous subparallel and anastomosing veins (or dikes) 2-3 m thick, each of them surrounded by a distinct alteration envelope. The band is about 100 m wide and 700 m in length.

Three varieties of Be-bearing veins (desilicified pegmatites) are present: (1) muscovite-plagioclase and muscovite veins with beryl; (2) beryl, muscovite, fluorite veins and (3) beryl, muscovite, quartz

Table 29-9. Rare elements pegmatites of "intermediate depths", selected Phanerozoic examples

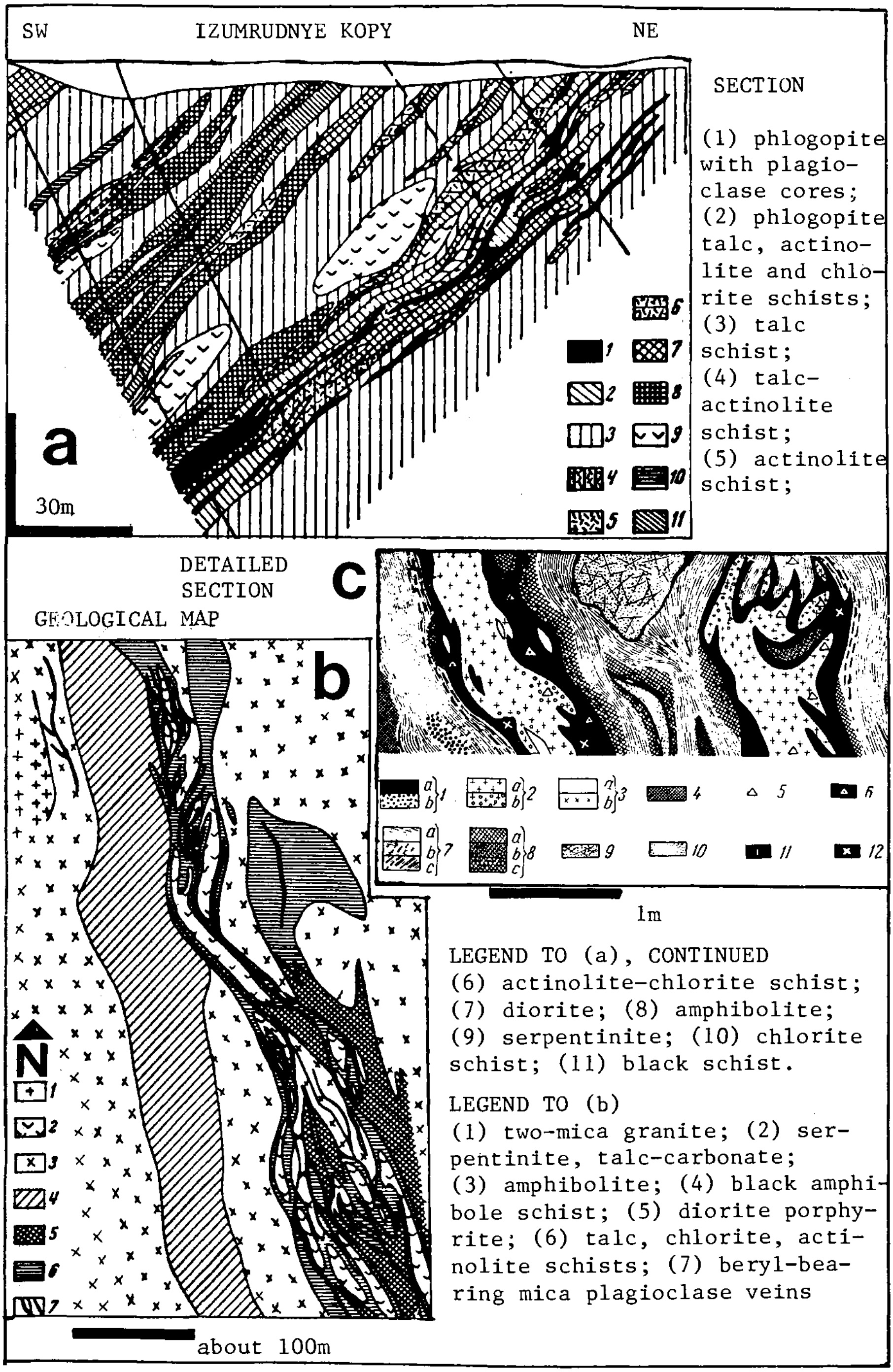
LOCALITY	ENCLOSING ROCKS	PARENT INTRUSION	PEGMATITE	REFERENCES
Carolinas Tin-Spodumene Belt, U.S.A. (91 depos.)	PZ_1 amphibolite, schist, gneiss, deform.,metam.Dev.	D, quartz monzon. biot.-musc. granite	several groups of unzoned microcl.,alb.,qtz.,spodumene beryl,phosph.,columb.-tantal., cassit.pegm. 500 t Sn, X0 t Be	Kesler (1942)
Harding pegmatite, Taos Co.,New Mexico, U.S.A.	PCm amphibolite, schist	granite containing sphene	pegm.lens 305x183x18 m,zoned, spodum.,albite, musc.,lepidol. replac.pegmat.,microlite,tantalite,beryl. 85 t Ta/0.082%	Berliner (1949)
Moldanubian Massif W. Czechoslovakia Rožná,Jeclov,Dolní Bory,Písek,etc.	PCm biot.gneiss, schist,amphibolite,marble; PZ_3 plutons	PZ_3 musc.-biot. and biot.kata-to Mesoz.granites about 300 m.y.	widespread "common" pegmatites (e.g.Dol.Bory); Albite,lepidolite,spodum.,Li-tourmal. pegm.,minor beryl,columb.-tantalite, cassiterite	Svoboda, ed., (1966)
Central Urals pegm. region (Murzinka, Izumrud.Kopy,etc.) U.S.S.R.	Pt,PZ gneiss,ophiolites,bimodal metavolcanics	Cb,two mica gran. younger phase of composite batholiths	"normal" pegmatites; albite, Li-pegmatite contains columb.-tantalite; beryl most in hybrid pegm. in ultramafics and mafics	Fersman (1960)
Kalba-Naryn Ranges E.Kazakhstan, U.S.S.R.	PZ schist,quartz-rich litharenite	PZ_3 granite	"normal" graphic pegm.with tourm.cont.rarely scheel.and cassit.,grade to greisens, veins; albite-spodum.pegm. have rare dissem.cassiterite	Fersman (1960)
Nuristan and Hindukush Mts.,Eastern Afghanistan	Pe-Tr schists, quartzite,marble, unconf.on PCm gneiss and migmat.	Cr_1-T_1 two mica granite, qtz.diorite,granodior.	2 // pegm.belts,N.E.,large number of albite,spodum.,lepidol.,beryl,tantalite pegm. 5,580 t Be, also Ta	Rossovskiy and Chmyrev (1976)

Table 29-10. Brief list of metallic mineralizations in pegmatites

Be (beryl); low-alkalies, yellow, light green beryl is common in the wall, intermediate and core zones; widespread, e.g. Nuristan high-alkalies beryl, present in albitized and Li pegmatites; white, bluish; widespread
Be (chrysoberyl); in desilicified pegmatites intruding ultramafics, amphibolites; rare; Izumrudnye Kopy, Urals; Maršíkov, Czechosl.
Sn (cassiterite); in Li-pegmatites with spodumene; Kings Mountain, U.S.A.; Rožná, Czechoslovakia in K-feldspar pegmatites, transitional to greisens; Fabulosa, Bolivia; Kalba, Kazakhstan
Sn (stannite); rare, in quartz, amblygonite, microcline, cassiterite, phosphates pegmatite; Vernéřov, Czechoslovakia
Ta-Nb; columbite-tantalite, wodginite, microlite in Li pegmatites; widespread in small quantities, economic in Nuristan
REE; monazite, xenotime, samarskite, fergusonite, gadolinite, ilmenorutile, etc. in albitized pegmatites (Nuevo, California); monazite, accessory in small quantities in ordinary mica pegmatites, concentrated in placers (Catawba, Piedmont)
REE, orthite; sometimes with cerite, parisite, etc. in hybrid pegmatites in ultramafics; Borzovka, S. Urals; orthite (allanite) is common in "normal" pegmatites, particularly when emplaced into marbles, skarns, amphibolites
Zr; zircon, common accessory mineral in most pegmatites; reworked into placers; disseminated zircon in wall and border zones of "normal" pegmatite, Zirconia distr., N.C.; many "Zr pegmatites" are of alkaline affiliation (Chapter 33)
Th, thorianite, rare accessory in normal and albitized pegmatites, e.g. in Soafia, Betroka, Madagascar
U; uraninite, occasionally in K-feldspar or albitized pegmatite, e.g. Bemasoandhro, Madagascar; New Hampshire
Mo; molybdenite, in red blocky orthoclase pegmatite gradational into quartz veins, Skalsko, Czechoslovakia
Al, corundum; alone in desilicified pegmatite in marble, Pokojovice, Czechoslovakia; with vermiculite, chlorite, plagioclase at Corundum Hill, N.C., in southern Urals
As,Bi,Sb, etc. sulphides; occasionally present in arsenopyrite, löllingite, bismuthinite, e.g. Dolní Bory, Czechoslovakia

Fig. 29-23. Izumrudnye Kopy, the Urals, U.S.S.R. beryllium ore field. Cb desilicified pegmatite bodies in PZ_3 ultramafics.

Legend to (C): 1a=phlogopite glimmerite; 1b=non-oriented biotite; 2=pegmatite; 2b=kaolinized pegmatite; 3a=gray quartz; 3b=ferruginous quartz; 4=schists; 5=light beryl; 6=emerald; 7=talc schist; 8=actinolite schist; 9=granodiorite, diorite dikes; 10=aplite dikes; 11=tourmaline; 12=apatite. From Beus (1956) and Fersman (1960).


SW
IZUMRUDNYE KOPY
NE
SECTION
(1) phlogopite with plagioclase cores;
(2) phlogopite talc, actinolite and chlorite schists;
(3) talc schist;
(4) talc-actinolite schist;
(5) actinolite schist;
a
30m
DETAILED SECTION
c
GEOLOGICAL MAP
b
N
1m
LEGEND TO (a), CONTINUED
(6) actinolite-chlorite schist; (7) diorite; (8) amphibolite; (9) serpentinite; (10) chlorite schist; (11) black schist.
LEGEND TO (b)
(1) two-mica granite; (2) serpentinite, talc-carbonate; (3) amphibolite; (4) black amphibole schist; (5) diorite porphyrite; (6) talc, chlorite, actinolite schists; (7) beryl-bearing mica plagioclase veins
about 100m

veins. The (1) veins are most common (Fig. 29-23b). They consist of a plagioclase core kaolinized near surface. The core is zonally surrounded by a rim of phlogopite, up to 6 m thick, grading outward into an actinolite zone, chlorite zone, talc zone and unaltered serpentinite. The bulk of the beryl is contained in the phlogopite, where a small proportion of it is in the form of gem quality emerald. Additional minerals in this zone are phenacite, chrysoberyl, margarite, tourmaline, bavenite, fuchsite, molybdenite and apatite. Lesser quantities of scattered beryl crystals are present in the pegmatite, accompanied by rarer columbite and molybdenite. The chlorite zone contains phenacite, chrysoberyl and lesser beryl.

The type (2) veins are hosted by diorite. They are rare and less persistent than the veins of type (1). Typically they are 1.5 m thick and 20 m long. They contain up to 50-60% beryl in large grains 1-5 cm across, intergrown with fluorite. Small quantities of apatite, molybdenite and native bismuth are present. The Be-rich cores are rimmed by muscovitic glimmerite and plagioclasite (probably a wall pegmatite zone). No quantitative data are available for the Izumrudnye Kopy field, but a conservative estimate is about 2,000 t Be.

29.8. RETROGRADE METAMORPHICS, MYLONITES, CATACLASITES

29.8.1. General

Retrograde (retrogressive) metamorphism (or diaphtoresis) is a lower pressure and temperature rank metamorphism superimposed on a rock assemblage produced under higher pressure-temperature conditions. Its results are extremely relative in time, space, cause and effect and overlap with many of the mineralization systems already desribed earlier or with those that will be treated later (e.g. hydrothermal deposits hosted by high-grade metamorphics, Chapter 28; ores associated with "rifting", Chapter 30; etc.).

In order to produce retrograde effects in a higher-grade metamorphosed protolith, uplift into higher crustal levels is a first prerequisite. There, however, the bulk of the metamorphics remain as unmodified relics for unlimited periods of time, as the presently outcropping metamorphic terrains indicate. Retrogression, thus, is not automatic but a selective, localized process controlled by focussed tectonism along shear zones, lineaments and faults. The intensity of the retrogression is proportional to the depth at which it took place and pressure under which it took place. Its products range from cataclastic rocks, breccias and fault gouges near the surface through mylonites and ultramylonites into blastomylonites, phyllonites and retrogressed schists in depth. Higgins (1971) presented a comprehensive review of cataclastic rocks together with examples of their field distribution along major fault zones (Fig. 29-24).

The retrogression could be either "dry" or "wet". Retrogressed schists generated from completely dehydrated progenitors, such as

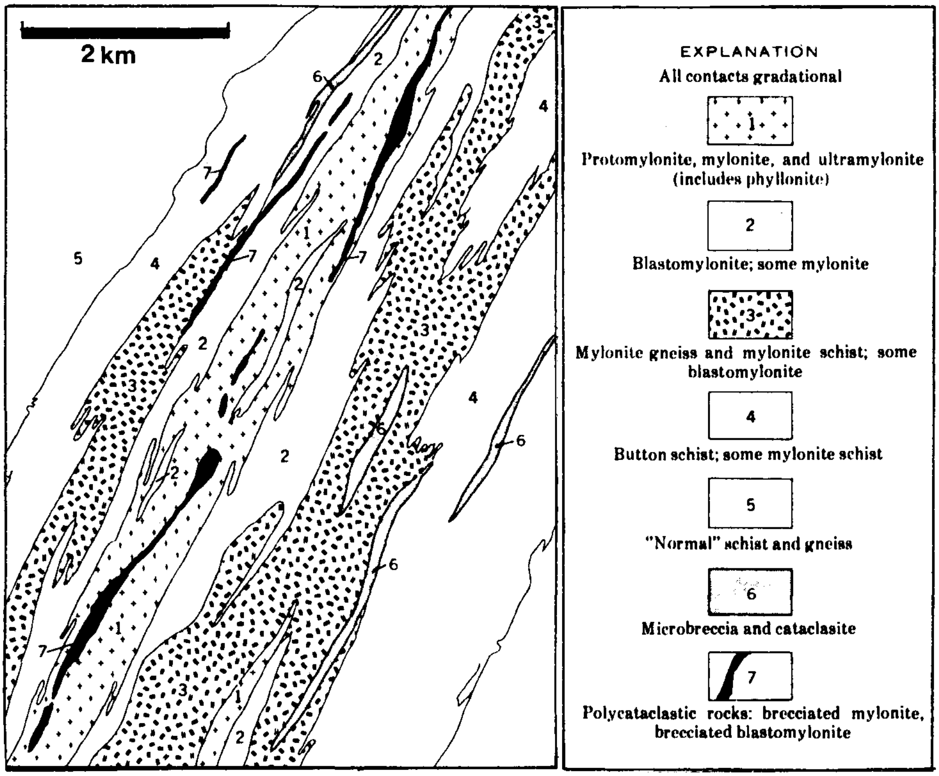


Fig. 29-24. Distribution of rocks resulting from high to medium level of retrogressive dynamometamorphism along major fault and shear zones. A hypothetical situation, strongly influenced by conditions along the Breward Fault, southern Appalachians, U.S.A. From Higgins (1971).

granulites required hydration, so they must have formed under "wet" conditions. Dry retrogression has a negative metallogenic balance because it results in destruction (dispersion) of earlier orebodies (when it coincides with an orebody), without creating any new mineralization. Wet retrogression, on the other hand, may produce new orebodies from metals introduced by the migrating fluids, in addition to the partial or complete remobilization of earlier orebodies. As a consequence, retrograde-metamorphogenic (i.e., metamorphism created) mineralization is virtually always hydrothermal and converges, overlaps and merges with structurally and lithologically controlled ores in intrusive aureoles or zones of fluid convection driven by any heat source.

The truly metamorphogenic mineralization (the one unrelated to igneous intrusions) depends on two fundamental genetic varieties of fluids: (1) depth-derived fluids, mostly components of the metamorphic fronts moving as a result of metamorphic dehydration in depth or (2) convecting groundwaters heated by geothermal gradient and/or radioactive decay. Belevtsev (1979) devoted an extensive coverage to the retrogressive-metamorphogenic hydrothermal process causing enrichment of lean iron formations and concentration of uranium in albitites, considered the two most common and rather convincingly interpreted manifestations of the process. Upward-migrating albitizing and NaCl-containing metamorphic fluids are probably connected with K-feldspar blastesis at greater depth (Suk, 1983). Albite blastesis at the expense of K-feldspar or muscovite, in turn, releases potassium into solution to cause sericitization, biotitization, or higher-level K-feldspathization. Other varieties of fluids carry silica, fluorine (probably displaced from earlier micas or added from subcrustal sources), barium, iron, carbonates, and other components. In anomalously metal enriched or previously mineralized terrains any metals can be redeposited. The metamorphogenic and/or convective fluids either react with their wallrocks to produce metasomatites (alterites), or they fill available dilations (rock pores, fissures, breccia zones) resulting in impregnations, veins and breccia cements. There is a convergence among the metasomatites and hydrothermal feldspathites and pegmatites.

The products of retrograde metamorphism at a variety of levels are best apparent in old high-grade crystalline massifs ("tortured massifs"), repeatedly subjected to several phases of shallow or intermediate level reactivation (rejuvenation) under alternating compressional and tensional regimes. Median massifs in divergent orogens (e.g. Hesperian, French Central, Bohemian massifs in the Hercynian belt of Europe; the Alpine massifs such as the St. Gotthard, Aar, Belledonne, etc.), as well as portions of Precambrian shields and platforms (such as the Aldan Shield, Azov Block, etc.), are the most frequently discussed examples. In areas where block-faulted, reactivated or retrogressively metamorphosed crystalline blocks are partly or fully covered by a thin veneer of young sediments and volcanics, the mineralization in the basement often overprints into the cover sequence. This establishes a link with some of the ores treated in Chapter 18. In this section, the coverage is restricted to the regions retrogressively metamorphosed and mineralized after the Precambrian.

29.8.2. Pitchblende deposits in mylonite-filled reactivation faults, Bohemian Massif

The Bohemian Massif (Svoboda, ed., 1966; Škvor, 1979) centered in western Czechoslovakia, but also including portions of German, Austrian and Polish territories, is a rhomb-shaped, periodically rejuvenated Proterozoic rigid block of approximate dimensions 300 x 300 km. It is fault-bound and surrounded by Hercynian and Alpine mobile belts, or sediments of the Mesozoic-Cainozoic platformic cover. The middle Proterozoic metamorphic basement (Moldanubicum) is interrupted by several superimposed late Proterozoic to Devonian "graben-style" mobile belts, and transformed by Carboniferous periplutonic metamorphism.

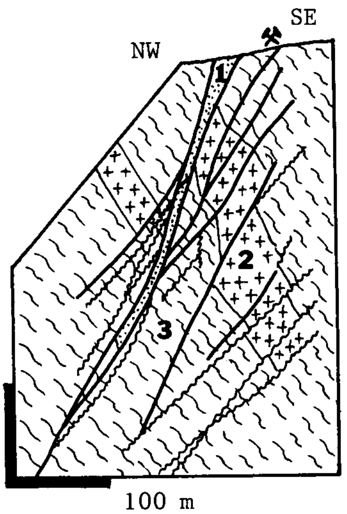
The late Palozoic granitic plutonism is responsible for the numerous Au, Pb-Zn, Sn-W and U deposits, mostly contained in veins. Several deposits, however, including to some extent, the important Příbram and Jáchymov (Chapter 28), significantly postdate the assumed cooling period of the plutons. The Bohemian Massif is disturbed by a network of repeatedly rejuvenated N.E., N.W., and N.-S. regional faults and weakened zones and this system controls the post-Carboniferous epigenetic mineralization as well as (in northern Bohemia) the emplacement of Tertiary alkaline volcanics (Chapter 33). The post-lower Permian (post-intrusive) hydrothermal mineralization is represented by pitchblende in quartz or carbonate-filled or unfilled shears and mylonitized zones, by fluorite-barite deposits, by minor occurrences of Pb-Zn and Au and by the Ni,Co,Bi,Ag,U arsenide association.

A group of uranium deposits hosted by Moldanubian biotite-sillimanite gneisses in the western part of the Bohemian Massif (Zadní Chodov, Dametice, Ústalec, Altransberg, Tirschenreuth, Wölsendorf, etc.; Ruzicka, 1971) is typically associated with a system of persistent N.W. and N.E. zones of silicification and quartz veining. The quartz is fringed or interrupted by graphite-rich mylonite and blastomylonite. In Altransberg (Bavaria; Bultemann and Hofmann, 1982), pitchblende with pyrite and rare coffinite fills thin fractures in the extension of feather-joint quartz veins. The mineralized zone of upper Permian age is 3 m wide and averages 0.1% UO_2. Torbernite, metatorbernite, autunite, phosphuranylite, parsonite and kasolite are present in the oxidation zone.

In the Dametice deposit (Janout, 1972; Fig. 29-25), Moldanubian biotite migmatite intruded by granodiorite porphyry is intersected by a series of steeply N.W.-dipping faults with mylonite filling. The most persistent fault is filled by at least three generations of quartz grading into silicified gneisses and mylonites, up to 30 m wide. The U ore is located in several mylonite, graphitic gouge, quartz and calcite-filled faults postdating the main generation of quartz. Pitchblende is the only hypogene uranium mineral, and it exists mostly in the form of thin veinlets and lenses in mylonite and the carbonate gangue.

Similar probably late Paleozoic hypogene pitchblende, galena, sphalerite and chalcopyrite vein filling in Moldanubian gneisses near Okrouhlá Radouň, S. Bohemia (Mrázek, 1972) was reactivated during the period of Tertiary block faulting, and the U dispersed along faults and in mylonite in the form of sooty pitchblende.

In addition to high-level, open faults, the vein U mineralization in high-grade metamorphics of the Bohemian Massif is controlled by the host rock lithology. Graphitic schists yielding graphite-rich mylonites, are preferentially mineralized. In the Rožínka-Olší U belt, central Czechoslovakia (Jürgenson and Hájek, 1980), mineralized faults are developed in biotite-hornblende gneiss alternating with amphibolite, calc-silicate gneiss and marble. The ore is absent where



1. "Pfalz" quartz filling a fault zone, grading to silicified mylonite and cataclastic gneiss
2. PZ_3 granodiorite porphyry
3. Pt_{2-3} biotite gneiss, migmatite

Fig. 29-25. Damětice vein uranium deposit, western Czechoslovakia. Simplified after Janout (1972).

the fault intersects with advanced migmatites.

Other regions

Comparable U ores hosted by brecciated and mylonitized fault and shear zones are known in many other regions and overlap with the granite-hosted localities reviewed in Section 28.20). At Urgeiriça, N.Portugal (Rich et al., 1977) veinlets, coatings and sooty dispersions of pitchblende with or without a cherty quartz gangue of Cretaceous age (80-100 m.y.) are located in reactivated structures superimposed on late Paleozoic granites and Cambrian metamorphics. At Val Vedello in the Central Alps of northern Italy (O.E.C.D., 1979; 1,000 t U/0.1%), uranium minerals are found in a mylonite zone along a tectonic contact between the crystalline basement and overlying Permo-Carboniferous continental sediments.

29.8.3. Wet Mountains, Colorado, Th and REE province

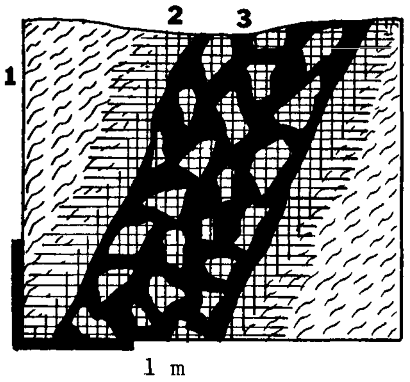
The Wet Mountains are a small portion of the Colorado Rocky Mountains S.W. of Pueblo (Christman et al., 1959; Armbrustmacher, 1979). The bedrock is composed of middle Proterozoic (1.72-1.45 b.y.) granite gneiss, migmatite, amphibolite, metagabbro, metapyroxenite, metaquartzite, calc-silicate gneiss, etc. The high-grade metamorphics to ultrametamorphics are locally retrogressed, and intersected by numerous long shear, mylonite and breccia zones. Some of these zones are filled or fringed by local patches of pink to red K-feldspar or albite and quartz, barite, carbonate, galena and sphalerite. Thorogummite, thorite and other Th minerals occur sporadically in the above association and are in most cases decomposed and megascopically invisible, masked by "limonite". About 800 small Th occurrences have been recorded in the Wet Mountains (Fig. 29-26), having an aggregate tonnage of about 3,564 t Th (grade better than 0.088% Th).

In the early stages of research, the Th mineralization was believed to be genetically affiliated to a Precambrian syenite body and to a lower Cambrian albite syenite stock and associated breccias, dikes and quartz-feldspar veins. These were considered by some to be products of retrograde metamorphism, comparable with the uranian and thorian albitites and K-feldspathites discussed by Belevtsev (1979), mostly from the Precambrian terrains of Siberia (Aldan Shield) and the Ukraine (Zheltye Vody). The subsequent discovery of Cambrian alkaline syenite, nepheline syenite, gabbro, pyroxenite, carbonatite and alkaline lamprophyre bodies in the Wet Mountains, caused a re-interpretation. The Th orebodies are now considered to be related to the alkaline magmatism, or to the interaction of the alkaline fluids with their retrogressed environment. There is a remarkable convergence between the effects of alkaline contact metasomatic feldspathization as found in zones of fenitization (Chapter 33), and the retrogressive metamorphic feldspathization as well as carbonatization.

29.8.4. Pb,Zn,Ag provinces

Vein or replacement deposits of galena, sphalerite and associated minerals in quartz, carbonate, barite or fluorite gangue are very common in partially retrograded, rejuvenated and deep-faulted high-grade metamorphic terrains (e.g. the Colorado Mineral belt, Massif Central, Vosges and Schwarzwald Mts, Bohemian Massif, Rhodopen, Menderes Massif, etc.). In many regions mineralized in this way the Pb-Zn bodies show spatial and temporal association with large plutons, with small intrusive stocks and dikes, with geophysically buried plutons, with surficial andesite to rhyolite volcanism or with alkaline magmatism. Abundant deposit examples have been treated in the corresponding chapters. The above affiliations, however, need not exert the complete control and genetic over-generalization could be harmful in exploration. It can be assumed that orebodies equivalent to the above can also accumulate from hydrotherms driven by the more obscure agents (geothermal or radioactive decay heat, metasomatic fronts, etc.).

In the Bohemian Massif, a belt of small Pb,Zn,Ag deposits controlled by the Blanice Furrow, a distinct narrow N.N.E.-trending fault graben in the Moldanubian metamorphics, completely lacks any apparent magmatic agents of mineralization. The Furrow is bordered by a discontinuous, pinching and swelling system of mylonite-filled faults, to which are locally adjacent short, diagonal feather faults. Quartz, barite, ankerite, sphalerite, minor arsenopyrite, tetrahedrite



1. Pt migmatite, amphibolite, pegmatite
2. red altered (bleached, partly feldspathized) rocks
3. fragments of red altered and feldspathized ("albite syenite") wallrocks in a matrix of drusy gray to smoky quartz. The quartz contains patches of barite and calcite with scattered thorite. At surface, calcite is leached and substituted by Th-containing residual ocher

Fig. 29-26. Wet Mountains, Colorado, detailed section of a Th-bearing lode near Rosita. From LITHOTHEQUE.

and Ag sulphosalts-filled veins in the Stříbrná Skalice, Ratibořské Hory, Rudolfov and other fields (cumulative production about 170 t Ag), preferentially fill the feather faults. The prevalent wallrock alteration is a slight sericitization and chloritization.

In the Pb,Zn,Ag fields in the Rhodopen Massif (Bulgaria and Greece, e.g. Madan; Iovchev, 1961), the ore shoots fills are often breccia and mylonite-filled faults in the crystalline basement, tens of kilometres long. The mineralization is believed to be coeval with the Eocene-Oligocene continental volcanism and at some deposits (e.g. Madzharovo), epithermal orebodies are hosted by the volcanics. This, however, need not be valid universally.

29.8.5. Gold deposits

Gold deposits hosted by high-grade metamorphics are usually closely associated with "granites" or with subvolcanic intrusions, and localities lacking this association are rare. One example is the Roudný deposit in the Blanice Furrow, Bohemian Massif, a structure mentioned in the previous paragraph (Koutek, 1963). This deposit is hosted by Proterozoic biotite-sillimanite gneisses and migmatites containing numerous bodies of aplite, pegmatite and orthogneiss. The orebody has the form of a westerly plunging fault-bound triangular prism, framed by a massive to brecciated quartz lode 10-150 cm thick and gradational into quartz stockwork in the adjacent silicified gneiss. The ore minerals are scattered pyrite, arsenopyrite, lesser sphalerite, tetrahedrite and galena. The grade ranges between 4 and 25 ppm Au, and the gold has a low purity (0.675). Some 6.6 t Au was produced or remains in the tailings.

29.8.6. Antimony and mercury deposits

Small stibnite deposits are occasionally associated with faults of activation superimposed on high-grade metamorphic complexes. Shcheglov (1967) mentioned the Boguchan Sb deposit in the Bureia median massif, E. Siberia (chalcedony, fluorite, stibnite veins and mineralized zones in Cretaceous sandstones and tuffs above crystalline basement) and the Ribkovo Sb deposit in southern Bulgaria.

A series of cinnabar deposits associated with open faults and mylonite zones in high-grade metamorphics of the Menderes Massif, W. Turkey, has recently been described by Yildiz and Bailey (1978). At the Haliköy mine (3,509 t Hg/0.254%; Fig. 29-27), cinnabar, metacinnabar, quartz, pyrite and marcasite form veinlets and disseminations along the footwall in a clayey gouge-filled zone up to 35 m wide. The zone is a E.-W.-trending, north-dipping thrust fault separating micaschist from a granitic gneiss. In the Turkonü deposit, cinnabar and pyrite are disseminated in a steep E.-W. fault. The ore zone 1-5 m thick and 500 m long is contained in a granitic augen gneiss and the production has been 242 t Hg. Similar but smaller deposits are found in the Tire area.

29.8.7. Fluorite and barite veins

Fluorite, barite and usually quartz, carbonate veins (or replacements in carbonates) are by far the most characteristic mineralizations associated with shallow retrogression, faults, fault breccias and mylonite zones. Their description has been delayed because these are nonmetallic commodities. Metallic minerals are, however, often associated in small quantities and the veins grade to one of the metallic fillings discussed earlier. In the review by Shcheglov (1967), fluorite and barite deposits are always the youngest products of "activation", significantly postdating plutonic intrusive activity and the older generations of hydrothermal deposits. Important fluorite belts are particularly common in the crystalline basement of median massifs and their covers.

One of the largest examples is the Eastern Mongolian fluorite belt which is 1,000 km long and 300 km wide. Lesser occurrences are found in the Hesperian, French Central, Morvan, Schwarzwald (Wieden), Bohemian (Moldava) and Rhodopen (Slavianka) Massifs, as well as in the Colorado Rocky Mountains (Poncha Springs), in the Santa Catarina crystalline complex, S.E. Brazil (Morro da Fumaca) and elsewhere. Of the minor metallic minerals, galena and sphalerite are the most common. Small production of Pb,Zn and Ag was realized from the Schwarzwald (e.g. from Wieden and Badenweiler; the latter is a Tertiary silicified mylonitized zone), from the Massif Central (e.g. Ussel field, upper Triassic-Jurassic fluorite, galena, sphalerite veins) and other localities.

Uranium minerals are known in small quantities in several fluorite deposits, and the fluorite itself is often radioactive. At Kletno in

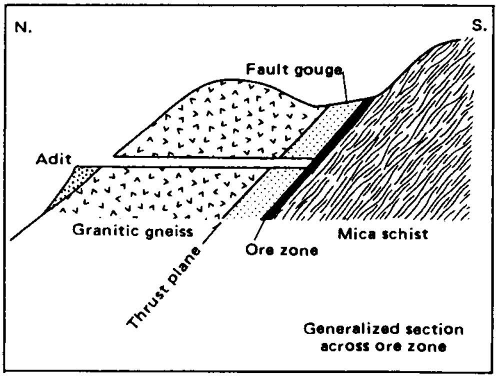


Figure 29-27

Haliköy mine, Turkey, an example of a cinnabar deposit along fault in high-grade metamorphics. From Yildiz and Bailey (1978)

the Polish Sudeten Mts. (Banaś and Mochnacka, 1974), quartz-fluorite veins located in a N.N.W.-trending overthrust of augen gneisses and marbles over micaschists, contain nest-like accumulations of U,Cu and Se minerals. Chalcopyrite, chalcocite and pyrite are most common, pitchblende, uranophane, torbernite, gummite, clausthallite and umangite occur in lesser quantities.

29.8.8. Fe and Mn deposits

These are of minor importance. The Jurassic Mn veins near Romanèche (eastern tectonic margin of the Massif Central, France; Lougnon, 1956; about 160 Tt Mn, up to 1 Tt W content) consist of quartz, barite, fluorite and psilomelane. The veins are up to 20 m thick, and controlled by fault zones in the basement metamorphics and Carboniferous granite. Locally, the veins are gradational into psilomelane replacements in Jurassic limestones of the platformic cover. Similar veins are found in the Schwarzwald (Eisenbach).

29.8.9. "Alpine" veins

"Alpine veins" are mineralized fissures (often just groups of mineral crystals sitting on walls of empty clefts or fissures), particularly well developed in the crystalline massifs of the Alps (Parker, 1923). The mineral association, prized by collectors, consists of a variety of nonmetallic silicates and oxides (quartz crystal, epidote, adularia, sphene, zeolites, chlorite) with only small quantities of Ti and REE metallic minerals (rutile, anatase, brookite, aeschynite, synchisite, gadolinite, etc.). The minerals crystallized from hydrothermal fluids at temperatures ranging from 450 to 100^{o} C, during the retrogressive phase of gneisses and schists. The vein components have been leached from the wallrocks and are often accompanied by quartz gangue. Except for specimen minerals, the only economic product of the "Alpine veins" has been piezoelectric quartz.

"Hebung, Spaltung, Vulkanismus".
Hans Cloos in Geol. Rundschau v. 30,
p. 401-527, 1939.

CHAPTER 30

Continental Fragmentation, Rifts and Paleo-Rifts

30.1. INTRODUCTION

Rift zones are "regions of stretching where the crust is somewhat thinned and the mantle has a lower than normal density" (Milanovskii, 1972). The word "rift" is used as a synonym for rift zones, or as a summary term for a broad tectonic environment involving crustal fragmentation and the affiliated lithologic associations. "Rift" is usually used in the general (time unconfined) sense, but many authors using the term imply contemporary geotectonic environment: in other words, the processes and forces generating rifts that are at work at present and can be observed and measured.

Remnants of tectonic structures and characteristic lithologic associations interpreted as being a result of "rifting" but with the tectonic activity that ceased a long time ago, are usually termed paleo-rifts. A sharp division between contemporary, active rifts and paleo-rifts does not exist and many regions of Mesozoic (e.g. St. Lawrence Graben, Canada) or even Paleozoic rifting are still seismically active at present.

An extensive literature on "rifts" and "rifting" has been generated in the past 30 years (e.g. Illies and Mueller, eds., 1970; Girdler, ed., 1972; Milanovskii, 1976; Grachev, 1977; Neumann and Ramberg, eds., 1978; Morgan and Baker, eds., 1983) and it offers numerous, often conflicting definitions and interpretations of rifts and associated features (Fig. 30-1). Particularly uncertain are the limits of rifts, that is, where they start and terminate. "True rifts" are gradational into "aulacogenes" and into a variety of graben and horst-and-graben systems and extensional (taphrogenic) lineaments. Aulacogenes (=failed rifts, failed tripple arms of rifts) are wedging-out graben-like depressions, often forming re-entrants oriented at an angle to rifted continental margins or mobile belts. They contain a thick fill of terrigenous sediments, basalts, and are often folded; e.g. Salop and Scheinmann (1969), Burke (1977).

Although "typical" continental rifts are established within "cratons" (platforms), comparable, although usually lesser-scale, taphrogenic systems can be found in mobile belts as well. There they are either (1) relatively late, superimposed on an assemblage that had passed earlier through phases of intensive marine sedimentation and volcanism ("geosynclinal stage"), metamorphism, deformation and batholithic emplacement ("orogenic or batholithic stage", e.g. the Rio Grande Rift, New Mexico) or (2) relatively early, controlling the initial stages and facies of the "geosynclinal" deposition.

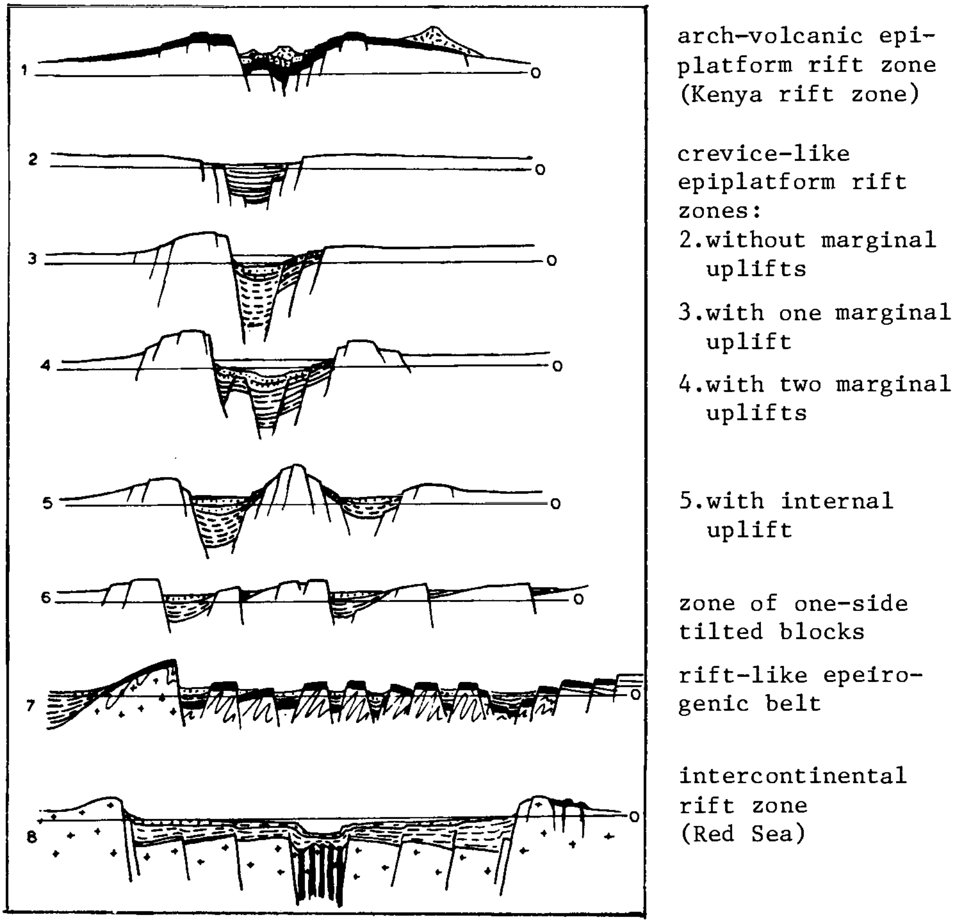


Fig. 30-1. Characteristic structural types of rift zones. From Milanovsky (1972).

Mineralization associated with the "rifting" episodes in orogenic belts is treated in Chapters 6, 26, 28 and 29.

Milanovskii (1972) distinguished three relatively objective, empirical categories of the rift zones of the earth, differentiated by the type of crust involved: (1) continental (intracontinental) rifts, where both the rift floor and shoulders are composed of thinned continental crust (e.g. East African Rift); (2) intercontinental rifts, narrow waterways where the rift (its axial part) has an oceanic crust (the Red Sea, Gulf of California) and (3) oceanic (intraoceanic) rifts, where the axial graben is bordered by oceanic crust (e.g. the Mid-Atlantic Ridge). The latter category was treated in Chapter 4.

"Rifts" and "rifting" have variable roles in the generation of ore deposits (Fig. 30-2; Table 30-1). Certain mineralizations are so intimately affiliated to the process of active rifting that they can be designated with much credibility as "rifting-generated" (e.g. the metalliferous brines and young ore precipitates in the axial trough of the Red Sea). The latter are treated in the present chapter. Other ores are immediately genetically associated with characteristic parent rocks (e.g. alkaline rocks such as nepheline syenites, carbonatites, etc.) which, in turn, are one of the characteristic lithogenetic consequences of rifting, so occurrences of such ores are also, to some extent, (indirectly) controlled by rifting. In many cases, however, the rift structures are obscure or not obvious at all, so only the lithologic association remains. Consequently, ore occurrences associated with rifting-generated lithologic associations are treated with the latter, in the following chapters: 24 (recent sediments of rift lakes); 31 (plateau basalts) and 33 (alkaline rocks).

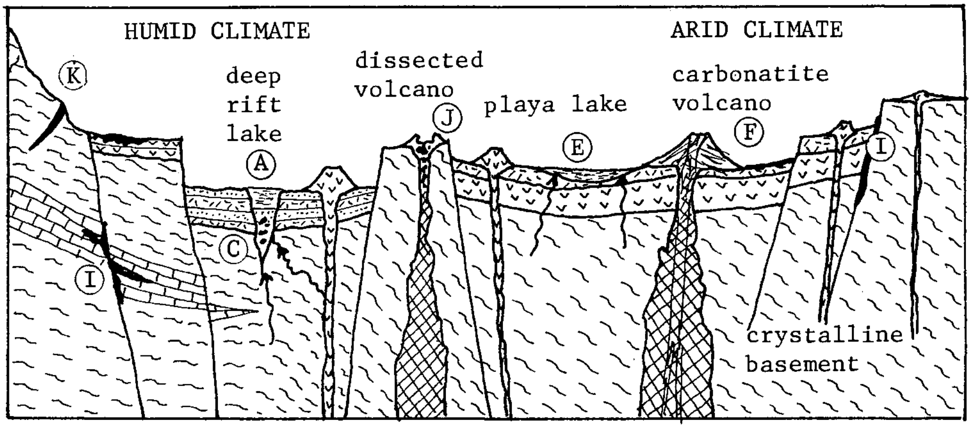
It is easy to understand why the most convincingly interpreted "rifting-generated" ores are Recent, or geologically very young (Tertiary). It is often because their origin can still be directly observed (e.g. the Red Sea metalliferous brines and sediments). Alternatively, in some instances, even when the actual ore formation has already ceased, the paleo-environmental configuration is still so well preserved that a credible genetic interpretation can be suggested. Although the model for the origin of the Red Sea metalliferous muds has been applied to several ancient ore deposits such as Sullivan, Canada; Mount Isa, Lady Loretta, Broken Hill, etc., Australia; Bawdwin, Burma; Rammelsberg, Germany and others (Blissenbach and Fellerer, 1973; Sawkins, 1976, 1978, 1984; Robbins, 1983; etc.), the credibility of interpretation is low and numerous alternative rift-unrelated models have been offered to explain the origin of the above deposits. As a rule, only those interpretations of "rifting-generated" ore deposits that offer good empirical evidence of rifting still preserved in the area and applicable in actual exploration, are treated in this chapter.

30.2. STAGES OF RIFTING AND RECENT EXAMPLES

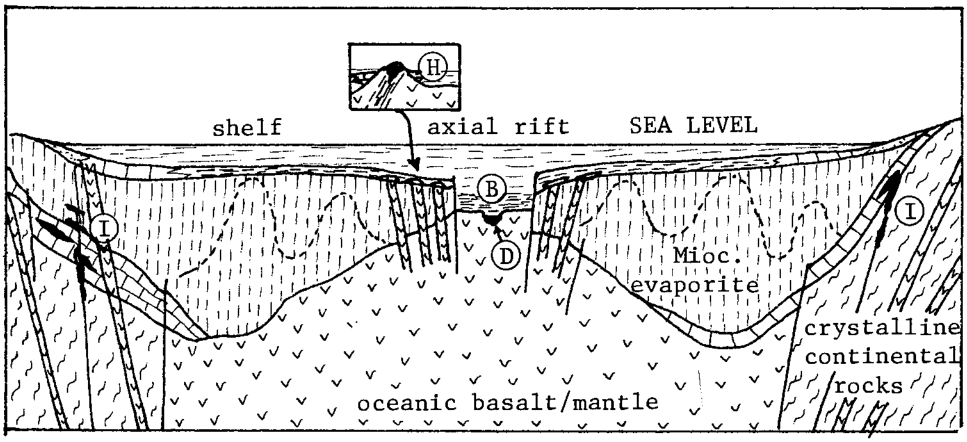
Intracontinental rifting is a long-lasting, dynamic and additive process (Fig. 30-3). It is initiated in the earlier stabilized continental crust and terminates when, at a site under consideration, the continental crust is completely destroyed (most probably removed by spreading and/or replacement) and substituted by oceanic crust. The same process then usually continues, but has a character of intraoceanic spreading. Although intracontinental and intraoceanic rifting and spreading systems may converge (become identical) in the subcrustal region, they differ in terms of interaction with the crustal environment.

The rift stage marked by the formation of conspicuous laterally extensive fault, graben and horst systems usually accompanied by dominantly mafic or bimodal alkaline or tholeiitic volcanism, is preceded by uplift, block faulting and predominantly felsic

CONTINENTAL RIFT (EAST AFRICAN RIFT)



INTERCONTINENTAL RIFT (RED SEA)



NOT TO SCALE

Fig. 30-2. The major sub-environments, lithologic associations and mineralization styles in the Recent continental and intercontinental rift environment (see Table 30-1 for explanation of letter codes). From Laznicka (1984).

Table 30-1. Principal mineralization styles in the Recent continental and intercontinental rift environments

(A)	Anomalous metal (Zn,Pb,Cu,etc.) and F content in the water of rift lakes (e.g. L. Kivu) and feeder springs
(B)	Anomalous metal contents in highly saline, thermal seawater and in the feeder springs (Red Sea; Mn,Fe,Zn,Cu,Pb,Ag,etc.)
(C)	Anomalous base metal contents (Mn,Zn,Mo,etc.) and diagenetic metallic minerals (Mn-Fe oxides, carbonates) in bottom sediments of rift lakes
(D)	Metalliferous sediments (muds, oozes) filling depressions in the axial zone of rift seas (Red Sea); about 10 Mt Mn, 2 Mt Zn, 500 Tt Cu, 150 Tt Pb, 6 Tt Ag
(E)	F, trace metals (U,Zn) and minor metallic minerals in recent evaporites of rift playa lakes
(F)	U and other metals in calcretes over alkaline volcanics in arid climatic zones
(G)	Residual bauxites over alkaline volcanics in humid tropics
(H)	Ni-silicate infiltrations in saprolitic mineralized serpentinite ("oceanic" islands in the Red Sea); 250 t Ni
(I)	Fissure veins, epigenetic replacements and ? stratiform bodies of fluorite, barite, galena, sphalerite, Mn-ores, etc. in pre-rift rocks (mostly young carbonates)
(J)	Ores at deeper levels of the alkaline igneous association (e.g. pyrochlore); see Chapter 33.
(K)	Various pre-rift mineralizations exposed in the uplifted basement blocks on rift shoulders

calc-alkaline (to peralkaline) volcanism and intrusive activity (Cloos, 1939). The latter activity and its rock products have been treated in the Soviet literature as "tectonomagmatic activation", a term now used with increasing frequency in the western literature as well. Some authors (e.g. Sawkins, 1978) consider rifting as a part of activation, whereas the Russian school usually treats "activation" and "rifting" separately.

There is indeed continuity and overlap between both regimes and it is impossible to make a sharp distinction, but there is a different emphasis. Lithogenesis and mineralization influenced by tectonomagmatic activation of the continental crust are treated in Chapters 24,25,26, 28,29,31-33. The recent "rifts" (i.e., regions undergoing the rifting stage of development) are represented by two outstanding example areas, that serve as models for interpretation of the less perfectly developed areas elsewhere: (1) the East African Rift System represents the less advanced stage of rifting developed fully (at the present level of exposure) within the continental crust and (2) the Red Sea, a representative of the advanced stage of rifting in which oceanic lithosphere already floors the axial portion of the rift, but the continental lithosphere on both flanks is still well in sight and involved in the lithogenesis and metallogeny.

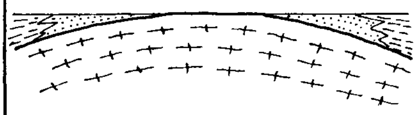
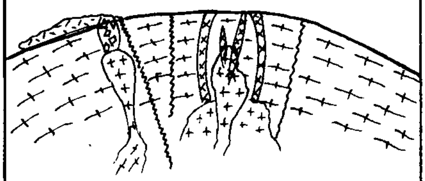
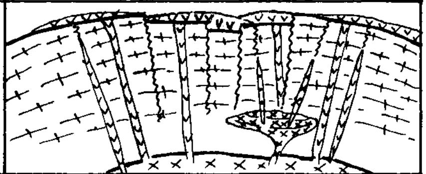
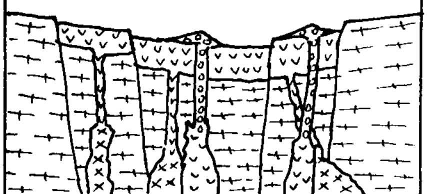
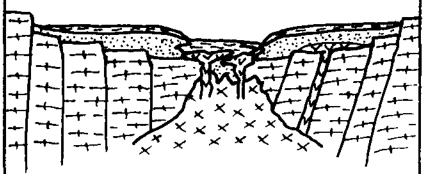
1 Incipient gentle doming within sialic cratons (may influence facies of platformic sediments)	
2 Mantle upwelling and modest thinning of the continental crust; "anorogenic" granite, rhyolite, syenite, trachyte, etc. magmatism; may grade into or overlap with (3) to form bimodal associations	
3 Fracturing, light crustal extension, mantle rise, plateau basalt volcanism; diabase diking, formation of high level mafic magma chambers in the continental crust	
4 More intensive fracturing, horst and graben formation (rifting), accompanied by alkaline magmatism (as in the East African Rift)	
5 Increased crustal spreading, subsidence of axial troughs, rise of mafic magmatic systems, attenuation and ultimately interruption of the continental crust; oceanic basalt flows, diabase dikes, gabbro intrusions; evaporites accumulate in restricted basins (as in the Red Sea)	
6 Growth of oceans	

Fig. 30-3. Idealized stages of rifting. From Laznicka (1984).

30.3. EXAMPLES OF MODERN RIFT AND TAPHROGENIC SYSTEMS

30.3.1. East African Rift (EAR)

The classical East African Rift system (Dixey, 1956; McConnell, 1967; Khain, 1971; Fig. 30-4) is an epiplatformic orogenic system of block uplifts interrupted by a system of anastomosing grabens and faults. It is more than 4,000 km long. The system can be traced from the Zambezi River valley in the south through Malawi and Zambia to southern Tanzania. From there, the western branch follows lakes Tanganyika, Kivu and Albert in the border region of Zaïre, Burundi, Rwanda and Uganda. The eastern branch (Gregory Rift) continues to Kenya and Ethiopia. In Ethiopia, the central graben widens to form the Afar Triangle, a site of a triple junction. There, the EAR loses its identity and the Red Sea and Gulf of Aden extend in the form of a N.W. and N.E. arms, respectively.

McConnell (1967) argued that much of the EAR has been superimposed in the Cainozoic time on an ancient network of mylonite and blastomylonite-filled shears and lineaments in the Precambrian basement. The individual EAR structures are true rift valleys (elongated sunken areas descended between parallel faults, 30-60 km wide and several hundred km long), as well as assymetrical narrow fault and tilted block, and fault and flexure, structures. The floors of both are intensively faulted. In its present configuration, EAR has been most active tectonically during the past 15 m.y., and the seismic activity continues. The Precambrian uplifted blocks have predominantly been regions of erosion except for local sections, where they are covered by Cainozoic volcanics or intruded by igneous rocks. The rift valleys have been areas of continental volcanism and sedimentation, both subaerial and subaqueous-lacustrine. The deep rift lakes remain important depositional basins.

The EAR volcanism (King, 1970) operated in several stages, and generally displayed a change from a pre-rift fissure areal volcanism (basalt and phonolite flows and shield volcanoes) to rift-controlled central volcanoes (basalt, trachyte, phonolite, nephelinite, peralkaline rhyolite, minor carbonatite). The volcanism is strongly to mildly alkaline and although the volcanic centres are most common within rift valleys and along rift faults, they are widespread on the rift flanks as well up to a distance of about 300 km from the rift axis (Fig. 30-5). The metallogeny of the rift-controlled alkaline volcanic and intrusive suite is treated in Chapter 33. The young volcanics are almost devoid of mineralization, whereas subvolcanic to intrusive stock carbonatites exposed in several dissected centres, carry the expected accumulations of Nb, REE, apatite, Sr, etc.

The rift valley lakes (Fig. 30-6) form a string extending over 3,000 km along the rift trace. Those located in the high rainfall area are typically narrow and deep. They accumulated a considerable thickness of sediments (up to several kilometres; Degens and Ross, 1976). The lake sediments are mostly mud, silt, reworked volcanic ash or tuff, minor diatomite, aragonitic carbonate and minor evaporites.

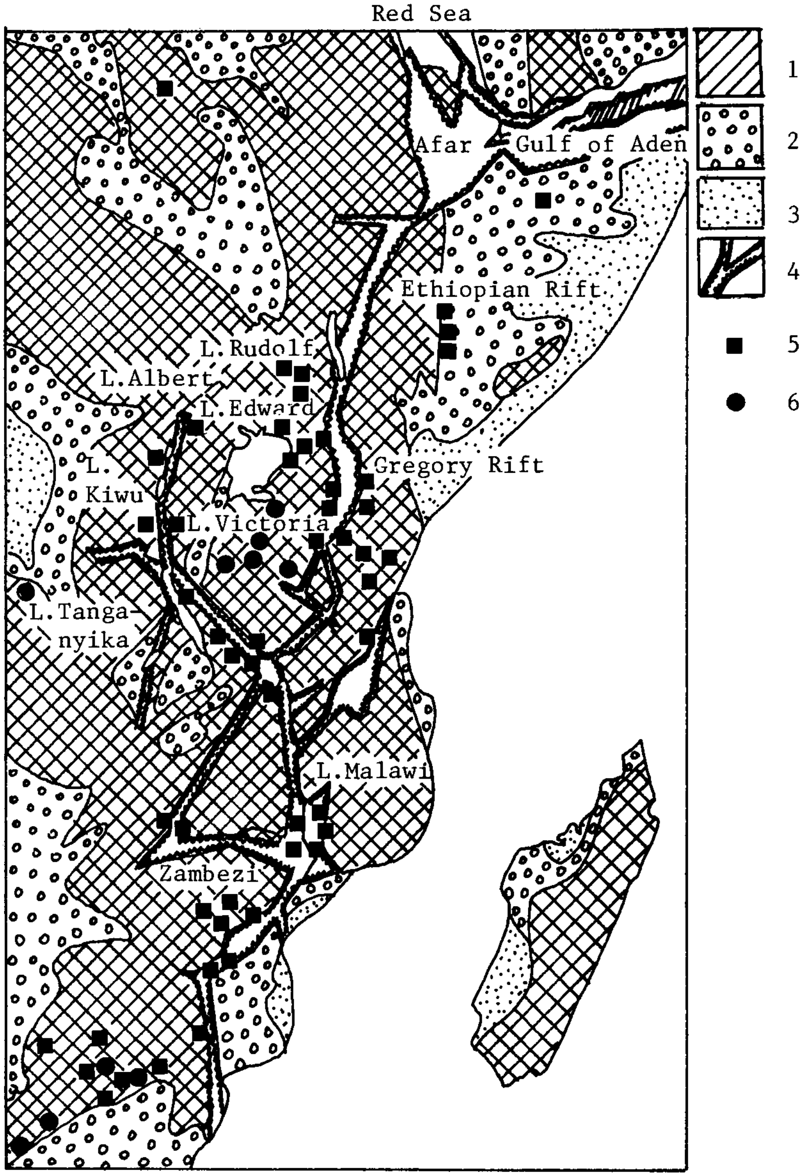


Fig. 30-4. The East African Rift. 1=PCm crystalline basement; 2=Pt_3 to PZ platformic cover; 3=MZ-T platformic cover; 4=rifts; 5=alkaline magmatic centra including carbonatites; 6=kimberlites. From LITHOTHEQUE.

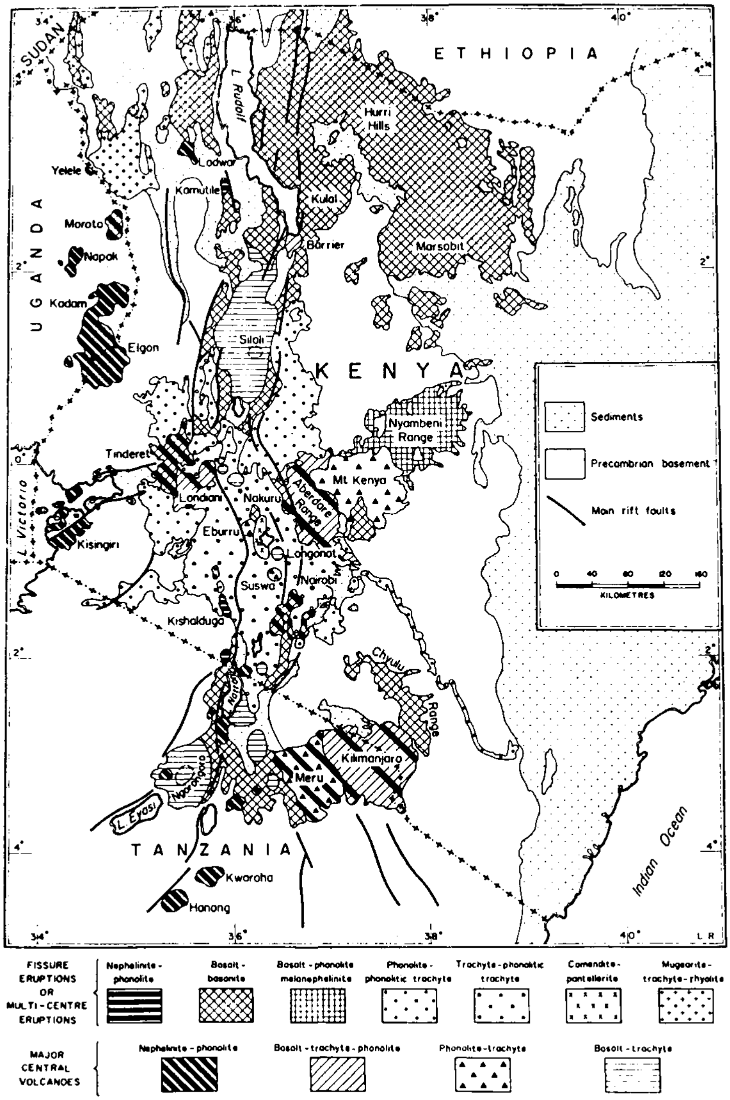


Fig. 30-5. East African Rift volcanism along the Gregory Rift in southern Kenya and northern Tanzania. From Williams (1969). Reprinted from Nature, with permission; © 1969, Macmillan Journals.

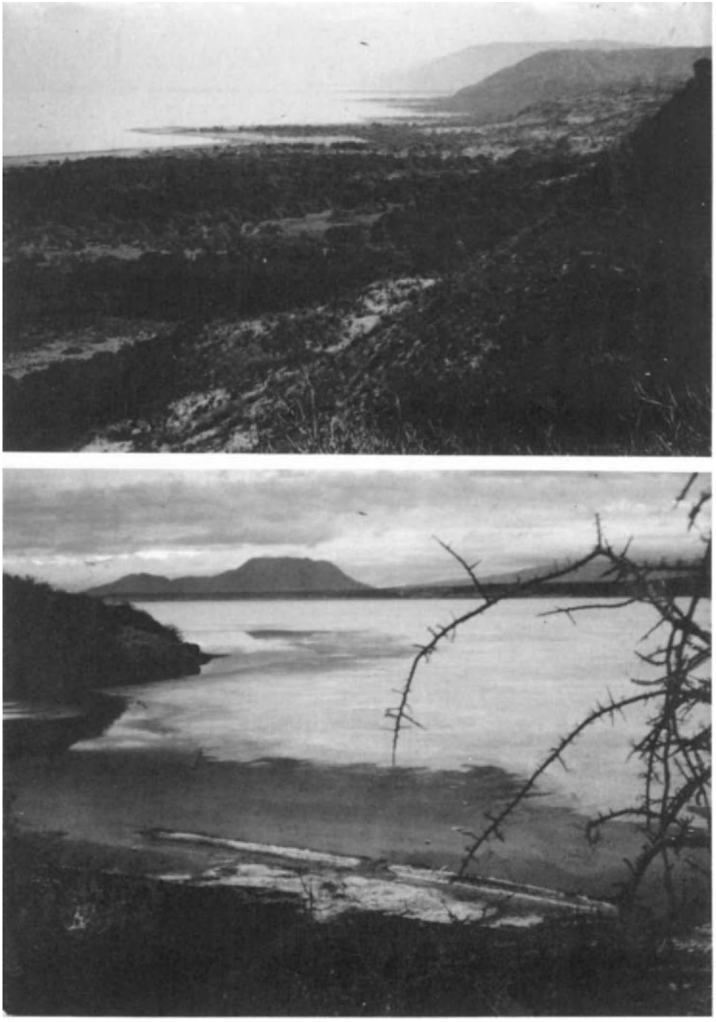


Fig. 30-6. East African Rift, lakes of the semi-arid zone. Top: Lake Manyara, Tanzania (the rift escarpment is on the right); bottom: soda Lake Magadi, Kenya.

Evaporites are more characteristic of the shallow ephemeral lakes such as Natron and Magadi, located in the dry grassland climatic belt. The African rift lakes, at present, yield only nonmetallics (trona, possibly fluorine), and no industrial metallic occurrence has been discovered so far. Several interesting geochemical metal anomalies, however, have been recorded and studied and they contribute considerably to our understanding of the rift lacustrine metallogeny.

A portion of such metallogeny is comparable with ore occurrences recorded in lakes in general, treated in Chapter 24 (e.g. heavy mineral placers in lacustrine beach sands such as monazite in Monkey Bay, Lake Nyasa, McNaughton, 1958, authigenic manganosiderite or rhodochrosite nodules in terrigenous mud or clay, Lake Kivu; Degens and Ross, 1976). The remainder is unique, being the result of interaction of the rift volcanism (particularly hot springs) and pluvial lake sedimentation. Most of the available information comes from the research done by Degens and co-workers (Degens et al., 1972; Degens and Kulbicki, 1973; Degens and Ross, 1976) in the Lake Kivu.

Lake Kivu located in the border region of Zaïre and Rwanda, is situated about 1,500 m above sea level, surrounded by active volcanoes of the Virunga Range. It extends to a depth of 500 m and reducing conditions prevail below about 50 m. The lake is fed by both rainwater and salty hydrothermal springs. The springs are the major source of water in the restricted Kabuno Bay. The Lake Kivu water itself has an anomalous zinc content (2 ppm Zn, that corresponds to 1 Mt dissolved or suspended Zn in the entire lake), much of which is bound in micron-size spheres of sphalerite enclosed in resin globules, suspended in the water. The lake floor sediments present in the reducing zone contain chemically precipitated nodules of Mn-Fe carbonates and high-Ni pyrite, as well as anomalous trace contents of Pb,Zn,Mo and Cu. The heavy metals are probably bound in organic complexes.

Müller and Förstner (1973) described an occurrence of nontronite, limonite, opal and vivianite, currently forming in aerated shallow parts of Lake Nyasa (Malawi) near Nkhota. The minerals form pellets with 20-45% Fe, accumulated in a layer, over 80 cm thick, topping diatomite or detrital sediments.

Harris (1961) recorded an unusual occurrence of thick phosphatic beds, developed around a small basement outcrop of Archean gneisses projecting through recent sediments of Lake Manyara, Tanzania. The phosphate is radioactive and is possibly a result of guano accumulation on an island. Mineral occurrences in buried Cainozoic sediments of the African lakes have rarely been reported probably because of the lack of drilling core. Harris (1961) recorded a bed of uraniferous strontianite at a depth of about 70 m in the Bahi depression near Dodoma, Tanzania.

Fluorine is a widespread element in EAR, clearly associated with rifting. Up to 22% villiaumite (NaF) and 6% fluorite is present in trona in the playa Lake Magadi, Kenya (van Alstine and Schruben, 1980). Fluorite is also frequent in tuffaceous lake beds. A substantial (9 Mt ore with 50% CaF_2) fluorite mineralization has been described from Kerio Valley in W.C. Kenya (Nyambok and Gaciri, 1975). There, fluorite lodes replace marbles of the Mozambique System along rift faults. The mineralization is interpreted as being of low-temperature hydrothermal origin and appears to be associated with basalt dikes.

30.3.2. The Salton Sea, California, hydrothermal brines

Salton Sea is a recently formed lake located in Imperial Valley (California and Baja California), a complex rift graben situated in the northern extension of the Gulf of California. Drilling for geothermal energy has outlined areas, measuring several square kilometres, underlain by a highly saline brine with an extraordinarily high content of metals (600 ppm Zn, 85 ppm Pb, 2.7 ppm Ag, 2,000 ppm Mn, 6 ppm Cu; White, 1967). Gray travertine deposited at the surface and in drillhole casings contained 10% Mn, 0.7% As, 0.07% Zn, 0.0015% Cu, in the form of Mn oxide and Mn calcite with finely dispersed sulphides. Megascopic sphalerite, chalcopyrite, tennantite and other minerals were discovered in well cuttings at depth. The Salton Sea active hydrothermal system serves as a model for fracture and paleoaquifer-controlled fossil hydrothermal mineralizations in paleorifts.

30.3.3. The Red Sea, summary of geology and mineralization

The Red Sea occupies an elongated N.N.W. depression over 2,000 km long, between north-eastern Africa and Arabia (Fig. 30-7). Its width ranges from 28 km in the southern narrows to 360 km at the latitude of Asmara. The geology of the Red Sea has been summarized by Coleman (1974). A pre-Miocene downwarp between the Arabian and African Precambrian basement swells was filled by a considerable thickness (over 3 km) of Miocene evaporites and clastic sediments with minor interbedded plateau basalts. These rocks, covered by Pliocene and Quaternary coral reef limestones, marginal clastics and marine oozes, underlie a broad shelf along both shores of the Red Sea. The shelf continuity is interrupted by an axial trough, 48-74 km wide, formed in the Pliocene time and related to a major rift. The trough is a steep-walled depression with basaltic floor covered by a thin vener of sediments. The basalt is interpreted as being oceanic tholeiite to alkali basalt and is believed to represent a newly formed oceanic crust along a spreading center.

Intermittently distributed on the seafloor of the axial trough are local depressions marked by anomalous heat flow, highly saline brine pools, hydrothermal sediments and sometimes metal accumulations. Thirteen brine pools had been discovered by the early 1970s (Schoell et al., 1974), five of which carried appreciable mineralization. The first discovered and largest metallic accumulation, the Atlantis II Deep, has been most extensively studied and is described in a large volume of literature (e.g. Degens and Ross, eds., 1969; Hackett and Bischoff, 1973; Backer and Richter, 1973 and others). It has already been test-mined. Its reserves are now estimated to be 1.7 Mt Zn, 400 Tt Cu and 5 Tt Ag in a 4-8 m thick layer distributed over 4.5 km^2 of the seafloor (Mining Magazine, 1981).

The Atlantis II mineralization (Fig. 30-8) is covered by about 2,000 m of normal seawater, and about 200 m of warm brine at 60-65° C

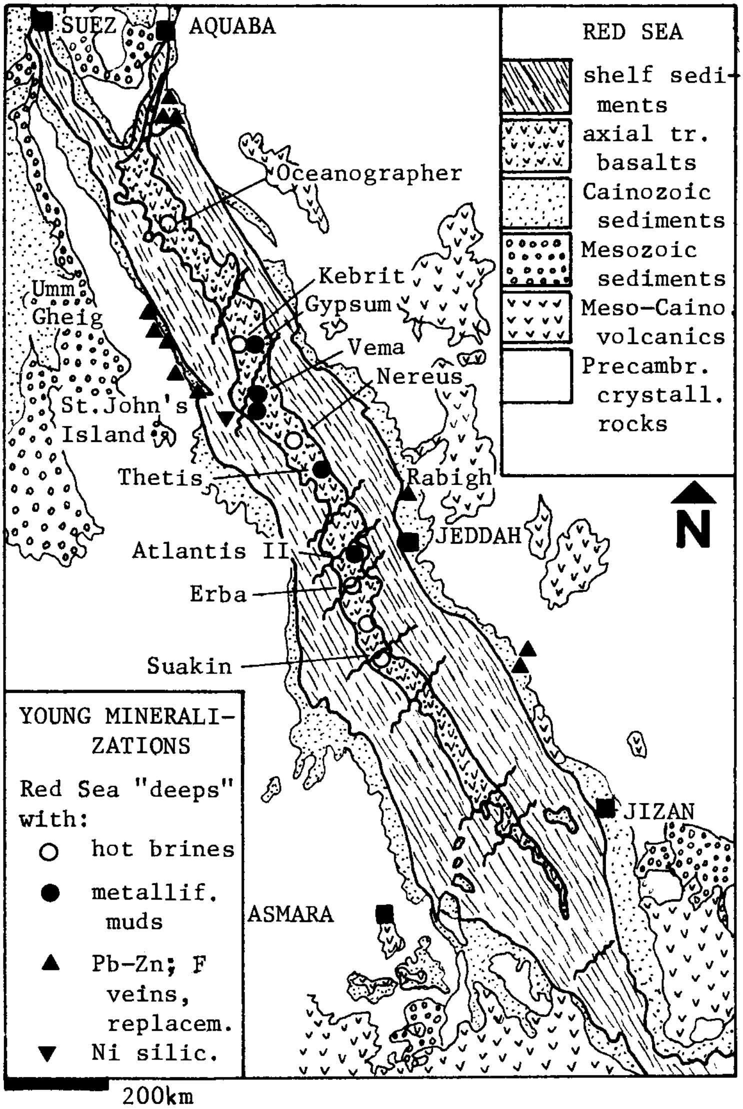


Fig. 30-7. Red Sea, geology and Cainozoic mineralization; geology after Coleman (1974).

with 44 to 56^{o} salinity, stratified by temperature. The metals are present as suspended matter in the brine, from which they gradually settle to form the seafloor metalliferous sediments. The 12 to 30 m thick layer of hydrothermal sediments rests on a basaltic bedrock and is compositionally zoned (from top to bottom: amorphous hydrosilicates → smectites with sphalerite, pyrite, manganosiderite, chalcopyrite → Fe-hydroxides, manganite → lower sulphide zone →

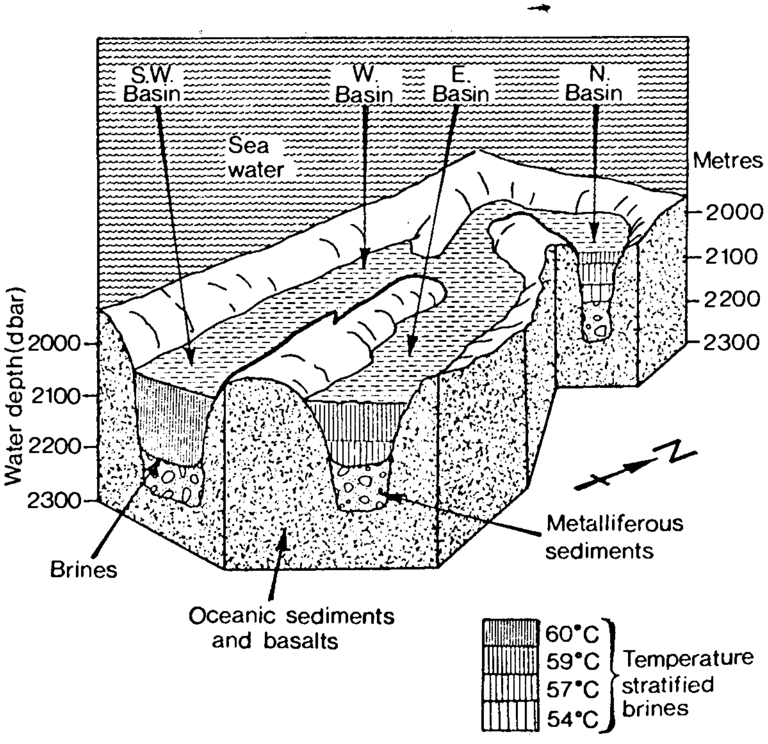


Fig. 30-8. Atlantis II Deep and its metalliferous brines and sediments. After Schoell, reprinted with permission from the Mining Magazine, August 1981.

coquina, limonite, minor sulphides).

The "ore" is black, fine grained and of paste-like consistency. It is usually interpreted as being a product of chemical precipitation from a subsurface brine. The brine is: (1) heated and driven by basaltic volcanic heat; (2) deriving its high salt content from the subsurface Miocene evaporites and (3) leaching its constituent metals from rocks en route, in particular from the Precambrian metamorphics. The Atlantis II Deep sulphide facies contains from 15.74 to 20.31% Fe, 1.11 to 2.81% Mn, 5.31 to 10.93% Zn, 1.34 to 2.22% Cu, 0.11 to 0.18% Pb and increased contents of Ag,Hg,Co. The same elements are anomalously concentrated in the oxide and silicate facies of sediments, but in sub-grade amounts (Bignell et al., 1976).

The young (Pliocene to Recent) Red Sea basalts occassionally crop out under subaerial conditions. One well-known occurrence is situated on the small St. John's Island (about 75 km S.E. of Berenice on the Egyptian coast). In addition to basalt and coral reefs, this island consists of serpentinized peridotite (Garson and Shalaby, 1976) and it is not known whether the peridotite is a tectonically emplaced raft or a member of the Cainozoic orogenic assemblage. In the peridotite, narrow and short, but rich infiltration zones of limonite and garnierite formed (5-6,000 t ore with 4.86% Ni, 0.93 ppm Pt), probably derived from "primary" disseminated or massive sulphides.

30.3.4. Afar Triangle

The Afar Triangle of eastern Ethiopia (Tazieff et al., 1972) is considered to be a displaced segment of the axial (rifted) portion of the Red Sea, recently uplifted so that the ocean ridge basalts and thick evaporites recently deposited subaqueously are now subaerally exposed. Bonatti et al. (1972b) described the En Kafala Fe-Mn deposit, interpreted as having formed some 200,000 years ago by submarine hydrothermal activity in a Red Sea-style brine pool. The mineralization is similar to the manganese deposits of Cuba, Efate (New Hebrides) and other localities, generated in an island arc setting. A basalt foundation is overlain by a basalt conglomerate locally cemented by Mn-oxides. These, in turn, are topped by a goethite-rich and manganite (birnessite) and pyrolusite layer. The Fe-Mn oxide layers are around 2 m thick and are capped by a reef limestone. Tooms (1976) mentioned occurrences of Cu-rich brines, copper deposits topping gypsum beds and manganiferous horizons in the Northern Ethiopia Rift Valley.

30.4. EXPOSED PALEO-RIFTS

Paleo-rifts, the sites of former rift systems that are no longer active, can be identified using a set of criteria (Table 30-2): (1) relic morphology, such as fault and relic graben pattern comparable with the EAR (e.g. the St. Lawrence Valley, Kumarapeli and Saull, 1966); (2) characteristic rock association and rock body configuration (e.g. alkaline ring complexes) or (3) both. Compared with the recent rifts, paleorifts carry substantially more widespread and important metallic mineralization than the former. This is clearly due to the greater depth of erosion exposing subvolcanic and plutonic levels of the rift magmatites. Since obvious rift grabens have rarely been preserved and faults may have been partly healed (e.g. by intrusive dikes) or draped by younger sediments, establishment of a paleorift requires a painstaking reconstruction and the degree of uncertainty is often high.

In some areas (e.g. in the Irish Zn-Pb province hosted by Carboniferous carbonates) where orebodies that usually occur associated with intrusive rocks lack such association, tentative suggestions have been made that orebodies might be related to rifting-generated fault systems, in particular by fault intersections (e.g. Russell, 1968; Vokes, 1973). The ore, faults, rifting relationship may be only conjectural, but it is widely used. A genetic connection between rifting and an epigenetic Pb-Zn

Table 30-2. Some criteria for the interpretation of paleorifts

GEOPHYSICAL
-thinned continental crust (shallow MOHO)
-shallow earthquakes usually associated with Phanerozoic paleorifts
-large negative Buguer anomaly over the broad uplifted arch
-sometimes, narrow zones of gravity maxima over axial grabens
-commonly increased heat flow
PETROGRAPHIC
-intimately associated alkaline intrusions (Chapter 33)
-loosely associated tholeiitic (exceptionally oceanic) basalts
-regionally associated bimodal (basalt-rhyolite) association, high-level granite plutons
-thick sequence of evaporites
STRUCTURAL
-relic rift valleys, about 50 km wide
-bifurcating tectonic pattern, short angular deflections, dimensions comparable with the East African Rift system
-dense network of longitudinal (parallel) faults
GEOMORPHOLOGIC
-remnants of fault scarps and fault-line scarps
-tilted blocks and horsts
-remnants of grabens, often interrupted by rivers
-frequent hot springs

mineralization has been proposed to explain the origin of the Proterozoic Nanisivik Zn-Pb deposit, Baffin Island, Canada (Jackson and Iannelli, 1981); the Zurak-Abakaliki Pb-Zn belt in the Benue Trough, W. Africa (Burke et al., 1972); the Pb-Zn replacements in Miocene carbonates along the western shore of the Red Sea, Egypt (e.g. Umm Gheig) and eastern shore in Saudi Arabia (Motti et al., 1981); Pb-Zn and barite-fluorite veins south of the Ottawa Valley, Ontario (Kumarapeli, 1976) and others.

Sawkins and Rye (1979) offered an interesting paleorift-related interpretation of the origin of the important Messina (Transvaal) copper field, hosted by the Archean metamorphics of the Limpopo mobile belt. The Messina orebodies are Cu sulphide mineralized breccia pipes, disseminated replacements and fissure filling veins dating from post-Karoo (Mesozoic) age, aligned along a N.E. trend for a distance of 20 km. Supposedly they formed by precipitation from heated saline brines controlled by a Mesozoic paleorift. The brines acquired their Cu content from the rift-floor basalts believed formerly to have been topping the hydrothermal convection system.

30.5. ASSYMETRICAL PORTIONS OF PALEORIFTS PRESERVED UNDER "ATLANTIC-TYPE" CONTINENTAL MARGINS; PALEORIFTS WITHIN SHELVES COVERED BY YOUNG SEDIMENTS

Association of terrigenous sediments (particularly of the red-beds facies), evaporites, mafic volcanics and intrusions, is frequently present as a block-faulted fill of fault-bound troughs and grabens, now buried under a thick pile of continental shelf sediments under the Atlantic-type continental margins. These rocks represent the remnants of intercontinental and intracontinental rifts dismembered by continental drift and are particularly common under the Atlantic shelf of North America and under the North Sea sediments off western Europe (e.g. Sheridan, 1974; Ballard and Uchupi, 1975). Salt doming is widespread. Most of these buried occurrences are known from geophysical work and confirmed by oil drilling, and no economic mineralization has been reported so far, although metals (particularly copper) could be expected by analogy.

30.6. HYPOTHETICAL, METAMORPHOSED PALEORIFTS

Increasingly often, the paleorift interpretation is offered in the literature to interpret metamorphosed associations of amhibolite, marble, schists, and strata-related ores mostly Cu,Zn or Pb. This is particularly true in the instances where such associations form narrow lithologic belts supposedly generated with a significant taphrogenic component (e.g. Wopmay Orogen in northern Canada, Easton, 1981; "Amphibolite Belt" of Namibia; Goldberg, 1976; Mount Isa shale belt, Queensland; Sawkins, 1976, see Volume 2). Continental rift models have also recently been proposed to explain the formation of the Precambrian greenstone belts (e.g. Anhaeusser, Windley, Hunter, and others; see summary in Condie, 1981, p. 349-354).

Selected examples of mineralized rifts and paleorifts are listed in Table 30-3 and their location is marked in Fig. 30-9.

Table 30-3. Selected examples of mineralized rifts and Phanerozoic paleorifts

RIFTS ACTIVE IN THE CAINOZOIC
East African Rift system
A system of block uplifts over 4,000 km long, interrupted by anastomosing grabens and faults, established on Precambrian crystalline basement. The central grabens are filled by arid to humid continental sediments. Deep lakes in the humid zone have terrigenous and volcanogenic sand to mud (high proportion of euxinic mud). Widespread areal and central tholeiitic, bimodal and alkaline

volcanism and intrusive activity in Neogene and Quaternary. ORES: rare Mn nodules in lake sediments; slightly metalliferous (mainly Zn) lake muds and waters; high F in playa evaporites and brines; apatite, minor pyrochlore in high-level Cainozoic carbonatites. McConnell, (1967); Khain, (1971); Mitchell and Garson (1981).

Red Sea

A N.N.W. depression, over 2,000 km long and 28-360 km wide. Over 3 km of Miocene evaporites and clastics fill a Precambrian basement swell, topped by Pl-Q tropical shelf sediments. These are interrupted by a Pl-Q steep-walled axial trough 18-74 km wide, with a basalt floor, covered by a thin veneer of euxinic sediments. ORES: Hot brine pools and metalliferous muds are known from several sites in the axial zone (largest: Atlantis II deep, 1.7 Mt Zn). Numerous fault-controlled fluorite, minor Pb-Zn vein and Pb-Zn carbonate replacement deposits, are along the margin of the Sea, in Neogene sediments or PCm basement. Coleman (1974); Degens and Ross, eds. (1969); Mitchell and Garson (1981).

Bekaa, Dead Sea, Wadi Arabah rift valley

A N.N.E.-trending continental extensional graben, 360 km long and 5-20 km wide, filled by up to 10 km of Oligocene to Recent sediments (fluvial, lacustrine) and some basalt flows. Up to 4 km of evaporites. ORES: small infiltration occurrences of Cu silicates and carbonates and Mn oxides. Bender (1975)

Mongolia, Baikal, Yakutia rift system, Siberia

A chain of assymetrical grabens and horsts, 2,500 km long and up to 300 km wide. The grabens are filled by up to 5 km of Ol-Q alluvial, paludal and lacustrine sediments and minor olivine basalt and trachybasalt flows. ORES: Minor Mn oxide nodules on Lake Baikal floor. Florensov (1966).

Rhine Graben

An Eocene to Quaternary seismically still active graben, 300 km long and 36 km wide, flanked and underlain by Hercynian crystalline blocks. Filled by continental sediments, minor flood basalts, centres of alkaline volcanism and intrusive activity including rare carbonatite (Kaiserstuhl). ORES: Small pyrochlore deposit in Kaiserstuhl carbonatite. Illies and Mueller, eds. (1970).

Gulf of California, Imperial Valley

(Transitional to oceanic spreading ridges and transform fault systems).

Succession of closed marine basins separated by fault scarps in continuation of the East Pacific spreading ridge. Deltaic to normal marine sediments, euxinic muds, diatomites. Arid continental sediments on land, minor rhyolite plugs and obsidian. ORES: Salton Sea, metalliferous hot brines in depth, geothermal area. Subaqueous present hydrothermal activity in Guaymas Basin with Fe,Cu,Zn sulphide mounds. The bedded Neogene Boleo (Santa Rosalia) deposit is considered by some to be related to the initial stage of the rifting. Byrne and Emery (1960), Sawkins (1984).

PRE-TERTIARY PALEORIFTS (INCLUDING AULACOGENES)

Newark Trough, eastern North America

A Triassic system of N.E. faults and grabens up to 100 km wide, traceable from Nova Scotia to the subsurface of Florida. Filled by red-beds continental fluvial and piedmont fan sediments, minor flood basalts, diabase and gabbro dikes. ORES: Numerous small occurrences of "red beds" Cu infiltrations in sandstones, traces of U, Mn. Significant skarn and replacement magnetite and Co-pyrite at limestone/diabase contacts (e.g. Cornwall). Burke (1977).

Oslo Graben, Norway

Remnants of a Permian graben formed within a Proterozoic basement and lower Paleozoic platformic sediments. The structure is almost entirely filled by Permian flood basalts and syenite, monzonite, granite subvolcanic and epizonal intrusive complexes (typical are circular cauldrons). Minor alkaline intrusive rocks. ORES: large number of small ore occurrences associated with the granites and syenites (Bordvika, Drammen: stockwork Mo; small magnetite skarns and Zn-Pb replacements in limestones; Pb-Zn veins) and with marginal faults and diabase or gabbro dikes (Kongsberg Ag veins). Vokes (1973).

Pripyat'-Donetsk aulacogene (south-western U.S.S.R.)

A graben system over 1,000 km long, up to 100 km wide, established in Devonian, active till Mesozoic. Filled by a sequence of Pe-Cb red beds and coal association 5-12 km thick and intruded by minor Jurassic intrusive stocks, alkaline dikes and lamprophyres. ORES: Minor "red beds Cu" deposits in reduced sandstones, lesser Pb-Zn in shales and sandstones. Cu,Pb,Zn,Ag veins (Nagolnyi Kryazh) affiliated with Mesozoic intrusive activity and so is probably the fault-controlled Nikitovka cinnabar deposit (cinnabar hosted by Pe-Cb sandstone, shale and coal. Novikova (1964).

Pachelma aulacogen, southern Russia

This is located between Voronezh and Volga-Uralian Massifs. Pt_3 to PZ_1 red-beds sequence including continental sandstones, red dolomite, marls, black argillites, minor basaltic tuffs. Buried under younger sediments of the Russian Platform. ORES: Substantial stratiform accumulations of Ti-magnetite in tuffs and reworked mafic tuffs in the Yastrebovsk Horizon (near Nizhnyi Mamon); Cu-Ni "sandstone" impregnations. Novikova (1964).

St.Lawrence River Rift and Ottawa-Bonnecherre Graben, E.Canada

E.-W.-trending broad area of updoming, interrupted by several graben systems in the Precambrian basement. Mainly Cretaceous, but still seismically active. Little Mesozoic sedimentation, but scattered Cretaceous small alkaline intrusive centers; largest: Monterregian Hills) dominated by nepheline syenite varieties. Minor carbonatites. ORES: Oka and St.Honoré pyrochlore carbonatite mined; probable Pb-Zn and barite, fluorite veins. Kumarapeli and Saull (1966).

Benue-Abakaliki Trough, Niger Delta, Africa

N.E.-trending graben system developed on PCm crystalline basement. The basal Cretaceous suite up to 7 km thick formed in an "aulacogene" and consists of a folded shale and arkose fill. This is topped by up to 4 km of Cr3-Eo ordinary marine quartz arenite and shale. Minor mafic volcanics. ORES: Pb-Zn veins and replacements in the Zurak-Abakaliki belt. Burke (1977).

Mississippi Embayment, south-central United States

N.E.-trending complex of subparallel narrow horsts and grabens within Paleozoic platformic sediments and their Precambrian basement. Transgressively overlain by Cretaceous and younger nearshore detrital sediments of the Gulf Plain. Minor alkaline intrusions (dikes, diatremes; e.g. Hicks Dome). ORES: Fluorite, lesser barite, Zn-Pb veins in the Illinois-Kentucky district; minor REE occurrences in diatremes.

→

Fig. 30-9. Rifts and related structures of the earth, showing principal localities treated in Table 30-3.

1=epiplatform arch, volcanic rift zones; 2=epiplatform crevice-like rift zones; 3=epeirogenic rift zones and belts; 4=intercontinental rift zones; 5=mid oceanic ridges with axial rift valleys; 6=as 5 but without rift valleys; 7=mid oceanic ridges with important volcanism; 8=large scale faults active in T. Paleorifts: 9=MZ_3 and T; 10=MZ_1; 11=PZ; 12=Pt_3; 13=areas of T volcanism outside of alpine orogenic belts; 14=zones of T epiplatform orogenesis; 15=Q deep sea troughs; 16=Q "geosynclines"; 17=zones of T folding; 18=zones of MZ folding; 19=zones of PZ folding; 20=zones of Pt_3 folding and regeneration; 21=pre-Pt_3 platforms; 22=oceanic floor with sub-oceanic crust; 23=deep sea depressions with sub-continental crust; 24=oceanic basins with oceanic type crust.

LOCALITIES: BR=Baikal Rift; BT=Benue Trough; DA=Pripyat'-Donetsk Aulacogene; DS=Bekaa, Dead Sea, Wadi Arabah; EAR=East African Rift; GA=Gulf of Aden; MV=Midland Valley; NT=Newark Trough; OG=Oslo Graben; OK=Orsha Krestzov Aulacogene; P=Pachelma Aulacogene; RG=Rhine Graben; RS=Red Sea; SL=St. Lawrence Rift; RG=Rhine Graben; RS=Red Sea; SL=St. Lawrence Rift. From Milanovskii (1972), localities added.

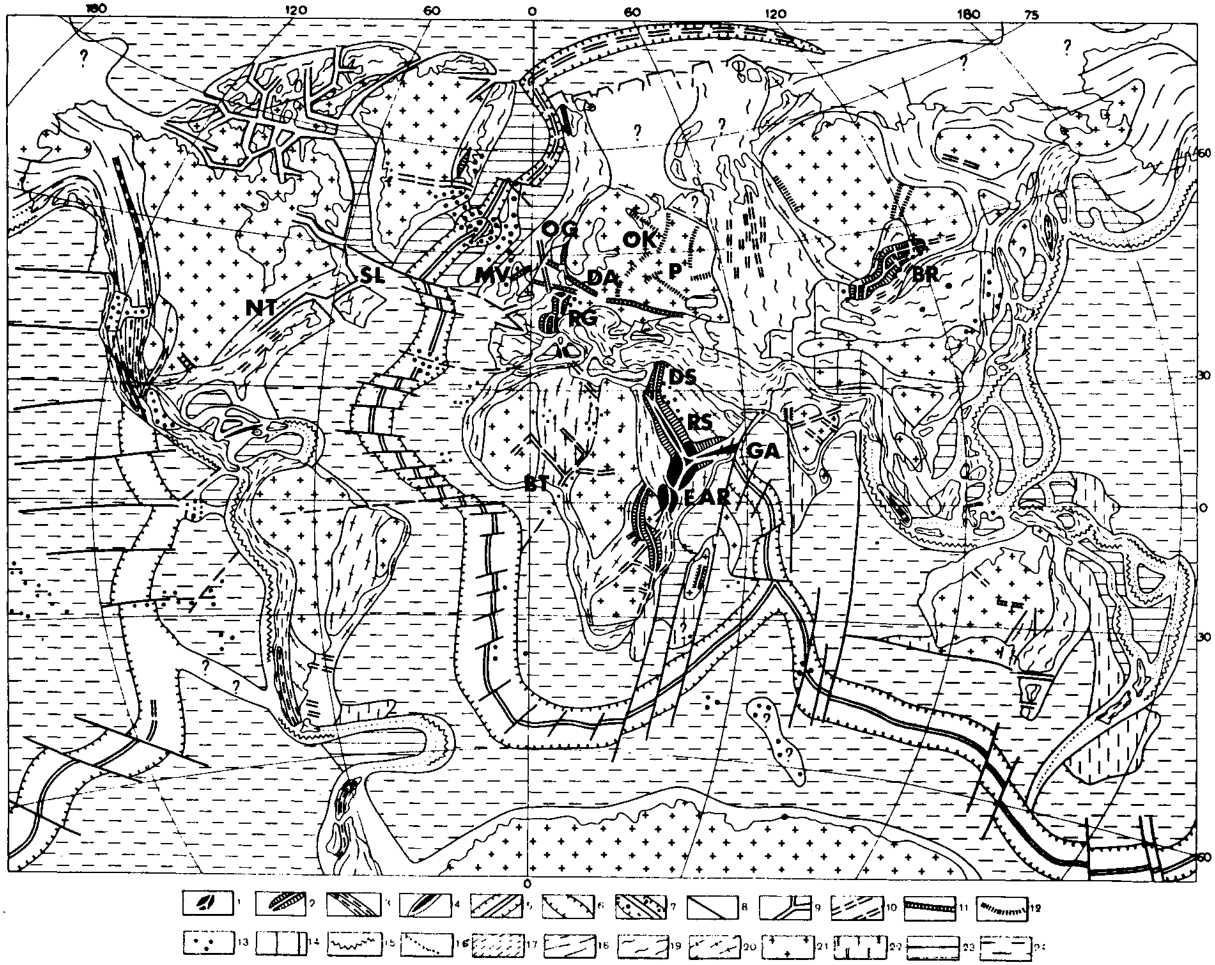

NT
SL
MV
OG
OK
DA
P
RG
DS
RS
GA
EAR
BT
BR

Plate 11. Quaternary continental basalt lava and cinder cones at the Sunset Crater near Flagstaff, Arizona.

"The arrangement of many transitional types (of ore deposits) into the (genetic) system is basically a matter of choice of the individual". Paul Ramdohr in The Ore Minerals and Their Intergrowths, 1969.

CHAPTER 31

Continental Plateau Basalt and Bimodal Volcanic Association

31.1. INTRODUCTION

Basalts are the greatest continental lavas in terms of volume and the majority are tholeiitic (that is, predominantly plagioclase-clinopyroxene, minor olivine, spinel, ilmenite, magnetite assemblages (Carmichael et al., 1974). Gradations to alkali basalts, however, are widespread and sharp distinction between these two series cannot be made in the field. Consequently, alkali basalt provinces are included here, whereas alkaline association (with feldspathoids) is excluded and treated in a separate Chapter 33.

Areally the most widespread and covering areas of up to 1.2 million km^2, are the massive accumulations of subhorizontal, fissure-fed lavas. The thickness of their central portions is typically 1-3 km, but in exceptional cases it reaches 5 or 6 km. These are usually designated as being plateau or flood basalts in the literature. The synonymous term "trap" (or trapp, trap-rock) is widely used in the European, Soviet and Indian literatures. The petrology and petrogenesis of plateau basalts is treated in Carmichael et al. (1974), the volcanology in Williams and McBirney (1979). The Basaltic Volcanism Study Project (1981) provides the most comprehensive summary covering these and other (e.g. geotectonics) subjects. The metallogeny of plateau basalts has mostly been treated in the framework of local areas, and the work of Oleinikov (1979) with the emphasis on metallogeny of the platformic mafic suite of Siberia, is among the most comprehensive. Two major contrasting types of volcanicity are recognized in most plateau basalt regions: (1) fissure eruptions that generate flood-basalt sheets of regional extent, underlain or fringed by feeder dikes or sills and (2) localized eruptions emitted from major central volcanoes (Williams and McBirney, 1979).

The basaltic sheets are composed of individual lava flows which have thickness in metres to tens of metres, and each flow usually shows distinct variation throughout, from massive base and centre through increasingly amygdaloidal upper third to scoriaceous, brecciated and often oxidized (brown in contrast to the green remainder) flowtop. Tops of individual flows often contain lenses or horizons of interflow continental sediments, such as fine brown argillite, siltstone, sandstone and conglomerate. The volcanic sequence near its margin and at the top frequently interfingers with fluvial or lacustrine sediments. Although most plateau basalts have erupted subaerially (and some flowtops are regolithic), subaqueous flows often occur: in subglacial environments, in continental lakes, river valleys, etc., where pillow lavas and/or hyaloclastites may occur. Basalts that have invaded water-saturated sediments (invasive flows of Swanson and Wright, 1981) have a sill-like appearance with glassy upper selvedges, and often grade to pépérites (mixed granular basalt and sediment). Plateau basalts may also grade into submarine flows, which are often pillowed. In large plateau basalt provinces, the lava deposition has often been cyclic (four cycles in the Paraná Basin).

In the subsurface, plateau basalts are represented by mafic dikes, sills, sheets and layered intrusions. Dikes tend to form swarms, usually oriented at right angles to the direction of crustal extension. Sills, where present, may be the immediate precursors of surface eruptions (Baragar, 1977). In Mesozoic plateau basalt provinces, such as the Paraná Basin, a zone of abundant diabase dikes or sills occurs on the flanks of the continuous basalt lava sheet. In many deeply eroded Precambrian regions of the world such as in the crystalline basement of the Canadian Shield, swarms of diabase dikes are present without spatially associated surficial basalts. The regional ratio of diabase sills to basalt flows is, according to Baragar (1977), governed by the quantity and availability of easily intruded sediments at the site of eruption. Where basalt overlies a thick sedimentary sequence, sills emplaced along the bedding planes of sediments are dominant. Where only a thin sediment covers a consolidated basement, flows are abundant and sills negligible.

Layered intrusions may occur at subvolcanic levels of platau basalt provinces and are usually interpreted as being shallow magma chambers. Compared with flood basalts and diabase dikes, such plutons are relatively rare, and only in exceptional instances are consanguinous lavas, dikes and plutons preserved in a single province (such as the Proterozoic Keweenawan basalts and Duluth Complex pair preserved in the Lake Superior region, or the Coppermine basalts and Muskox intrusion pair in northern Canada). More frequently, layered mafic plutons occur separately and the largest recorded example, the Bushveld complex of South Africa, is a classical locality. Even so, virtually all the layered intrusions exposed at present are of Precambrian age, and so have been treated in Volume 2.

The localized (central) eruptions in plateau basalt associations mostly display the characteristics of small cinder cones and low stratovolcanoes that emit lavas and pyroclastics compositionally identical with the flood basalts. The two styles of volcanicity usually overlap. Mafic pyroclastics are particularly common in the Siberian Platform and Deccan Plateau basalt provinces. Contrast differentiated (bimodal, i.e., mafic-felsic) central complexes are rarer, but petrographically and structurally highly variable lavas, pyroclastics and neck facies coexist and some complexes have a compositional range that extends from ultrabasics to rhyolites.

Usually, contrast-differentiated complexes are younger than the main bodies of plateau lava sheets over which they may be superimposed. Alternatively, such complexes may crop out along the plateau basalt fringe. Deep dissection has often exposed the subvolcanic (mafic and felsic dikes) and plutonic (small mafic and felsic stocks and plutons) levels. In deeply eroded ancient terrains the volcanic level is usually missing, and exposed plutons can only occasionally be assigned to a particular plateau basalt cycle.

In many plateau basalt provinces, the latest stages of continental magmatism are alkaline (see Chapter 33). Compared with magmatic complexes of mobile belts, there was very little interaction between the bulk of tholeiitic magmatic rocks and the earlier rock suites into which they were emplaced, as well as among volcanic flows and the contemporary overlapping sediments (when the latter are present at all). There are, however, exceptions many of which are associated with important metallic mineralizations.

Continental tholeiitic association emplaced into continental crust ranges in age from Archean to Recent (Baragar, 1977), and although the orthomagmatic conditions and characteristics of the association changed only slightly due to evolution, the colour and general appearance of the lavas changed as a consequence of ageing (diagenesis) and burial metamorphism, generally from gray in the recent basalts to green in the ancient ones. Because the present field appearance is of fundamental importance in the practical fieldwork, and because several important mineralizations in the supracrustal members appear to be controlled by post-depositional events, the colour of the basalts was taken into account in the subdivision that follows. The colour is usually proportional to the geological age.

31.2. GEOTECTONIC SETTING AND ORIGIN

Continental tholeiites are said to be the characteristic volcanics of the stable crust (cratons, platforms; Baragar, 1977). However, all occurrences of plateau basalts and their deeper-seated feeders or equivalents, are also associated with distention of the continental crust (taphrogenesis). In this way fissures were generated along which magma from the subcrustal region ascended. The degree of distention varies greatly, from tenths to several tens of percent of the original area. Large plateau basalt or diabase dike provinces correlate with major events of continental break-up. Generally, one can distinguish intracratonic provinces (such as the Paraná and Karoo Basins), and continental margin provinces (the Brito-Arctic Province, Atlantic coast of Brazil). Small plateau-basalt provinces are frequently linear and often discontinuous. They are controlled by grabens or "aulacogens" (i.e., failed rifts), superimposed on cratons. Comparable provinces also formed by taphrogenesis during the closing stages of orogenic belts development. These are mentioned briefly in Chapter 26.

Tholeiitic magma is believed to have been derived from the upper mantle, by partial melting above mantle plumes and plume-ridges (Baragar, 1977). This was followed in many cases by fractional crystallization in small magmatic chambers within the continental crust. Most continental tholeiites show signs of crustal contamination (Carmichael et al., 1974), and they are generally distinguishable from the "geosynclinal" volcanics by a higher content of "incompatible" elements.

31.3. ORE DISTRIBUTION AND ECONOMIC IMPORTANCE

The continental plateau basalt association has a typically "platformic" characteristic of distribution of metallic deposits. The bulk (over 90%) of the territory composed of subhorizontal lavas and sills is completely devoid of any metallic mineralization (except for the low factor of concentration ores of Al, Fe and Ti generated by tropical weathering). There is, however, significant mineralization confined to small local areas both inside and outside the monotonous lava or sills terrain. The bulk of this mineralization is (1) the product of magmatic differentiation in the feeder or magmatic chamber apparatus in depth (e.g. the Bushveld complex); (2) the product of interaction of intrusions with their environment (e.g.the Noril'sk district, Duluth Complex) and (3) a product of metal-concentrating mobilizations superimposed on the lavas (Keweenaw Peninsula-Cu, bauxites, Fe-ores).

The members of the continental plateau basalt association treated in this chapter contain about 20 Mt Cu, 7-10 Mt Ni, 6 Bt Fe, 30-40 Mt Al (in bauxites) and about 10 Tt Pd+Pt metals, that are distributed in the very few deposits that are economic at present, or are likely to be in the near future. There seems to be a good potential for future, very low-grade metal sources. Figure 31-1 and Table 31-1 summarize the major known mineralization styles.

Continental tholeiites are transitional into oceanic tholeiites (Wilkinson, 1981) and to basalts of the continental margin mobile belts, with which they share many lithogenetic and metallogenetic characteristics (see Chapters 4, 10, 12). Alkaline volcanics and intrusions (Chapter 33) frequently occur in terrains underlain by plateau basalts (Paraná, Deccan, Siberian Platform), in which they are usually geologically younger. Depth equivalents of plateau basalts, diabase or gabbro dikes emplaced into the continental crust and layered complexes of the Bushveld style, are treated in Chapters 32 and in Volume 2. Tholeiitic basalts located in narrow, linear, tectonic grabens within cratons (Chapter 26) are treated separately and so are the minor occurrences of basalts in the predominantly sedimentary sequences, for example the "red-beds" (Chapter 25).

31.4. MAJOR SUB-ASSOCIATIONS AND THEIR METALLIC ORES

31.4.1. Cainozoic (dominantly "gray") plateau basalts

The archetype of the young plateau basalts is a medium to dark gray, fine crystalline to aphanitic massive basalt, that occurs as subhorizontal flows which display characteristic columnar jointing. Small olivine phenocrysts are sometimes megascopically recognizable. At least 75% of the outcrop in plateau basalt provinces is composed of this extremely monotonous rock, ignored by exploration geologists for its apparently complete lack of mineralization potential. The most common other structural or textural variation of plateau basalts encountered in the field are the vuggy, scoriaceous and brecciated basalts of lava flowtops, and the cinders, scoria and spatter of the central vents. Many of the porous rocks listed above are oxidized (red). The pores remain unfilled. Some flows are covered by, or interbedded with, continental sediments.

Deep (several km) burial caused diagenetic or metamorphogenic migration of the mobile components and healing of the pores by calcite, zeolites, or silica. Walker (1960) demonstrated the correlation between pore filling minerals in basalts and the depth of burial, in Iceland.

METAL GEOCHEMISTRY AND METALLOGENY

Common tholeiitic lavas (and magmas) are enriched in the "basaltophile" trace metals to an extent, several orders of magnitude greater than the crustal average (Cr, 200-500 ppm, Ni: 70-300 ppm, Co: 30-50 ppm, Cu: 70-200 ppm). In olivine-rich rocks (olivine basalts that are most common near the base of thick sequences of tholeiitic flows, picritic basalts and picrites), the Cr, Ni and Co content increases further, to reach values of 0.18-0.22% Cr_2O_3 and 0.1-0.12% NiO, as in the Tertiary olivine tholeiites of Baffin Island (Canada) and Swartenhuk (W.Greenland; Clarke, 1977). The unusually high magnesium content and low proportion of incompatible elements-containing lavas in the Baffin-Western Greenland Province are exceptional among the Cainozoic basalts. They are considered by Clarke (1977) to be examples of unmodified (primitive) partial melts of the mantle, comparable with komatiites.

Alkali basalt lavas have appreciably lower trace Cr,Ni,Co and Cu contents (clarke to sub-clarke values). They have, however, slightly super-clarke contents of Al (12-20% Al_2O_3), Fe (10-15% Fe oxides) and Ti (1.0-3.5% TiO_2), but are low in sulphur. At the volcanic (near-surface) level, and during the magmatic stage, processes or agents of further concentration of the geochemically enriched metals are almost lacking, and consequently metallic deposits do not form. Rare, uneconomic metallic occurrences in basalts such as the emery (ie., a physical mixture of granular corundum and magnetite with minor hercynite and rutile) showing near Quirindi, N.S.W., Australia, are

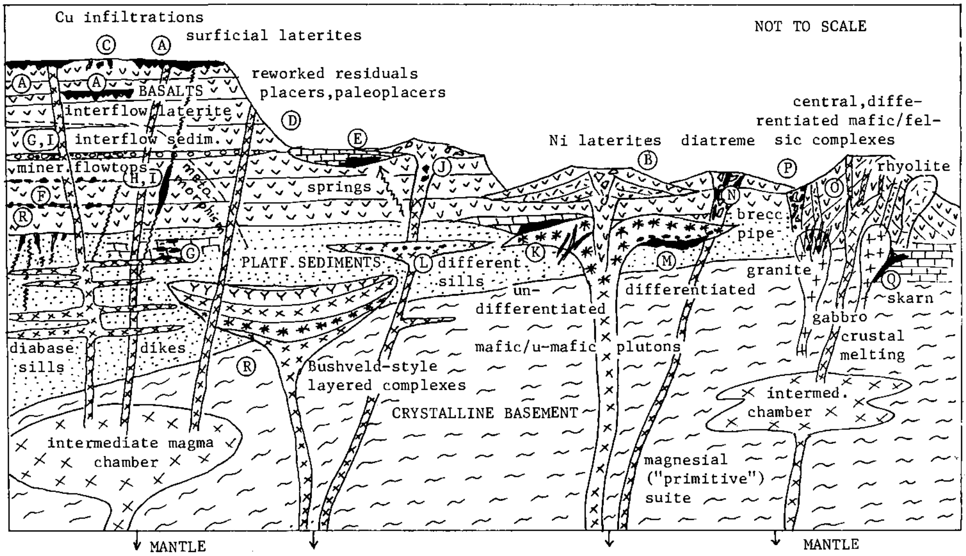


Fig. 31-1. Principal lithologic sub-associations and mineralization styles in the continental plateau basalt and bimodal associations (see Table 31-1 for an explanation of the letter codes). Some of the Precambrian associations and styles treated in Volume 2 are shown.

Table 31-1. Principal mineralization styles in the continental plateau basalt and bimodal associations
NOTE: Precambrian paleo-basalts described in Volume 2 are partly included in this table

	WEATHERING CRUSTS
(A)	residual bauxite and Fe oxides (50 Mt Al, 10 Mt Fe)
(B)	Ni laterites and saprolites formed on picrites, high-Ni olivine gabbros, norites, ultramafics
(C)	Cu silicates, carbonates, oxides, infiltrations in regolithic amygdaloidal metabasalts
	PRODUCTS OF SEDIMENTOGENIC REWORKING
(D)	ilmenite, Ti-magnetite, zircon, etc. in placers and paleoplacers (partly 10 Mt Ti)
(E)	PRECIPITATES FROM HOT SPRINGS DRIVEN BY BASALT HEAT; HYDROTHERMAL REPLACEMENTS (e.g. El Bahariya; controversial)
	GREEN (ALTERED) METABASALTS
(F)	native Cu, peneconcordant orebodies in prehnite-pumpellyite alteration assemblage (e.g. Keweenaw Pen.; 3 Mt Cu)

(G)	native Cu in interflow conglomerate, sandstone (Hecla, Calumet; 2.5 Mt Cu)
(H)	native Cu in discordant fissure veins in metabasalts, near flowtops (150 Tt Cu)
(I)	Cu sulphides in veins, breccias, hosted by altered amygdaloidal basalts (100 Tt Cu)
	DIABASE, BASALT, GABBRO DIKES, SILLS, CLOSELY AFFILIATED WITH PLATEAU BASALTS
(J)	native iron, disseminations and lumps in basalt dike, W. Greenland
(K)	magnetite disseminations, veins, stocks in diabase dikes and sills and their contacts (100 Mt Fe)
(L)	disseminated pyrrhotite, pentlandite, chalcopyrite in differentiated mafic sills (50 Tt Ni, Cu)
	DIFFERENTIATED MAFIC INTRUSIONS
(M)	disseminated and massive Ni-Cu sulphides in picritic gabbro-diabases (Noril'sk); about 10 Mt Ni, 15 Mt Cu, Pt,Pd,Au
(N)	magnetite veins, masses in diatremes and vent breccias (e.g. Angara-Ilim); 4 Bt Fe
	FELSIC INTRUSIONS
(O)	porphyry Cu-Mo occurrences in porphyries, granites, granophyres (e.g. Tribag; 200 Tt Cu, Mo; subeconomic)
(P)	sulphides in breccia pipes, breccias (Tribag; 400 Tt Cu)
	INDIRECTLY ASSOCIATED ORES, MISCELLANEOUS
(Q)	magnetite skarns on contacts of granite and limestone in bimodal volcanic-intrusive centres (10 Tt Fe)
(R)	Pb,Zn,Cu,Ag,U, etc., veins, replacements. disseminations in exocontacts of basalt, diabase sills, dikes

exceptional and of controversial origin.

Continental basalts have practically no hydrothermal phase, but they can heat groundwater in the intruded sediments to produce hot springs. These, in turn, are capable of metal leaching and redeposition, if suitable metal sources are locally available. The economically important but genetically controversial Fe-Mn deposit Bahariya in Egypt (hematite, magnetite and Mn oxides replace Tertiary limestone near Miocene plateau basalts; Basta and Amer, 1969), is interpreted in such a manner. Said (1962) gave more examples of Pb-Zn and U ores in Egypt, presumably deposited from hot springs driven by the heat of basaltic volcanism.

Conditions of ore deposition in plateau basalt terrains were presumably more favourable at the subvolcanic and plutonic levels and in load metamorphosed ("green") lavas, but the deeper levels are rarely exposed in the Cainozoic plateau basalts. Minor disseminated native copper occurrences in zeolitized and prehnitized flowtops of Tertiary plateau basalts have been recorded in the Faroe Islands (Cornu in Butler and Burbank, 1929) and malachite fracture coatings in amygdaloidal basalts have been recorded from the Deccan "traps"(Sahasrabudha, 1978).

Supergene processes superimposed on the volcanics remain the only agent responsible for the formation of economic metallic deposits known from Cainozoic tholeiitic and alkali-basalt volcanic terrains. Lateritic bauxites generated by Eocene tropical weathering on the Deccan "traps" in north-western India (states Gujarat and Maharashtra), represent a reserve of some 60-70 Mt. of ore containing from 38% to 63% Al_2O_3. The bauxites, both nodular and massive (blocky) with the relic texture of the source volcanics, favour basaltic pyroclastics (Sahasrabudha, 1978; Fig.31-2).

Over one hundred separate but small deposits of lateritic bauxites with an aggregate tonnage of about 22 Mt. of low-grade ore (35-52% Al_2O_3), are known from eastern Australia (Owen, 1954; Townsend, 1965). The deposits are the residual product of early- to mid-Tertiary humid tropical weathering, superimposed on Paleocene to Eocene alkali basalts. The major gibbsite and minor boehmite bauxites range from a hard, pisolithic variety to earthy bauxites, and most deposits have only recently been exhumed from under the cover of younger Tertiary sediments including coal (Gippsland in Victoria), or from under younger basaltic flows (Tamborine Mt., Inverell-Emmaville, etc.). Comparable fossil residual ferruginous and titaniferous bauxite deposits formed on plateau basalts in Oregon and in northern Ireland (Antrim County). There, gibbsitic bauxite occurs in two lateritic horizons sandwiched between 66-61 m.y. old tholeiitic flows. It is topped locally by an iron oxide-rich crust, mined in the past as an iron ore (Glenravel, 2 Mt. Fe produced Dunham et al., 1978). Several bauxite deposits in northern Ireland formed by residual weathering of rhyolite, obsidian and felsic tuff. 30 Mt of 20% Al bauxitic laterite and saprolite formed over Tertiary basalts on the Jan Mayen Island in the northern Atlantic (Patterson, 1967). The extremely low-grade (10-20% Fe) remnants of Tertiary limonitic pisolithic laterites topping Neogene basalts in the German Vogelsberg, were mined during the World War II emergency.

Weathering resistant and heavy accessory minerals of basalts (ilmenite, Ti-magnetite, zircon) released by weathering and transported by streams, contributed the economic substance to some alluvial and beach heavy mineral placers (e.g. those along the Pacific coast in Queensland and New South Wales).

INDIRECT INFLUENCE OF YOUNG PLATEAU BASALTS ON MELALLOGENY AND EXPLORATION

Cainozoic basalts are usually considered to be a nuisance, because they cover many areas with promising basement mineralizations and inhibit exploration (e.g. in the Victoria Goldfields, Australia; in

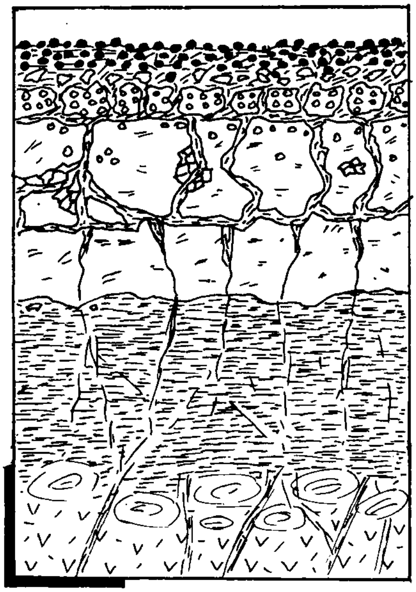


Fig. 31-2. Schematic profile of residual Eocene bauxite developed over plateau basalt tuff, Deccan Plateau, N.W. India. Based on data in Sahasrabudha (1978).

Tasmania; in New England, N.S.W.; in Oregon and Idaho; in central British Columbia and elsewhere). The positive role of the basaltic cover, however, is that of preserving the earlier mineralizations. Many Tertiary and older surficial ores nonresistant to erosion, such as placers (also laterites, gossans and supergene enriched zones over sulphide deposits, infiltration deposits), have been preserved until now thanks only to their burial under the protective cover of Cainozoic volcanics, including plateau basalts. The buried deposits have only been recently exhumed. Examples include many of the "deep lead" gold placers in Victoria; "deep lead" cassiterite placers near Emmaville and Torrington, N.S.W. (Weber, 1974), in the Jos Plateau, Nigeria and elsewhere; infiltration uranium deposits in soft Tertiary conglomerates under basalts near Beaverdell, British Columbia and others (compare Laznicka, 1985f). It may be assumed that many metallic deposits are still buried under Cainozoic basalts.

31.4.2. Pre-Cainozoic (dominantly "green") plateau basalts

Some Cretaceous and Jurassic basalts still remain "gray", but the proportion of gray basalts decreases in geologically older sequences, where they are substituted by the "green" basalt variety (this is often called "melaphyre" or "diabase" in the European literature). The green colour is caused by the partial or full development of metamorphic actinolite (uralite), pumpellyite or chlorite at the expense of pyroxene. The calcic plagioclase tends to be zeolitized, analcitized or albitized. The above changes, essentially hydration at elevated temperatures, can be the consequence of various processes: (1) hydrothermal autometasomatism at the time of the magmatic rock emplacement; (2) hydrothermal metasomatism triggered by the heat of a younger, often felsic, intrusion or (3) hydration and metasomatic recrystallization under the conditions of zeolite to greenschist facies burial (load, regional) or dynamic metamorphism. It is usually difficult to determine accurately the cause of the hydrothermal metasomatism, and several causes may combine.

A hydrothermal metasomatism superimposed on basalts not only caused pseudomorphic changes in the original minerals, but also triggered migration of the mobile components ($CaCO_3$, SiO_2, hydrous silicates), that were gradually filling available spaces: vugs, pores in breccia and scoria or fractures. As a consequence, amygdaloidal basalts, hydrothermal minerals-cemented scorias and breccias, or completely replaced rocks (e.g. Jolly and Smith, 1972), substitute for the initially porous varieties of mafic volcanics. In the flow top region of the dominantly "green" basalts, patches of brown, hematite-pigmented amygdaloids, breccias and scoriaceous basalts frequently occur.

Large Mesozoic intracratonic plateau basalt sheets (Paraná, Karoo, Siberian Platform) are usually located near the top of thick sequences of epiclastic or (bio)chemical sediments-filled basins. There, the volcanics are often interbedded with mature sediments such as quartz arenites, or with carbonates. Interaction of sediments with "green" plateau basalts and associated rocks is more intensive than the similar interaction involving the "gray" basalts, and has important metallogenic implications.

Because of the deeper erosional dissection achieved, at least locally, by the pre-Cainozoic plateau basalts, subvolcanic and plutonic equivalents are more widespread in recent outcrops. In the Siberian Platform, Permo-Triassic deep equivalents of plateau basalts, such as gabbro and dolerite sills, laccoliths and shallow intrusions, are densely distributed in an area surrounding the basalt-filled Tunguzka Basin, and are more voluminous than the basalts themselves (Vilenskii,1967). In Tasmania, Jurassic diabase sills and dikes are the only representatives of the continental tholeiite suite present (McDougall,1962).

METAL GEOCHEMISTRY AND METALLOGENY

The pre-burial metal geochemistry and metallogeny of the "green" basalts are identical with those of the "gray" basalts, described earlier. The hydration and metasomatism of the rock-forming minerals of basalts and particularly the short- to long-distance migration of the mobile components are important for metal concentration. Many trace metals migrate along with the major rock-forming elements. The Proterozoic native copper province of the Keweenaw Peninsula, Michigan (Volume 2), is considered to be a type area of such processes. The native copper deposits are located in altered metabasalt flowtops and in thin sedimentary interbeds. Amstutz (1977) placed the hydration and metal migration event responsible for the formation of Keweenaw ores into the deuteric hydrothermal stage of the host lavas, on the basis of a supposed congruency between mineralogic distribution and primary textures. Smith (1974), working in the same region, associated the hydration and metal migration event with burial metamorphism. Jolly (1974) and Jolly and Smith (1972), presented a rather convincing model of metamorphogenic mobilization of the trace coper in basalts, as a mechanism for the formation of the native copper ores. They demonstrated that the 5,000 m thick pile of tholeiitic lava flows is metamorphically zoned. At the top chlorite (12% H_2O) and pumpellyite (6% H_2O) metadomains formed by hydration of the volcanics, whereas the epidote metadomain at the base (2% H_2O) formed by dehydration. Copper, averaging 70 ppm in the hydrated basalts, was leached and expelled upward from the epidote zone undergoing dehydration. It was then added to the hydrated zone containing pumpellyite, prehnite, laumontite and chlorite. The coper-bearing, sulphur-deficient fluids may have contained up to 2,000 ppm Cu, and a portion of this copper precipitated in "stratabound" permeable zones (scoriaceous and amygdaloidal lava flow tops and interflow conglomerates). The precipitation was facilitated by the presence of impermeable barriers, for example diabase dikes. Numerous variations of the process described above are plausible. Copper ores in sediments associated with "green" basalts could have received their copper from Cu-bearing fluids, released from hydrated basalts. The widespread occurrences of native copper and Cu sulphides in brecciated interflow limestones, adjacent to altered plateau basalts and tuffs in the Arylakh and Kharaelakh areas, Siberian Platform (Dyuzhikov et al., 1976), probably formed in such a way.

The supergene metallogeny of "green" basalts and diabases is comparable with that of the "gray" basalts, at least in the case of bauxites and iron ores. Small residual ferruginous bauxite occurrences formed on basalts of the Paraná Basin and on Devonian basalts in the Central Timan bauxite region, U.S.S.R. The Miocene lateritic ironstone on Paraná basalts in the Misiones district, eastern Argentina (Haude and Weber, 1975), represents 20 Mt ore with 28-35% Fe and up to 4% TiO_2. Numerous but small occurrences of Cu oxides chrysocolla, tenorite, malachite, etc.) hosted by amygdaloidal basalts (as in the Alto Uruguai area, Brazil; Szubert et al., 1981) and interflow felsic conglomerates (e.g.Allouez Mine, Michigan) may, however, have a different origin. They could be the products either of supergene degradation of earlier sulphide or native copper accumulations, or they could be the equivalent of "exotic deposits" in which copper dissolved in groundwater was precipitated by the reaction with silica, possibly released from a volcanic glass undergoing devitrification.

NATIVE COPPER DEPOSITS IN PREHNITE-PUMPELLYITE ALTERED AMYGDALOIDAL AND SCORIACEOUS THOLEIITIC FLOWS AND INTERFLOW SEDIMENTS ("Michigan type")

In the classical copper-producing area of the Keweenaw Peninsula (total production 4.9 m.t.Cu), several hundred copper deposits and occurrences have been mined and described in the monograph by Butler and Burbank (1929). All of them are hosted by the Proterozoic Portage Lake Lava Series, which is a sequence over 5,000 m thick, of several hundred discrete continental flows of low-olivine meta-tholeiite. Between the flows are sandwiched several thin lenses of rhyolite conglomerates. Three fundamental styles of native copper deposits can be distinguished and all have a tabular form: (a) concordant to peneconcordant orebodies in amygdaloidal and scoriaceous lava flowtops (about 58% of the total production; W. S. White, 1968); (b) concordant to peneconcordant orebodies in thin lenses of interflow conglomerates and (c) fissure veins, discordant with the strike of the host amygdaloids. These are described in Volume 2.

Small native copper deposits and occurrences in plateau basalts, comparable with the "Michigan-type", have been recorded from various areas of the world (Table 31-2). In southern Brazil and Uruguay frequent showings are associated with the deposits of amethyst and agate (Jacques and Cassedanne, 1975), but the copper mineralization is always erratic and unpredictable. This tends to support the opinion of many geologists that the "Michigan type" is a poor exploration target. A sharp drop of the cut-off grade of copper ores in the future (to 0.1-0.2% Cu), however, could possibly make economic certain regions (or discrete basalt flows) with a large number of small Cu occurrences, as in the Itapiranga area, Brazil (large reserves of 0.145% Cu ore; Szubert et al., 1981). Comparable native copper occurrences are found in the amygdaloidal and scoriaceous metabasalts of orogenic belts (e.g. Novaya Zemlya, Kamchatka, Yukon, etc; Chapter 10), and basalts that are members of the "volcanic red-beds" association (Chapter 25).

COPPER SULPHIDE DEPOSITS IN LOW-GRADE ALTERED THOLEIITIC AMYGDALOIDS

Minor calcite-chalcocite seams and stringers that crosscut the native copper-bearing amygdaloids, are relatively common in the Keweenaw Peninsula district (Volume 2). A more significant mineralization that is predominantly sulphide in nature (chalcocite and minor digenite, bornite, chalcopyrite and pyrite in quartz, chlorite, epidote and calcice gangue), was recently described from Mt.Bohemia (M. Robertson, 1975). The ore is hosted by concordant amygdaloids, as well as by discordant andesite dikes. Rich, massive

Table 31-2. Selected localities of native copper mineralization in plateau (meta)basalts*

LOCALITY	AGE	MINERALIZATION	REFERENCES
Kharaelakh Mts., Sukhariki Basin, N.W. Siberia, U.S.S.R.	Pe-Tr	XO occurrences of nat.copper in amygd.basalts, lava breccias, tuffs, and tuffac.sedimentary interbeds (particularly limestones). Peneconc. bodies to veins; 0.2-4.45% Cu, up to 163 ppm Ag	Dyuzhikov et al. (1976)
Serra Geral Fm., Paraná Basin, S.Brazil (e.g. Itapiranga)	J-Cr	pod-like patches of chrysocolla, malachite, nat.copper, chalcocite in amygdaloidal and brecciated basalt flowtops	Szubert et al., (1981); Jacques and Cassedanne (1975)
Orozimbo Fm., Maranhão Basin, N.E.Brazil (e.g. Grajau)	J-Cr	native Cu or Cu-sulphide occurrences in amygdaloidal basalts, assoc.with zeolites, chlorite, prehnite, amethyst	Abreu (1973) Nunes et al. (1973)

* Precambrian native copper occurrences are treated in Volume 2; occurrences in mobile belt basalts (e.g. Buena Esperanza, Chile; the Philippines; etc.) are in Chapters 10,12,13.

chalcocite fissure veins and low-grade disseminations of chalcocite in a meta-basalt dike, have been mined near Mamainse Point on the Ontario (northern) shore of Lake Superior. The host rocks and ores are of the same age as the native copper deposits in Michigan (Keweenawan). Widespread showings of chalcocite and secondary Cu minerals have been recorded in the Cambrian Antrim Plateau amygdaloidal basalts of northern Australia (North. Territ. Geol. Surv., 1975).

The presence of felsic subvolcanic intrusions and plutons postdating the plateau basalts is common to both the areas mentioned above, and there is probably a genetic connection. The intrusions could have provided the heat and possibly sulphur, while the basalts provided the copper. These mineralizations are thus transitional into those more intimately related to the felsic intrusions often located along the fringe of plateau basalts and are described later.

31.4.3. Diabase feeders to plateau basalt

Diabase (dolerite) dikes and sills represent the subvolcanic equivalent of plateau basalts, to which they are compositionally identical. The dikes fill tensional fractures, and swarms of hundreds of dikes (most are several tens of metres wide, but some extend 100 to 300 m) are a convincing indication to the degree of crustal extension achieved in the magmatic period. The bulk of diabase (dolerite) dikes and sills are petrographically extremely monotonous and homogeneous, even more so than the plateau basalts. Thermal metamorphism and metasomatism at dikes and sills contacts is usually limited and inconspicuous, restricted to zones of baking and hornfelsing a few centimetres wide. They are apparent chiefly in sedimentary exocontacts.

The pre-Cainozoic diabases are green, containing partly or fully uralitized pyroxene. Mobile components released during deuteric or metamorphogenic mobilization fill fractures that are fairly common. White, coarse calcite is an almost universal fracture filling mineral. White or pink laumontite (zeolite) fracture coating, quartz, pyrite and prehnite veins also occur frequently. Calcite veins with asphalt-filled vugs are abundant near Rio Claro (São Paulo, Brazil), near diabase contacts with Permian oil shales.

The following examples of economically unimportant metallic occurrences have been recorded from diabase dikes intimately associated with plateau basalts:

(a) local pegmatitic schlieren that could contain coarse bunches of ilmenite;

(b) small-size inhomogeneities (schlieren, veinlets) within the diabase, or thin quartz or calcite veinlets reaching into the wallrocks, that could carry minor chalcopyrite in the form of scattered grains;

(c) small concentrations of magnetite, for example in fractures. These can grade into magnetite stockworks or thick veins in faulted or sheared diabase or in the adjacent supracrustal rocks, as in the

Tunguska Basin, Siberia (Pavlov,1960) and
(d) rare occurrences of native iron in disseminated grains and occassional boulders of controversial origin, recorded from western Greenland (Disko Island, Kitdlit; Fundal, 1975).

Massive replacement bodies of magnetite in reactive sediments (carbonates) adjacent to diabase sills as in the Severnaya River field, N.W.Siberia (Pavlov, 1960; Fig.21-3) is one of the few economic ore styles, directly associated with diabases. Tropically weathered diabases, like basalts, can yield ferruginous lateritic bauxites (e.g. at Ouse, Tasmania, where 15 small deposits of clayey bauxite contain 703,500 t ore with 40.4% Al_2O_3; Owen, 1954). Residual ilmenite or Ti magnetite reworked from argillized or lateritized diabases could accumulate in alluvial and beach placers (as along the Atlantic coast of south-eastern Brazil) and in paleoplacers.

31.4.4. Differentiated tholeiitic sills

Carmichael et al. (1974, p.437-451) provided an adequate description of tholeiitic diabase and gabbro sills from the petrological point of view. Many individual sills are over 300 m thick and traceable for tens of kilometres. They formed by injection of tholeiitic magma at liquidus temperatures into undisturbed sediments, or along unconformities. The thick sills tend to be gravity-differentiated, but the differentiation is chiefly expressed by variation of the mafic index only. Few sills have granophyric tops (e.g.Hamilton, 1965), and the olivine-rich (picritic, troctolitic) basal members are even less common. The latter, however, are the only sills that interest the exploration geologist directly, because some of them may carry small quantities of nickel sulphides and platinoids.

Differentiated sills are transitional into Bushveld-style layered mafic intrusions, and have some points in common with the Noril'sk-style differentiated mafic plutons described later. The most frequently quoted example of nickel-mineralized tholeiitic sill (intrusion) is the Mesozoic Insizwa sill (Nolagoni Massif, Mt.Ayliff district, Transkei, Southern Africa; Dowsett and Reid, 1967; Scholtz, 1936). It is a subvolcanic equivalent of the Karoo plateau basalts, represented by an undulating gabbroic sheet, up to 600 m thick, injected into Karoo sediments. Three main petrological zones can be recognized: (a) basal zone, consisting largely of picrite, troctolite and olivine hyperite; (b) central zone, composed of gabbro and (c) roof zone, that contains the felsic phase (granophyre) of the intrusion. Subeconomic, massive and disseminated Ni-Cu sulphide mineralization (pyrrhotite, pentlandite, chalcopyrite and cubanite with small quantities of Au,Ag and Pt metals) at Waterfall Gorge, is confined to the ultramafic members in the Basal zone and to the hybrid footwall contact. This locality has been considered to represent a classic example of magmatic ore formation by differential segregation and gravitational settling.

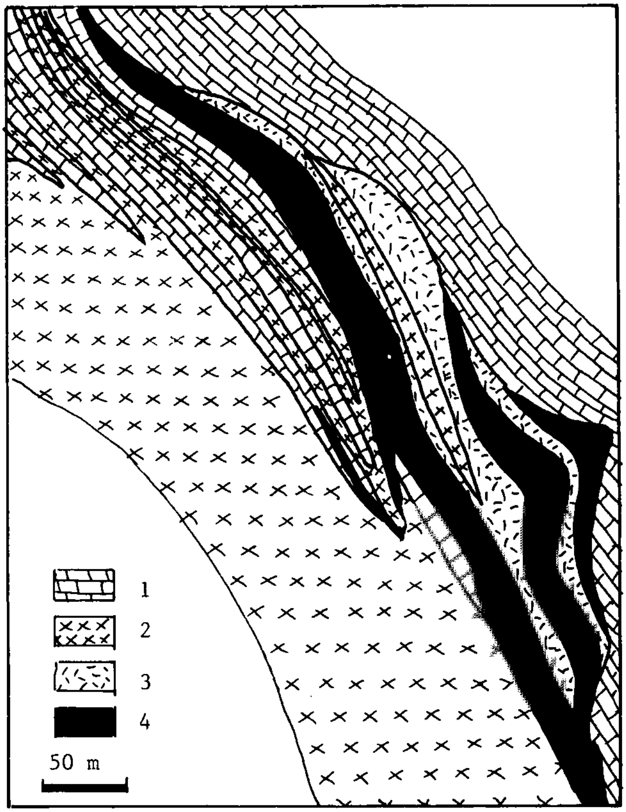


Fig. 31-3. Severnaya River iron field, N.W. Siberia, a contact metasomatic magnetite mineralization related to Pe-Tr gabbro-diabase sills. 1=Or marbles; 2=Pe-Tr sills of uralitized gabbrodiabase; 3=skarn; 4=magnetite. After Pavlov (1960).

Ni-Cu sulphide mineralization of the "Kureika-type" associated with diabase-troctolite sills (intrusions), is a member of the Permo-Triassic plateau basalt and diabase association of the Siberian Platform (Rundkvist, ed., 1978). The ore minerals in the Kureika showings (pyrrhotite, chalcopyrite, pentlandite, minor millerite, pyrite) are disseminated in olivine-rich layers distributed throughout the intrusion, but are most extensive in the middle and upper layers. Rich sulphide schlieren occur sporadically in the central parts of the disseminated ore horizons.

31.4.5. Central, explosive volcanic-intrusive complexes and the mafic-felsic bimodal suite

Tertiary central volcanic-intrusive complexes associated with the continental plateau basalt activity and usually younger than the earlier phase of fissure basalt eruptions, are known to exist in various parts of the world. The Brito-Arctic Province is considered to be a classical area, and differentiated central complexes have been described in the Scottish Hebrides (Mull, Skye, Ardnamurchan; Richey et al., 1961), in northern Ireland (Slieve Gullion Complex, Carlingford Volcano; Preston, 1981) and from Iceland (Breiddalur Volcano, Walker, 1963; Thingmuli Volcano, Carmichael, 1964). Other Tertiary occurrences are situated in South Yemen (Greenwood and Bleackley, 1967) and elsewhere. Pre-Tertiary central complexes suffer from fragmentary preservation.

A petrologically characteristic feature of most central complexes is the presence of abundant felsic members associated with basalts. The lack of intermediate members results in a distinct bimodal mafic-felsic suite. At the volcanic level, tholeiitic to alkali basalt lavas and pyroclastics represent the mafic mode, whereas trachyte and rhyolite lava domes, breccias, agglomerates and tuffs are members of the felsic mode. The latter have a tendency to accumulate in the core of volcanoes. At the subvolcanic and plutonic levels, diabase and gabbro dikes, stocks and plutons are dominant, and felsites, granophyre, quartz feldspar and feldspar porphyry, syenite and minor granite, are subordinate. Highly hybrid sections have occassionally resulted from the mixing of acid and mafic members in intrusive stocks under some central volcanoes (e.g.in Asturhorn, S.E. Iceland).

The lithologic complexity, the presence of vents and the frequent interaction of mafic and felsic members of central complexes (such as in the cone-sheet dominated Central Mull and Ardnamurchan, Scotland; compare the maps and sections in Richey et al., 1961) makes these centres favourable for ore deposition, but very few ore occurrences have actually been found. The small magnetite orebody located in skarn in the Skye (Scotland) volcanic centre is one of them. Small pipe and ribbon-like bodies of magnetite with minor Cu,Zn and Pb sulphides developed on contact of a small granite stock, and Cambro-Ordovician limestone. Only a few thousand tons of about 40% Fe ore have been mined (Dunham et al., 1978).

The scarcity of mineralization is probably due to the general lack of hydrothermal alteration. Propylitic alteration has been described by Walker (1963) from the core of the Breiddalur paleovolcano in S.E. Iceland, and although no mineralization has been reported from this particular locality, numerous small Cu and Cu-Mo showings and geochemical anomalies have been reported from S.E.Iceland, particularly from the Höfn area. The best-known occurrences described by Janković (1972) are those in the Ossura River zone, near Svinhöler farm (Fig. 31-4). There, chalcopyrite and minor galena and sphalerite occur in blebs and disseminations in a breccia pipe composed of fragments of rhyolite and basalt. The pipe was emplaced into Tertiary plateau basalt flows. Small copper sulphide occurrences are relatively common in felsic volcanics associated with pre-Tertiary plateau basalts (for example, in the Indian Mine, Michigan; Butler and Burbank, 1929), but economically important occurrences are, so far, lacking.

31.4.6. Small differentiated mafic plutons : Noril'sk-style

The discovery and development of the Noril'sk-Talnakh district of Siberia (the second largest accumulation of sulphide Ni and third largest accumulation of platinoids of the world), focussed attention on its setting and the nature of its host rocks. Over one thousand citations dealing with Noril'sk are now available, both in the Russian original (e.g.Zolotukhin and Vilenskii,1978; Sobolev et al., 1978; Urvantsev et al., 1975; Dobin et al., 1971) and in English translations (e.g.Glazkovsky et al., 1974; Ivankin et al., 1971; Tarasov, 1968).

The Noril'sk-Talnakh ore district and several tens of showings (about 40 known Ni-Cu sulphide occurrences) are located near the

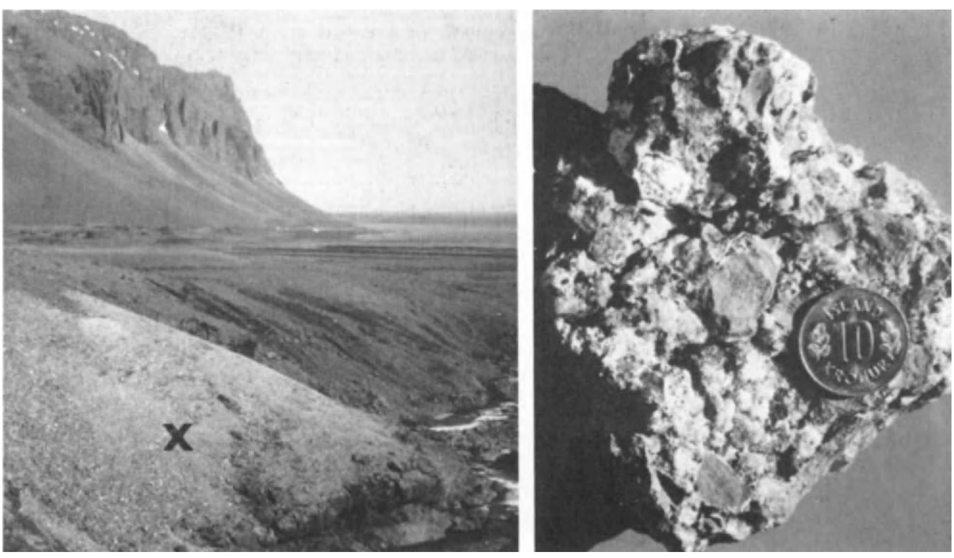


Fig. 31-4. Chalcopyrite-mineralized breccia pipe in Tertiary rhyolite (left, X) at Ossura River, S.E. Iceland. Chalcopyrite with quartz is located in the matrix and in vugs interstitial to rhyolite fragments (right).

north-western margin of the Siberian Platform, in a region of numerous N.N.E. and N.E. deep faults and lineaments (see the description of the Siberian Platform later). There, the Proterozoic basement is overlain by an Ordovician to Permian sequence of platformic sediments, that includes Devonian evaporite unit (anhydrite, gypsum, halite, carbonates) and a Permo-Carboniferous coal-bearing unit. These units occur in the immediate vicinity of the sulphide mineralization.

The plateau basalt volcanism commenced in the Permian period and continued through the Triassic period. The second, Triassic phase of central mafic explosive volcanism, produced several hundred paleovolcanoes and their subvolcanic-plutonic equivalents. In the Noril'sk area, the volcanics fill series of elliptical basins, subdivided by basement highs (Fig. 31-5). Most of the mafic plutons crop out in the "highs" and intrude the Paleozoic sediments. The majority have a simple gabbro-diabase composition and are undifferentiated. Only about 1% of the intrusions are differentiated, and even here the differentiation is, at most, within the gabbro-diorite to troctolite range. Felsic differentiates are rare and separate bodies of ultramafics are not known. The ore-bearing intrusions are usually elongated, some 100-300 m thick, peneconcordant with the enclosing sediments or mafic lavas. They are members of the high-magnesium, evolutionarily primitive suite and the olivine-rich members have a high trace Ni content (0.11-0.2% Ni).

In the ore-bearing intrusions (Figures 31-5 and 31-6), the ore minerals pyrrhotite, pentlandite, chalcopyrite, bornite, cubanite and numerous rare Ni,Cu, Pt-Pd, Bi,Sb,Te, etc., minerals occur as: (1) low-grade (0.4-0.8% Ni) disseminations in troctolites and gabbro-diabases or norites ("taxites") in the basal endocontact of the intrusion; (2) massive and brecia-cementing ores along the footwall contact or (3) veinlet and stringer ores in altered Paleozoic footwall metasediments (Fig. 31-7). The orebodies, particularly those in the exocontact, are accompanied by intense hydrothermal and contact metamorphic alteration. The dominant and most widespread alteration is albitization (in sandstones and gabbros), skarnization in carbonates, hornfelsing in shales, and local biotitization in gabbros. Scapolitization occurs locally. Chloritization occurs on the fringe and along faults.

The Noril'sk-Talnakh district supplies 67% of the Soviet nickel production, and is credited with a minimum production and reserves of abut 5.5 million tons of Ni in ores with an average grade 0.5% Ni and 0.8% Cu. The richer ores have 1.23% Ni, 2.16% Cu, 0.1% Co, 11 ppm Pd+Pt and some Au,Ag and Te (Wagner and Berthold, 1979). The actual regional potential is probably several times higher, of the order of 10-15 Mt Ni.

The recent Soviet monographs quoted earlier present lists of criteria used to estimate the nickel potential of the Siberian "differentiated trap intrusions", which include: (1) association of intrusions with deep faults; (2) abundance of endo- and exocontact metasomatites, including skarns; (3) abundance of picritic basalts and subalkaline traps in associated volcanics; (4) presence of

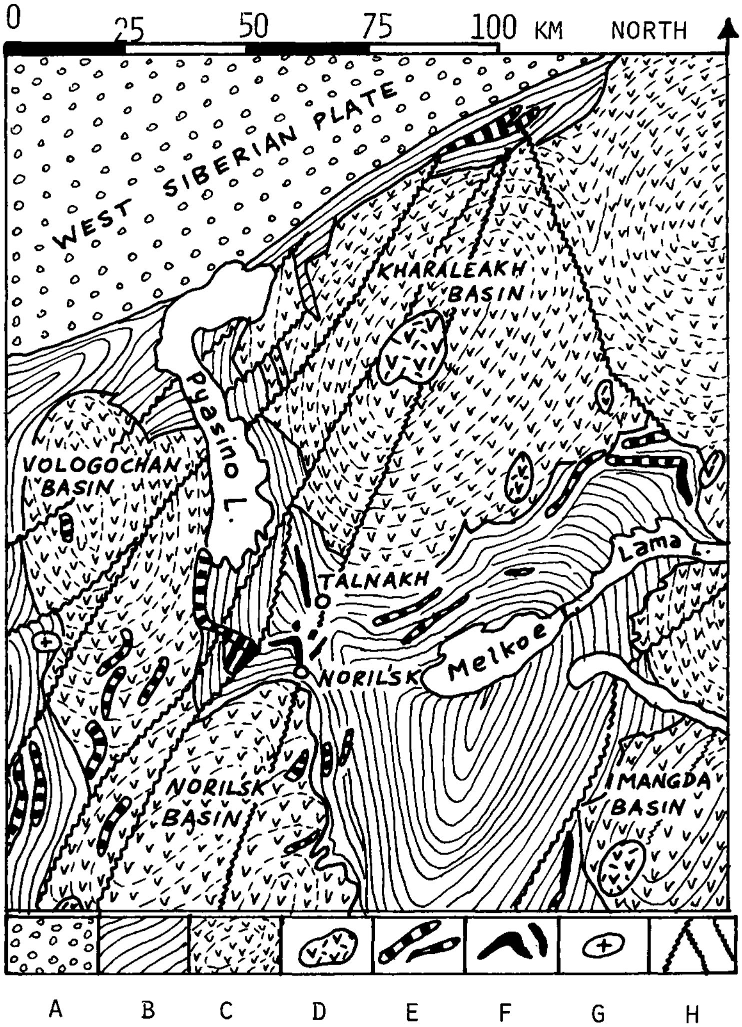


Fig. 31-5. Noril'sk-Talnakh Ni,Cu,Pt district, N.W. margin of Tunguska Basin, Siberian Platform, U.S.S.R.

A=MZ sediments of the West Siberian Plate; B=Pt_3 to Pe platformic sediments; C=Pe_3-Tr_1 plateau basalts-filled basins, isopachs are shown; D=volcanic centres; E=Pe-Tr undifferentiated mafic intrusions (diabases); F=Pe-Tr differentiated and Ni-Cu bearing mafic intrusions; G=granite porphyry intrusion; H=faults.

Modified after Akad. Nauk S.S.S.R., "Sul'fidnye medno-nikelevye rudy Noril'skikh mestorozhdenii", Nauka, Moscow, 1981.

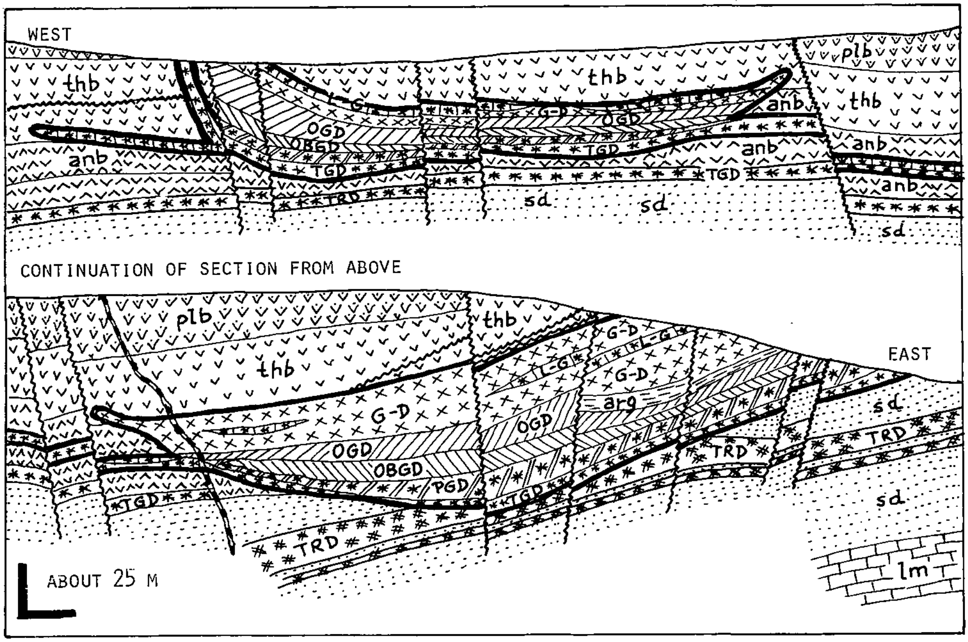


Fig. 31-6. Geological cross section of the Noril'sk I differentiated mafic intrusion (outlined by solid black line). D contact metamorphosed and altered sediments: lm=limestone; sd=sandstone; Tr_1 basaltic volcanics: plb=plagioclase basalt; thb=tholeiitic basalt; anb=andesitic basalt; Tr_1 plutonic members of the Noril'sk intrusion: TRD=trachydolerite; G-D=gabbrodiorite; LG=leucocratic gabbro; PGD, PD=picritic gabbrodiabase and diabase; OGD=olivine gabbrodiabase; OBGD=olivine biotite gabbrodolerite; TGD=taxitic gabbrodolerite. After Dobin et al. (1971).

anhydrite and/or gypsum in the exocontact sediments; (5) presence of taxitic (i.e., those with inhomogeneous texture) gabbro-dolerites; (6) presence of felsic hybrid rocks in the roof of intrusions as well as a series of petrochemical criteria.

So far, the unique "Noril'sk-style" of mineralized mafic intrusions has not been found outside the Siberian Platform. Most points of similarity with Noril'sk outside the U.S.S.R. can be found at several localities in the Thulean and Baffin Island-West Greenland Provinces, where some central volcanic-intrusive complexes are associated with high-nickel picritic lavas. Differentiated ultramafic to felsic intrusions on the fringe of the Paraná Basin in Brazil (e.g. the Cretaceous Iporá Group intrusions in Goiás; Guimarães et al., 1968), resemble Noril'sk in some respects. They have a silicate-based nickel-rich early ultramafic phase (dunite), followed by a felsic or mafic to felsic alkaline suite. In this regard, the Iporá magmatites

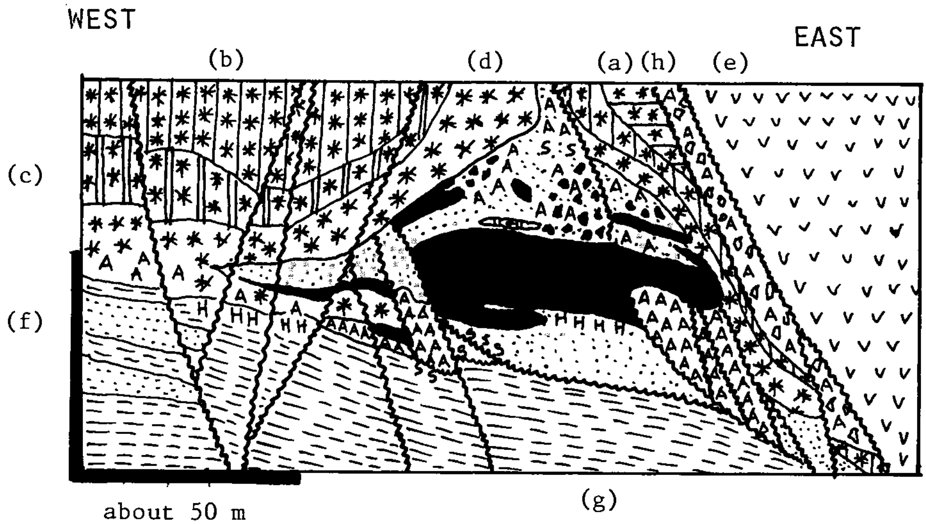


Fig. 31-7. Detailed section across the zone of exocontact Ni-Cu sulphide mineralization; northern ore shoot in the S.W. portion of the Talnakh ore deposit. a=olivine gabbrodiabase; b=picritic gabbrodiabase; c=troctolitic gabbrodiabase; d=taxitic and contact gabbrodiabase; a-d are members of Tr_1 Talnakh Intrusion. e=Pe-Tr plateau basalt; f=Cb sandstone; g=argillite, siltstone; h=fault breccia to mylonite. Black area: massive sulphide ore. Alterations: A=albitization; S=skarnization; H=hornfelsing. Modified after Tarasov (1974).

seem to bear a closer relationship to members of the "ultramafic-alkaline" association, developed separately in the Siberian Platform, for example in the Meimecha area (Bilibina et al., 1976).

Whereas the "Noril'sk-type" Ni-Cu ores are associated with highly magnesial members of the "trap" association, unique and economically important iron ores (reserves of 4-5 billion tonnes of iron in high-grade ores) are associated with the Triassic iron-enriched "trap" intrusions of the Siberian Platform. Vein and irregular replacement bodies of magnesian magnetite in the most productive Angara-Ilim region, are located in breccia pipes (diatremes) emplaced into Paleozoic platformic sediments (shales, sandstones, carbonates; Fig. 31-8). The magnetite replacements in carbonates are enveloped by pyroxene-actinolite and scapolite skarns, and some diatremes are surrounded by radial and concentric fractures filled by gabbro-diabase dikes (Pavlov, 1960). There is also a unique deposit where magnetite replaced sedimentary halite.

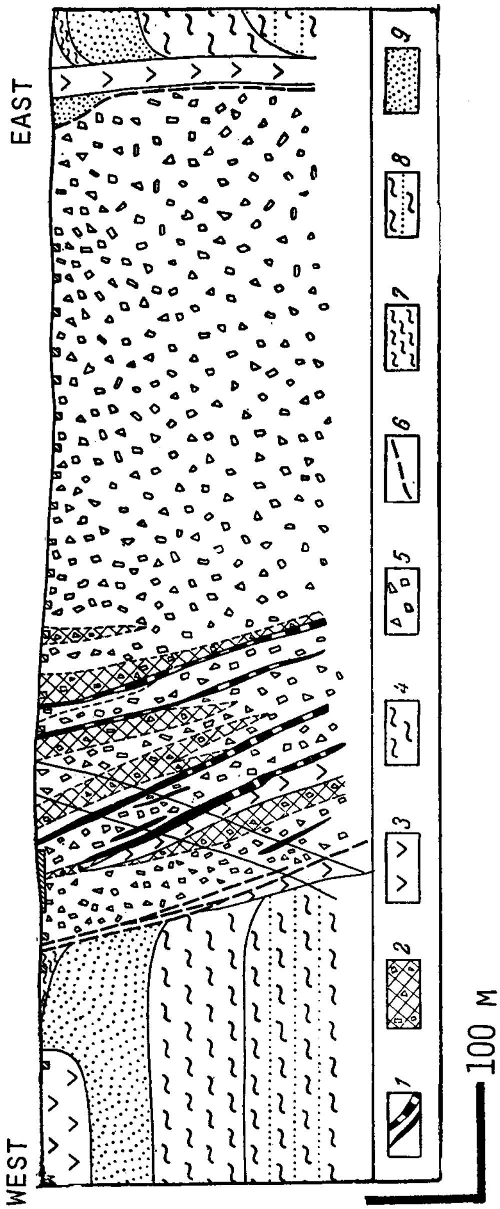


Fig. 31-8. Krasnoyarovskoe magnetite deposit, Angara-Ilim district, Siberian Platform, a Triassic mineralized explosive pipe (diatreme). 1=Magnetite veins; 2=disseminated magnetite; 3=Pe_3-Tr_1 dikes and sills of diabase; 4=S red argillite; 5=Tr_1 volcaniclastics and tuff breccias; 6=pre-ore faults; 7=Or argillites and calcareous shales; 8=sandstones and shales; 9=gray and yellow sandstones. From Pavlov (1960).

31.4.7. Miscellaneous lithologic associations and mineralizations indirectly associated with plateau basalts

Plateau basalt magmatism, particularly at the deep levels, introduces a considerable amount of heat into the continental crust. This heat can produce hydrothermal metal leaching and redepositing systems, and may generate palingenetic felsic magmas complete with a hydrothermal phase of their own, out of the continental lithosphere.

The hydrotherms or secondary felsic magmas can interact with members of the plateau basalt association to produce interference mineralization. Alternatively, they can evolve completely outside the plateau basalt complex, so that the relationship between the resulting mineralization and the plateau basalt magmatism is indirect, usually controversial and sometimes lost. The selected examples of mineralizations that follow have been included to focus the attention of an exploration geologist on ores that might be expected to be spatially associated with plateau basalt regions, although there may be little component relationship.

HYDROTHERMAL VEINS AND REPLACEMENTS IN SEDIMENTS.

Quartz-carbonate or barite, fluorite, fissure veins or replacements in carbonates mineralized by chalcopyrite, galena or sphalerite, occur locally in platformic sediments topped by, or interlayered with, plateau basalt flows or diabase sills. Staritskii and Tuganova (1971) recorded about 50 Pb-Zn occurrences in the Paleozoic sediments, genetically related to the plateau basalts, scattered over the Siberian Platform. They compared them with the American "Mississippi Valley-type".

MINERALIZED BRECCIA PIPES

The economically important Messina ore field, Transvaal (production 300 Tt Cu; Sawkins, 1977), contains several brecia pipes emplaced into Archean granulite facies metamorphics, and mineralized by copper sulphides. The mineralization dates from the Karoo (210-170 m.y.)age and is located about 50 km from the present edge of the Karoo plateau basalts. It is considered to be associated genetically with the late Karoo peralkaline magmatites. Further examples of hydrothermal metallic mineralizations associated with peralkaline to alkaline felsic intrusions, postdating the nearby plateau basalts, are reviewed in Chapter 33.

31.5. EXAMPLES OF PLATEAU BASALT PROVINCES

The two examples of plateau basalt provinces described below, i.e. the Brito-Arctic Province and the Siberian Platform Province, illustrate two principal age groups, the Cainozoic and the Paleozoic-Mesozoic. Additional examples are tabulated in Table 31-3 and their geographic distribution is shown on Figure 31-9. Proterozoic and Archean plateau basalt provinces are treated in Volume 2.

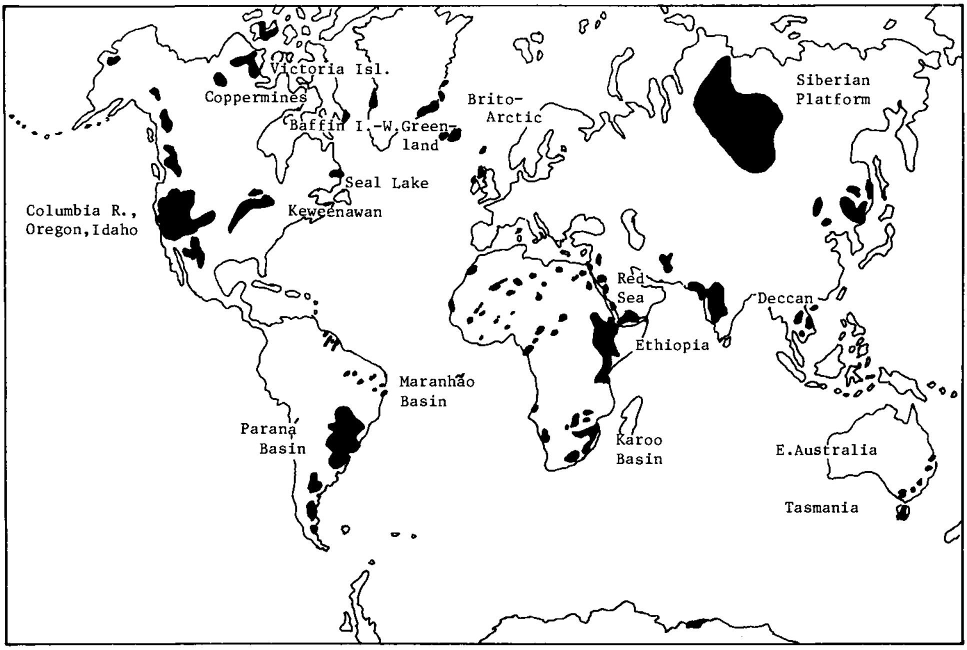


Fig. 31-9. Location map of the principal plateau basalt provinces of the world (see Table 31-4 for a brief listing).

THE BRITO-ARCTIC (THULEAN) PROVINCE

The Brito-Arctic Province (Fig. 31-10) comprises a transitional tholeiitic to alkali basalt association which has an area of at least 163,000 km^2 and reaching a thickness of up to 12 km in eastern Iceland. Still more of it is covered by the sea and the Greenish ice cap. The basalts erupted between 66 m.y. (upper Cretaceous) and 50 m.y. (Eocene) ago, in the initial stage of rifting, continental fragmentation and the North Atlantic opening. The province is dominated by fissure-errupted plateau basalts (dominantly tholeiites), and diabase (dolerite) dike swarms. Rare picrites, andesites, dacites and rhyolites also occur. Central, erosion dissected volcanic-plutonic complexes comprise the bimodal mafic-felsic suite (mildly alkaline basalts, such as hawaiites and mugearites; trachytes, rhyolitic pitchstones, rhyolites, felsites; gabbro, granophyre and granite in depth). The islands of Skye and Mull in the Inner Hebrides are type localities of cone sheets. Central plutonic intrusions of granophyre and granite are known in Skye and Rhum in the Hebrides, in Mourne in Ireland and in S.E. Iceland. Several layered, differentiated mafic to ultramafic complexes have been unroofed by erosion (e.g. Cuillin Hills on Skye; Rhum; Skaergaard in eastern Greenland; Richey, 1961; Preston, 1981; Carmichael et al., 1974).

Figure 31-3. Major Phanerozoic plateau basalt (diabase) provinces of the world

PROVINCE	AREA OR VOLUME	AGE	GEOLOGY	MINERALIZATION	REFERENCES
Brito-Arctic (Thu- lean); Scotland, Ireland, Iceland, E.Greenland	600T km^2 most under water, ice	Cr_3-Eo	plateau basalt flows, dole- rite dikes, differ. central felsic compl., different. mafic/ultramaf. complexes	bauxite (Antrim) rare Cu in basalts, Cu in rhyol. breccia magnetite skarn	Richey et al. (1961) Preston (1981)
Red Sea Flanks (Egypt, Soudan, Ara- bia), Ethiopia	about 200T km^2	Eo-Mi	dominantly alkali basalt flows in desert envir., grade to submarine	Fe-Mn oxide replac. in sedim. near ba- salt (hot springs?)	Said (1962) Basta and Amer (1969)
Baffin Island (Ca- nada)-Western Greenland	45T km^2	Pc-Eo	tholeiitic flows incl. lo- cal picrites; minor tra- chyte, interm. and acid py- rocl. Doler. sills, intrus.	up to 0.12% Ni in picrites; native Fe in basalt dikes (Disko Island)	Clarke (1977)
Columbia R., Wash. Oregon, Idaho, centr. Br. Columbia	500T km^2	Mi-Pl	highly uniform tholeiitic basalt lavas; local pil- lows, vents, minor dikes	ferruginous bauxite in Oregon	McDougall (1976)
Deccan Plateau, India	518T km^2	Cr_3-Eo	tholeiitic flows domin., locally abundant tuffs; minor picrite, rhyolite	variety of Eo bau- xites; 60-70Mt ore	Poldervaart and Sukhes- wala (1958)
Paraná Basin, Bra- zil, Uruguay, Argentina	1.2M km^2	J_3-Cr_1	basalt flows interb. with aeolian sedim.; diabase sills and dikes along edge	nat. Cu in amygdal. basalt, minor Cu at dike contacts	Leinz et al. (1968); Abreu (1973)
Maranhão Basin, N.E. Brazil	50T km^2	Tr_3-Cr_1	3 units of tholei. basalt flows, diabase and gabbro sills, rare mafic intrus.	native Cu in amyg- daloidal basalts	Nunes et al. (1973); Abreu (1973)

Karoo Basin, S.Africa, Lesotho, Namibia, Zambia	140T km^2	Tr_3-J_2	tholeit. lavas, diabase sills and dikes, differentiated mafic sills; minor granoph.,followed by alkaline suite	Ni-Cu sulphides in different.gabbro sill; minor native Cu in basalts; Cu in breccia pipes	Du Toit and Haughton (1953)
Tasmania dolerite sills province, Australia	15T km^2	J_1	contin. tholeiitic suite; exclusively sills, dikes; minor granophyre	minor lateritic bauxite in regolith	McDougall (1962)
Eastern Australian contin. margin province	discont. 3,000x300 km belt	Cr_3-Q	alkali basalts, minor tholeiite flows, volc.centres rhyolite, trachyte	lateritic bauxite in over 100 small deposits	Ewart (1981) Owen (1954)
Siberian Platform, U.S.S.R.	1.5M Km^2	Pe_3-Tr_1	4 major eruptive cycles; doler. dikes, tholeiite flows; primitive picrites; mafic volc. centres, differentiated mafic intrusions	major Ni-Cu sulphides in different. intrusions; Cu in amygdaloids; magnetite in diatremes and at diabase contacts	Vilenskii (1967) Oleinikov (1979)

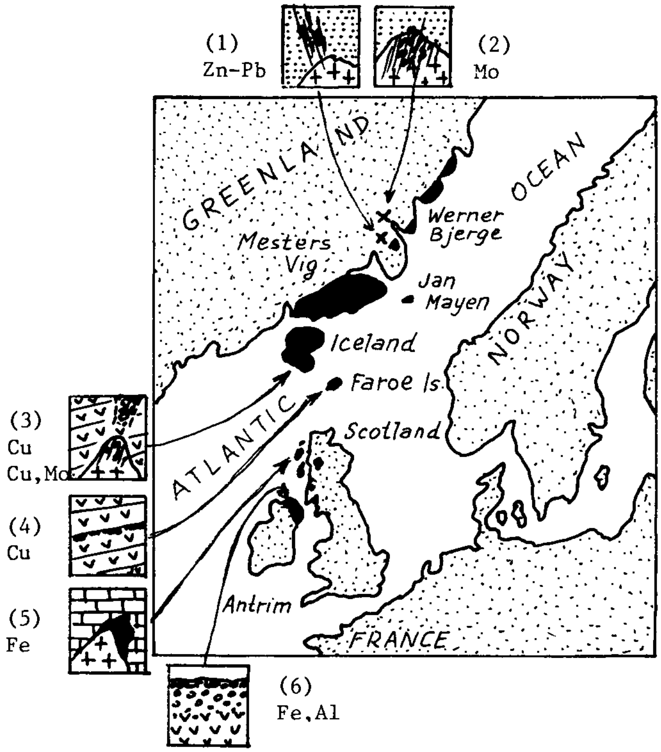


Fig. 31-10. Brito-Arctic (Thulean) plateau basalt province (in black), prior to rifting 60 m.y. ago. Mineralizations: (1) Mesters Vig, hydrothermal Pb-Zn in sediments; (2) Werner Bjerge, stockwork Mo in felsic intrusion; (3) S.E. Iceland, Cu in rhyolite breccia pipe, Cu-Mo in felsic intrusions; (4) Farøe Islands, native Cu in basalt amygdaloids; (5) Skye, magnetite skarn; (6) Antrim, residual iron oxides and bauxite.

Considering the petrographic variety and excellent outcrop along the rocky shores, it is surprising that very little metallic mineralization directly connected with the plateau basalt association is known. Only two metallic commodities have ever been mined: iron (in the small Broadford skarn deposit on Skye, located in Paleozoic limestones at the contact with a Tertiary granite member of a central compled and in ferruginous laterites formed on plateau basalts near Glenravel, Antrim, northern Ireland), and aluminium (in bauxites in Antrim County). Small copper showings have been reported in basaltic amygdaloids in the Farøe Islands and in a felsic breccia pipe probably related to granophyre in the Ossura River area, S.E. Iceland (Janković, 1972). Several molybdenite occurrences are associated with the felsic intrusions in the same area. Economically important Zn-Pb

(Mesters Vig) and molybdenite (Werner Bjerge) deposits located near the edge of plateau basalts in eastern Greenland, are related to the post-basalt peralkaline intrusions, treated in Chapter 33.

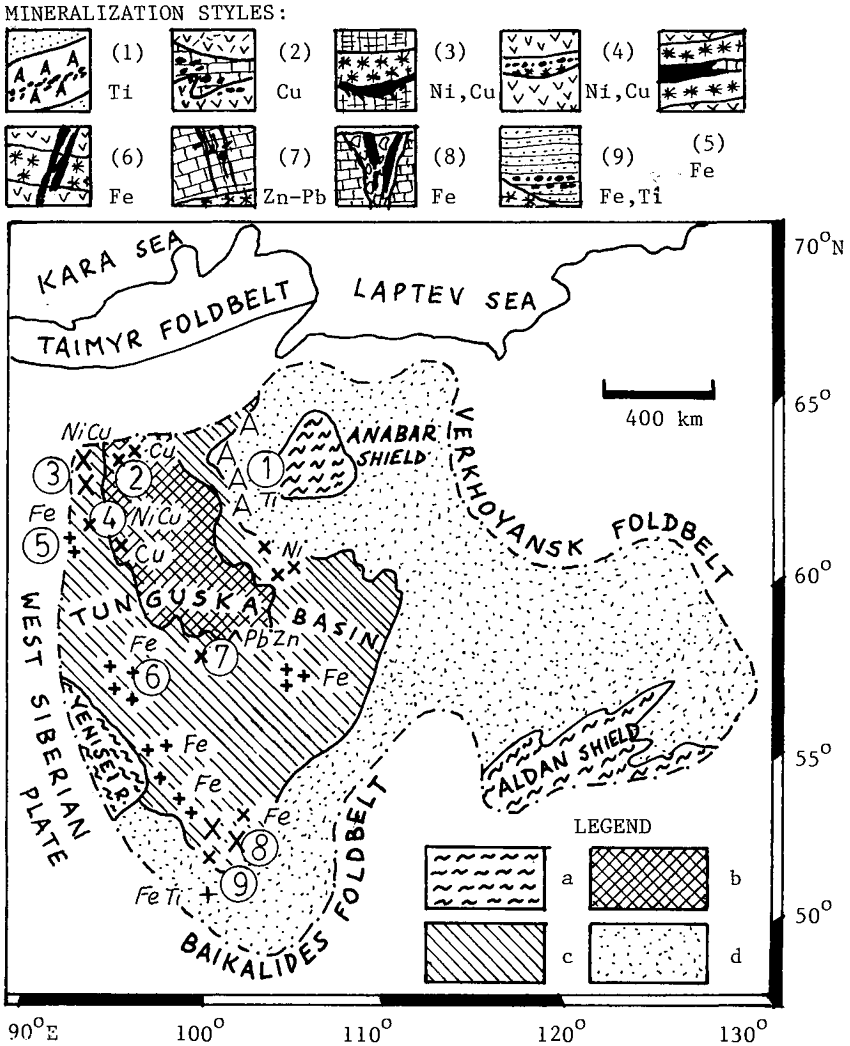
PERMO-TRIASSIC PLATEAU BASALT PROVINCE OF THE SIBERIAN PLATFORM

The Siberian Platform contains the world's most extensive plateau basalt province ("trap" in the Soviet literature). The area continuously covered by the Permo-Triassic lavas and densely intruded by contemporary sills and dikes, is estimated to exceed 1.5 million km^2 (Bilibina et al., 1976; Zolotukhin, 1964; Figure 31-11). The Platform has a consolidated Precambrian crystalline basement that crops out along its fringe (Yenisei Range, Aldan Shield), and in the centre (Anabar Shield). The basement is overlain by Ordovician platformic shallow-marine to continental sediments. The "trap" magmatism was initiated in the late Permian period (250 m.y. ago) and continued until the early Triassic period (210 m.y. ago). Subsequently, until the Jurassic age, several small alkaline basalt (Del'kan Suite) and alkaline-ultrabasic complexes (including kimberlite; Maymecha Suite), formed (Makarenko, 1976).

The core of the "trap" province is the Tunguska Basin, a broad depression filled by subaerial basalt lava flows which, locally, have a high proportion of basaltic tuffs. The subaerial volcanism reached its maximum intensity around the Permian-Triassic boundary and the volcanics range from tholeiites to alkali olivine basalts. Along the fringe of the Tunguska Basin, and over an extensive area south of it, diabase dike and sill fields predominate. The younger, lower Triassic phase of magmatism was dominated by explosive mafic volcanism, and numerous relics of paleovolcanoes are preserved, showing a transition from the central neck facies into the outer lava and tuff sheets. Diatremes are common. Compared with the Brito-Arctic Province, felsic differentiates are rare among the Siberian "traps" but, on the other hand, evolutionarily primitive magnesian magmas were prominent along the north-western margin (Noril'sk and Kureika areas).

The early stage "trap" intrusions are mostly undifferentiated diabases, that form sills to basin-like concordant intrusions, controlled by bedding or formational contacts of the enclosing Paleozoic sediments (Zolotukhin,1964). In the middle and closing stages of the "trap" magmatism in the lower Triassic phase, crosscutting, steep plutons became more common. About 1% of such plutons in the Noril'sk-Talnakh area are differentiated. Dominant gabbro-diabases grade into picrites, troctolites, teschenites or analcite dolerites, and there are prominent metasomatites formed in both endo- and exocontacts.

The Siberian "trap" province has the most complete metallogeny of all the plateau basalt provinces in the world, with the exception of metalliferous weathering crusts most of which were removed by the Quaternary glaciation. Economically outstanding is the Ni-Cu sulphide and platinoid mineralization associated with the differentiated


MINERALIZATION STYLES:
(1) Ti
(2) Cu
(3) Ni,Cu
(4) Ni,Cu
(6) Fe
(7) Zn-Pb
(8) Fe
(9) Fe,Ti
(5) Fe
KARA SEA
LAPTEV SEA
TAIMYR FOLDBELT
ANABAR SHIELD
VERKHOYANSK FOLDBELT
TUNGUSKA BASIN
WEST SIBERIAN PLATE
YENISEI R.
ALDAN SHIELD
BAIKALIDES FOLDBELT
400 km
LEGEND
a
b
c
d
70°N
65°
60°
55°
50°
90°E
100°
110°
120°
130°

◁▬ Fig. 31-11. Siberian Platform plateau basalt province (patterned). (a) PCm basement outcrops (shields); (b) area continuously covered by Pe-Tr plateau basalts; (c) PZ sediments densely intruded by Pe-Tr diabase dikes, sills and mafic intrusions; (d) PZ to T sedimentary cover, occasional Pe-Tr mafic dikes and intrusions. AAA=alkaline provinces.

Major mineralizations: (1) Meimecha-Kotui ilmenite and Ti-magnetite layers and disseminations in alkaline intrusions; (2) Arylakh, native Cu along plateau basalt and carbonate contact; (3) Noril'sk and Talnakh Ni-Cu sulphides with Pt+Pd at footwall of differentiated mafic intrusions; (4) Kureika, Ni-Cu sulphides disseminated in lightly differentiated gabbro sills; (5) Tunguska Basin, magnetite layers in or near contacts with gabbro and diabase sills; (6) Podkamennaya Tunguska, Bakhta Fe district; magnetite veins and sheets in or near dolerite sills; (7) Tunguska Basin, sphalerite, galena veins or replacements in PZ carbonates near diabase sills; (8) Angara Ilim district, magnetite veins in diatreme breccias; (9) southern Siberian Platform: magnetite, ilmenite, zircon paleoplacers in J sandstone.

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gabbro-dibase plutons (Noril'sk-Talnakh), described earlier. In the Kureika region, Ni-Cu sulphides which, so far, have been uneconomic, are disseminated in differentiated gabbroic sills. Significant magnetite reserves are present in a variety of mineralization styles associated with diabase sills and intrusions (schlieren within sills, contact replacements in carbonates, veins and replacements in diatremes; Pavlov,1960). Economically, the most important are the mineralized breccia pipes in the Angara-Ilim region in the south.

Hydrothermal mobilization events superimposed on plateau basalts and dolerites generated widely distributed, but so far uneconomic, native copper occurrences in prehnite-pumpellyite to zeolite altered zones. They probably also contributed copper to the vein and replacement Cu sulphide deposits in the adjacent sediments (Dyuzhikov et al., 1976). In the Arylakh field, native copper mineralization is hosted by several stratigraphic horizons of brecciated carbonates, carbonate-rich tuffs and basalts. Scattered hydrothermal vein and replacement sphalerite and galena occurrences in Paleozoic sediments in the vicinity of diabase dikes and sills, probably formed by the mobilization of Pb+Zn from the sediments with the assistance of magmatic heat (Staritskii and Tuganova, 1971).

Ilmenite, rutile and zircon paleoplacers in lower Jurassic arenites in the southern part of the Platform, formed by reworking of the heavy resistates from weathered Triassic "trap" intrusions.

Plate 12. Old silver workings near Kongsberg, southern Norway. Calcite-native silver veins are closely associated with diabase dikes, transecting metalliferous schists (fahlbånds).

"L'utilité des mines ne se borne pas seulement à extraire du sein de la Terre des substances utiles: semblables en cela à la navigation, elles ont contribué à faire naitre et à étendre les sciences qui leur servent de guides".
Élie de Beaumont

"Study of geology sprang originally from the empirical observations of those engaged in mining for the useful minerals".
S. F. Emmons, 1886.

CHAPTER 32

Diabase, Gabbro and Similar Dikes and Sills

32.1. INTRODUCTION

In American usage, "diabase" is an intrusive rock composed of labradorite and pyroxene and characterized by ophitic texture (A.G.I. Glossary of Geology). It is the hypabyssal equivalent of basalt and gabbro. Dolerite, a term widespread in the British, South African, Australian and European literature is mostly a synonym for diabase, although it is sometimes used for rocks of diabasic composition with a doleritic texture. Diabase grades into gabbro and the terms diabase, dolerite, gabbro and sometimes diorite, are used interchangeably in the literature and need not indicate any substantial difference between rocks so named. One should be aware, however, that in the older European literature "diabase" means a "green" (i.e., pyroxenes partly altered to amphibole or chlorite) paleo-basalt, as well as the dike or sill rock.

Diabase dikes and sills are extremely widespread, being most conspicuous in old fractured and extended cratons, and common in young mobile belts as well. In the oceanic domain, dense swarms and sheets of diabase dikes underlie basalt flows. The overwhelming majority of diabase bodies formed as hypabyssal equivalents of surficially erupted basalts, filling feeder fissures (dikes); Fig. 32-1, or available lateral dilations (sills, sheets, laccoliths). They are members of the same petrochemical kindreds applicable to basalts (compare Basaltic Volcanism Study Project, 1981). When the connection of diabase with surficial basalts was obvious, both rocks were treated in the same chapter (4, 7, 10, 12, 25, 31). In deeply eroded regions, however, most of the superficial volcanics have been removed, yet diabase dikes and sills remained, often prominently exposed. Such an occurrence can be designated "independent diabase", and is treated in this chapter.

The overwhelming majority of "independent diabase" bodies occur in stabilized segments of the continental crust. The majority are related to distinct taphrogenic events, have the composition of

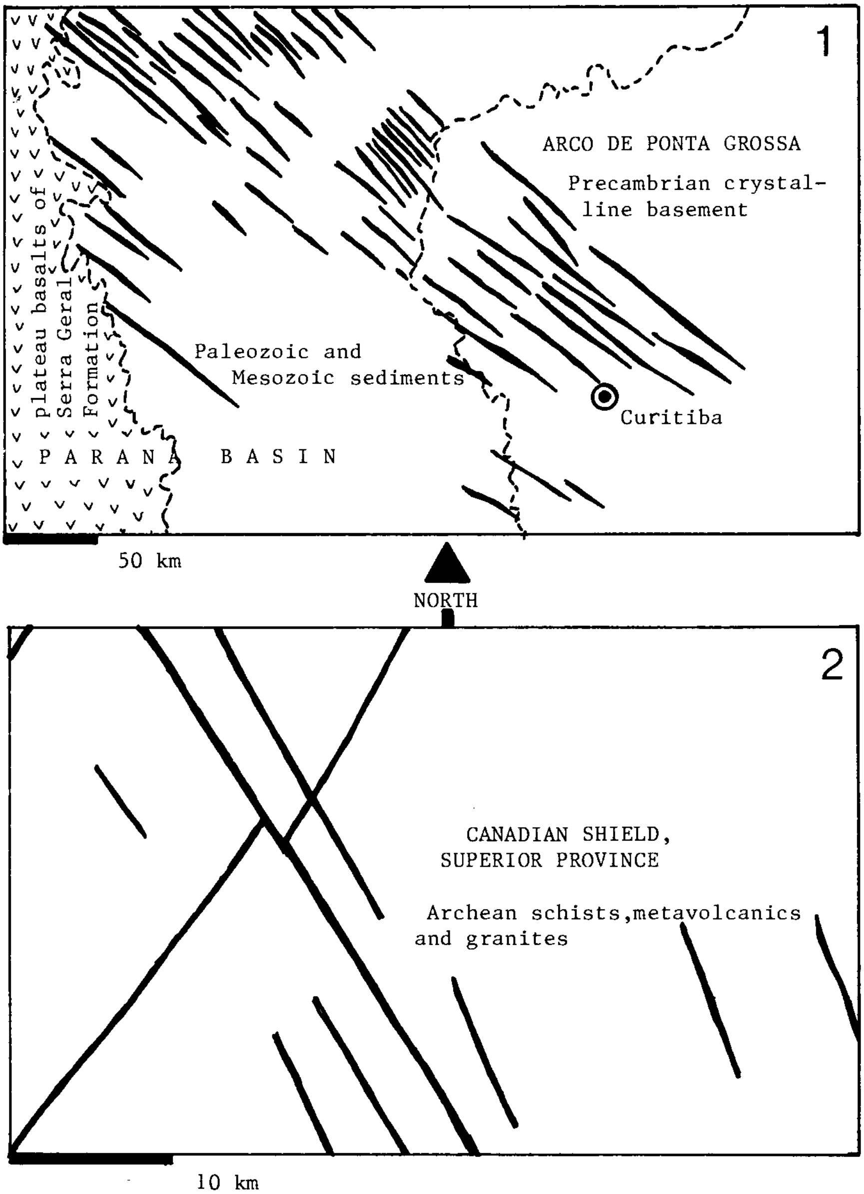


Fig. 32-1. The two characteristic regional distribution patterns of diabase dikes (shown in black). (1) Swarm of J-Cr diabase dikes in the Paraná State, S.E. Brazil, feeders to the plateau basalts of the Serra Geral Formation (after Carta Geol. do Brasil 1:1 million, sheet Curitiba, 1974). (2) The two major systems of Proterozoic diabase dikes in the Canadian Shield metamorphics south of Hearst, Ontario (after Ontario Geol. Surv. Map 2166, Hearst-Kapuskasing Sheet).

continental tholeiite and represent feeders to plateau basalts. Such diabases tend to be remarkably homogeneous and monotonous both compositionally and texturally. They are rarely associated with contemporary igneous rocks of contrasting composition. When they are, such rocks are usually felsic (granophyre, syenite porphyry, felsite or granite), resulting in a bimodal mafic-felsic association.

The minority of continental diabase bodies are spatially associated with granitic plutonism (Chapter 28) where they are most common in the earliest (pre-granite) and latest (post-granite) intrusive phases. Such diabases display a far greater petrographic diversity and are often accompanied or substituted by a variety of hypabyssal equivalents of diorite, granodiorite or granite.

The petrology of diabase is described in most textbooks (e.g. Carmichael et al., 1974). Frankel (1967) reviewed the diabase forms and structures. Both subjects are further treated in a variety of publications dealing with local areas (Walker and Poldervaart, 1949, Karoo, S.Africa; Blackadar, 1956; Fahrig and Wanless, 1964, Canadian Shield; McDougall, 1962, Tasmania; Hamilton, 1965, Antarctica and others).

Diabase dikes and sills are one of the rock bodies that show least evolutionary change with geological time, so there is no substantial difference between, say, lower Proterozoic and Cretaceous diabases except for their host association. For that reason, Phanerozoic and Precambrian diabases cannot be clearly distinguished and a complete ignorance of the latter in this volume would deprive the reader of a significant number of mineralization examples that can be found associated with the Phanerozoic rocks as well. For that reason, Precambrian diabases receive a "light" coverage in this chapter. For a more detailed description, the reader is referred to Volume 2.

32.2. METALLOGENY AND ORES ASSOCIATED WITH DIABASE DIKES AND SILLS

32.2.1. General

Abdullaev (1957), Lewis (1955) and others reviewed the relationship between metallic ores and dikes or sills in general and this included diabase dikes. They distinguished two fundamental relationships: (a) genetic and (b) structural. The (a) relationship is largely geochemical. Metal migration that parallels the various stages of the petrologic development of diabase, or the migration triggered by the interaction of diabase (mostly its heat) with the surrounding rocks, could have resulted in a local ore accumulation. In the (b) relationship, ores genetically independent of the diabase merely filled the same type of spaces (fractures, bedding planes, etc.) occupied by diabase dikes or sills, or post-solidification fractures in diabase. The fractures formed preferentially due to the higher competency (brittleness) of diabase and its baked hosts compared with the commonly incompetent wallrocks, e.g. sediments. The two relationships often overlap.

Metallic mineralization genetically associated with diabase (Fig. 32-2 and Table 32-1) is rare and, so far, of little importance economically although there are some exceptions (e.g. Cobalt, Ontario; a major silver camp). This contrasts with the wide distribution of diabase, most of which is completely devoid even of traces of metallic accumulations. Since it appears that most of the diabase-associated ores are a product of remobilization of earlier metal concentrations

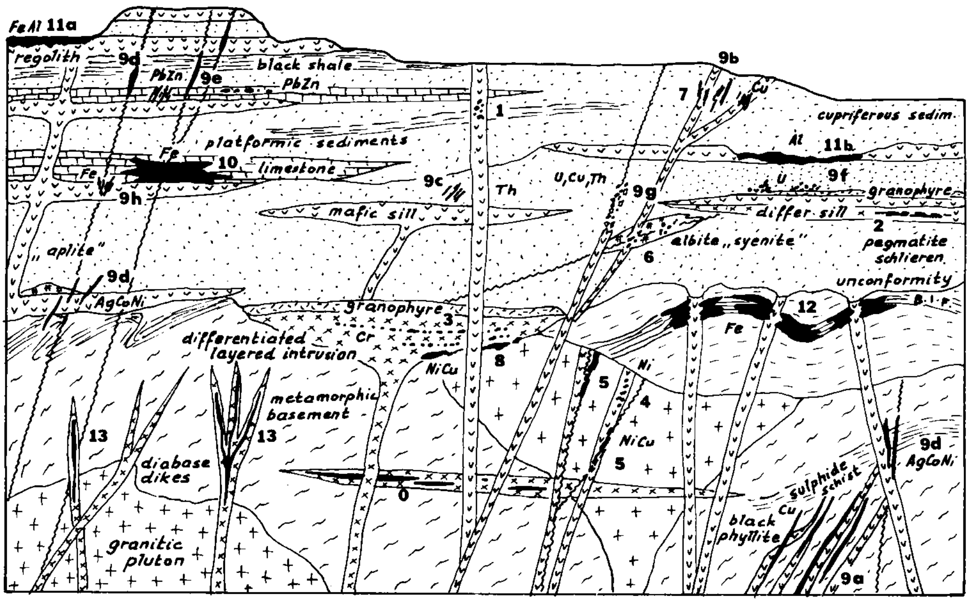


Fig. 32-2. Diagrammatic representation of the more common metallic mineralizations associated with independent diabase or gabbro dikes and sills (see Table 32-1 for explanation of the numerical codes).

Table 32-1. Principal mineralization styles associated with independent diabase and gabbro dikes and sills. NOTE: Some Precambrian mineralizations described in Volume 2 are included in this table

	ORES IN DIKES AND SILLS
(0)	Lenses of Ti-magnetite in gabbro-anorthosite sills, W. Australia (Precambrian); 130 Mt Fe, 45 Mt Ti, 1.96 Mt V
(1)	Sparsely disseminated sulphides (chalcopyrite, pyrrhotite, pentlandite, sphalerite, chalcocite) or platinoids, scattered grains and xenoliths of native iron (W. Greenland)

(2)	Pegmatitic schlieren containing oversized grains of Ti-magnetite, ilmenite; disseminated chalcopyrite
(3)	Disseminated ore minerals (chromite, pyrrhotite, pentlandite, chalcopyrite) in differentiated sills grading to layered intrusions (see Volume 2)
(4)	Disseminated to massive pyrrhotite, pentlandite, chalcopyrite in xenoliths-rich zones near gabbro or diabase contacts (about 15 Tt Ni, 18 Tt Cu)
(5)	Disseminated to massive pyrrhotite, pentlandite, chalcopyrite along shears and faults cutting thin diabase dikes (about 8 Tt Ni, 10 Tt Cu)
(6)	Disseminated specularite, chalcopyrite; uraninite, brannerite, Ti,Th minerals; etc., in light-coloured "syenites", "aplites" and breccia affiliated with mafic dikes (50 Tt Cu, 2 Tt Th, 500 t U)
(7)	Hydrothermal Cu (Ni) veins, veinlets, stockworks transecting fractured gabbro or diabase (about 100 Tt Cu)
	ORES AT OR NEAR CONTACTS OF MAFIC DIKES OR SILLS
(8)	Ni-Cu massive, breccia, stringer sulphides on the base of differentiated sills or layered complexes (see Volume 2)
	Hydrothermal veins in (meta)sediments and (meta)volcanics intruded by gabbro or diabase dikes:
(9a)	Cu veins hosted by lustrous slates (about 200 Tt Cu)
(9b)	Cu veins hosted by cupriferous sandstones, siltstones (about 100 Tt Cu)
(9c)	Th (Cu) veins in quartzite (about 500 t Th)
(9d)	Ag (Co,Ni,As,Bi,U) veins, Cobalt "type" (about 20 Tt Ag, 35 Tt Co)
(9e)	Pb,Zn (fluorite, barite) veins (about 50 Tt Pb+Zn)
(9f)	U veins, disseminations, replacements (about 200 t U)
(9g)	U, Th, specularite, chalcopyrite, etc. in albitized, hematitized, carbonatized breccia near or in the extension of gabbro, diabase dikes (1 Tt U+Th)
(9h)	Magnetite veins, stockworks, disseminations in altered gabbro or diabase (about 5 Mt Fe)
(10)	Magnetite or pyrite replacements in carbonates near gabbro-diabase sills, dikes (Cornwall, Pa.); 60 Mt Fe, 40 Tt Co
	WEATHERING CRUSTS
(11)	Residual bauxites and Fe-oxide laterites; (a) surficial, (b) buried at unconformities; 100 Mt Al, 10 Mt Fe
(12)	High-grade Fe oxides formed by enrichment of banded iron formation along mafic dikes
	MISCELLANEOUS
(13)	Ores in mafic dikes associated with differentiated granitic terrains

in the diabase intruded rocks, the exocontact association deserves as much or possibly more attention as the intrusions themselves when interpreting the diabase metallogeny.

32.2.2. Ores in diabase dikes or sills

Most diabase, gabbro and diorite dikes and sills are compositionally uniform and carry an ordinary complement of accessory metallic minerals (Ti-magnetite, ilmenite) which is too low (1-5% by volume) to be of practical importance.

The group of occurrences of native iron in the Tertiary plateau basalt province on western Greenland (Disko Island, Nugssuaq, Jakobshavn, etc.) has already been mentioned in Chapter 31. The iron, sometimes accompanied by pyrrhotite, forms scattered grains and inclusions of variable size and weight (from milligrams to 22.7 ton blocks) in basalt flows as well as in basalt and diabase dikes. The host rocks to the irons at the best known localities Uivfaq and Kitdlit are mafic dikes to breccias. Bird and Weathers (1977) reviewed the existing genetic interpretations of the native iron occurrences and concluded that the iron was derived from the sub-lithosphere mantle and brought to the surface as xenoliths.

Sulphides in diabase occur occasionally, in very insignificant quantities. Pyrite and pyrrhotite are the most common, followed by chalcopyrite. In the Coppermine area, northern Canada, the Willow Lake gabbro dike, traceable for over 8 km, contains sparsely disseminated pyrite and chalcopyrite and it grades around 0.1% Cu (Kindle, 1972). Similar occurrences are numerous in the nearby Bathurst Inlet area. Pentlandite can sometimes be microscopically determined in the minor pyrrhotite in diabase, and sphalerite in 0.015 mm large grains, was found by Desborough (1963) in the mafic intrusions in the Ozark Mountains, Missouri. Rare platinoids have occasionally been reported as disseminated accessories in diabase dikes, e.g. from Tilkerode in the Harz (East Germany).

Chilled margins of some mafic dikes and sills often show substantial variation in their trace metal content. Granger and Raup (1969) recorded an almost twofold increase in titania in the chilled zone (4.26% TiO_2), compared with the rest of the intrusion (2-3% TiO_2), in the Sierra Ancha sheet in Arizona. Local pegmatitic facies occur as small schlieren in some diabase bodies and often contain scattered mineralogical quantities of visible sulphides (pyrrhotite, chalcopyrite) as well as large phenocrysts or nests of the accesory ilmenite or Ti-magnetite.

Some mafic sills or dikes are multiple, composite or differentiated, showing a variety of rock types. One such variation is towards ultramafic members (picrite, troctolite), the other towards felsic members and alkali enrichment (syenite, granophyre, granite). There is much controversy as to whether such non-uniform rock bodies originated by an in-situ differentiation from a single surge of magma; whether the parent magma was pure, mantle-derived partial melt or a mantle melt modified by assimilation of the crust or whether the magma was an entirely crust-derived melt (compare Blackadar, 1956 and Basaltic Volcanism Study Project, 1981, for further discussion).

There is further controversy as to whether certain igneous-looking rocks associated with diabase, particularly the albite-rich felsic members (albite "syenites" and "aplites", albitites) are magmatic differentiates or hydrothermally metasomatized earlier rocks. If they are metasomatites, what was the timing of their conversion: deuteric and autometasomatic (of and by the diabase), or post-consolidation, unrelated to the diabase magmatism? The problem of albitic rocks runs parallel with the spilite problem, already reviewed in Chapters 10-12.

The hydrothermal-alteration origin of a red or pink albitic "aplite" in the Cobalt, Ontario, district, was proposed relatively early by Bastin (1935) and has been reported several times since. In the Dolores Creek Cu (Fe,U,Th) camp in the Yukon (Laznicka and Edwards, 1979), numerous gabbro dikes intrude Proterozoic fine clastic sediments and impure carbonates. Bodies of pink, coarse to fine albite-chlorite rock of syenitic appearance occur in the extension and near contacts of the gabbro dikes and appear to have formed by hydrothermal albitization of the gabbro as well as breccias. Specularite and local chalcopyrite are disseminated, producing low-grade orebodies of a sodic alteration equivalent to "porphyry coppers". There is evidence indicating that the trace copper has been released from the gabbro in the process of pyroxene destruction.

Copper showings of similar style modified by local conditions are relatively common, e.g. in the Luiri Hill area, Zambia (Phillips, 1959). Even more common is a variety of Cu-sulphide (usually chalcopyrite) mineralized hydrothermal veins, veinlets and stockworks in faults and fractures transecting the diabase (e.g. Kumarina mine, Bangemall Basin, Western Australia; Gee, 1975; numerous occurrences in the vicinity of the early Proterozoic Nipissing diabase sill, Lake Huron area, Ontario; Pearson, 1978). In the Lewis Range, southern Canadian Cordillera, gabbro dikes intrusive into Proterozoic sediments cause local remobilization of a weak stratabound mineralization (Morton et al., 1973). Altered mafic sills near Yarrow Creek and Spion Kop Creek contain abundant interstitial copper sulphides. Other sills intruding Proterozoic dolomites, carry disseminated sphalerite and galena, in addition to the Cu sulphides.

Diabase dikes transecting Cu-mineralized continental basalt flows as in the Coppermine area, Northern Canada (Kindle, 1972), often contain disseminated chalcocite. In the VIC showing, the zone of a diabase body contains 0.46% Cu in an area over 400 m long and 12 m wide. The gray chalcocite is very inconspicuous and when secondary minerals (malachite) are not developed, it is easy to overlook it .

Thick diabase sills grading to layered intrusions containing olivine-rich members and centrally situated or basal Ni-Cu sulphides (Kureika, Insizwa), have already been described in Chapter 31. Examples of Ni-Cu sulphide accumulations in relatively thin diabase dikes are much rarer, and most of them appear to be the result of post-solidification, hydrothermal alteration and mineralization along shears or faults intersecting the mafic dikes, or their proximal exocontacts. In the small Sohland-Rožany ore field near Šluknov, N.W. Czechoslovakia and S.E. East Germany (Beck, 1909; Kopecký et al., 1963), thin diabase dikes, measuring 5-20 m, intrude a late Proterozoic cataclastic granite. Massive lenses, veins and impregnations of pyrrhotite and pyrite with minor chalcopyrite, pentlandite and ilmenite form ore shoots, up to 400 m long, within the diabase. In the Thomson River Cu,Ni,Au, Pt-Pd mine east of Melbourne, Australia (Keays and Kirkland, 1972), a bulging Devonian diorite-pyroxenite dike contains massive to disseminated chalcopyrite, pyrite and minor pyrrhotite, pentlandite and Pt-Pd minerals along "contact shears".

32.2.3. Ores at or near contacts of gabbro or diabase dikes, sills

The contact effects of most diabase or gabbro dikes and sills are slight and usually limited to rims a few centimetres wide. Thermal metamorphism is most pronounced in mudstone hosts, where narrow zones of biotite and sometimes cordierite hornfels may develop. In the Middelburg, Ermelo, Wakkerstroom area, South Africa (Hammerback, ed., 1976), originally hematitic ironstones interstratified with sandstone and shale are converted by Karoo diabase sills into a hard, compact magnetite. This represents a mere 230 Tt ore with 67-69% Fe.

Arenites and crystalline rocks are usually unaffected, and dolomites transected by diabase dikes are often de-dolomitized (converted to calcitic marbles). The most unusual effects of thermal maetamorphism can be seen at diabase-coal contacts, as in the Natal Coalfield, South Africa. There, anthracite, natural coke or graphite formed in the exocontact. Under certain conditions, the hot mafic magma may transfer suitable country rocks into a plastic state capable of intrusion, to form rheomorphic dikelets and veins filling dilations in both endo- and exocontact of a diabase body (Frankel, 1967).

Thermal metamorphism alone, however, seems to be unimportant as an ore-generating process. This requires a widespread hydrothermal transfer. Because basaltic magmas are relatively "dry", hydrothermal systems in mafic dike or sill fields contemporary with the mafic magmatism are almost always the result of heating of the water, contained in the enclosed rocks. Hydrothermal systems younger than the mafic magmatism and superimposed on the diabase bodies can have diverse origins, e.g., emplacement of felsic plutons in depth. Hydrothermal veins were reported on both sides of diabase contacts, although the exocontact veins are substantially more common.

COPPER VEINS

Copper accounts by far for the greatest number of mineralized occurrences in the contact area of gabbro and diabase dikes and sills. In the Racing River-Gataga River area, N.E. British Columbia (Carr, 1971; Preto, 1972; 115Tt Cu/3-4%; Fig. 32-3), numerous swarms of thin but high-grade ankerite, quartz, chalcopyrite fissure veins are developed in Proterozoic black lustrous slates, densely transected by diabase dikes. Both veins and dikes fill the same dilations and overlap in time. The majority of the diabase dikes are slightly younger than the ore veins and many veins have been destroyed by diabase engulfment. The ore veins as well as some diabase dikes are fringed by a narrow halo of decarbonization.

In the Inyati mine, Zimbabwe (Roberts, 1973), chalcopyrite fissure veins are associated with basic dikes, subsequently intruded by granites.

MAGNETITE VEINS AND REPLACEMENTS

Magnetite forms common small occurrences in mafic dikes and sills. Puffer and Peters (1974) recorded a small locality near Laurel Hill,

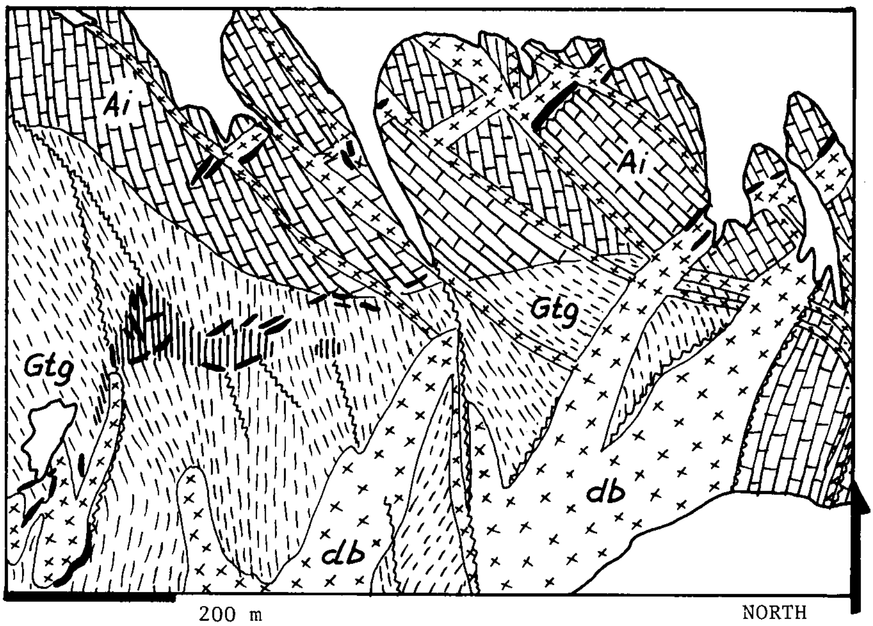


Fig. 32-3. Bronson Mountain group of Cu-mineralized veins (black) in the Racing River-Gataga River area, N.E. British Columbia, showing their close association with diabase dikes. Ai=Pt_3 carbonate, minor slate; Gtg=slate and phyllite; db=diabase. Vertical ruling: bleached phyllite with chalcopyrite mineralized quartz veinlets. White: glaciers and snowfields. From LITHOTHEQUE, modified after Preto (1972).

New Jersey, where parallel magnetite veins fill joints surrounded by bleached diabase. They interpret the magnetite as being a product of local lateral secretion of iron by deuteric fluids.

Much more extensive migration and entrapment of locally ? deuterically released iron, resulted in the economically important magnetite deposits of the "Cornwall-type" in S.E. Pennsylvania (Eugster and I-Ming Chou, 1979; Lapham, 1968; Fig. 32-4). The largest Cornwall deposit contains two major orebodies, replacing a Cambrian limestone directly above and below a saucer-shaped sheet of Triassic diabase. The ore is either massive, homogeneous, or it incorporates the relic banding of the host limestone. It consists of dominant magnetite, actinolite and subordinate hematite, pyrite, chalcopyrite and chlorite. The alteration and mineralization was multistage. The early-formed diopside, tremolite, phlogopite hornfels was faulted and modified by fissure-controlled localized K-feldspar metasomatism, chloritization, actinolitization and magnetite emplacement. Cornwall has produced over 100 Mt ore with 39.4% Fe, 0.29% Cu and 0.02-0.056% Co. Cobalt is concentrated in pyrite. The Grace mine located in the same area (Sims, 1968) is comparable, but smaller.

Numerous showings of mineralized "skarns" in the Lake Huron area, S.C. Ontario, developed in lower Proterozoic limestones at the contact with the Nipissing diabase sill, have been recorded by Pearson (1978). In addition to magnetite and chalcopyrite, one occurrence (Cobden River) caries scheelite in idocrase, diopside and garnet skarn.

Ag (Pb,Zn,Cu; Co,Ni,As,Bi) VEINS

Several well-known high-grade silver deposits and fields (Cobalt-Gowganda, Great Bear Lake, Kongsberg, etc.) are associated both in space and time with diabase dikes or sills. The Cobalt-Gowganda district, Ontario, has been a major metal producer (about 14.5 Tt Ag, 12 Tt Co, 1.3 Tt Ni), with the metals derived from several hundred thin and short steeply dipping fissure veins in the vicinity of a thick Proterozoic Nipissing Sill. The sill intrudes Archean greenstone terrain containing a horizon of metalliferous "exhalites", and Proterozoic detrital sediments locally pyritic and arsenopyrite-bearing. Cobalt-Gowganda and Great Bear Lake districts are treated in Volume 2.

The historical silver mines in Kongsberg, S. Norway (Ihlen and Vokes, 1978; Fig. 32-5), produced 1.4 Tt Ag from about 130 workings. Native silver accompanied by small quantities of pyrite, sphalerite, chalcopyrite, argentite, Ni-Co arsenides, etc., occurs in steep, narrow (5-10 cm) and short (max. 100 m) white calcite veins. The veins shortly postdate emplacement of diabase dikes in the area, and most are enclosed in Proterozoic metamorphic schists and gneisses containing bands of disseminated chalcopyrite, sphalerite and galena conformable with schistosity ("fahlbånds"). The silver occurrence is confined to (or is richer in) the vein segments intersecting the

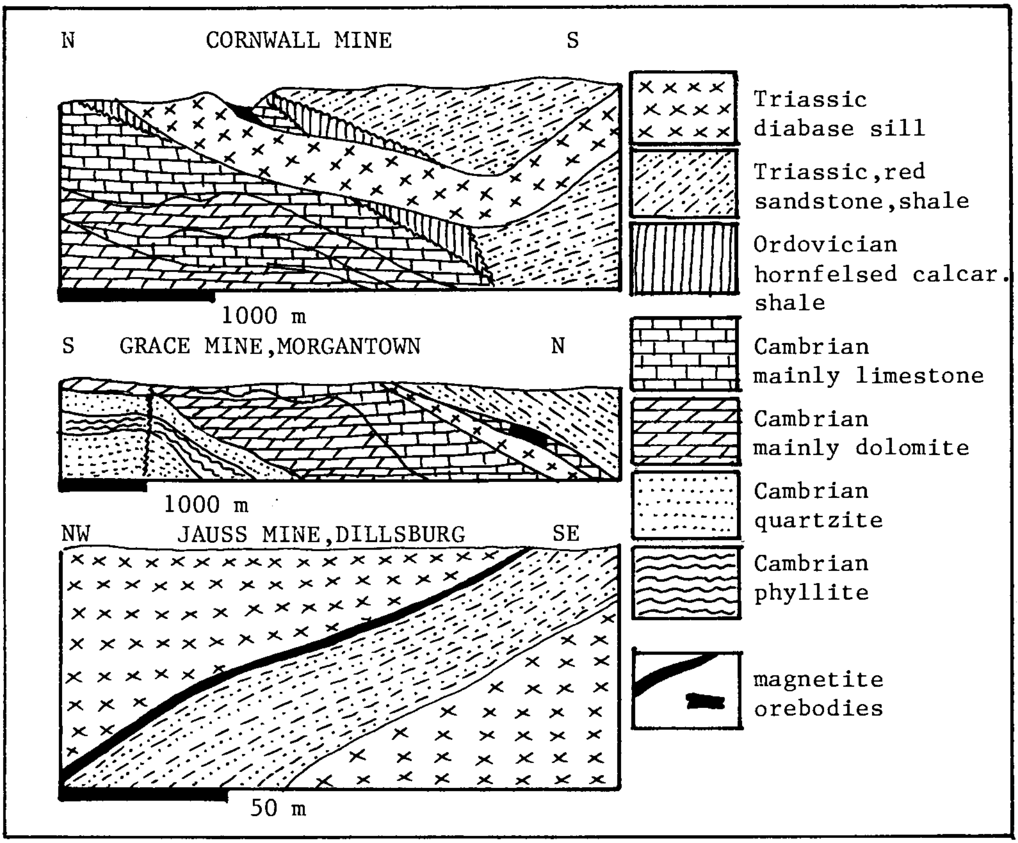


Fig. 32-4. Examples of replacement magnetite deposits of the "Cornwall (Pennsylvania) type", adjacent to Triassic diabase sills. From LITHOTHEQUE, modified after Lapham (1968), Sims (1968) and Spencer (1908).

sulphide schists, from which it is generally believed to have been extracted during the period of Permian rifting in the adjacent Oslo Graben.

Small vein, veinlet, dissemination, replacement, etc. occurrences of galena and sphalerite in quartz, calcite, fluorite or barite gangue are quite common in sediments adjacent to diabase dikes (at the Argent Station near Pretoria, South Africa, Hammerback, ed., 1976; in the Igarapé Xituba region in the Amazon Basin, Brazil, Rezende and João, 1980 and elsewhere).

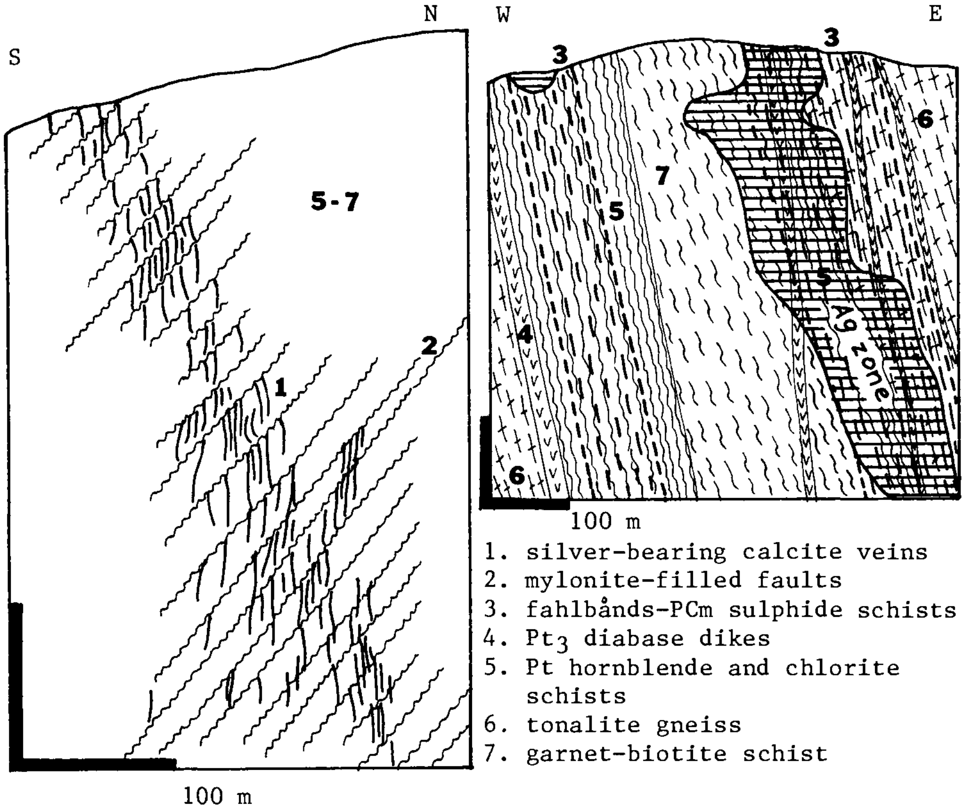


Fig. 32-5. Silver veins hosted by the Overberget fahlbånd, Kongsberg, southern Norway. From LITHOTHEQUE, after Bugge (1917) and Neumann (1944).

U and Th VEINS, MINERALIZED BRECCIAS, IMPREGNATIONS

Spatial association of radioactive mineralization and gabbro or diabase intrusions has been recorded from various localities (e.g. Nabarlek, N. Australia; Port Radium, N. Canada; Montreal River area, Ontario; Paukkajanvaara, Finland), but insufficient work has been done to determine the metallogenic function of the mafic bodies, if any. The small U deposits hosted by the Dripping Springs Quartzite (Gila County, N. Arizona; Granger and Raup, 1969; 21.3 Tt ore with 0.205% U_3O_8), probably give the best insight into the problems involved.

The Quartzite is a formation of the middle-upper Proterozoic Apache Group, a sequence of red to gray feldspathic sandstone, siltstone and shale resting on lower Proterozoic crystalline basement and topped by limestone. Intercalated minor flows of plateau basalts, and widespread diabase sills and dike feeders, are also present.

The U mineralization is represented by veinlets, blebs and disseminations of uraninite and small quantities of Cu,Pb,Zn and Mo sulphides in quartz, carbonate and chlorite gangue. The U occurrences occupy poorly outlined structures, usually gradational into the altered quartzite wallrock. The best-outlined veins are steeply dipping tabular bodies of disseminated uraninite, the central part of which is marked by a core of breccia or a narrow fissure filling. Most of the U orebodies show dual control: (1) confinement to the gray unit of the upper Member of the Dripping Springs Quartzite (=stratigraphic control) and (2) proximity to diabase sills, particularly to a suite of felsic rocks of intrusive appearance (granophyre, syenite and aplite) formed on both sides of the diabase-feldspathic sandstone contact. Smith and Silver (1975) argued convincingly that the felsic rocks were derived from the Dripping Springs Quartzite by an extensive interaction between the mafic magma and the feldspathic country rock, facilitated by the influx of groundwater into the magmatic roof region. The detrital sediments, often carbonaceous, appear to have been the source of U of infiltrational origin, comparable with the "sandstone uranium-vanadium" mineralization style (Chapter 25). The U is thus the product of remobilization of a stratabound U enrichment by secondary magmatic-hydrothermal processes triggered by the magmatic heat.

Similar effects of remobilization can be observed on small scale in, for example, the Laguna mine in New Mexico, but there the peneconcordant U ore in arenites is the dominant ore style, so that the local modification by diabase dikes has never been emphasized. The U occurrences discussed above have many common links with the widespread but so far uneconomic U (in uraninite) and U-Th (in brannerite) occurrences affiliated with unusual altered breccias and locally intervening diabase and gabbro dikes and metasomatic "syenites" in the Wernecke and Ogilvie Mountains in the Yukon. The Dolores Creek camp mentioned earlier represents an example locality where Cu is prominent, but other occurrences in the area (e.g. Quartet Lakes; Bell and Delaney, 1972) are Th-U dominated.

The thorium-bearing veins at Hall Mountain near Porthill, Idaho (Staatz, 1972; Fig. 32-6) are hosted by a Proterozoic quartzite in the upper contact of a quartz diorite (or gabbro) sill. The sill is a member of a middle Proterozoic swarm of "Purcell Sills". Quartz and calcite are the principal gangue minerals, and chlorite, magnetite, pyrite and biotite occur in lesser quantities. Brown crystals of thorite sometimes accompanied by allanite, chalcopyrite, specularite and other minerals are very erratically distributed in the gangue (the grade varies between 95 ppm to 21% Th). Although Hall Mountain appears to be of little economic importance at present, it constitutes a possible link with the more important Th accumulations such as the Lemhi Pass (Idaho and Montana), where mafic dikes are much less prominent.

32.2.4. Mineralizations in mafic dikes affiliated with differentiated granitoid terrains

This subject is treated in Chapter 28. The reader, however, should be aware that spatial affiliation of granitic rocks and diabase dikes does not necessarily imply a genetic relationship between the two, so that the possibility of a link with the subjects and problems treated in this chapter cannot be excluded. Preferential emplacement of ore veins into dikes of diabase and lamprophyre is particularly common in some deeply eroded block faulted plutonic aureoles, as in the Bohemian Massif, Czechoslovakia. There, the Příbram Pb,Zn,Ag field is by now almost a classical example of the close ore-diabase association, an association applied in exploration (Kutina and Tělupil, 1966; Fig. 32-7). Additional examples include the Krásná Hora stibnite-gold lodes hosted by kersantite dikes (Bernard et al., 1968); Premier Au-Ag mine, N.W. British Columbia and several localities listed by Lewis (1955).

32.2.5. Weathering crusts over diabase dikes and sills

Tropical weathering superimposed on gabbro and diabase intrusions could produce residual lateritic bauxite or iron ores. Small deposits

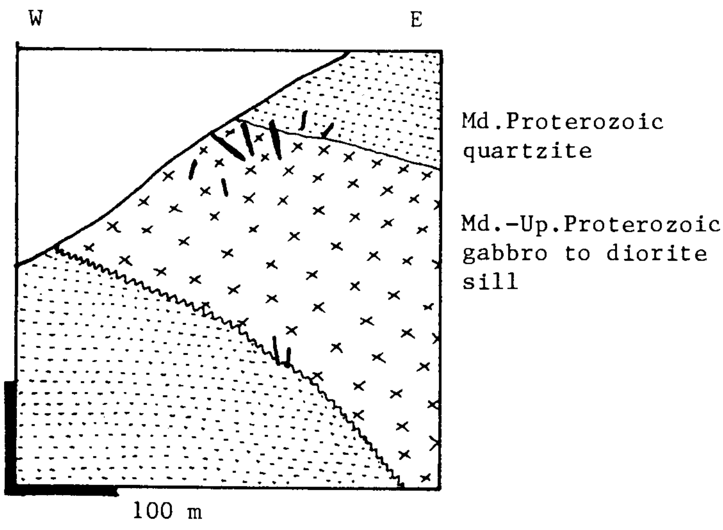
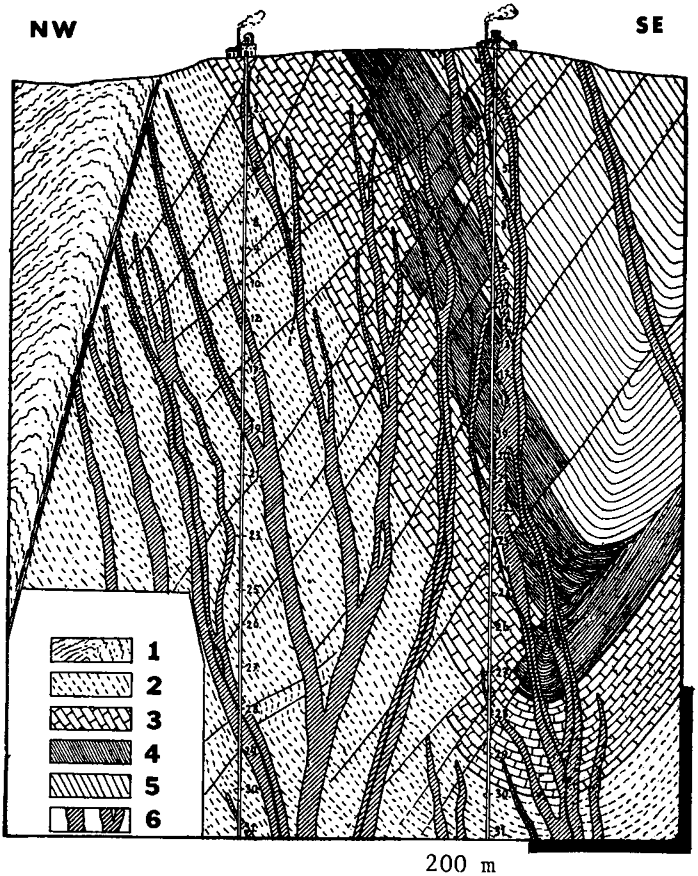


Fig. 32-6. Hall Mountain, Idaho, Th-bearing veins associated with a diorite sill. Diagrammatic section, ore veins (in black) projected on the plane of section. From LITHOTHEQUE, data from Staatz (1972).



1. Pt_3 slate, minor meta-spilite
2. Cm_2 lithic arenite
3. quartz pebble conglomerate
4. shale
5. lithic conglomerate to sandstone
6. diabase dikes

BLACK: quartz, siderite, carbonate, galena sphalerite, boulangerite, Ag-sulphosalts fissure veins

Fig. 32-7. Březové Hory Pb,Zn,Ag field, Příbram district, Czechoslovakia. Ore veins are controlled by late Paleozoic diabase dikes, postdating emplacement of a tonalite pluton. After Kettner (1918).

of this sort found in Tasmania have already been mentioned in Chapter 31, and numerous but ususally poorly documented occurrences exist in the humid tropical belt of western Africa. In the bauxite districts of Guinea (Tougue-Dabola, Boke, Fria, Fatala, etc.; de Kun, 1965), diabase sills and dikes are consistently listed as one of the parent rocks (perhaps the most important one) to the lateritic bauxite.

In some Lake Superior Proterozoic iron ore districts, diabase dikes and sills are closely associated with high-grade iron oxide orebodies formed by residual enrichment (leaching out of SiO_2, CO_2, Ca, etc.) of the low-grade banded siliceous iron formation. In the Marquette Fe ore district (Gair and Tsu-Ming Han, 1975; Fig. 32-8), the diabase bodies acted mainly as impermeable barriers, impounding and confining the groundwater flow through the iron formation so that their

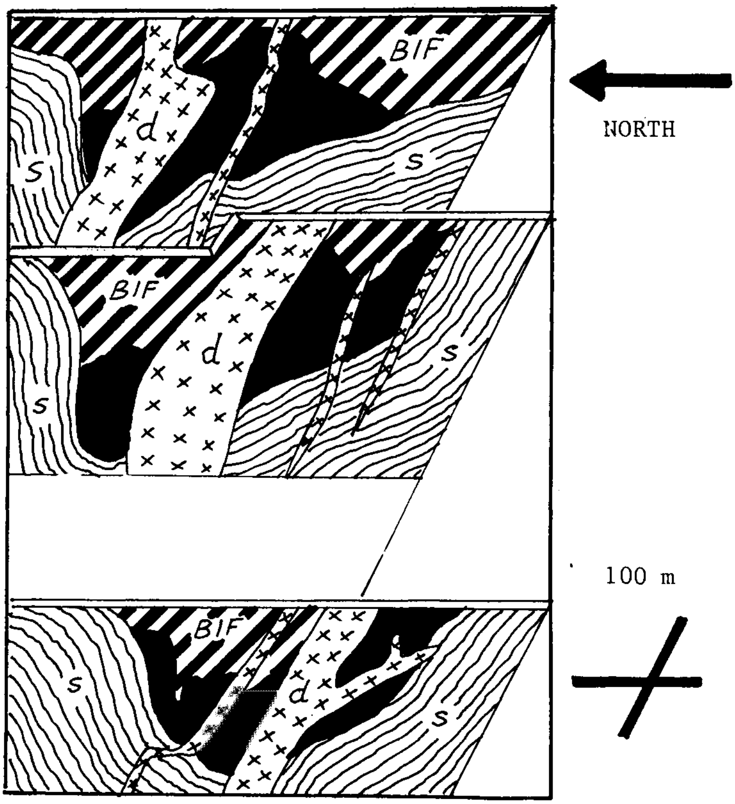


Fig. 32-8. Athens-Bunker Hill orebody, Marquette Fe district, Michigan; a set of isometric cross-sections showing the close association of diabase dikes (d) and "soft" Fe oxide ore (black), formed by residual enrichment of a lean Proterozoic oxide and carbonate banded iron formation; s=slate. After Gair and Tsu-Ming Han (1975).

contribution to the rich iron ore genesis was largely structural.

32.2.6. Placers derived from diabase dikes and sills

Diabase dikes and sills contributed ilmenite and Ti-magnetite to many placers and paleoplacers, but proximal occurrences of heavy minerals closely affiliated to parent diabase are rare. Nielsen (1973) reported the existence of sands containing 37-74% ilmenite in raised beaches in the Thule region, N.W. Greenland, adjacent to mafic dikes intruding Precambrian metamorphics.

"There is now general agreement that no single parent magma is responsible for the formation of alkaline rocks, since alkaline rocks occur in many petrological associations".
H. Sørensen, 1974.

CHAPTER 33

Alkaline Igneous Association

33.1. INTRODUCTION

33.1.1. General

The terms alkaline and alkalic rocks have different meanings to different investigators, and "the very definition of an alkaline rock is fraught with difficulty and controversy" (Currie, 1974; see also the historical review in the introductory chapters in Sørensen, ed., 1974). The brief definition stating that "alkaline igneous rocks are characterized by the presence of feldspathoids and/or alkali pyroxenes and amphiboles", either in the rock itself or in the chemical analysis recalculated into the C.I.P.W. norm, will be followed approximately here. To this have been added two categories of rocks transitional between the alkaline and calc-alkaline families that may lack the feldspathoids (peralkaline rhyolite/granite and feldspar trachyte/syenite associations).

The field of alkaline igneous petrography is burdened by a long list of rock names, many of them unnecessary (at least for the purpose of metal exploration). Fundamental rock class names (such as syenite, gabbro, phonolite) preceded by a qualifier, which in most cases is the name of a prominent mineral (e.g. nepheline syenite, analcite phonolite), have been used whenever possible here. The numerous rock names reflecting minor variations in accessory minerals, texture, petrology and local preference (such as tinguaite, foyaite, juvite, etc.) have been avoided and used only sparingly, mostly in cases where a certain variety controlled a particular mineralization. Whenever possible, the alkaline rock terminology outlined in Sørensen, ed. (1974) has been followed.

Strictly alkaline rocks (in the petrographic sense) are quite rare and their outcrop occupies no more than a few tenths of a percent of the present Earth surface. In most regions of concentrated occurrence (alkaline petrographic provinces) the alkaline rocks, often in the minority, are associated with alkali rocks (e.g. alkali basalts, those that contain 0-10% of feldspathoids), and also with tholeiitic and calc-alkaline rocks. The coexisting petrochemical kindreds cannot be clearly distinguished and many initially tholeiitic or calc-alkaline provinces often develop into alkaline provinces with the passage of time (e.g. Carmichael et al., 1974).

Compared with the plateau basalt association (Chapter 31), alkaline rocks are more localized and rarely form extensive bodies of uniform composition. In Cainozoic alkaline provinces, lava flows and pyroclastics are of limited areal extent and can usually be attributed to a discrete central volcano. Most of the alkaline volcanic provinces that have been described are wholly subaerial. Subaqueous equivalents have rarely been recognized and described although they do exist and could have interesting metallogenic implications.

The subsurface equivalents to alkaline volcanics occur as dikes, laccoliths, stocks and plutons. Simple, undifferentiated sills are rare, but ring dikes and composite ring complexes are common and characteristic. Layered alkaline intrusions comparable in terms of structure with the Bushveld (Lovozero, Ilímaussaq) are rare and controversial. Interaction of alkaline rocks with the environments into which they were emplaced is of variable intensity, ranging from zero to extensive alkaline metasomatism (fenitization) in the exocontact. Certain alkaline complexes are interpreted as being entirely of metasomatic origin, (for example those of the Urals Mts.). The influence of the environment on alkaline rocks in the endocontact is still imperfectly known and highly controversial, as are the effects of "ageing" (diagenesis and metamorphism), which may involve de-alkalization. Metamorphosed equivalents of the alkaline association are poorly known and rare.

Alkaline rocks are known that date from the Proterozoic age, although the majority are Phanerozoic. To prevent fragmentation, the Precambrian occurrences received only brief coverage in this chapter when warranted, and their more detailed description appears in Volume 2.

33.1.2. Geotectonic setting and origin

Like plateau basalts, alkaline igneous rocks are characteristic of (but not confined to) the highly stabilized continental crust (platforms, cratons). They appeared later in the geological record, when a sufficient quantity of such a crust had been generated. The actual emplacement of alkaline magmas into the continental crust, however, coincided with periods of extensional faulting (taphrogenesis, especially rifting) of variable intensity. Some peralkaline silicic rocks (e.g. comendites and granites) were emplaced as a consequence of the pre-rifting "epeirogenic doming" (Bowden, 1974). Certain bodies of alkaline rocks (e.g. kimberlites) initially required nothing more than a very minor crustal dilation, usually at an intersection of two prominent joint systems in the host rocks, to reach the surface. Others, such as the alkaline intrusions east of the Paraná Basin in Brazil (Fig. 33-1), were controlled by faults and narrow grabens. The most prominent alkaline provinces in the world are localized by major graben and horst systems (e.g. the East African Rift, Oslo Graben), which are members of the global rift system.

The belief that alkaline magmas originate at considerable subcrustal depth (between 40 and 100 km), in the mantle, is often

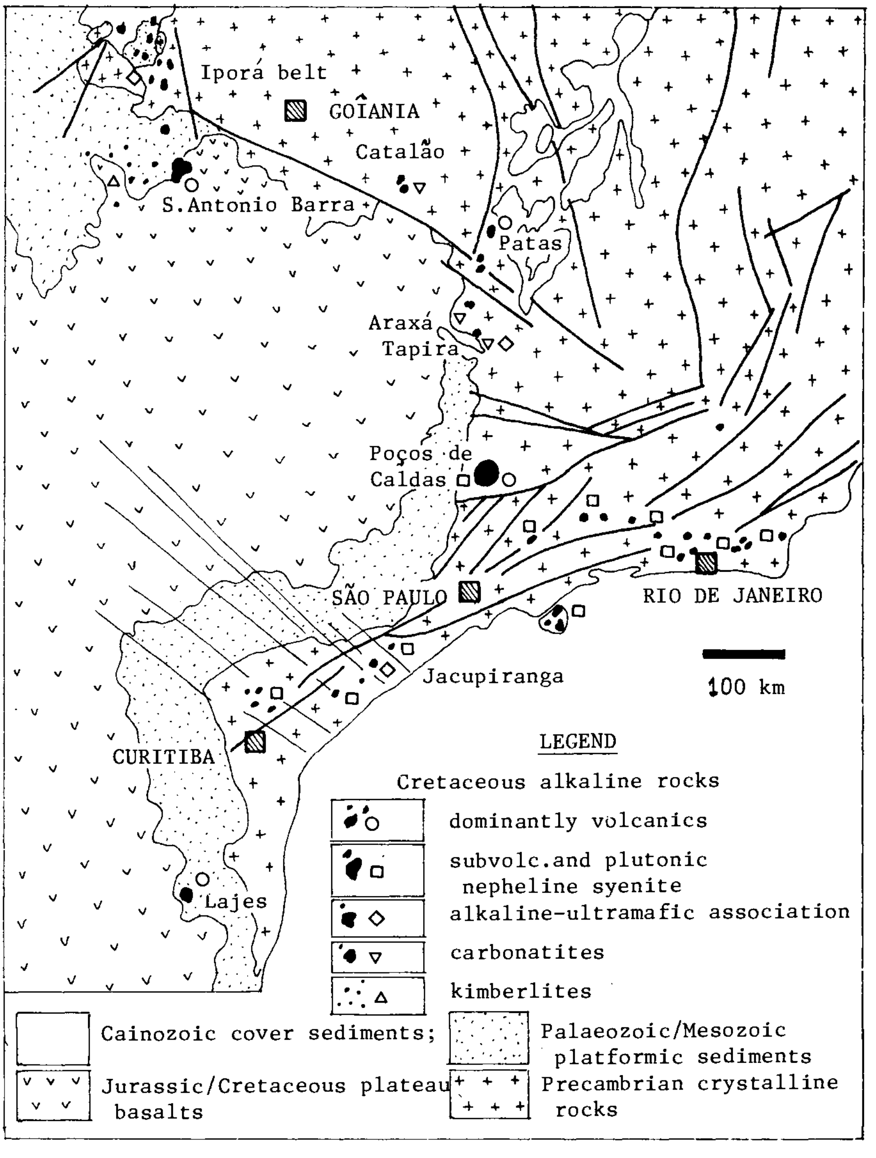


Fig. 33-1. The alkaline province of south-eastern Brazil (fringe of the Paraná Basin). From LITHOTHEQUE.

quoted in the literature (e.g. Carmichael et al., 1974; their Chapter 10). Bailey (in Harris and Bailey, 1974) concluded that felsic alkaline magmas are generated in the deep continental crust. The depth of derivation of alkaline rocks usually quoted is greater than the depth of derivation of tholeiitic magmas. The evidence of deep derivation is particularly compelling for kimberlites, rocks that often carry distinctive high-pressure minerals (e.g. diamond) as well as distinctive abyssal inclusions (garnet peridotite and eclogite).

The actual process of alkaline magma generation is now usually considered to be a partial melting of the mantle and/or the continental crust above "hot spots" (i.e., mantle plumes); compare Burke et al. (1981) for a review. Carmichael et al. (1974) suggested a considerable diversity of magmatic parentages, a variety of differentiation models and crustal contamination as agents of the alkaline lithogenesis.

33.1.3. Ore distribution and economic importance

The economic geology of all the alkaline rocks has been summarized briefly by Semenov (1974), and that of carbonatites alone by Deans (1966), Ginzburg et al. (1958), and others. Despite their very limited occurrence, the alkaline rocks as outlined in this chapter hold a virtual monopoly (over 90%) on the occurrence of niobium and the rare earths (about 35 Mt Nb; 42 Mt REE) and furthermore contain significant quantities of Zr,Ti,Ta and Th (about 200 Mt Ti, 250 Mt Zr, 1.5 Mt Th, 300 Tt Ta). The above tonnages are very unevenly distributed, the bulk being in few giant ore accumulations (e.g. Araxá, Lovozero, Ilímaussaq). Smaller but still significant quantities of Cu,Fe,Al, U,Be,Sn, Mo,Au,Ag, Pb,Zn, etc. are produced from, or are known to exist in, deposits affiliated with the alkaline rocks.

As a class, alkaline rocks appear to be highly mineralized, but the ore occurrence is selective. Carbonatites, that account for less than 0.01% of the area occupied by the alkaline association, contain the bulk (some 80%) of the economic metals listed above (that excludes the presently uneconomic, low-grade resource of Zr and some Ti). The intrusive alkaline equivalents are frequently ore-bearing, while the alkaline volcanics are rarely so. The predominantly volcanic alkaline provinces, such as the České Středohoří-Doupovské Hory region of western Czechoslovakia and the province of the East African Rift have, until recently, been dismissed as "barren" by the economic geologists. This notion is now slowly changing, thanks to new discoveries of metallic accumulations in sedimentary basins derived from the volcanics (e.g. the U-Zr infiltrational ores in northern Bohemia, Chapter 25); the utilization of new, low-grade materials for metal extraction (e.g. high-Ti and Al residual and reworked clays tested as a possible substitute of bauxite and a source of titanium) and the new, interesting data on metallogeny (e.g. the heavy metals dissolved or suspended in rift lakes) that may result in the discovery of new economic ore accumulations.

33.1.4. Major alkaline sub-associations and their mineralization

Occurrence of alkaline igneous rocks is highly nonuniform, ranging from single kimberlite pipes emplaced into platformic sediments and showing a high degree of individuality and separation from the host environmemt, to extensive volcanic-intrusive complexes composed of a wide variety of intermixed rocks that are not only alkaline. As a consequence, subdivision of the alkaline igneous association into sharply outlined sub-associations having a regional uniformity is difficult if not impossible. The petrochemical classifications of alkaline rocks (e.g. Currie, 1974) are beneficial mainly when used with small, homogeneous objects, ranging in size from hand specimens to small, uniform magmatic bodies. When exact classifications are applied to actual field areas, it is appreciated in most cases that although some local rocks qualify as members of a particular selected petrochemical class, other rocks (often in volumes exceeding the former) are members of different classes, many of which are not alkaline at all. This is well illustrated by the silicic peralkaline sub-association, popular with exploration geologists because of its affiliation with the "Nigeria-type" Sn provinces. The truly peralkaline members of this association in Nigeria (e.g. riebeckite granites), however, are in the minority in the field and rarely carry tin. Tin is associated with biotite granites that are little different from the "tin granites" of the plutonic association of orogenic belts, treated in Chapter 28.

The confusion resulting from "scale jumping" and the simplified designation of petrographically diverse provinces by names of certain rock groups alone is typical in geology and impossible to fully eliminate. The reader should bear this in mind. The nine subdivisions into which the alkaline association has been broken down are just convenient categories believed most suitable for a prospector. They overlap and are mutually transitional.

33.1.5. Alkaline provinces

This term is being frequently used in the petrographic literature (e.g. Carmichael et al., 1974; Sørensen, ed., 1974), but the "provinces" treated are not uniformly outlined and named. This is directly due to the virtual impossibility of outlining them accurately. The worldwide distribution of alkaline rocks ranges from relatively large, densely occupied regional occurrences of uniform geological age in which the ratio of alkaline to non-alkaline rocks approaches 50:50 (such as the Tertiary alkaline province of the Massif Central, France), to areally insignificant (0.X km^2) occurrences of kimberlite diatremes or dikes distributed over entire continents. Fig. 33-2 and Table 33-1 use a much looser form to indicate briefly

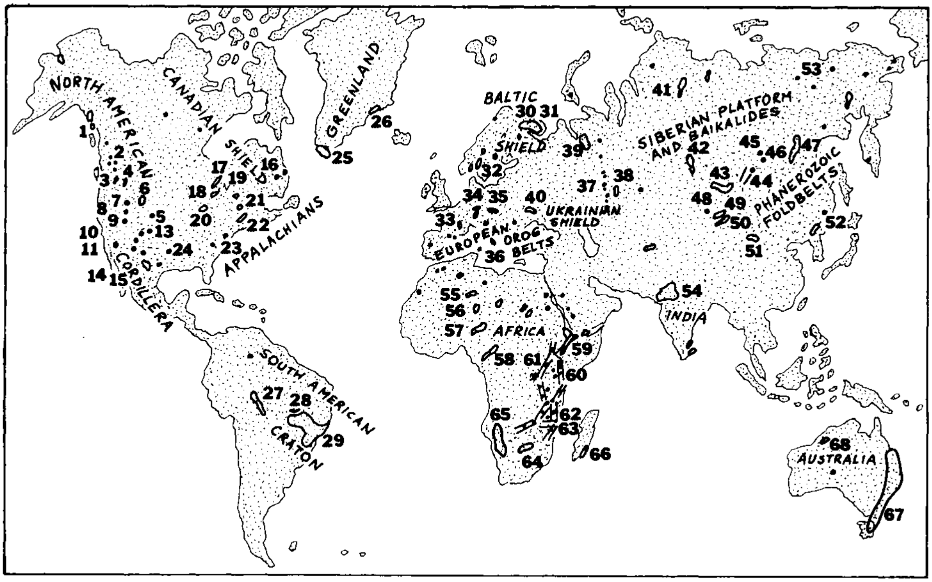


Fig. 33-2. Index map of mineralized alkaline occurrences and areas of the world, listed in Table 33-1.

Table 33-1. Principal areas of distribution of mineralized alkaline occurrences of the world (Figure 33-2)

NO.	AREA OR LOCALITY	AGE	ROCK ASSOCIATION EMPLACEMENT LEVEL	METALS IN ORE DEPOSITS
NORTH AMERICAN CORDILLERA				
1.	Bokan Mt., S.E. Alaska	Cr	A,s,p	U,Th
2.	Lonnie, C.Brit. Columbia	?	C,G,p,m	Nb
3.	Osoyoos-Penticton area, southern Brit. Columbia	Eo	B,D,v,s,p	U,Ag
4.	Crowsnest Volc.,Alberta	Cr	E,B,v,s	Cu,Mo
5.	Black Hills	T	C,A,v,s	Au,Pb,W
6.	Highwood Prov.,Belt Mts., etc., Montana	Eo	E,H,C,v,s,p	U,Pb-Ag,Au
7.	Libby, Montana	Cr?	F,p	Fe,V,Ti
8.	Lemhi Pass, Idaho, Montana	T	I,p	Th,REE
9.	Sawtooth Range, Idaho	T?	A,p	U,Ta,Nb
10.	Wet Mts., Colorado	Cm	D,G,p	Nb,REE,Th
11.	Powderhorn, Colorado	Cm	F,D,G,p	Ti,Fe,Nb, REE,Th
13.	Cripple Creek, Colorado	Mi	C,B,v,s	Au,Ag,Te
14.	Hopi reserve, Ariz.,N.Mex.	Pl	C,H,s	U,Cu

15.	Terlingua, Texas	T	C,D,A,v,s	Hg
CANADIAN SHIELD				
16.	Red Wine-Letitia, Labrador	1.5-1.6	D,G,p,m	Zr,U,Be
17.	Kapuskasing zone, Ontario	1.0-1.1 1.5-1.7	D,G,F,p	Nb,Fe,REE
18.	Port Coldwell, Ontario	1.1	B,D,p	Fe,Cu
19.	Nipissing Lake, Ontario	Cm	D,G,p,s	Nb,U
20.	Wausau, Wisconsin	Cm	B,D,p	Th,Zr
APPALACHIANS, ST.LAWRENCE GRABEN				
21.	Monteregian Hills and continuation, Quebec	Cr	D,F,G,s,p	Nb,REE
22.	White Mountains, N. Hampshire	D,Tr,J	D,B,A,p	U,Pb-Zn
23.	Elberton, Georgia	Or?	B,p	Mo,Cu
24.	Magnet Cove etc.,Arkansas	Cr	D,F,G,H,s,p	Ti,V,Nb, Al,REE
GREENLAND				
25.	Gardar Prov.(Ilímaussaq, Ivigtut)	1.25	D,A,G,v,s,p	Zr,REE,Nb Th,U,Be
26.	Werner Bjerge	Cr3-Tl	B,A,p	Mo,Pb-Zn
SOUTH AMERICAN CRATON				
27.	Rondônia-Velasco Province	0.94	A,p	Sn,Au
28.	Iporá belt, Goiás, Brazil	Cr	F,H,v,s,p	Ni
29.	Eastern fringe of Paraná Basin (Araxá,Poços de Caldas)	Cr	D,F,G,H,C,p,s,v	Nb,REE,U, Zr,Th,Al
BALTIC SHIELD				
30.	Kola P., Caledonian suite (Kovdora, Af:rikanda)	Cm-Or	F,G,p	Fe,Ti,Th REE
31.	Kola P.,Hercynian suite (Lovozero, Khibiny)	D	D,p	Zr,REE,Ti
32.	Oslo Graben, Norway	Pe	B,A,C,v,s,p	Fe,Mo,Pb
EUROPEAN OROGENIC BELTS				
33.	Auvergne, Massif Central, Fr.	Mi-Q	C,v	F
34.	Rhine Gr., Vogelsberg, Pfalz	Mi	C,D,G,v, rare s	Nb,F
35.	Bohemia, Silesia; Czechosl.	Mi-Q	C,D,E,H,v, rare s	Al,Ti,Pb
36.	Tuscany, Rome Prov., Pantelleria; Italy	Pl-Q	C,A,v,s	Hg,U
37.	Ural Mts., U.S.S.R.	D	D,I,p,m	Zr,Nb,REE
38.	Turgai Downwarp, Kazakhstan	D	F,D,G	Fe,Ti,U Nb,REE
39.	Timan Range, U.S.S.R.	D?	F,p	Fe,Ti
40.	UKRAINIAN SHIELD (Mariupol)	1.7-1.9	D,F,p	Ti,Zr,REE
SIBERIAN SHIELD AND BAIKALIDES				
41.	Meimecha-Kotui area	Pe-Tr	F,G,D,H,p,s	Ti,Fe,REE

Table 33-1 (continued). Principal areas of distribution of mineralized alkaline occurrences of the world (Figure 33-2)

NO.	AREA OR LOCALITY	AGE	ROCK ASSOCIATION EMPLACEMENT LEVEL	METALS IN ORE DEPOSITS
42.	Yenisei Range	PZ	D,F,G,p	Al,Nb,REE
43.	Eastern Sayan (e.g. Aksug)	PZ	D,A,B,p	Ta,Be,REE, Nb,U,Th
44.	N.E. Lake Baikal (Synuyr)	Cm,MZ	D,E,G,p	Fe,U,Nb
45.	Inagly, Aldan Shield		F,p	Fe,Pt
46.	Central Aldan district	MZ	F,D,p	Au,U,Pb
47.	Sette-Daban		G,F	Nb,REE
PHANER. FOLDB., SIBERIA, MONGOLIA				
48.	Kuznetsk Alatau, Minussinsk	Pe,MZ	D,A,p	Th,U,REE
49.	Eastern Tuva (e.g. Sangilen)	D-T	D,A,F,G,p,m	Nb,REE,Ta Th,U
50.	Northern Mongolia	D	D,p	Be,Zr,REE
51.	Southern Gobi, Mongolia	J	A,g	Ta,Nb,REE
52.	Sikhote Alin, Bureia Massif	J	F,D,G	Nb,REE
53.	E. Chukotka-W. Alaska	Cr?	D,A,C,p, less v,s	Ta,Be,Nb
54.	INDIA, Deccan Plateau	T	D	Al
AFRICA				
55.	Hogar (Ahaggar)	Cr-Q	C,B,v,s	Sn,U
56.	Aïr Massif, Niger	295	A,s,p,v	Sn,U
57.	Nigeria (Jos-Bauchi) etc.	J	A,C,B,p,s,v	Sn,Nb
58.	Benue, Cameroon	T,Q	A,C	Sn,Au
59.	Aden, Afar, Ethiopia	Mi,Q	C,G,H,D,v,s	Nb,REE
60.	Kenya, Uganda, Tanzania	Mi,Q	C,G,H,D,v,s	Nb,REE
61.	Virunga, Toro-Ankole, Kivu	Mi-Q	E,v	F
62.	N.W. Malawi (Ilomba)	650	D,p	Nb
63.	S. Malawi (e.g. Lake Chilwa)	J-Cr	A,D,G	Nb,REE
64.	Pilansberg, Transvaal	Pt	D,p	REE,Th
65.	Erongo, etc.,Namibia	J,Cr	A,B,D,G,p,s	Sn
66.	Southern Madagascar	Or	A	Ta
AUSTRALIA, OCEANIA				
67.	E. Australian volc. prov.	Eo-Mi	C,B,D,v,s,p	Fe,Ti
68.	W. and E. Kimberleys		E,H	

ABBREVIATIONS:

DOMINANT ROCK ASSOCIATION: A=peralk. granite or rhyolite; B=syenite, trachyte; C=nephelinite, basalt, phonolite, tephrite, trachyte; D=nephel. syenite, alkal. gabbro; E=potassic alk. rocks; F=alkaline ultramafics; G=carbonatites; H=kimberlites; I=subtle alkaline rocks

DOMINANT EMPLACEMENT LEVEL: v=volcanic; s=subvolcanic; p=plutonic; m=metamorphosed and tabulate the distribution of the important areas containing alkaline rocks in the world.

33.2. DOMINANTLY VOLCANIC ALKALINE PROVINCES AND OCCURRENCES

33.2.1. General

Alkaline volcanics are covered by a voluminous petrological literature (e.g. Carmichael et al., 1974) but they are rarely mentioned in economic geology textbooks and compilations because, in comparison with the intrusive alkaline equivalents, they appear virtually to be devoid of metallic deposits. Most alkaline volcanic provinces are located on old "stable" cratons and controlled by extensional tectonism, particularly rifting. Most of the volcanic piles, however, lie on rift shoulders (particularly on uplifted horst blocks) or near principal faults, rather than in the rift graben itself (e.g. in central Europe; Wimmenauer, 1974). Isolated alkaline volcanic centres have been recorded in mobile belts (e.g. the North American Cordillera), where they often merge with the dominant calc-alkaline volcanics (e.g. Cripple Creek, Colorado). The occasional alkaline volcanic occurrences in the oceanic domain were treated in Chapter 4.

Intracratonic alkaline volcanics have been almost exclusively emplaced subaerially and attacked by erosion shortly after their emplacement. The erosion exposed the subvolcanic and plutonic levels and removed a considerable portion of the volcanics in the geologically older terrains, so that in the pre-Tertiary alkaline provinces the intrusive equivalents are dominant and are treated separately in the following sections. As a consequence, most representatives of alkaline volcanics are late Cainozoic and correspond in their style of occurrence, freshness, etc. to the "gray basalts" reviewed in Chapter 31.

Alkaline volcanics rarely occur in isolation. In most extensive continental volcanic provinces the older, "main phase" of volcanism starts with alkali (subalkaline) basalts, the mafic members of the tholeiitic and calc-alkali magma series (Wilkinson, 1974). Clinopyroxene, plagioclase ("normal" basalts) and clinopyroxene, plagioclase, olivine (olivine basalts) are the most common rocks. Alkaline basalts (those with feldspathoids: basanite, tephrite, nephelinite, leucitite, etc.) appear later, preferentially arranged aroud discrete centres. The felsic rocks show a similar succession. Earlier, "normal" (without feldspathoids) trachytes are succeeded by light-coloured feldspathoidal rocks, mostly phonolites. Most petrographic provinces containing abundant alkaline volcanics are essentially bimodal, rich in mafic and felsic phases but lacking significant quantities of intermediate andesites, dacites and equivalents.

In the recent alkaline volcanic terrains, lavas and pyroclastics are approximately equally common. In the geologically older terrains, pyroclastics have been described substantially less frequently than alkaline lavas, but this could, to some degree, be due to the chemical instability of feldspathoids. Feldspathoids in the porous pyroclastics are soon converted into zeolites or clay minerals by weathering and diagenesis and disappear. Feldspar persists much longer. Many trachytes and phonolites, moreover, have been emplaced under a thin cover of usually soft platformic sediments acting as domes with "endogenic" structures (Sørensen, ed., 1974), without reaching the surface. From there they have been exhumed over a period, short in geological terms and are often indistinguishable from true surfical lavas.

Breccia-filled volcanic necks, diatremes, maars, and similar types of eruptions are common. Subvolcanic bodies (dikes, sills, laccoliths) and rare intrusive stocks are also exposed in Tertiary alkaline volcanic terrains. Buried intrusive equivalents are to be expected in the subsurface of all volcanic terrains, and such bodies seem to have maintained hydrothermal activity resulting in zones of alteration and mineralization, sometimes hosted by rocks of the volcanic level or by older, non-alkaline rocks. Even if no exposures of the subvolcanic and plutonic rocks are present among the alkaline volcanics, samples of these together with samples of the basement, can be found as xenoliths in lavas or as "exotic" components in pyroclastics.

33.2.2. Trace metal geochemistry and mineralization

Certain alkaline volcanics have a high alumina content (e.g. the phonolite from Špičák near Most, N.W. Czechoslovakia, 23.01% Al_2O_3, Kopecký in Svoboda, ed., 1966; phonolitic pumice tuff from the Laacher See district, West Germany, up to 23.09% Al_2O_3, Wimmenauer, 1974), which makes these rocks potential sources of aluminium of the future. In the meantime, the high Al_2O_3 content of phonolites and trachytes together with the lack of quartz, facilitates the formation of high-alumina residual clays and bauxites, themselves used for aluminium extraction. Titania is also highly enriched in some alkaline volcanics. There is 5.72% TiO_2 in the nepheline leucitite from Stráž nad Ohří, N.W. Czechoslovakia (Kopecký in Svoboda, ed., 1966). This content, however, although substantially higher than the TiO_2 content in many heavy mineral beach placers, cannot be recovered economically using the existing technology. Further TiO_2 enrichment took place in saprolitic phonolites and in residual clays, for example, in the Chomůtov region of Czechoslovakia and an industrial process to recover this titania could become available in the near future.

Alkaline volcanics are enriched in the same suite of trace elements as their deep-seated equivalents (Zr, REE, Nb, Th, etc.), but the enrichment appears, on average, to be about one order of magnitude lower (e.g. 0.02% ZrO_2 in phonolite, Špičák near Most) and discrete accessory minerals other than zircon and melanite (Ti-garnet) are rarely recognizable. The coarse crystalline, olivine rich protoenclaves common in olivine basalts and usually interpreted as being samples of the undepleted mantle, are high in trace Cr (1-5% Cr_2O_3). The Cr is bound in chrom-diopside and Cr-spinels, but no cases of additional Cr enrichment have been reported.

As mentioned earlier alkaline volcanics have a reputation, among exploration geologists, of being poor targets for metalliferous exploration. Although this is generally true, there are exceptions (e.g. Cripple Creek, Colorado; over 600 t of gold produced). Most of these exceptions are hydrothermal ores generated by convective systems driven by the heat of the subsurface intrusions. Cripple Creek, despite being hosted by, and affiliated to, alkaline and subalkaline volcanics and subvolcanic intrusions (phonolite, syenite), is comparable in all other respects with the calc-alkaline volcanic-intrusive complexes of the orogenic belts hosting the epithermal vein and stockwork systems (as in Nevada, W. Rumania, etc.), treated in Chapter 26.

33.2.3. Principal mineralization styles (Fig. 33-3; Table 33-2)

METALS OR MINERALS DISPERSED OR DISSEMINATED IN ALKALINE VOLCANICS AND PYROCLASTICS

Known examples of this style are few and heterogeneous. Barbosa (1967) described several occurrences of Cretaceous platiniferous (0.8-4 ppm Pt metals) melteigitic tuffs and re-sedimented volcaniclastics, in the Mata da Corda Plateau, M.G., Brazil. The platinum is probably finely disseminated together with perowskite. The host volcaniclastics are mildly phosphatic and carbonatic, suggesting carbonatite affiliation.

Some alkaline volcanics and pyroclastics are radioactive, for example in the Agur Lake area near Penticton, British Columbia (Anonymous, 1979a). The highest U and Th values (over 100 ppm U, 500 ppm Th) are associated with biotite and clay-altered fault zones in Tertiary crystal tuffs and syenites which are probably comagmatic suggesting epigenetic hydrothermal mineralization. In the Kaiserstuhl (West Germany) phonolites, opal veinlets and coatings filling fractures, in places contain 0.2-0.9% U (Wimmenauer, 1966).

HOT SPRINGS PRECIPITATES

Hot springs, the highly diluted, near-surface hydrothermal solutions, are commonly discharged along faults in both currently active and formerly active (e.g. Tertiary) volcanic areas. Within the East African Rift system, numerous hot springs leach trace elements from the young volcanics (as well as from their host rocks). The springs that discharge on the bottom of rift lakes, contribute to the high metal content of some lake waters and bottom sediments (e.g. Lake

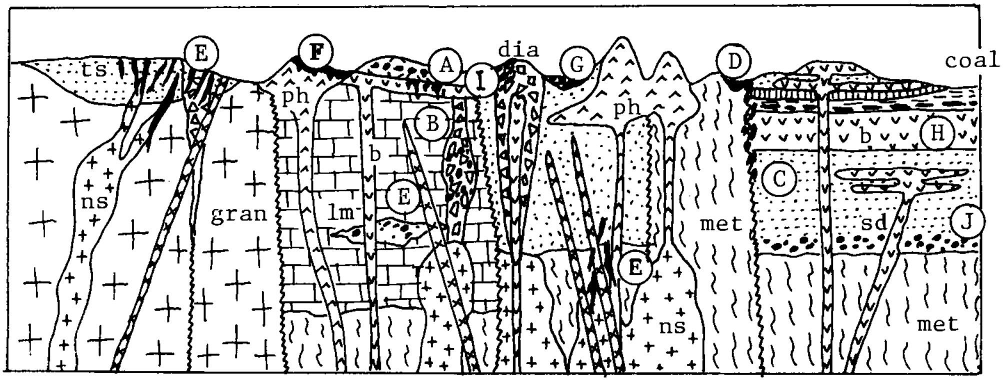


Fig. 33-3. Principal mineralization styles in continental alkaline volcanic terrains (see Table 33-2 for an explanation of the letter codes). Abbreviations: b=basalt; dia=diabase; gran=granite; lm=limestone; met=metamorphics; ns=nepheline syenite; ph=phonolite; sd=sandstone; ts=tuffaceous sandstone.

Table 33-2. Principal mineralization styles in continental alkaline volcanic terrains

(A)	Metals or minerals dispersed or disseminated in volcanics and pyroclastics (e.g. Pt)
(B)	Metallic minerals on fractures in volcanics (e.g. U)
(C)	Hot springs precipitates on the surface or along faults (U,F,Ba)
(D)	Continental lakes with anomalous dissolved metal content in waters or in bottom sediments (F,Fe,Mn,Zn)
(E)	Hydrothermal veins, stockworks, mineralized breccias, replacements (e.g. Cripple Creek); X0 Tt Pb,Zn; 620 t Au; 50 t Ag; 4.5 Tt Hg
(F)	Metalliferous weathering crusts; bauxite (20 Mt Al), Ti-clays
(G)	Coluvial or alluvial sands or gravel with detrital ore minerals reworked from alkaline volcanics (X Mt Ti, X0 Tt Zr, low-grade)
(H)	Reworked clays, claystones, shales (Al, Ti potential)
(I)	U infiltrations in sediments and volcanics in diatremes
(J)	Infiltration U-Zr deposits in sandstones intruded by melilitic volcanics (N. Bohemia)

Malawi, Fe; Lake Kiwu, Zn; see Chapter 30).

In the Děčín, Teplice, Duchcov region in the Sub-Erzgebirge Graben, N.W. Czechoslovakia (Sattran et al., 1966), recent hot springs have generated numerous small veins and veinlets of quartz, fluorite and barite, filling fissures in Permian rhyolites and Cretaceous sandstones. Some veins contain small quantities of pyrite, galena, sphalerite and sooty U oxides. The dark purple fluorite has a high U content, and also carries 0.01-0.03% Be and REE (Bernard et al., 1969). The small veins and impregnations of Mn oxides running along fractures in Tertiary trachyte at Špičák near Teplá (N.W. Czechoslovakia), are also attributed to hot springs activity.

HYDROTHERMAL VEINS, STOCKWORKS, REPLACEMENTS

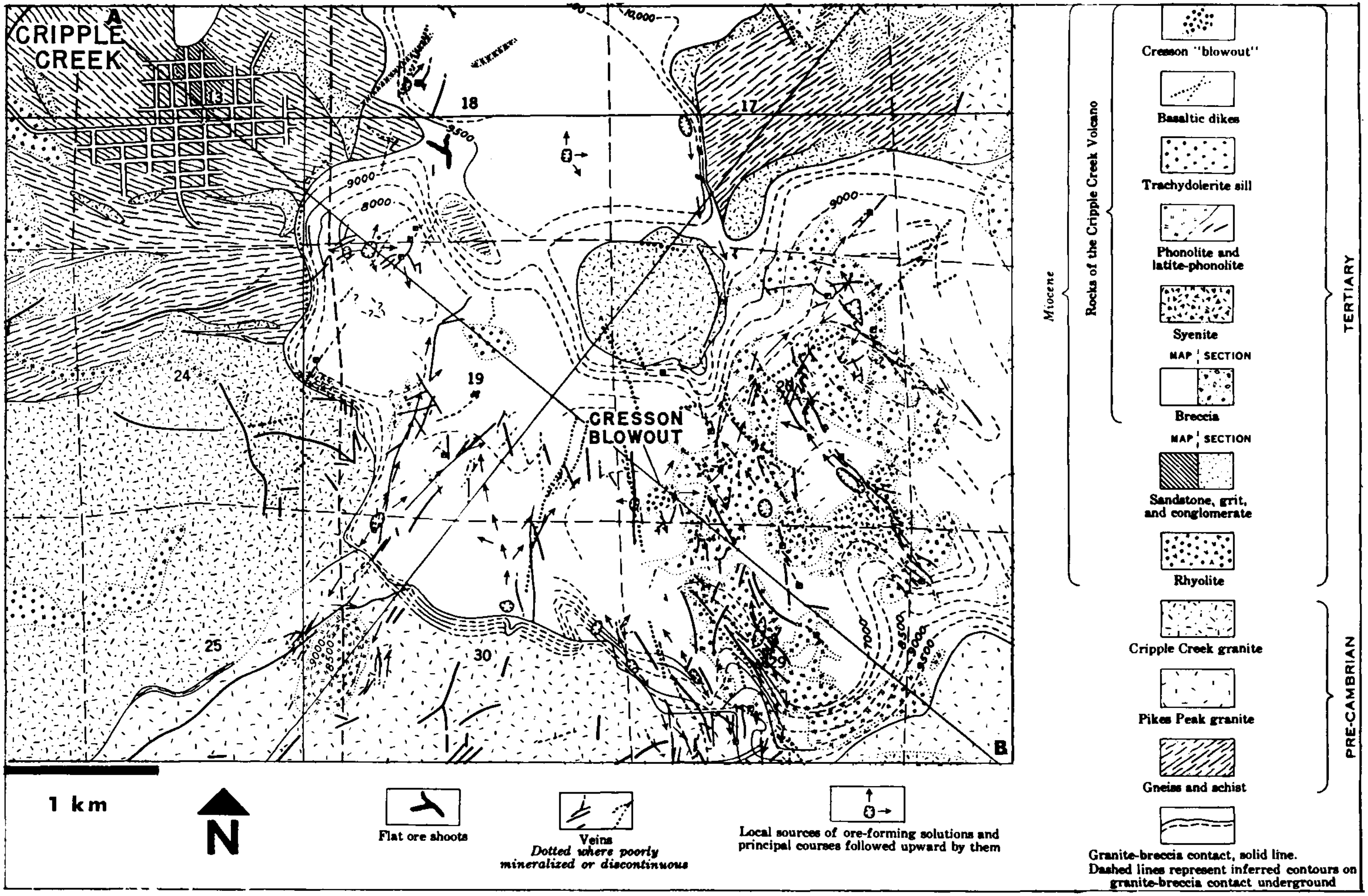
Hydrothermal ores in alkaline volcanic terrains mostly formed at subvolcanic or plutonic levels of burial, so a substantial depth of erosion was needed to expose such mineralizations. By analogy with the calc-alkaline volcanic provinces (e.g. the San Juan Mountains, Colorado; Chapter 26), the intrusive equivalents rather than the surficial volcanics are credited with driving the metal leaching, transporting and depositing hydrothermal systems. The hydrothermal activity was most productive in the vaning stages of the magmatic cycles.

In the classical, intracratonic provinces of alkaline volcanism (e.g. Auvergne, Vogelsberg, České Středohoří, East African Rift), metalliferous veins are exceedingly rare. In Roztoky nad Labem, České Středohoří Mts. (N.W. Czechoslovakia), inhomogeneous late Tertiary syenodiorite stock is emplaced into Cretaceous sediments and cut by numerous alkaline dikes (bostonite, monchiquite, etc.). The intrusion is enveloped by high temperature metasomatites (wollastonite, epidote, grossularite skarns) and intersected by three parallel N.W.-trending fissure veins. The veins are filled by quartz, barite, pyrite, Ag-rich galena, and high-Ga and In sphalerite (Kopecký, Chrt and Losert in Krutský, ed., 1964). The available ore tonnage probably does not exceed a few tens of thousands of tons of ore.

Scattered mineralized Au,Ag,Hg, etc. occurrences associated with Tertiary transitional to alkaline volcanics, subvolcanic and plutonic intrusions are located in the Cordilleran foreland (e.g. Black Hills, Little Rocky Mountains, Judith Mountains, Little Belt Mountains, etc., in Montana and South Dakota, reviewed later) and in the Cordilleran frontal belt (e.g. Cripple Creek, Colorado; Terlingua, Texas).

The Cripple Creek district (Koschmann, 1949; Lovering and Goddard, 1950; Fig. 33-4), has produced about 596 (or 620) t Au and 6 t Ag from a large number of high-level, high-grade hydrothermal bodies. It is located in an approximately elliptical Miocene fault-bound basin surrounded by Paleozoic crystalline rocks. The basin is filled by more than 1,000 m of water-laid sediments of mixed provenance (epiclastic detritus derived from the Proterozoic basement and volcaniclastics produced by explosive volcanism in the area contemporary with the basin subsidence) and intruded by dikes, sills, small plugs and necks of phonolite, phonolite with plagioclase phenocrysts and syenite, as well as alkali dike rocks. Undersaturated basalt cements a mineralized elliptical heterogeneous breccia pipe in the Cresson mine.

The Cripple Creek ore deposits are (1) simple veins or fissure veins; (2) irregular stockwork and impregnation deposits in shattered rocks and (3) pipe-like rubble or corroded fragments coated by ore



A
CRIPPLE CREEK
13
18
17
19
24
25
30
CRESSON BLOWOUT
B
1 km
N
Flat ore shoots
Veins
Dotted where poorly mineralized or discontinuous
Local sources of ore-forming solutions and principal courses followed upward by them
Cresson "blowout"
Basaltic dikes
Trachydolerite sill
Phonolite and latite-phonolite
Syenite
MAP | SECTION
Breccia
MAP | SECTION
Sandstone, grit, and conglomerate
Rhyolite
Cripple Creek granite
Pikes Peak granite
Gneiss and schist
Granite-breccia contact, solid line.
Dashed lines represent inferred contours on granite-breccia contact underground
Miocene
Rocks of the Cripple Creek Volcano
TERTIARY
PRE-CAMBRIAN

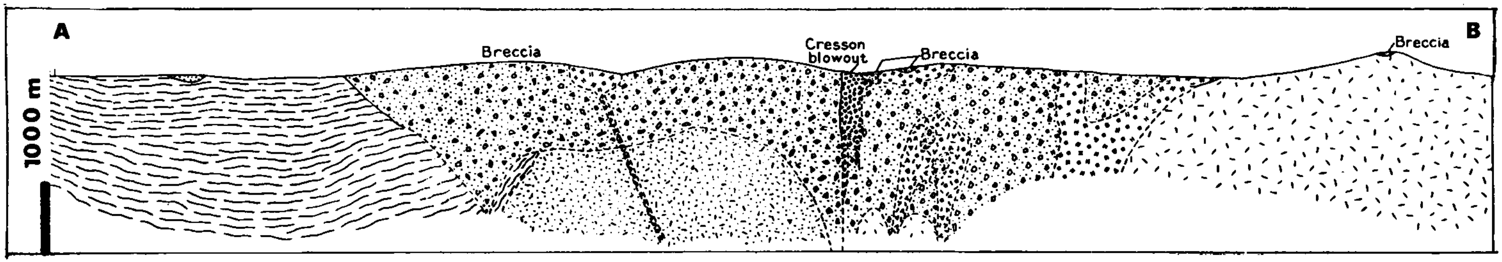


Figure 33-4. Map and section across the Cripple Creek, Colorado, sedimentary basin and volcanic-intrusive centre, showing the distribution of hydrothermal gold mineralization. The Cresson Blowout is a heterogeneous breccia of phonolite and dike rock fragments in a dense matrix of alkaline basalt and basaltic tuff. It is sericite-pyrite altered and hosts several hydrothermal veins. From Lovering and Goddard (1950).

minerals. The principal gangue and ore minerals are chalcedonic and cherty quartz, minor fluorite, pyrite, adularia, carbonates, barite, galena, sphalerite, native gold, Au-Ag tellurides and cinnabar. The wallrock alteration is slight. It is predominantly propylitization, argillization, carbonatization and bleaching.

In the Terlingua field, Texas (4.9 Tt Hg; Yates and Thompson, 1959; compare also Chapter 26), a variety of mercury ore styles is hosted by Mesozoic carbonates capped by continental volcanics and intruded by post-Oligocene dikes, sills and plugs of analcite gabbro and syenite, nephelinite, aegirine-riebeckite rhyolite and trachyte. The most common cinnabar orebodies are located in limestone and/or clay residue after carbonate dissolution, and in carbonate-clay breccia pipes. Only one locality is hosted by an intrusive rock. The ore is epigenetic and is attributed to the hydrothermal phase of the sodic alkaline magmatism.

WEATHERING CRUSTS

Alkaline volcanics lacking quartz (e.g. phonolite, trachyte) are very favourable substrata for the generation of low-iron residual bauxites (e.g. in the Poços de Caldas complex, Brazil). The relative scarcity of occurrences that have actually been recorded is due to the general scarcity of phonolites in the humid tropical belt.

Bauxitic residuals formed over alkaline volcanics, however, are not confined to the present tropical belt. Strnad (in Krutský, ed., 1964) described an 8 m thick regolith of middle Miocene age, formed over sodalite trachytes at Mariánská Hora near Ústí nad Labem, N.W. Czechoslovakia. The basal unit of the weathering profile is a grayish-green saprolite with a trachytic relic texture, some 2-3 m thick. It is abruptly topped by a zone of alternating white and red laterite which is 8 m thick. The laterite contains 43.47% Al_2O_3 and corresponds to a bauxitic claystone in which about one third of the Al_2O_3 is bound in gibbsite and the rest in kaolinite.

At other localities in N.W. Czechoslovakia (e.g. Braňany in the Chomůtov coal basin), Tertiary saprolite over kaolinized pohonolite in the footwall of a brown coal, contains up to 30% Al_2O_3 and has a a high TiO_2 content. There, kaolinite is the dominant clay mineral and gibbsite occurs only as an accessory. The material was tested as a possible aluminium source.

In the tropical regolith topping the occurrence of platiniferous tuffs near Mata da Cordo, Brazil (Barbosa, 1967), small quantities of Pt have accumulated in the limonitic "canga" (=ferricrete).

In arid regions, calcrete is often developed over young volcanics and it may cement pyroclastics (e.g. in the Lashain Hill, Ngorongoro crater and elsewhere in Tanzania). The true, groundwater-precipitated calcretes may host U deposits. Some "calcretes", however, may be carbonatite-related tuffs.

ORES IN SEDIMENTS FORMED BY REWORKING OF THE METALS OR MINERALS IN ALKALINE VOLCANICS

Detrital zircon derived from a variety of alkaline volcanic and subvolcanic bodies is present in small quantities (around 1%) in the Pleistocene pyrope-bearing colluvial gravels in N.W. Czechoslovakia (near Třebenice). The alkaline volcanic centres of N.E. New South Wales and S.E. Queensland, contributed a portion of the ilmenite, rutile and zircon recovered from the eastern Australian beach sands.

The Miocene sedimentary claystones in the footwall of brown coal in N.W. Czechoslovakia (Most-Chomůtov Basin; Sattran et al., 1966) contain 30-40% Al_2O_3, 4-15% TiO_2 and 0.2-0.4% V, and are expected to be mined and processed as an ore of these metals in the near future. The claystones formed by reworking of phonolite regoliths, followed by an additional metal enrichment during sedimentation and by diagenesis in freshwater lakes.

In the Hopi Buttes area, N.E. Arizona (Shoemaker, 1976; Figures 33-5 and 33-6) numerous, partly eroded maar-type Tertiary paleovolcanoes occur, associated with alkaline basaltic flows and tuffs. They were partly emplaced in a shallow Pliocene lake and a chaotic mixture of volcanic ejecta and lake sediments (siltstone, claystone, limestone) formed within and in the vicinity of the volcanic vents. In this setting small infiltrated uranium occurrences are located.

The Quaternary Rome volcanic province, central Italy (trachyte, latite, tephrite lavas, ignimbrites, volcanic fluviolacustrine deposits), was reviewed recently by Kimberley (1978a). The volcanics are enriched in U and Th by a factor of about ten above the clarke, and both metals are being actively redistributed by the action of hot springs, by CO_2 and H_2S-rich gas seepages and by groundwater. At the Sabatini deposit, dispersed uranium (about 500 ppm U) occurs in pyrite and marcasite lenses peneconcordant with bedding of kaolinized and silicified felsic pyroclastics. The mineralized layers have a total thickness of 5-10 m over an area of approximately 1 km^2.

Syka et al. (1978) described an unusual variety of a "sandstone U deposit" (Chapter 25) from the Stráž pod Ralskem area, Czechoslovakia, enriched in Zr (in baddeleyite). The zirconium was probably contributed by Miocene Zr-rich melilithic rocks in the area.

33.2.4. České Středohoří Mts., N.W. Czechoslovakia, as an example of a Tertiary alkaline volcanic province and its mineralization

České Středohoří (formerly Böhmische Mittelgebirge; Kopecký in Svoboda, ed., 1966; Wimmenauer, 1974; Fig. 33-6) is a N.E.-trending belt of Tertiary subalkaline and alkaline volcanics and minor intrusive bodies located in the northern part of the Bohemian Massif. The bulk of the Teriary magmatic rocks are controlled by the Sub-Erzgebirge Graben which is approximately 30 km wide, now reversed into an automorphic horst. The volcanics intrude and overlie upper

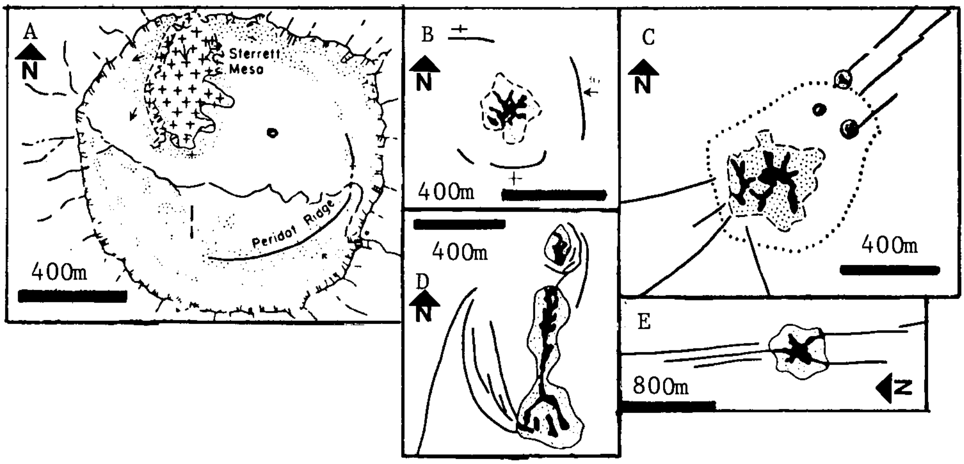


Fig. 33-5. Selected volcanic necks in the Navajo-Hopi fields, Arizona and New Mexico, U.S.A. (A) Buell Park, arcuate dike of leucite minette; other dikes of minette; lava cap on Sterrett Mesa ends southward in a depression among pyroclastic rocks; tuff-breccias, stippled. (B) Tuff-breccia neck, 8 km N. of Flying Butte, Hopi country, rises through horizontal Tr shales and is bordered by thin dikes of monchiquite; diagrammatic. (C) Shiprock; neck of minette tuff-breccia and dike of minette. (D) Boundary Butte, similar neck bordered by arcuate, vertical dikes. (E) Wildcat Peak, tuff-breccia necks associated with dikes of alnöite, monchiquite and related rocks. From Hunt (1956).

Cretaceous platformic sediments (quartz arenite, marl, claystone) and overlap a Tertiary brown coal-bearing sequence along the N.W. margin of the horst. The physiographically distinct core of the volcanic province (rounded and conical hills, exhumed necks, dikes) extends for about 80 km, but scattered magmatic occurrences including one major large composite paleo-volcano (Doupovské Hory), cover the entire northern half of the Bohemian Massif.

The volcanics belong to three eruptive phases (lower Miocene, middle Miocene and late Pliocene-Pleistocene), of which the first phase generated the bulk. The rocks are extremely variable compositionally, ranging from kimberlite to alkaline trachyte. Olivine basalts, trachytes and phonolites are the most widespread and conspicuous. The rock outcrops are abundant and generally fresh, and the region has been studied in considerable detail petrographicaly.

Metallic deposits directly hosted by the volcanics and their intrusive counterparts are extremely rare and only one locality (Roztoky, Pb,Zn,Ag veins) has ever been mined or explored. The residual and transported high Al and Ti clays derived from phonolites represent a large alternative resource of these metals for the future.

Indirectly associated ores are represented by the economically

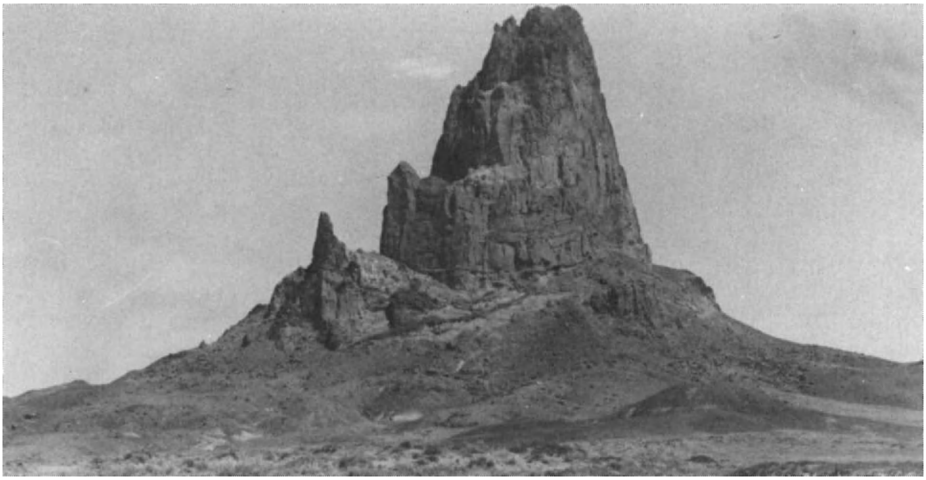


Fig. 33-6. Shiprock Butte, northern Arizona; eroded neck of minette tuff-breccia and dikes.

important SUV infiltration deposits formed in an aquifer at the base of the freshwater Cretaceous sandstones. In the east (Hamr, Mimoň) several alkaline plugs, necks and dikes pierce the uranium field but contribution, if any, of the Tertiary magmatism to formation of the U deposits, is unclear. The volcanics, however, probably supplied the Zr to form local baddeleyite and zircon-rich bodies. In the north-west (near Teplice), modern hot springs and precipitates of Tertiary hot springs (fluorite, barite, minor base metal sulphides) have formed contemporaneously with the infiltration uranium ores.

33.3. PERALKALINE GRANITE-RHYOLITE ASSOCIATION

33.3.1. General

Peralkaline silicic rocks (granites and rhyolites) have a molecular excess of alkalies over alumina, which sets them slightly apart from their more widespread calc-alkaline equivalents. In terms of petrochemistry, geotectonic setting and metallogeny, this class of rocks bridges the gap between alkaline and calc-alkaline felsic associations. Bowden (1974) has prepared a brief summary of peralkaline silicic rocks, and Murthy and Venkataraman (1964) discussed their global distribution. Peralkaline granites and peralkaline rhyolites (named comendite and pantellerite in the petrologic literature) are the most common members of the association.

Most of the granites are leucocratic rocks containing K-feldspar (usually perthite), albite, quartz, aegirine and

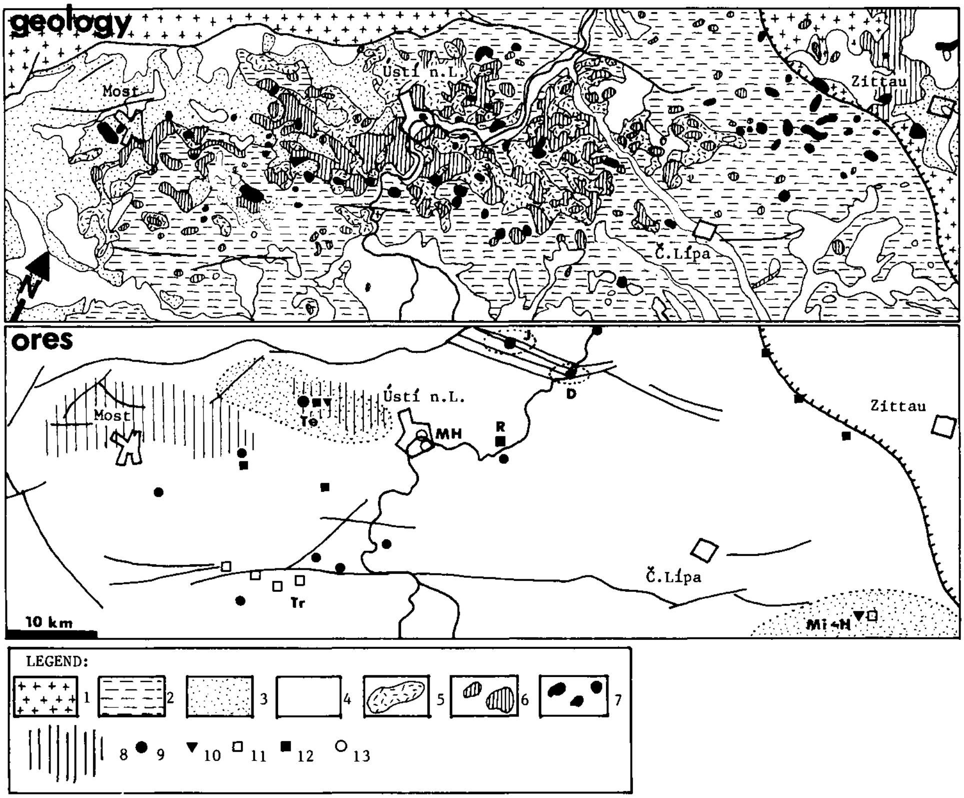


Fig. 33-7. České Středohoří Mountains, N.W. Czechoslovakia, geology and ore distribution. GEOLOGY: 1=Pe and older crystalline basement; 2=Cr_3 sediments; 3=T sediments; 4=Q unconsolidated sediments; 5=Mi volcanics, dominantly pyroclastics; 6=mafic lavas (basalt, nephelinite, tephrite, etc.); 7=felsic lavas (trachyte, phonolite). ORES: 8=High Al,Ti claystones, Most and Chomůtov areas; 9=fluorite veins, replacements; Te-Teplice; J=Jílové; D=Děčín; 10=infiltration U deposits in Cr sandstones; Mi-H=Mimoň, Hamr; 11=Zr ores, baddeleyite associated with U; Tr=Třebívlice, zircon in pyrope gravels; 12=Pb,Zn,Ag occurrences; R=Roztoky; 13=gibbsite, kaolinite residual clay; MH=Mariánská Hora. Simplified after Geological Map of Czechoslovakia 1:500,000 and Chrt and Bolduan (1966).

arfvedsonite-riebeckite as the principal minerals. The granites crop out in subvolcanic ring structures or as small stocks and massifs. The peralkaline rhyolites form lavas, tuffs or glass (obsidian) bodies, megascopically indistinguishable from calc-alkaline rhyolites. Quartz syenites, syenogabbros, gabbros and alkali basalts are sometimes associated, as are calc-alkaline biotite granites and muscovite-biotite leucogranites.

Most of the peralkaline silicic occurrences treated in this section are located in cratons, typically along structural domes of "epeirogenic" origin, marking the initial stage of tectonomagmatic activation (e.g. Jos, Aïr Mountains, etc., in W. Africa). Other occurrences are in or near intracratonic rifts (e.g. in Kenya, Ethiopia), or along extensionally faulted and attenuated continental margins underlain by a thick continental crust (e.g. Great Basin, Nevada). The rest is in orogenic belts, typically underlain by ancient sialic blocks.

Bowden (1974) discussed the origin of the peralkaline silicic magmas and concluded that while these rocks have their place in the evolutionary model of continental rifts, there is no unequivocal evidence to determine whether they formed by differentiation of a mantle-derived basaltic parent magma or by partial melting within the continental crust.

33.3.2. Trace metal geochemistry and metallogeny (Table 33-3, Figure 33-8)

Peralkaline silicic rocks are moderately to strongly enriched in some lithophile metals (Be, 6-56 ppm; Ga, 28-45 ppm; La, 95-580 ppm; Nb, 69-670 ppm; Sn, 5.7-52 ppm; Th, 17-23 ppm; Y, 73-490 ppm; data for peralkaline glasses, believed to correspond closely to the composition of the parent magmatic melt; Bowden, 1974). They are also high in fluorine (0.18-1.30% F). The Nigerian riebeckite granites contain 45 ppm Ga, 145 ppm La+Yb, 350 ppm Nb, 1,330 ppm Zr, 30-150 ppm Sn, 3-30 ppm Be and 0.76% F (MacLeod et al., 1971). These metals are contained either in the lattice of silicates, such as amphibole in the Nigerian albite-riebeckite granites (Olade, 1980) and biotite in biotite granites, or they form their own accessory minerals: pyrochlore and zircon in riebeckite granite or columbite and cassiterite in biotite granite.

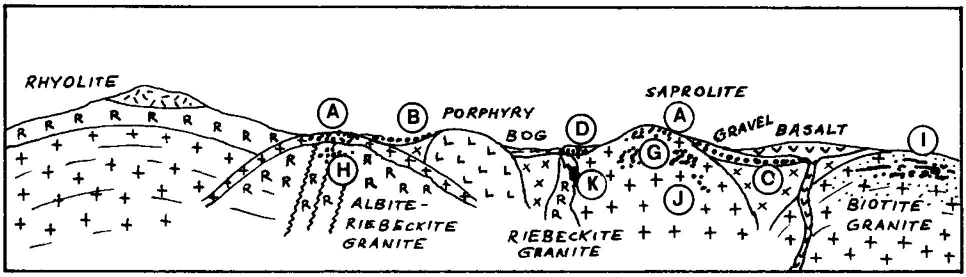
The trace Sn and Nb contents in "ordinary" granites, however elevated compared with the clarke, do not make ore, not even in the deeply weathered regions such as northern Nigeria, where resistate cassiterite and columbite accumulate in eluvial and alluvial placers. The dispersed accesory minerals are too fine grained to be physically recoverable. A more substantial accumulation is needed.

Locally, cassiterite or columbite grains accumulate in granite endocontacts to such a degree that they constitute low-grade disseminated orebodies the economy of which has been further improved by weathering and sedimentogenic reworking (the bulk of the Nigerian tin comes from placers). Strong (1980) explained the origin of the "primary" cassiterite deposits in which cassiterite is evenly disseminated throughout the intrusive rock as a consequence of retention of the late magmatic aqueous phase into which Sn (and Ta and Nb) normally partition. Escaping aqueous, Cl, F and alkali-rich fluids, on the other hand, may leach, transport, concentrate and deposit the above metals epigenetically in the apical portions of

Table 33-3. Principal mineralization styles in the intracratonic peralkaline granite-rhyolite association (Fig. 33-7)

WEATHERING CRUSTS	
(A)	Cassiterite, columbite, pyrochlore, etc. enriched in saprolite over a granite containing disseminated ore minerals
PRODUCTS OF SEDIMENTOGENIC REWORKING	
(B)	Exposed cassiterite and/or columbite alluvial placers
(C)	Alluvial placers buried under plateau basalt flows
(D)	U infiltrations in swamps or bogs
(E)	U infiltrations in sandstone hosts
ANOMALOUS TRACE METAL CONTENTS OR DISSEMINATED MINERALS IN GRANITES	
(F)	Anomalous trace U content
(G)	Disseminated cassiterite and/or columbite in (albitized) biotite granite
(H)	Disseminated pyrochlore in albite-riebeckite granite
VEINS, REPLACEMENTS, MINERALIZED BRECCIAS, PEGMATITES, ETC. IN GRANITE ENDOCONTACTS	
(I)	Cassiterite-bearing greisen pipes and lodes, fissure veins
(J)	Schlieren of cassiterite pegmatites
(K)	Cryolite + Be minerals (bavenite, phenacite) in altered zones in riebeckite granites
(L)	Cryolite-siderite masses (Ivigtut)
(M)	Zircon, xenotime, Th and U minerals, pyrochlore with fluorite in albitized, Li-mica replaced, etc. zones superimposed on riebeckite granites
(N)	Stockwork molybdenite deposits in sericite (and/or K-feldspar altered) peralkaline granites, hypabyssal level
(O)	Discrete molybdenite-quartz veins in granites, plutonic level
VEINS, REPLACEMENTS, ETC. IN GRANITE EXOCONTACTS	
(P)	Mineralizations in skarns at granite/carbonate contacts (Mo, scheelite, magnetite, helvite, etc.)
(Q)	Fluorite replacements in carbonates containing Be minerals (bertrandite, leucophane, etc.)
(R)	Mineralized (Zr,Nb,REE,Th, etc.) feldspathite (albite, microcline) replacement veins and other bodies
(S)	Sulphide-gold replacement bodies in limestone and lodes in blastomylonite near granite dikes (Central Aldan)
(T)	Fissure replacement veins, disseminations, mineralized breccias, etc., of base metals (Pb,Zn,Ag,Cu, etc.) in contact aureole of granites

A. NON-REACTIVE BASEMENT, MINIMUM OF INTRUSIVE INTERACTION



B. VARIABLE AND MORE REACTIVE BASEMENT, INTERACTION IMPORTANT

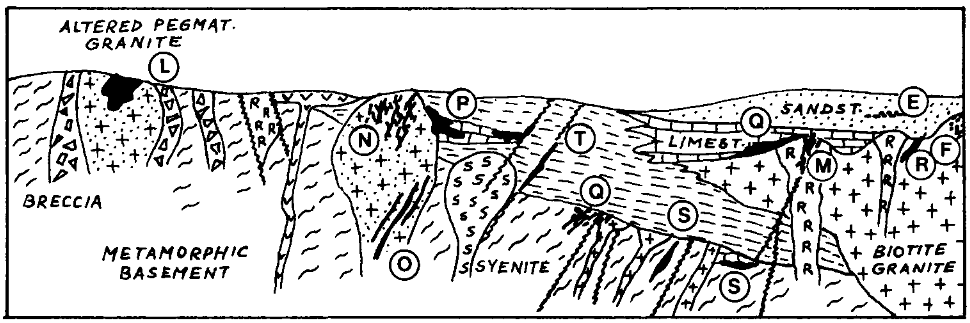


Fig. 33-8. Principal mineralization styles in the intracratonic peralkaline granite – rhyolite association; see Table 33-3 for an explanation of the letter codes.

granitic stocks and in their exocontacts. This is usually accompanied by a profound, often zonally arranged alteration (Na and K feldspathization, greisenization, etc.), most apparent in the "apogranites". Apogranites and the problems of granite-affiliated tin origin have already been discussed in Chapter 28 and will not be considered further here. The earlier conclusions are fully applicable to peralkaline granites as well.

33.3.3. Examples of major mineralization styles

DISSEMINATED Nb,Ta and Sn OXIDES IN PERALKALINE ASSOCIATION OF THE WEST AFRICAN "YOUNGER GRANITES"

The "Younger Granite Province" is a belt of over 60 magmatic complexes of Permian to Tertiary age, discontinuously distributed along an extensive N.-S.-trending strip in western Africa that measures 1,500 x 200 km (Black and Girod, 1970; see also Table 33-4). The most extensive and also economically the most important are the occurrences in northern Nigeria, particularly the Jos-Bukuru Complex. The latter is considered to be the type area for mineralized peralkaline granite complexes of the Western World.

The Jos-Bukuru Complex (MacLeod et al., 1971; Wright, 1970; Olade, 1980; Fig. 33-9), contains over 50 separate small occurrences of Jurassic high-level magmatic rocks, 90% of which are granites and rhyolites. The remainder are syenites, anorthosites, olivine gabbros and diabase. They intrude Precambrian high-grade metamorphics (migmatites, gneisses, local charnockites) and granites, and are in turn partly covered by Tertiary to recent basalt flows and alluvial sediments.

The felsic magmatites are well outlined topographically as hills, and they are circular or elliptical ring complexes, cone sheets, ring dikes, small stocks and massifs flanked by remnants of comagmatic felsic volcanics and pyroclastics. The dominant intrusive rock is biotite granite, followed by hornblende, pyroxene, fayalite granite; riebeckite, biotite granite and riebeckite aplite.

Cassiterite, columbite and pyrochlore are the three major minerals that locally form disseminated orebodies in the Nigerian granites. Cassiterite and columbite are associated exclusively with the altered apical portions (apogranites) of biotite granites. There, columbite forms true disseminations in the alteration feldspathized intrusion, but disseminated cassiterite in the same setting is exceptional and most of the Nigerian cassiterite came from numerous but small greisen lodes and small veins superimposed on the altered granite.

Three zones of disseminated columbite in the Nigerian apogranites grading close to 0.45% columbite (two in the Jos-Bukuru Complex, one in the Afu Granite in Benue Valley; MacLeod et al., 1971) contain about 70 Tt Nb_2O_5 in the soft surficial saprolite. Pyrochlore in greater than accessory concentrations (around 0.3% Nb_2O_5) is disseminated in albite-riebeckite granite in the Kaffo Valley, Liruei, and there are large reserves of this mineral in saprolite (360 Tt Nb_2O_5). Numerous additional pyrochlore occurrences are known in the riebeckite granite of the Jos-Bukuru Complex. Small showings of Be minerals (helvite, phenacite) and cryolite, have also been reported.

➡

Fig. 33-9. Geological map and section showing a portion of the Jos-Bukuru tin region, Nigeria. bg=Biotite granite; arg=albite riebeckite granite; rbg=riebeckite-biotite granite; rag=riebeckite aegirine granite; hpfg=hornblende, pyroxene, fayalite granite; bg=biotite granite; qp=quartz porphyry; gp=granite porphyry; r=rhyolite. Simplified after MacLeod et al. (1971).

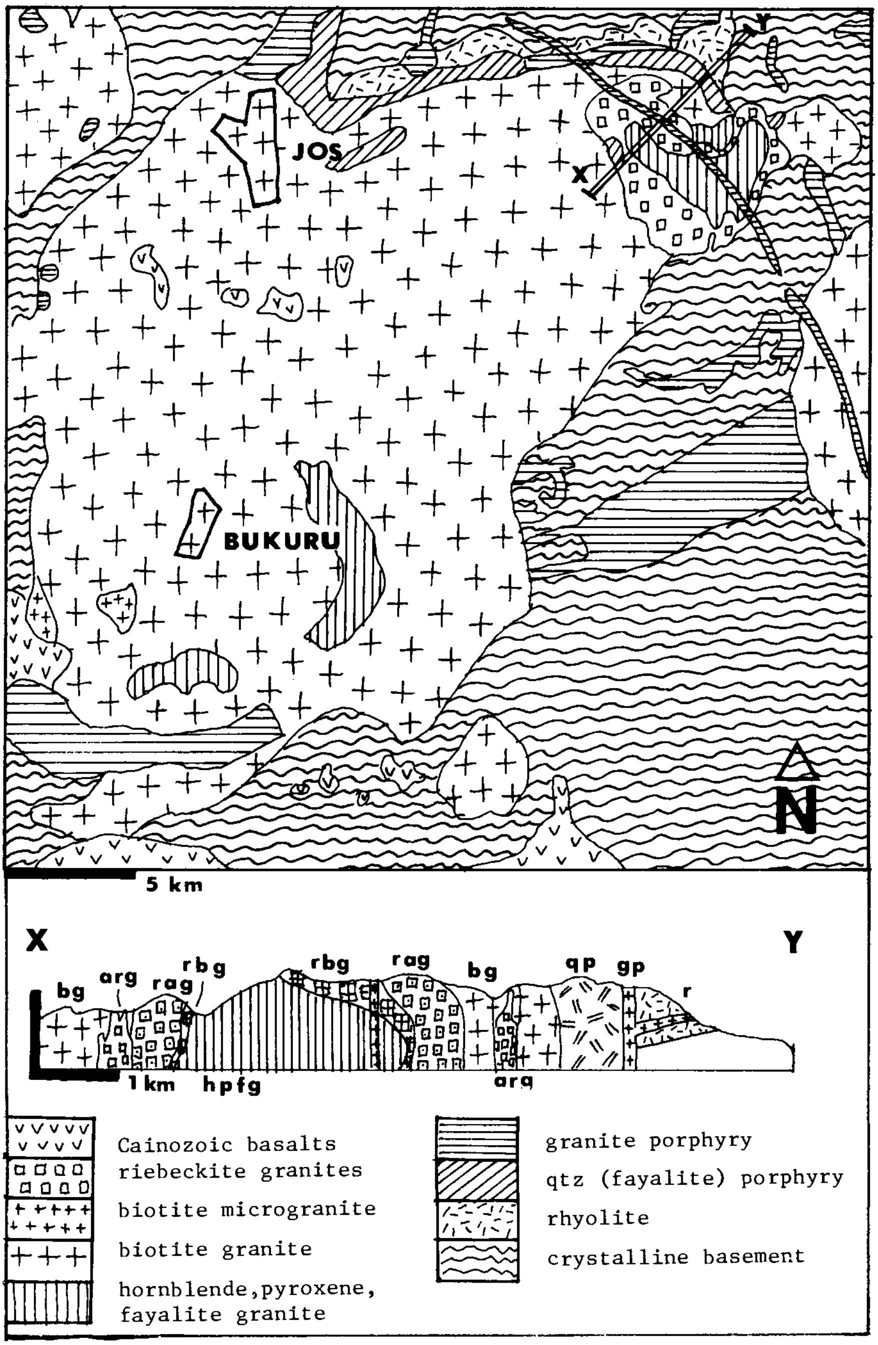

JOS
BUKURU
X
Y
N
5 km
X
Y
bg
arg
rag
rbg
rbg
rag
bg
qp
gp
r
1km
hpfg
arg
Cainozoic basalts
riebeckite granites
biotite microgranite
biotite granite
hornblende,pyroxene,
fayalite granite
granite porphyry
qtz (fayalite) porphyry
rhyolite
crystalline basement

Table 33-4. Phanerozoic peralkaline granite-rhyolite association, selected examples of mineralized provinces or occurrences

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Mesters Vig area (Werner Bjerge), E. Greenland	Cr_3-T_1 pyrox.,alk.granite,syenite,syen.porph.,intr.into Cb sedim.; diabase,gabbro,subvolcan.	stockw. of moly.,pyr.,qtz.,gal., sphal.,cp.fract.coatings,veinl. in gran.endocont.;K-feldsp.,sericite alter.; 1 m thick border zone of topaz greis.with wolfr. 175.5Tt Mo/0.15%	Nielsen (1973)
Bokan Mt.,Prince of Wales Island, S.E. Alaska, U.S.A.	8 km^2 boss of peralk. granite emplac. into D? metamorphics; Cr intrusion	minor zirc.,fluor.,uranothorite dissem.in gran.; uranoth. and uranin. veinl. in albitiz.zone // shear; prod.1957 102t U/0.64%	MacKevett (1963) Staatz (1978)
Topsails intrusion St.Lawrence,Newfoudland,Canada	minor peralkaline granite intrusion	fluorite veins, minor Pb,Zn,U occurrences	Strong (1980)
White Mts.Province Conway Granite New Hampshire, U.S.A.	Ms, Tr-J (185 m.y.);post-tect. peralk.plut.,gran.,syen.,monzon.,dior.,gabbro; aegirine-riebeckite granite, emplaced into D gneisses	granite trace U enriched Iron Mt.(Bartlett): repl.magnet., hemat.,danalite (up to 1.6% BeO) in granite; Silver Lake: gal., sphal.,qtz.,chlor.,veins in brec. near granite contact	Barker (1974) Cox (1970)
Sawtooth Massif S.W. of Stanley, Idaho, U.S.A.	T? pink peralkaline perthitic granite	10-2,000 ppm U, bound mainly in dissem.euxenite; euxenite accumulates in placers, U in bog	Killsgaard et al.(1970)
Velasco alkal.prov. eastern Bolivia (S.Ignacio de Vel.)	6 ring compl.Pt_3-PZ_1 of phonol., qtz.syen.,biot.and riebeckite gran.intr. PCm basem.gneiss	Cerro Manomo, cassit.,pyrochl., monaz.,topaz,fluor. dissem. in albitiz. granites	Fletcher et al. (1977)

Hoggar (Ahaggar) Mts., S. Algeria	Cr, several isolated intrus.of biot. and peralk. granite into PCm basem. gneiss // N.-S. shears and grabens	Ouan Rechla, dissem.cassit.,Li-musc.,minor monaz.,wolfr.,in al-bitiz.granite; Timgaouine distr., pitchbl. veins and stockw. in al-tered granite; 14Tt U; X00 t Sn	Black and Girod (1970) O.E.C.D. (1979)
Aïr Mts., Niger	295 m.y. biot. and peralk.gran. complex intr. PCm basement	cassit.dissem.and in stockw. in gran.,reworked to placers N.of Agades; 1,410 t Sn;	de Kun (1965)
Sabaloka ring com. Jebel Qeili, S. Soudan	porph.microgr.,biot. and musc.-biot. gran.,riebeckite-egirine syen.,acid lavas, empl. to PCm basement complex	biot.-musc. gran. contain grei-sens and qtz. stockw. with cassi-terite, wolframite	Whiteman (1971)
Jos-Bukuru compl., northern Nigeria	160 m.y. ring and circul. compl. of biot.,riebeckite, etc. grani-te intrude PCm cryst. basement	cassit.and lesser columb.wide-spr.in albitized (apogranites) apical biot.gran.,in narrow grei-sen veins and stringers; entire prod.came from placers; 590Tt Sn, 49Tt Nb,1.6Tt Ta, 500t W	McLeoe et al. (1971)
Kaffo Valley, Liru-ei, Nigeria	as above	dissem.pyrochlor in localized albitized zones in granite; 235.5Tt Nb/0.21%	ditto
Afu Granite,Benue Valley, Nigeria	J peralk. and biot. granite, ring and apical complexes	dissem. columbite in albitized zones of granite	ditto
Cameroon and Chad (Mayo Darle, Tapa-re, Poli)	T, 20 small peralk.intrus.plu-tons along a N.E. tect. zone	cassit. in placers probably deri-ved from stockworks in greiseni-zed apogranites	de Kun (1965)

Table 33-4 (continued). Phanerozoic peralkaline granite-rhyolite association, selected examples of mineralized provinces or occurrences

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Central Lake Malawi province, Malawi	450-600 m.y. ring compl., small stocks, dikes, empl. into PCm basem. complex; alkal. and peralkal. granites	pyrochlore is a common access., also allanite, zircon; U and Th occur in pegmatite	Bloomfield (1970)
Chilwa alkal. prov. southern Malawi	J_3-Cr, ring compl.; qtz. syenite, perthosite, alkal. granite, riebeckite granite	minor accessory pyrochlore in peralkaline granites	Woolley and Garson (1970)
Brandberg and Spitzkoppe, Namibia	J, 20 km diam. circular stock of granite empl. into Karoo sedim. and lavas and PCm gran. basem.; hornbl., biot., tourm., arfvedson. granite facies	fissure qtz., cassit., minor wolfr. and scheel. veins; dissem. cassiterite suppl. to placers; 3Tt Sn	Hodgson (1973) Martin et al. (1960)
Erongo, Namibia	J, circul. gran. stock and ring intrusive into Karoo lavas and sedim.	small pegmatite lenses and schlieren cont. qtz., cassit., scheel., molybdenite; 236t Sn	Martin et al. (1960)
S. Madagascar thorianite province	485 m.y. post-orog. peralk. granites intrude (and replace ?) diops., spinel, phlogop. pyroxenite of the PCm basement	thorianite, phlogop., zircon, etc. form banded dissem.; reworked into placers	Besairie (1959)
"Kazakhstan A" complex (Khorgos Complex ?), USSR	PZ_3?, two cupolas of riebeck., microcl., qtz., albite apogranite superimp. on biot. granite massif intr. Cb_1 sandst., slate assoc. Riebeckite albitites formed in exocont. sandstones	main Nb, REE, Zr, Be, Th and U mineraliz. is in fissure veins of albitite, lesser microclinite, with dissem. zircon, thorite, pyrochlo., gagarinite, gadolin., etc.	Beus (1968)

"Siberia A" alk. province (East Tuva ?),U.S.S.R.	PZ_{2-3} metasom. zoned riebeckite, microcl., albite massif emplac. into PZ metacarb. and diorite-granodiorite	zircon, columb.,pyrochl.,etc. are in fissure-controlled endo-cont.metasom.; fluorite, bertrandite,phenacite repl. in the exo-contact marbles	Ginzburg and Fel'dman (1974) Beus (1968)
Numurgin and Udzhigin complexes, Mongolian Tuva	PZ_3 granosyen.,riebeckite, egirine apogranite, etc. emplaced into Cm-D volc. and sedim.,PZ_2 granite pluton	acces. fergusonite dissem. in granosyenite	Marinov et al. (1977)
"Siberia B" alk. prov. (central Aldan Shield ?), U.S.S.R.	J-Cr albite-riebeckite granite intr. Cm carb.,shale along major faults; several massifs are in Arch. basement; skarns and Na,K feldspathites along contact	Zr,Th,REE in endocont. assoc. with albite and qtz.-albite bodies; Be(leucophane) miner. is in fluorite-rich exocont. metasom.	Zabolotnaya (1974)
Central Gobi alk. province,eastern Mongolia	J, calc-alk. and peralk.gran., peralk. rhyol.,carbonatite	Ta,Li,Cs,F miner.in albitized apogranites; assoc. agpaitic intrus. carry REE,Zr,Nb	Kovalenko et al. (1977)

DISSEMINATED ORE MINERALS IN PERALKALINE GRANITES OUTSIDE WESTERN AFRICA

Simple, sub-economic disseminations of pyrochlore and also zircon and allanite in unaltered or albitized peralkaline granites comparable with those in Nigeria, have been recorded by Bloomfield (1970) and Woolley and Garson (1970) in Malawi. They also occur in the Siberian and Kazakh apogranites (Beus, 1968) and elsewhere, but have rarely been reported.

Accessory cryolite disseminated in peralkaline granite occurs in Ivigtut, Greenland (Blaxland, 1976) and minor disseminated cassiterite has been reported from the Rondônia, Brazil, granites (Kloosterman, 1968). Some peralkaline granites have anomalously high trace uranium content (100 ppm U plus in the Conway Granite, New Hampshire; up to 200 ppm in granite of the Sawtooth Massif, Idaho), so that they have been considered a possible future resource of low-grade uranium. Disseminated zircon, xenotime, fluorite and uranothorite in albitized riebeckite-acmite granitoids is one of the mineralization styles described in the Bokan Mountain stock, Alaska (MacKevett, 1963).

Overall, however, it appears that "simple" disseminations of metallic minerals in "unaltered" (or feldspathized-only) peralkaline granites can rarely produce an economic deposit, particularly in areas free of the deep tropical weathering and cheap labour as in Nigeria. An added metal concentrating process is obviously needed to super-concentrate the broadly distributed trace metal content of the granite into a few smaller size, but rich orebodies. Some such processes were initiated before the complete solidification of the intrusion, so they did not markedly alter the host rock (e.g. pegmatites and monomineralic masses). Other were superimposed on the fresh or feldspathized granite or on the rocks of the exocontact, accompanied by hydrothermal alteration.

MINERALIZED PEGMATITES AND MONOMINERALIC ORE MASSES IN PERALKALINE GRANITES

Small pegmatitic schlieren and vein-like bodies are relatively common in peralkaline granites emplaced at the plutonic level, and they frequently carry scattered megascopic ore minerals. Such minerals are often identical to the fine-grained "invisible" accessories in the host granite, or at least carry the same elements in which the granite is enriched. U and Th minerals, for example, have been observed in the peralkaline granites of central Malawi (Bloomfield, 1970) and minor pegmatites contribute cassiterite to the Rondônia placers. The numerous but small drusy pegmatites in the Jurassic granites of Spitzkoppe, Brandberg and Erongo, Namibia (Martin et al., 1960), contain fluorite, beryl, cassiterite, chalcopyrite and arsenopyrite. Some 236 t Sn were recovered at Erongo, partly from placers. No large mineralized pegmatite occurrences, however, are known in this association.

Rich, almost monomineralic, ore masses hosted by what appears to be a hydrothermally little-altered granite are unique, and are exemplified by the Ivigtut cryolite deposit in S.W. Greenland. This is a Proterozoic mineralization and has been described in Volume 2.

HYDROTHERMAL-EPIGENETIC ORES IN ALTERED APOGRANITES AND ALONG THEIR CONTACT

The Soviet school (Beus, 1968) differentiated between two apogranite series: (1) the "normal" series developed over "orogenic" calc-alkaline granitic massifs (Chapter 28) and (2) the alkaline series, associated with peralkaline granites emplaced in "anorogenic" cratons. The fundamental alteration-mineralization and zoning pattern of both series is comparable, but the alkaline series tends to have higher proportion of Ta,Nb,Zr, Th,REE, and U. Sn and Be are of approximately equal importance in both series. Only the alkaline apogranites will be discussed here.

Beus (1968) further subdivided the alkaline apogranites into (a) biotite, microcline, quartz, albite apogranites with Nb and Zr mineralization, represented by an unnamed massif in Kazakhstan ("Kazakhstan-A") and (b) riebeckite, microcline, quartz, albite apogranite with Zr,Nb,REE,Th and U mineralization. The latter is represented by an unknown locality in the Caledonides of Siberia (probably in the Tuva-N. Mongolia alkaline province), designated here as "Siberia-A". Both apogranite types correspond closely to the apogranites developed over the biotite (a) and riebeckite (b) granites of Nigeria.

Hydrothermal-epigenetic mineralization in apogranites (exclusive of the disseminated minerals such as columbite and pyrochlore which were described earlier and which some authors interpret as being hydrothermal-epigenetic as well) is controlled by alteration-mineralization zones formed along fractures, faults, shears, porous or replaceable rocks at both sides of the granite contact. Economic metallic mineralization in this setting is known in less than 20 regions of the world and each region has its own special characteristics. Because generalizations are difficult to make, a few example localities will be reviewed briefly (see also Table 33-4).

<u>Tin-mineralized apogranites in the Jos-Bukuru region, Nigeria.</u>

Here, cassiterite is confined to albitized cupolas of biotite granite, in which it is disseminated in narrow, usually subhorizontal, fracture-controlled zones of patchy and diffuse greisenization (reminescent of Cínovec, Chapter 28) and also as scattered crystals in thin, joint-controlled quartz veinlets. The greisen lodes are sometimes enveloped by zones of K-feldspar, sericite and hematite alteration (MacLeod et al., 1971). The richest cassiterite concentrations correlate with the recently unroofed intrusions. Disseminated cassiterite in greisenized apogranite and in endo- and exocontact quartz veins, also occurs in the Proterozoic Rondônia tin province, Brazil (Kloosterman, 1968; see Volume 2).

Nb (Zr,Be,Th, REE)-mineralized apogranites.

The "Siberia-A" locality (Beus, 1968; Ginzburg and Fel'dman, 1974; Fig. 33-10) is a small (2 km^2) composite apogranite massif emplaced into marble and granodiorite, diorite environment. It is distinctly zoned compositionally. The core is composed of Li-mica, microcline, quartz, albite granite, and there is a locally intensive silicification that increases with depth. The following zone has riebeckite, microcline, quartz, albite apogranite, and the endocontact is dominated by microcline metasomatites. The exocontact in carbonates has a 10 to 50 m wide zone of intensive fluoritization that carries bertrandite and lesser phenacite. The main Nb orebodies contain hematite, magnetite, zircon, columbite, pyrochlore, fluorite, and several additional rare minerals and they are patchy, fracture-controlled albitites, microclinites and quartz-microcline replacement bodies best developed in the Li-mica altered core zone.

In the somewhat similar "Kazakhstan-A" locality (Table 33-4), the economic Zr,Nb,REE, Th,Be, etc. mineralization is in fissure-controlled replacement feldspathite veins developed mainly in the exocontact of an albite-riebeckite metasomatite.

Th,Zr,Be, etc., mineralized apogranites.

The example locality "Siberia-B" (Zabolotnaya, 1974), is probably located in the Central Aldan ore field (near the Lebedinskoe gold mine), where a strongly tectonized Archean crystalline basement is topped by Cambrian platformic carbonates and intruded by members of a Mesozoic alkaline complex. Peralkaline members are represented by riebeckite-albite granites, fringed by an exocontact aureole of alkaline skarn. The metallic minerals were superimposed in several phases. In the earlier phase, metasomatic albitites and quartz-albite veins containing Th and Zr minerals formed in the endocontact. In the second, main stage, a variety of replacement albite or microcline-fluorite bodies (veins, masses, lenses), formed along the granite-sediment contact. The principal ore mineral leucophane ($CaNa(BeSi_2O_6)F$) is accompanied by lesser phenacite, danalite and milarite. Th and REE mineralization (mainly gadolinite) formed at the same time in the endocontact.

U-Th mineralized apogranites.

These are best represented by the Cretaceous Bokan Mt. stock of mineralized peralkaline granite (S.E. Alaska; MacKevett, 1963; Staatz, 1978), emplaced into metamorphics possibly dating from the Devonian period. The intrusive outcrop is less than 7.5 km^2 and it is composed of a leucocratic quartz, albite, microcline, riebeckite, acmite granite, fringed by an aureole of albitization some 2.4 km wide. The economic orebodies formerly exploited by the Ross-Adams mine, are narrow veinlets of uranothorite and uraninite, developed in a north-trending zone of albitization along a shear.

The recently discovered Timgaouine uranium district in the Hoggar

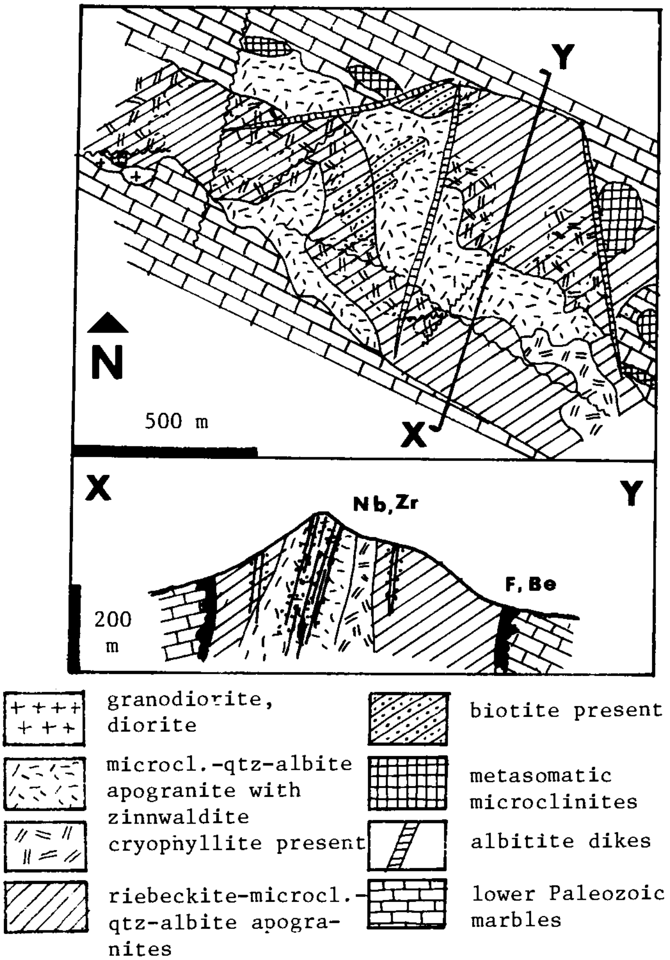


Fig. 33-10. A mineralized massif of albitic apogranites of the "alkaline series", located in Siberia (probably eastern Tuva). After Beus (1968), approximate scale and diagrammatic position of mineralization have been added (Nb,Zr: pyrochlore, columbite and zircon; Fe,Be: fluorite, bertrandite, phenakite exocontact replacements).

Mountains, S. Algeria (O.E.C.D., 1979), contains about 14 Tt U in three vein and stockwork deposits associated with muscovite-biotite "younger granite" emplaced along faults in a Precambrian metamorphic basement.

HYDROTHERMAL-EPIGENETIC ORES IN PERALKALINE GRANITES LACKING WIDESPREAD ALBITIZATION

Molybdenite-bearing peralkaline granite intrusions generally lack a widespread albitization. Instead, quartz, pyrite, molybdenite stockwork veinlets (at a shallow level, e.g. Bordvika in the Glitrevann Cauldron) or quartz-molybdenite veins (at a deeper level, near Drammen; both localities are in the Oslo Graben, Norway), are enveloped by quartz-sericite altered host rocks (Geyti and Scønwandt, 1979). Similar mineralization on a much larger scale (175 Tt Mo) formed in a lower Tertiary peralkaline granite stock at Werner Bjerge, eastern Greenland (Nielsen, 1973). The molybdenite localities mentioned above have many features in common with the "Climax-type" (White et al., 1981) stockwork Mo deposits of orogenic belts, treated in Chapter 28. The major contrast between the two settings of Mo deposits formerly considered to be important (the former in a "rift", the latter in a "mobile belt" environments) has been considerably weakened by the realization that the "Climax-type" deposits are also related to a graben formation. Petrochemically, the bulk of the "Climax-type" alkalies-rich granite porphyries are just below the treshold of the peralkaline class.

HYDROTHERMAL-EPIGENETIC ORES IN THE AUREOLE OF PERALKALINE INTRUSIONS

The exocontact mineralization adjacent to peralkaline granites is not substantially different from the same setting related to the calc-alkaline stocks (Chapter 28). The peralkaline parentage is sometimes reflected by high Be,Nb,Th, REE,Zr, etc. trace metal contents or accessory minerals in predominantly polymetallic, gold, iron, etc. veins or replacements. In an aureole of the Conway Granite (New Hampshire; Cox, 1970), small veins of galena and sphalerite also contain danalite $(Fe,Mn,Zn)_4Be_3(Si_4)_3S$. A larger accumulation of this inconspicuous, yellow to red-brown mineral, was recorded in a small skarn magnetite deposit in Bartlett. There, the Be content in the iron ore reaches as much as 1.6% BeO.

In the Central Aldan ore district, Siberia, two major gold fields (Lebedinskoe and Kuranakh; gold-sulphide veins and replacements in Cambrian carbonates) and numerous gold occurrences, are situated in a contact aureole of small Mesozoic alkaline and peralkaline intrusions. An unusual style of a gold ore, an auriferous quartz-orthoclase metasomatite in blastomylonite-filled lower Proterozoic faults, appears to be closely associated with dikes of Mesozoic peralkaline granite.

In the Oslo Graben, Norway (Bugge, 1978), several small magnetite skarn and Pb-Zn replacement bodies are contained in Silurian limestones at the contact with the Permian Drammen Granite. Pb,Zn,Ag fissure veins also formed in the granite endocontact.

RESIDUALLY ENRICHED ORE MINERALS IN WEATHERING PROFILES AND MINERALS, METALS REWORKED INTO SEDIMENTS

Those metallic minerals associated with peralkaline granites that are also heavy resistates, accumulate in a variety of placers (see Chapter 24). Over 95% of cassiterite produced from the peralkaline association (Nigeria, Rondônia) comes from placers.

Redeposition of the soluble metals leached from mineralized peralkaline granites in sediments has rarely been recorded. One example is the low-grade accumulations of U in the recent organic-rich bog sediments in Idaho (Killsgaard et al., 1970).

33.4. FELDSPAR SYENITE-TRACHYTE TRANSITIONAL ASSOCIATION

33.4.1. General

Small "anorogenic" or late orogenic syenite bodies are quite common in settings that are the same or similar to those in which the peralkaline granites are located, namely in terrains "frozen" in the initial stages of activation and "rifting", in the forelands of ensialic orogenic belts and within sialic blocks in marginal orogenic belts. Such syenites occur either alone, or as sub-members in (or a link to) other igneous associations such as the calc-alkaline diorite-quartz monzonite, peralkaline granite, bimodal basalt or gabbro-trachyte or syenite, agpaitic syenite, etc.

In the broad, discontinuous zone of small, high-level late Cretaceous to Tertiary intrusions emplaced into the little deformed platformic sediments in the eastern foreland of the North American Cordillera (Montana, Wyoming, South Dakota, Colorado, New Mexico, Mexico), syenite is a common member of a broad congregation of intrusive rocks that include quartz diorite to quartz monzonite, syenite, shonkinite and phonolite. Although often designated as an "alkaline province", only a proportion of the magmatic rocks is truly alkaline. Early laccoliths usually breached by later stage stocks and dikes are the most characteristic style of magmatic occurrence in the Cordilleran Foreland. The style is closely comparable with the laccolithic complexes of the Colorado Plateau, reviewed in Section 28.2.2.

In the Oslo Graben, Norway, Permian syenites together with remmants of their volcanic equivalents, are the most common rock type forming ring complexes and composite cauldron-filling bodies in an intrusive assemblage ranging from biotite granite through syenite, monzonite to nepheline syenite.

A variety of postmagmatic-hydrothermal deposits is associated with syenites. The low-grade Mo and Au stockworks, veins and replacement deposits appear to have the greatest potential, whereas Pb,Zn,Ag, W, Be, REE, etc. concentrations have, so far, been of limited importance.

One of the fundamental genetic problems involving feldspathic rocks of syenitic appearance is the uncertainty as to whether a particular rock is a magmatic crystallizate from a melt, or a metasomatite formed by essentially hydrothermal feldspathization of solid precursor rocks. Improved understanding of syenites is of considerable help for metallogenic interpretation, and facilitates exploration.

33.4.2. Example localities of mineralized syenites

Little Rocky Mountains, north-central Montana

The Little Rocky Mountains (Knechtel, 1944; Figures 33-11 and 33-12) form a subcircular dome about 30 km in diameter, composed of a core of unroofed late Cretaceous-early Tertiary intrusive sills, laccoliths and stocks, fringed by more than fifty faulted subordinate sedimentary domes probably floored by intrusive plugs in depth. The sediments are Cambrian to Cretaceous members of the carbonate and detrital platformic association of the North American Platform. The intrusions range from quartz monzonite to syenite and trachyte.

Gold placers and hydrothermal vein, stockwork and breccia pipes in the southern part of the igneous core (Zortman and Landusky fields) have been exploited since 1884, and since 1903 the district has been a pioneer in the application of cyanide leaching for the recovery of a very fine, low-grade gold; a process greatly improved and expanded in 1979 and in the years since (Fig. 33-13). Almost 14.8 t Au had been produced up to 1982.

The gold orebodies in the Little Rocky Mountains (Rogers and Enders, 1982) are structurally controlled, carry almost no base metals and are hosted by and related to the hydrothermal phase of the latest members (dikes) of the syenitic magmatism. Minor mineralization is contained in the Archean basement amphibolite and basal Paleozoic sediments in the intrusive exocontact. The orebodies are unpredictable funnel-shaped bodies marked by low to very low Au values (from cutoff of 1 ppm Au through average grade of about 3 ppm to maximum 60 ppm), lacking conspicuous alteration or a systematic preference for a particular intrusive or a sulphide enrichment. The ore cannot be recognized visually from waste and the selective mining is based entirely on assay data. In the Gold Bug orebody, for example, pyrite-veined wallrocks and a syenite breccia pipe are barren, whereas a fractured syenite along faults with an unimpressive limonite coating is the ore. The mine profitability is achieved by cheap recovery (heap leaching of blasted but uncrushed rock).

In the nearby Judith Mountains (Kendall), low-grade gold replaces sedimentary carbonate in the exocontact of a syenite similar to the one described above.

Little Belt Mountains, Montana

This is another mineralized Eocene laccolithic, volcanic and intrusive group of hills in central Montana, situated in the southern extension of the Highwood Mountains potassic province (Section 33.7.). It was recently described in detail and interpreted by Witkind (1973;

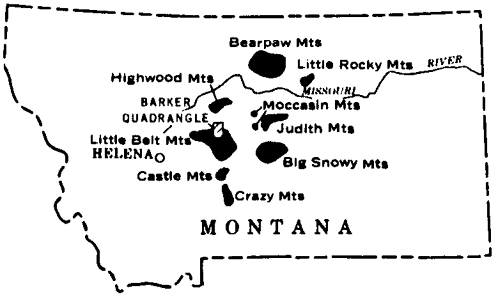


Fig. 33-11. Central Montana igneous province in the Cordilleran Foreland. From Witkind (1973).

Fig. 33-14) and it is representative of the wide variation in quartz saturation of the coexisting central Montana magmas. The prevalent intrusive and volcanic phases are quartz monzonite and quartz rhyolite porphyry, whereas syenite and shonkinite are minor. Eleven major intrusive bodies including one stock, eight laccoliths, a bysmalith and a buried ovoid pluton, are contained within an area measuring less than 30x20 km.

High-grade Pb,Zn,Ag vein and replacement deposits and scattered molybdenite and scheelite occurrence which were mined in the past occur in two ore fields (Barker and San Miguel), located within and on the margin of an intensively fractured Hughesville quartz monzonite stock and probably underlain by a buried pluton. Although the orebodies are younger than the stock, Witkind (1973) attributed the vein control by the stock to a long-lasting master conduit, repeatedly guiding the various magmas and mineralizing fluids towards the same site (Fig. 33-15).

Gallinas Mountains, New Mexico

In the Red Cloud District about 60 km N. of Carrizozo (Perhac and Heinrich, 1964), upper Cretaceous to lower Tertiary porphyritic trachyte, peralkaline leucorhyolite and various riebeckite and aegirine-containing high-level stocks, dikes and laccoliths intrude arched Permian sandstone and Precambrian granitic basement. Small breccia zones and mineralized faults in the sandstone close to trachyte bodies contained veinlets and cement of fluorite, galena, chalcocite, bornite, pyrite, barite and bastnaesite. A mere 4 Tt Cu and 60 t bastnaesite were produced.

Permian magmatic province, Oslo Graben

In this well-known igneous province, syenite and monzonite massifs together with remnants of their volcanic equivalents are one of the most common rock types. Numerous small replacement Pb-Zn sulphide deposits formed in skarns and marbles along the contact of syenite and Ordovician limey sediments, e.g. in the Grua area (Ineson et al.,

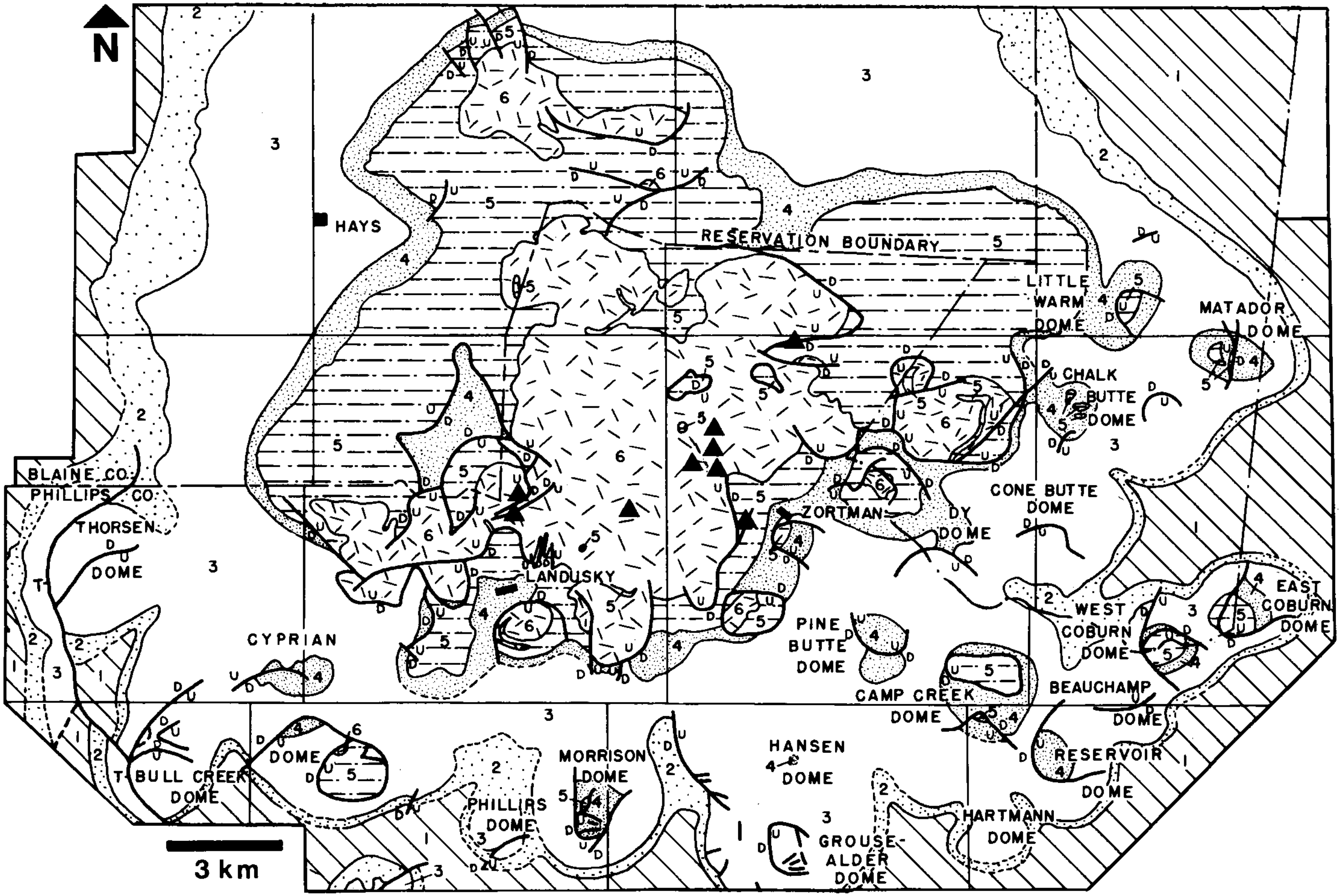

N
HAYS
RESERVATION BOUNDARY
LITTLE WARM DOME
MATADOR DOME
CHALK BUTTE DOME
CONE BUTTE DOME
DY DOME
ZORTMAN
LANDUSKY
BLAINE CO.
PHILLIPS CO.
THORSEN DOME
CYPRIAN
DOME
PINE BUTTE DOME
CAMP CREEK DOME
WEST COBURN DOME
EAST COBURN DOME
BEAUCHAMP DOME
RESERVOIR DOME
HANSEN DOME
MORRISON DOME
BULL CREEK DOME
PHILLIPS DOME
HARTMANN DOME
GROUSE-ALDER DOME
3 km

Fig. 33-13. Zortman, Little Rocky Mountains, Montana. Heap-leaching of blasted (but not crushed) rock made possible a profitable gold recovery from very low-grade auriferous stockworks and veins in syenite and quartz monzonite.

1975). Compared with the younger granite intrusive phase in the same area, the number and size of ore occurrences associated with syenite is substantially less. Fissure fillings of hematite and fluorite considered to be of fumarolic origin (that is, directly precipitated from magmatic gases) were mined near Baerums Verk (Holtedahl et al., 1960).

Mesters Vig, eastern Greenland

Several hydrothermal Pb-Zn deposits occur in the aureole of lower Tertiary alkaline syenite intrusives (Bondam and Brown, 1955). The largest deposit Blyklippen has been mined and produced 40 Tt Pb and 40 Tt Zn. There, galena and sphalerite in quartz gangue filled N.N.W.-striking veins, hosted by faulted upper Carboniferous sandstone, black slate and arkose.

⇐

Fig. 33-12. Little Rocky Mountains, N.-C. Montana, showing a largely syenite core hosting gold mineralization, and a fringe of small faulted domes. 1-3=Cr_3 shale and sandstone; 4=J-Cr_1 shale and sandstone; 5=Cm-Cb limestone, dolomite, basal sandstone; 6=T intrusions and minor PCm basement metamorphics. Triangles:principal Au-Ag orebodies. After Knechtel (1944); ore occurrences added.

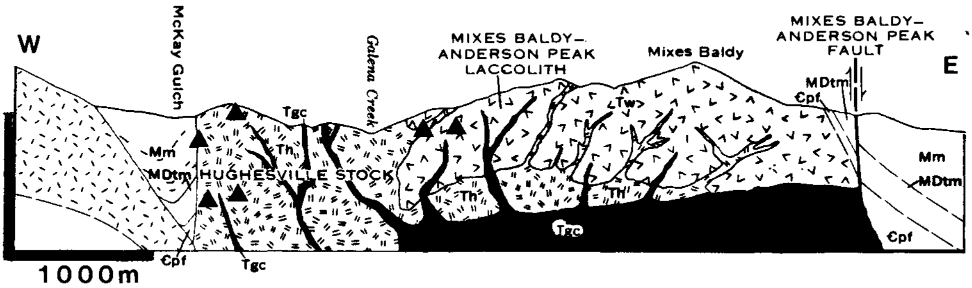


Fig. 33-14. Hughesville stock and adjacent intrusions, Little Belt Mountains, Montana, showing diagrammatically (by triangles) the usual setting of the Au and Pb-Zn mineralization. Tgc=Eo porphyry; Th=quartz monzonite; Tw=Eo porphyry; Mm, MDtm=D-Ms limestone and dolomite; Cpf=Cm limestone, shale, sandstone. From Witkind (1973), ore symbols added.

Wausau Complex, Wisconsin

A 560 m.y. old stock of medium to coarse syenite and minor nepheline syenite and pegmatite, intrudes an early Proterozoic basement of granite, greenstone, metaquartzite and metaargillite. Thorogummite, Th-zircon, zircon and allanite associated with hematite alteration, have been discovered in residual soil and in saprolite in the S.W. exocontact of the intrusion (Vickers, 1956). They have probably been derived from fissure veins, comparable with Th-bearing veins known in the western United States (e.g. Lemhi Pass).

Sivrihisar Kizilcaoren Th-REE deposit, Turkey

The O.E.C.D. (1979) reported the discovery of a significant deposit of thorium (min. 334 Tt Th/0.185%) and rare earths in bastnaesite and other minerals filling fractures and cementing breccia in the vicinity of a small granosyenite massif.

33.5. NEPHELINE SYENITE AND ALKALINE GABBRO-DOMINATED INTRUSIVE COMPLEXES

33.5.1. General

This category represents lithologic associations considered by an average geologist to be the "typical" alkaline rocks. Such rocks are undersaturated in silica and are members of the miaskitic (Na+K:Al=lesser than 1) and agpaitic (Na+K:Al=greater than 1) petrochemical classes. The miaskitic and agpaitic intrusives usually form equant, circular or elliptical central complexes, emplaced in a basement composed of a mature, stabilized continental crust (usually of crystalline rocks). Partly differentiated intrusive sills, dikes

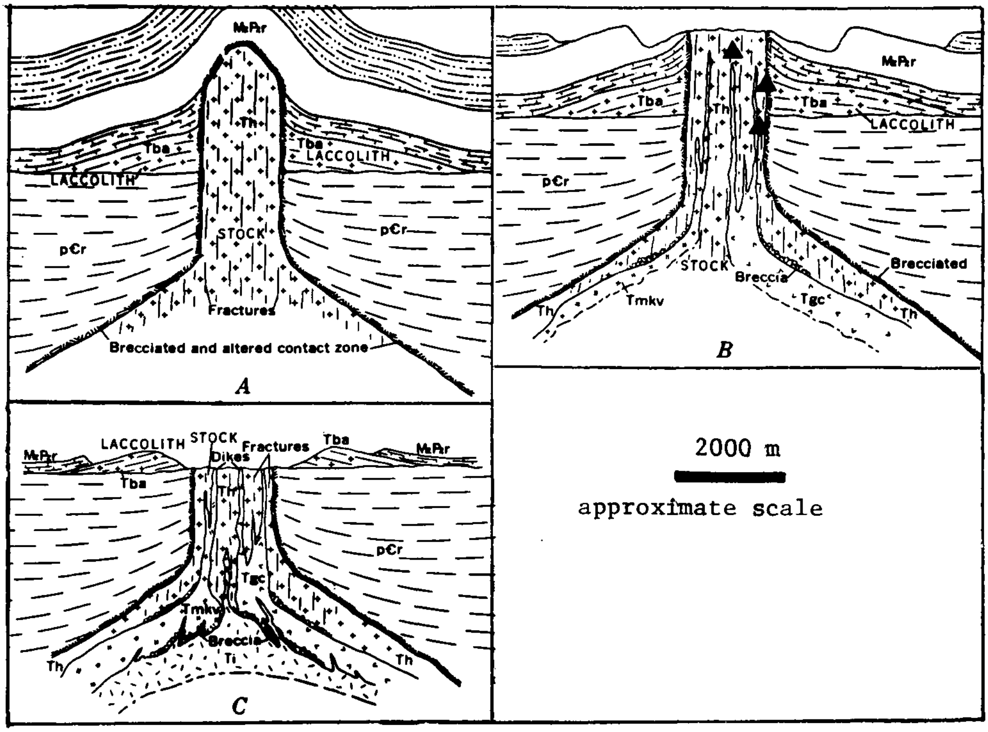


Fig. 33-15. Interpretation of magmatic and mineralization history of the Hughesville multiphase intrusive stock, Little Belt Mountains, Montana. (A): Magmas and ore solutions were channelled repeatedly into an old master conduit, presumably resulting in the radial pattern of laccoliths about the stock. (B): Intermediate magma concealed in the throat resulting in the Hughesville stock. The stock was later fractured, invaded by dikes and hydrothermal orebodies. (C): Subsequently, another pluton guided into the master conduit reactivated some fractures. From Witkind (1973).

and laccoliths, plugs, stocks, ring dikes and small homogeneous plutons also occur (Sørensen, 1974). Most complexes are considered to be "anorogenic" to postorogenic, controlled by crustal distention in cratons, and there is usually a substantial age difference between the alkaline intrusions and the basement.

In exceptional cases, minor occurrences of nepheline syenite and equivalent rocks have been reported in orogenic belts, where some may be broadly contemporary with the "regular" products of calc-alkaline magmatism. The Kruger alkaline syenite complex in the Similkameen Valley, British Columbia (Currie, 1974) is an example. It occurs along the margin of the Similkameen Pluton, a typical granitoid pluton in the Cordillera. It is of similar age.

Nepheline syenite and its varieties are the most widespread members of the present category, followed by alkaline gabbros. Carbonatites are commonly present, but in subordinate quantities. Complexes dominated by carbonatite are treated in Section 33.8. Alkaline complexes with more than one rock type are characteristically zoned, usually ranging from mafic on the outside to salic in the interior. Alkaline metasomatic aureoles (fenites) are usually developed, and some alkali metasomatites (e.g. feldspathites) are compositionally equivalent to rocks crystallized from magmatic melts (e.g. syenites) and hard to distinguish.

Syenitic rocks (including nepheline syenites) may also crystallize from an immiscible syenite magma produced from rheomorphically mobilized metasomatic rocks and crystallization of these melts may overlap with crystallization of the depth-derived alkaline magmas (Currie, 1974). This may have important metallogenic implications because crustally derived magmas or in-crust generated metasomatites would reflect the metallogenic character of the intruded environment rather than the expected subcrustal suite of metals known to be systematically associated with alkaline magmas.

33.5.2. Metal geochemistry and metallogeny

Uncontaminated, depth-derived alkaline magmas are strongly enriched in a distinct suite of trace metals (Gerasimovsky, 1974; Table 33-5). The enrichment factors of Zr and Nb, measured against the mean crustal content, exceed 20; that of REE,Ta, exceed 10; and that of Be,U,Th exceed 5. Other trace metals such as Cu,Cr,Ni are depleted in alkaline magmas. Of the major metals, the Al content of the light-coloured alkaline rocks is moderately enriched (up to 23% Al_2O_3 in some syenites) compared with the clarke, and the absence of quartz makes such rocks very suitable for an undiluted residual aluminium enrichment during lateritization. High-grade bauxites, therefore, form frequently on such rocks.

As a rule, the highest trace contents of the rare elements mentioned above are in rocks formed from strongly fractionated melts which are the end product of differentiation of alkaline basaltic magma. Petrographically comparable rocks interpreted as being of palingenetic origin (e.g. the nepheline syenites in the Mongol-Tuva alkaline province, Siberia; Gerasimovsky, 1974), have substantially lower contents of the same metals.

In intrusive rocks, the rare elements (Nb,Ta,Th,U,Be,Tl, etc.) (1) substitute in the lattice of the rock-forming minerals or of common accessories (e.g. in alkaline pyroxenes and pyriboles, in Ti-magnetite or ilmenite, in zircon); (2) are bound in complex accessory minerals (e.g. eudialyte, loparite, eucolite, lovozerite, catapleite, complex Ti-silicates and Zr-silicates) that are rare in the bulk of the alkaline rocks, but common or even dominant in rare alkaline rock types and (3) form their own rare minerals (e.g columbite-tantalite, pyrochlore, thorite, sørensenite, chalcothallite, etc.). Certain

Table 33-5. Trace elements highly enriched in alkaline intrusive rocks compared with the crustal average (in ppm). Data from Gerasimovsky (1974), Taylor (1964) and *estimated

	nephel. syenite Ilímaussaq	nephel. syenite Lovozero	nephel. syenite Khibiny	average nepheline syenite	average crust	enrichment factor
Li	330	55	20	30	20	1.5
Be	30	8.7	6.1	6	2.8	2.14
F	2,100	1,400	1,230	1,400*	625	2.34
REE	3,680	2,050	480	800*	174	4.6
Zr	4,735	3,480	625	550	165	3.3
Nb	525	696	152	200	20	10
Sn	115	10	6.6	12*	2	6
Ta	32	60	14	18	2	9
Th	38	35	14	20*	9.6	2.1
U	62	16.1	4.2	15*	2.7	5.5

magmatic differentiates become so anomalously enriched in either the category (2) or (3) minerals that they become low-grade ores having a relatively even distribution of the ore substance.

Ore occurrences having metal concentrations above the level of the "metalliferous rocks", however, require an additional mechanism of upgrading. Pegmatites produced from the volatile-enriched residual magmatic fluids do concentrate the rare elements and many (particularly those related to agpaitic rocks) become virtual "treasure troves" of rare minerals to collectors. The rare minerals, however, are scattered and few pegmatite bodies are persistent and extensive enough to constitute valuable industrial deposits. More valuable appear to be the local accumulations of some rare minerals with a minimum of gangue, that texturally and probably genetically resemble pegmatites. Such may be some of the bastnaesite veins (e.g. Ifasina in Madagascar; Chantraine and Radelli, 1970).

Hydrothermal processes associated with or superimposed on alkaline complexes as well as supergene leaching and residual enrichment are important agents of localized metal concentration that may generate important orebodies. Compared with the calc-alkaline "granitic" hydrothermal systems, however, the frequency and efficiency of the hydrothermal systems associated with alkaline complexes is very much subdued.

33.5.3. Major mineralization styles (Fig. 33-16, Table 33-6)

1. MAJOR MAGMATIC ROCK-FORMING MINERALS AS A METALLIC ORE

Nepheline syenite is frequently quarried as a nonmetallic mineral commodity for use in the ceramic and glass industries. In the U.S.S.R., a process has been developed for extracting metallic aluminium from raw nepheline syenite, or from nepheline concentrate (Rundkvist, ed., 1978). Three plants have, so far, been put into operation and one of them (in Leningrad) uses nepheline concentrate with 29-29.5% Al_2O_3 obtained as the by-product of processing of the Khibiny apatite ores.

2A. MAGMATIC ROCKS WITH ACCESSORY METALLIC MINERALS OR WITH HIGH TRACE METAL CONTENTS AS ORES, (A): LAYERED INTRUSIONS

Some alkaline layered intrusions, such as Lovozero or Ilímaussaq, have higher trace contents of certain elements (e.g. Zr) than "ores" of such elements currently mined on a commercial basis elsewhere (e.g. 0.47% Zr in the Ilímaussaq Complex versus 0.1-0.05% Zr in Florida heavy mineral sand deposits). In addition to Zr, Lovozero and Ilímaussaq contain high trace contents of REE,Nb,Ta,Th,U, etc., and their separate rock-forming minerals (e.g. nepheline, alkali feldspar) constitute important nonmetallic commodities. As a consequence, both massifs may be mined in the future and the ore processed as a complex raw material. Before this occurs, however, selective mining of discrete rock layers with substantially higher metal grades will probably have taken place, or is now taking place. Fig. 33-17 shows the grade-tonnage relationship of zirconium source materials in Lovozero and Ilímaussaq. Examples of metalliferous magmatic layers:

(a) Ilímauusaq Zr, Nb-bearing kakortokites (Nielsen, 1973; Bohse et al., 1971). Kakortokites are late stage agpaitic layered arfvedsonite, eudialyte, nepheline, feldspar syenites that are banded in a remarkably rhythmical manner. Within one rhythm, black (arfvedsonite-rich), red (eudialyte-rich) and white (feldspar and nepheline-rich) bands (in ascending order) are usually developed. Kakortokites contain 1.14% ZrO_2 in the black bands, 7.09% ZrO_2 in the red bands and 1.09% ZrO_2 in the white bands. The corresponding Nb_2O_5 contents are 0.05, 0.56 and 0.1%. The average content of the entire kakortokite is 1.2-1.4% ZrO_2 and about 0.13% Nb_2O_5 and they are estimated by Bohse et al. (1971) to contain about 51.6 Mt ZrO_2 and 5.4 Mt Nb_2O_5. This does not include the metal contents in the border pegmatite that must be considerable.

In Ilímaussaq, sphalerite is a widely distributed accessory mineral in the lujavrite layers, and 0.1% Zn contents have been recorded over large areas.

(b) Lovozero eudialyte lujavrites and eudialytites (Vlasov et al., 1959). The layered eudialytic lujavrites (mesocratic agpaitic nepheline syenites) constitute 18% of the Lovozero intrusion and form a rhythmic sequence 150 to 500 m thick, with an average content of 1.36% ZrO_2. Each rhythm consists of successive bands of leucocratic, mesocratic and melanocratic varieties, with gradual transition from one to the other. Eudialytites, eudialyte highly enriched conspicuously dark-red bands (up to 75% of eudialyte cumulus crystals in nepheline matrix), form lenticular intercalations ranging in thickness from a few millimetres to about 20-40 cm. In the Chivruái Valley (Fig. 33-18), 13 eudialytite bands form about 40% of a 3 m thick section of eudialytic lujavrite.

Eudialytites contain 6.76 to 8.68% ZrO_2, 0.39 to 0.93% $(Ta,Nb)_2O_5$ and 1.01 to 1.56% REE_2O_3 and they represent a resource of 10 to 100 Tt Ta, 100 to 1,000 Tt Nb, 100 to 1,000 Tt REE and some 4 to 40 Mt Zr (Rundkvist, ed., 1978).

(c) Lovozero loparite-bearing urtites and juvites (Vlasov et al., 1959). Loparite $(Ce,Na,Ca)_2(Ti,Nb)_2O_6$ in the form of black xenomorphic grains, is a widespread accesory mineral in the Lovozero layered intrusive rocks. Pure loparite contains about 8-10% Nb_2O_5, 0.65-0.75% Ta_2O_5, 0.62-0.76% ThO_2 and 16-17% REE_2O_3 When loparite content in an intrusive layer approaches about 10%, the layers can be selectively mined as a low-grade complex ore of REE,Nb,Ta,Th and U (Fig. 33-19). The loparite-rich layers are most common in urtites of the differentiated complex.

Rundkvist, ed. (1978) hinted that such layers containing 0.02-0.04%

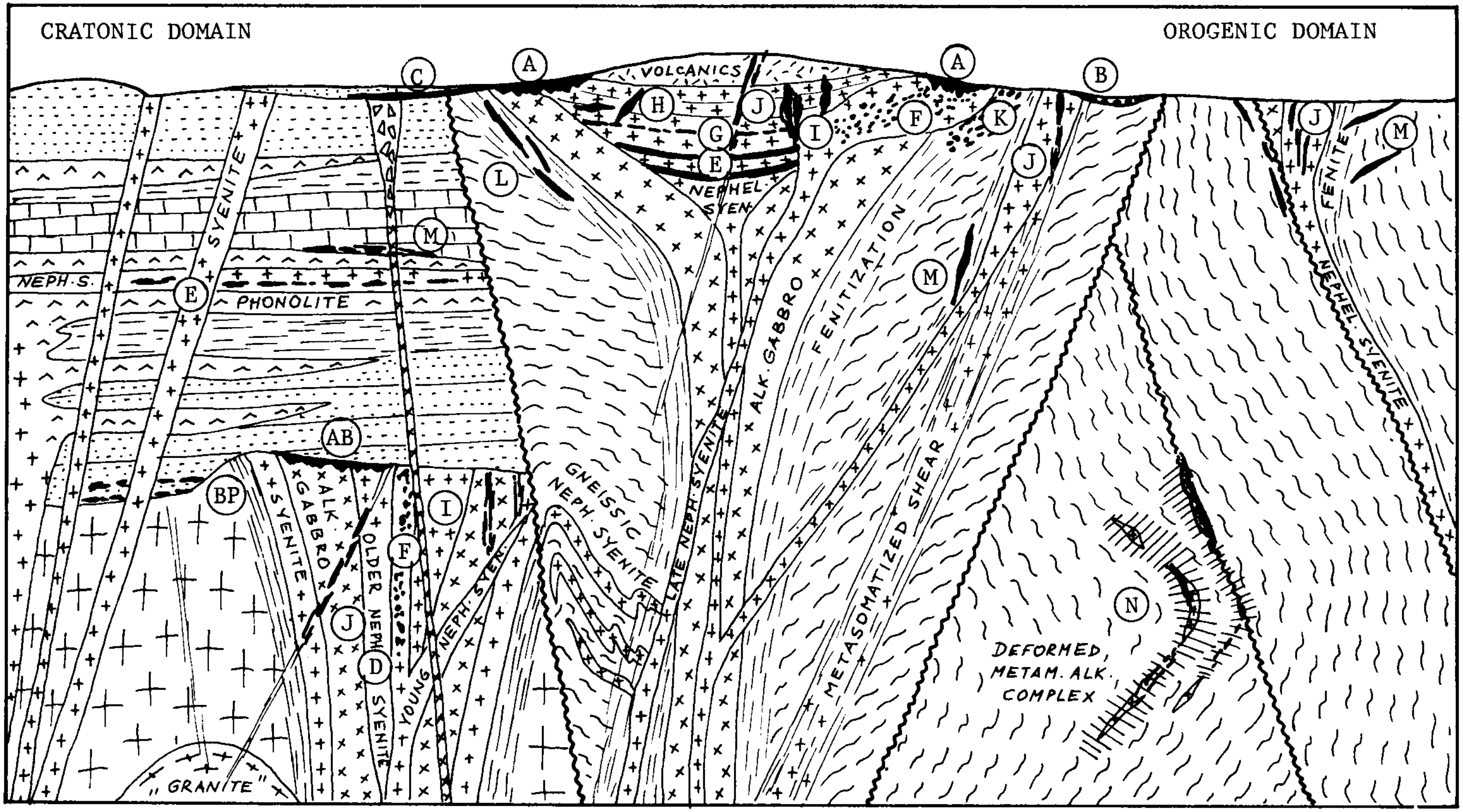


Fig. 33-16. Principal lithologic sub-associations and mineralization styles in the nepheline syenite-dominated alkaline complexes (see Table 33-6 for explanation of letter codes).

Table 33-6. Principal mineralization styles in nepheline syenite and alkaline gabbro-dominated alkaline complexes

	WEATHERING CRUSTS
(A)	Residual resistate minerals (Nb,Ta,REE,Zr); minerals formed by precipitation from leached components (Zr,U); residual bauxite over nepheline syenite and phonolite (60 Mt Al); residual Mn-oxides (500 Tt Mn) (AB) buried mineralized regoliths
	PRODUCTS OF SEDIMENTOGENIC REWORKING
(B)	Alluvial placers (caldasite, pyrochlore, zircon);(Zr,Nb,REE) (BP) paleoplacers
(C)	Resedimented bauxite (or sandy clay); Al (included in A)
	SYN-MAGMATIC ORES IN INTRUSIVE ROCKS
(D)	Major magmatic rocks and constituent minerals as metallic ores (e.g. nepheline syenite, nepheline, as future sources of Al)
(E)	Metalliferous magmatic layers: dominantly eudialyte-bearing syenites (min. 100 Mt Zr, 5 Mt Nb, 10 Mt REE, X0 Tt Ta, low-grade) pyrochlore, loparite, steenstrupine, lovozerite, etc. bearing syenites (min. 5 Mt Nb, 5 Mt REE, 50 Tt Ta, 500 Tt Th, low-grade)
(F)	Metalliferous non-layered magmatic rocks (massifs, sills, dikes); e.g. nepheline syenite with steenstrupine, monazite, thorite, etc. (40 Tt U, 85 Tt Th, 100 Tt REE)
	LATE MAGMATIC AND POSTMAGMATIC ORES IN INTRUSIVE ENDOCONTACT
(G)	Layered alkaline pegmatites, eudialyte rich (Ilimaussaq); possible 20 Mt Zr, 1 Mt Nb, low-grade
(H)	Patchy and dike alkaline pegmatites with murmanite, lovchorrite, etc. (about 20 Tt Nb,Ta, 10 Tt REE, 500 t Th)
(I)	Metasomatites (Be,REE,Nb,Th)
(J)	Hydrothermal veins genetically closely associated with alkaline intrusions (about 200 t Be, 280 Tt REE, 150 Tt Zr, 30 Tt Th, 1 Tt U, 160 Tt Ti, 17 Tt Mo); unaffiliated veins (Pb,Zn,Ag,Cu)
	HYDROTHERMAL ALTERATION AND MINERALIZATION IN INTRUSIVE EXOCONTACTS
(K)	Scattered, disseminated, patchy minerals in fenites (Fe,Ti,Zr,Nb, U, 50 Tt V)
(L)	Hydrothermal veins in fenitized aureole (U,Th,Ti,REE)
(M)	Ores in non-fenitized contact aureoles (Fe,Cu,Pb,Zn,Ag)
(N)	Syntectonic ores in deformed and metamorphosed alkaline complexes (Zr,Nb,Ta,U,Th,REE,Be)

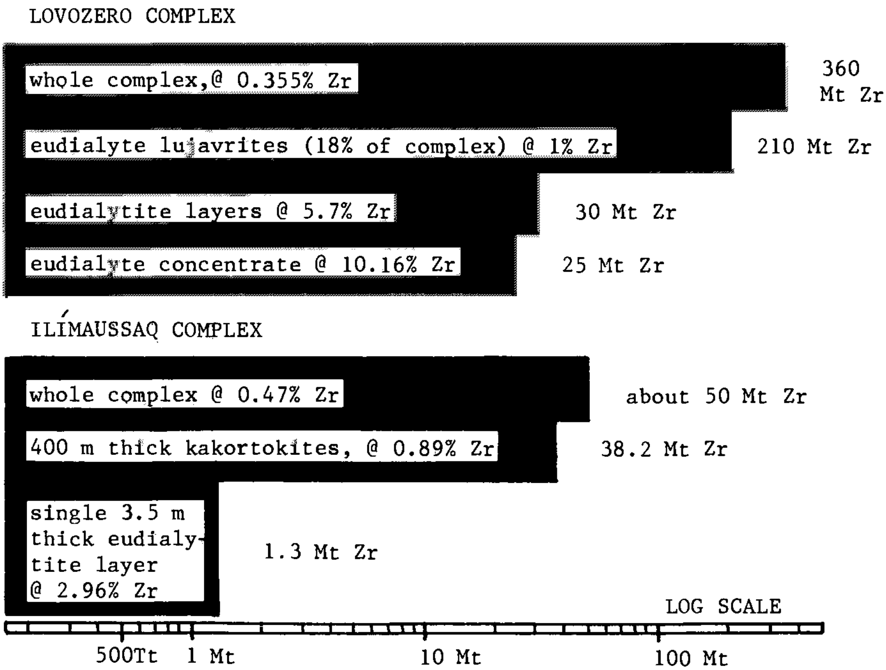


Fig. 33-17. Grade-tonnage relationship of zirconium source materials in Lovozero and Ilímaussaq alkaline complexes. Based largely on data in Vlasov et al. (1959) and Bohse et al. (1971), with gaps filled by estimates.

Ta, 0.2-0.4% Nb, 1-1.5% REE and probably 0.03% Th, may contain a mineable resource of some 1-10 Mt rare earths as well as 25% of the world's reserves of Ta (some 5-60 Tt Ta) and 12% of the world's reserves of Nb (some 5-8 Mt).

(d) Lovozero steenstrupine and lovozerite-bearing lujavrites. Steenstrupine $(Ce,La,Th,Ca,Na)_2(Mn,Fe)(SiO_3)_4 \cdot 5\ H_2O$, contains 14% REE_2O_3, 10.23% ThO2, 4.37% Nb_2O_5, 1.28% Ta_2O_5. Lovozerite $(Na,Ca)_2(Zr,Ti)Si_6O_{13}(OH)_6 \cdot 3\ H_2O$, contains 16.54% ZrO_2 and 0.56% REE_2O_3 (Vlasov et al., 1959). Both minerals occur in well-developed crystals and mineralogical quantities in some Lovozero pegmatites. They are much rarer accessories in the layered rocks, but recently several layers of steenstrupine and lovozerite-enriched lujavrites (mesocratic nepheline syenites) have been outlined. Beacause of the high REE,Th and Ta contents of steenstrupine, a rock with 1-2% of this mineral could become an industrial ore with 0.015-0.025% Ta, 0.2-0.3% Nb, 0.5% REE (Rundkvist, ed., 1978) and 0.X% Th. The potential Ta,Nb and REE resources in the steenstrupine and lovozerite lujavrites are only slightly less than the resources of the same metals in the

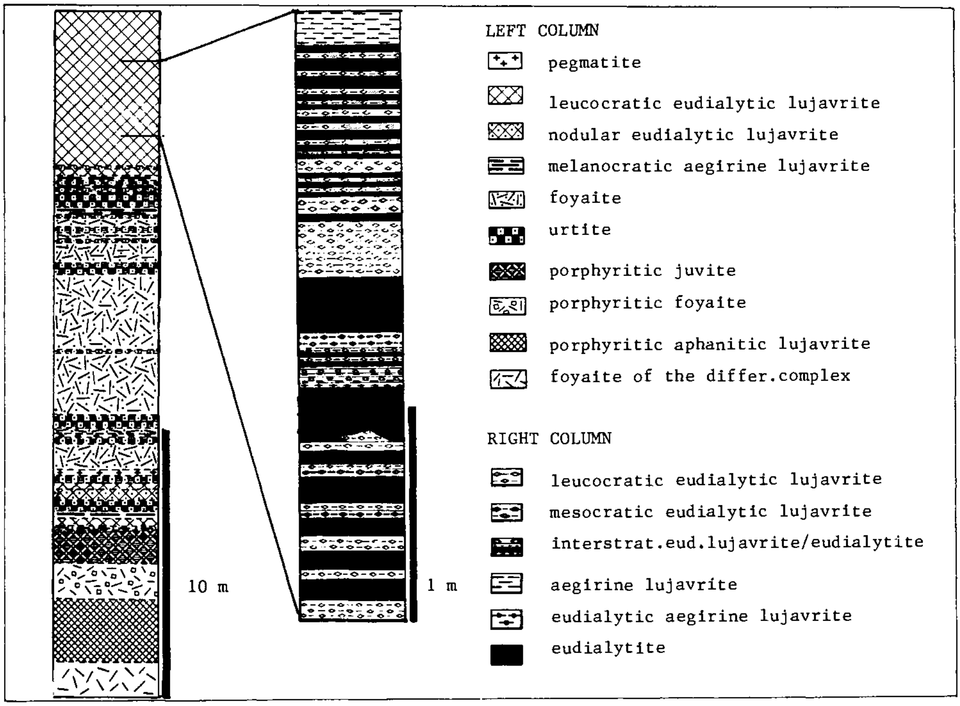
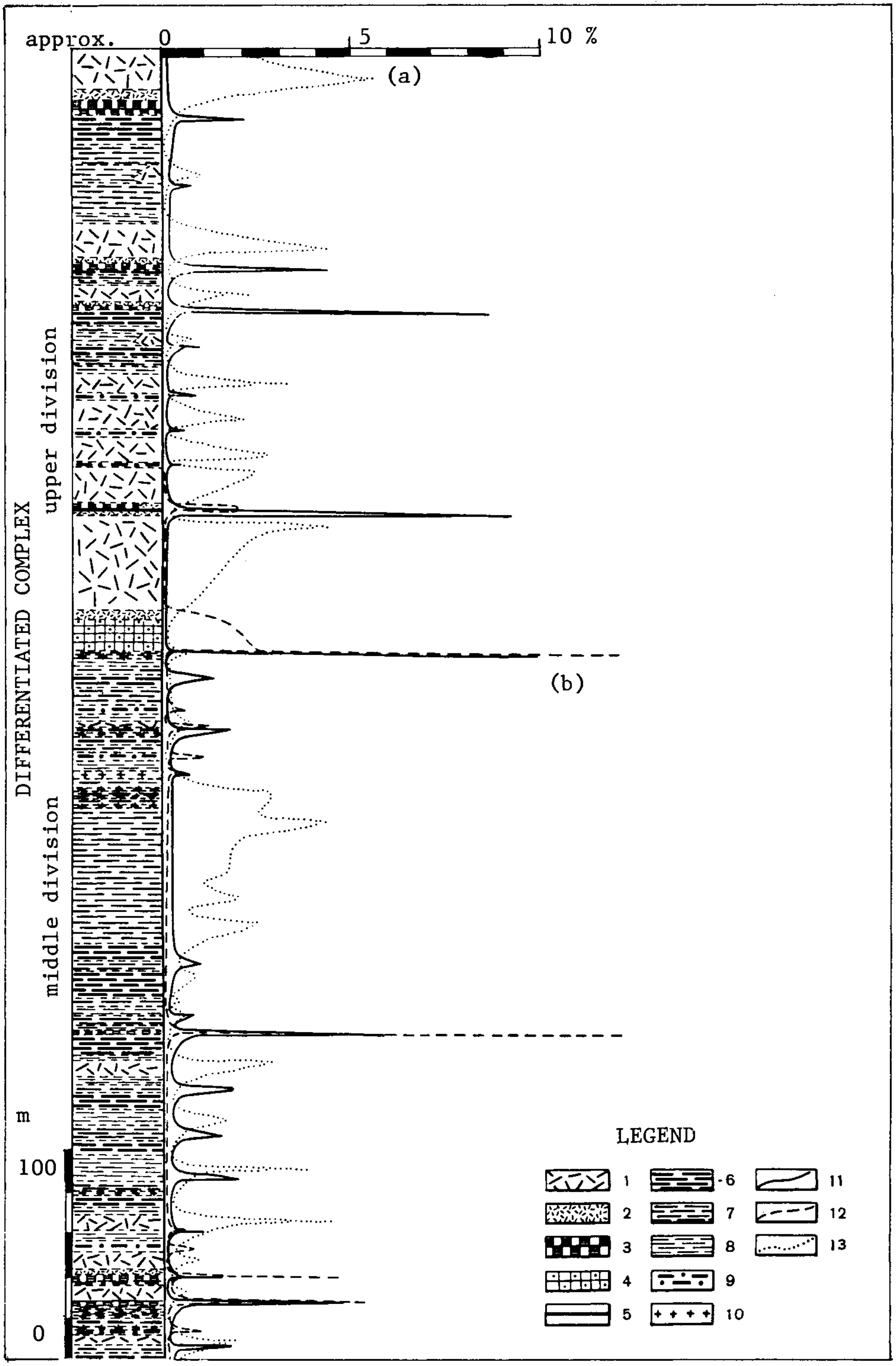


Fig. 33-18. Lovozero intrusion, columnar section of the basal portion of the eudialytic lujavrite complex (left) and detail of the eudialyte-rich 3 m thick interval in the Chivruai Valley (right). After Yeskova and Yeliseev, from Vlasov et al. (1959).

loparite ores, reported above.

(e) Metallic by-products of mining and processing of the Khibiny apatite. In the Khibiny Complex, a zone of brecciated aegirine nepheline syenite conformable with igneous layering, cemented and replaced by apatite, contains up to 65% of apatite and lesser quantities of Ti-magnetite, sphene and eudialyte. This zone is 2.4 km long and 160 m thick. The latter three minerals are recovered as by-products (Ivanova, 1963; Herz, 1976; Fig. 33-20). Sphene-rich layers in the hangingwall of the apatite orebody, moreover, contain 8-11% TiO_2 over a thickness of 5 to 30 m, and are periodically mined as a titania ore. The sphene concentrate contains 26% TiO_2.

The apatite in Khibiny and in other alkaline layered complexes usually contains a high trace content of the rare earth elements (almost 5% REE_2O_3), which is recoverable during the chemical processing of the apatite. Given the published apatite reserves of 2.7 Bt ore with 18% P_2O_5, this represents some 35 Mt REE_2O_3.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2B. MAGMATIC ROCKS WITH ACCESSORY METALLIC MINERALS OR HIGH TRACE METAL CONTENT, (B): NON-LAYERED INTRUSIONS

In this style, the ore substance distribution is comparable with the style (2A) reviewed above, but the host intrusive unit does not show rhythmic layering. Consequently, the ore minerals are distributed either evenly throughout the entire intrusive body (e.g. dike, sill, small plug), or form irregular ore-grade patches.

In the Kvanefjeld area of the Ilímaussaq intrusion, a late nepheline syenite (lujavrite) dike intrudes earlier brecciated alkaline intrusive rocks, and reaches into the exocontact of the layered intrusion (Nielsen, 1973). The dike is enriched in steenstrupine and lesser amounts of monazite and thorite. The whole rock contains 100-800 ppm U, 200-2,000 ppm Th, 1.21% REE and the reserves are currently estimated to be at least 18 Mt of ore, containing 43 Tt U and 86 Tt Th.

Carbonatite dikes occur frequently in nepheline syenite complexes or in their fenitized aureole. They may carry economic quantities of pyrochlore.

(3) PEGMATITES OF ALKALINE SYENITES

Pegmatites are widespread in nepheline syenite complexes, particularly the agpaitic ones. They are often zoned and carry a variety of rare minerals that are megascopically developed. From the standpoint of a field geologist, two sub-categories of pegmatites can be distinguished: (a) patchy pegmatites and (b) horizon (layer) pegmatites. In the Lovozero Massif (Vlasov et al., 1959), patchy pegmatites are abundant (particularly in the eudialyte lujavrite complex). Their dimensions vary between X and X00 m and they have no preferred orientation. They carry the same minerals as their enclosing rocks and are of no economic importance.

The horizon pegmatites are concordant or peneconcordant with the magmatic units, being most widespread at boundaries of petrographic

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Fig. 33-19. The character of REE, Nb and Ta mineralization in the layered differentiated complex, Lovozero intrusion, illustrated by distribution curves for loparite and lomonosovite-murmanite. The lomonosovite-murmanite peak (a) of 5.1% corresponds to a grade of about 0.27% $(Nb,Ta)_2O_5$. The loparite peak (b), about 11%, has an approximate grade of 1% Nb_2O_5; 0.07% Ta_2O_5; 0.08% ThO_2; and 3.5% REE_2O_3. The loparite-rich horizons are presumably mined selectively. 1=Foyaite; 2=juvite; 3=urtite; 4=ijolitic urtite; 5=malignite; 6=melanocratic lujavrite; 7=mesocratic lujavrite; 8=leucocratic lujavrite; 9=hornblende lujavrite; 10=pegmatite; 11=loparite distribution curve; 12=apatite curve; 13=lomonosovite-murmanite curve. Modified after Yeskova, from Vlasov et al. (1959). Approximate scale added.

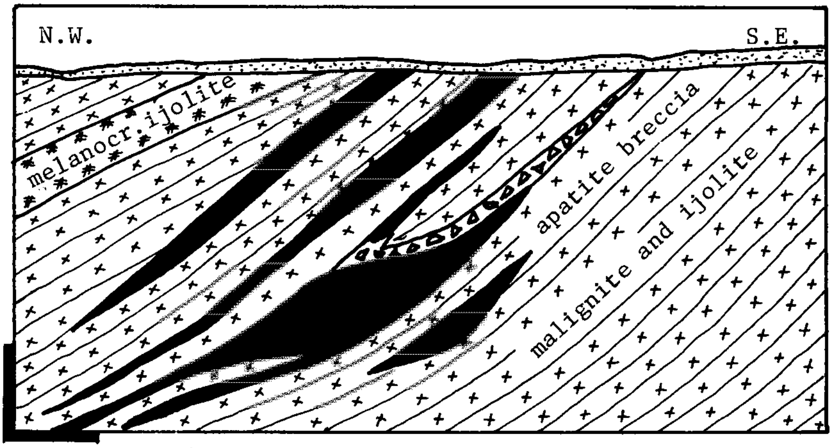


Fig. 33-20. Khibiny alkaline complex, Kola Peninsula, U.S.S.R. Cross-section of an open pit apatite mine near Kirovsk. Black areas: bodies of rare earths-rich apatite ore. After Pogrebitskii et al. (1968).

units ("marginal pegmatites"). The pegmatitic horizon beneath the ijolitic urtites in the Lovozero Complex consists of up to six subparallel pegmatitic layers ranging in thickness up to 2.5 m and traceable for several kilometres. The pegmatites are usually symmetrically zoned and typomorphic minerals are present in each zone. This facilitates selective mining and separation of the valuable minerals. Murmanite $Na_2(Ta,Ti,Nb)_2Si_2O_9$) content, for example, may reach up to 10% in the intermediate pegmatite zone. The greatest proportion and greatest thickness of the Lovozero pegmatites is in the poikilitic syenite complex. There, they contain the greatest diversity of rare minerals, and have an increased proportion of Th,REE and Be.

In the Ilímaussaq intrusion, the marginal pegmatite bordering the layered kakortokite unit against the marginal augite-syenite is one of the most impressive alkaline pegmatites known (Bohse et al., 1971). It is about 50 m thick and contains the same minerals as the kakortokites. The mineral distribution, however, is substantially more heterogeneous, yet the mean ZrO_2 content in the pegmatite is 2%, which is higher than the kakortokite average (1.2% ZrO_2).

In the Khibiny Complex (Ivanova, 1963), rare minerals-bearing pegmatites are widespread. At the Yukspor locality (near Kirovsk), a W.N.W.-trending swarm of several hundred K-feldspar, aegirine, lesser nepheline, arfvedsonite, apatite and lovchorrite pegmatite dikes up to 200 m long, was mined for its rare earths content (Afanasyev, 1937). The principal ore mineral was a dark yellow to brown lovchorrite $(Na_2Ca_4(Ce,La)(Ti,Nb)(Si_2O_7)_2(F,OH)_4$.

Outside the three important layered alkaline complexes mentioned above, nepheline syenite pegmatites are widespread but of little economic importance. Eudialyte pegmatites have frequently been reported (e.g. at Kipawa River, W. Quebec, Currie, 1974; Poços de Caldas, Brazil and numerous localities listed by Pavlenko, 1974, in the Mongol-Tuva province, Siberia). Langensundfiord in southern Norway (Brøgger, 1890) and Mount St.-Hilaire, Quebec, are famous mineral collecting localities in alkaline pegmatites.

4. ALKALINE METASOMATITES IN INTRUSIVE ENDOCONTACTS

Metasomatism is widespread in all phases of development of an alkaline intrusion. The products of intramagmatic and early postmagmatic metasomatism in alkaline complexes which presumably formed as a result of reaction of the volatile-rich residual fluids with the earlier crystallized consanguinous magmatites, are particularly distinct. Usually they form gradational patches, schlieren or veins controlled by fracture systems, zones of brecciation, contacts, etc. The composition, appearance and grain size of the metasomatites is variable and most striking are the coarse crystalline ones, that resemble pegmatites.

The majority of metasomatites are sodic, and albite is a particularly widespread constituent. Albite metasomatites often carry scattered minerals of Nb,Ta,REE,Zr,Th,Be (pyrochlore, thorite, zircon, sphene, apatite, allanite, etc.). K-feldspar (microcline)-rich metasomatites are most abundant where an alkaline intrusion is hosted by terrigenous (meta)sediments or granites (Omel'yanenko, 1974) and could be the result of remobilization of the earlier rock-forming potassium.

A variety of unusual mineralized metasomatites have been described in the Ilímaussaq Complex (e.g. by Engell et al., 1971). They include: (a) "lujavritized syenite", a metasomatite composed of albite and arfvedsonite, replacing nepheline syenite; (b) aegirine-replaced naujaite; metasomatic aegirine, partially or completely replacing a sodalite-rich agpaitic syenite. A portion of it carries scattered crystals of chkalovite $Na_2(BeSi_2O_6)$. Analcite-replaced naujaite formed in the same setting, and it is a relatively porous light-coloured rock with chkalovite, epistolite and Li-mica in crystal-lined miaroles. (c) an albitized arfvedsonite nepheline syenite dike offshoot in the Taseq area contains great number of Be minerals of several generations. The earliest chkalovite was later altered to tugtupite, which in turn changed to eudidymite and epididymite. This reflects the long-lasting, continuing history of alteration and mineralization in the area. The metasomatized intrusive rocks grade, without interruption, into the shear and fissure-filling mineral veins, treated in the next paragraph.

5. HYDROTHERMAL VEINS IN INTRUSIVE ENDOCONTACT

Hydrothermal veins cutting alkaline intrusions have frequently been recorded and some are important economically. Two end-member types are present: (a) veins that appear to be closely associated with the development of the host intrusion ("affiliated", "consanguinous", etc. veins). Such veins are often gradational into the metasomatites or pegmatites described earlier and when mineralized, the veins carry the alkaline suite of trace metals; (b) veins that do not reflect the mineralogical and geochemical characteristics of the host intrusion ("unaffiliated", "strange", etc. veins), and often correspond to or resemble the mineralizations known to occur outside the alkaline intrusion (for example, associated with the hydrothermal phase of calc-alkaline batholiths).

(a) Affiliated veins

In the Ilímaussaq complex, Be-mineralized hydrothermal veins formed by extension of the same process that produced some of the metasomatites reviewed earlier. In the Kvanefjeld area (Engell et al., 1971), albite and natrolite veins and veinlets carry scattered Be minerals chkalovite, tugtupite, beryllite and bertrandite, and several additional Nb minerals. Some of the veins persist into the exocontact formed by sheared mafic lavas, anorthosites and augite syenites. There, analcite is the principal gangue mineral, and the Nb_2O_5 and Ta_2O_5 contents of 0.6% and 0.008%, respectively, are in pyrochlore, epistolite $(Na,Ca)(Nb,Ti)(OH)SiO_4$ and murmanite $(Na(Ti,Nb)(OH)SiO_4$; Hansen (1968).

The largest Be accumulation in the Ilímaussaq and one that might become economic in the future (estim. reserves 180 Tt ore with 0.1% BeO; Engell et al., 1971), is contained in the Taseq slope area. There, a zone of hydrothermal veins and veinlets is superimposed on a steenstrupine-bearing arfvedsonite nepheline syenite dike. The main Be mineral is chkalovite, contained in albite-fluorite gangue. Analcite veins hosted by coarse nepheline syenite in the same area carry sodalite, natrolite, sørensenite, pyrochlore, neptunite, monazite, chkalovite and beryllite.

In the Poços de Caldas complex, a variety of hydrothermal veins, breccia fillings, stockworks, impregnations, etc. carry economic quantities of Th,REE,Zr,U and Mo. At Morro do Ferro (Cavalcante et al., 1979; Wedow, 1967; 300 Tt REE_2O_3, 35 Tt ThO_2, by-product Ti-magnetite), the mineralization is in a steeply dipping magnetite stockwork to massive vein, cutting altered phonolite and nepheline syenite. Th and REE are finely dispersed in colloidal form in the clay, and a lesser part of them is hosted by the magnetite. At present, the orebody is interpreted as being initially hydrothermal (magnetite, minor allanite, bastnaesite, cerianite and thorogummite fringed by a K-feldspar alteration envelope) and subsequently decomposed and further remobilized during lateritization.

The numerous though small "caldasite" (=mixture of zircon and baddeleyite) veins in the Poços de Caldas plateau follow fractures and small faults in phonolite and nepheline syenite. With rare exceptions all the veins are extremely shallow and developed in saprolite, so that the character of "caldasite" veins in the unweathered rocks is not well understood. Guimarães (1948) reported several thin veins of zircon in almost unaltered rocks and abundant accessory eudialyte in nepheline syenite at a depth of 85 m under the Serrote "caldasite" mine (Fig. 33-21). The "caldasite" is a very inconspicuous (except for its considerable specific weight) gray or hematite-pigmented material, the fragments of which are embedded in residual clay filling the vein structures. Crystalline, light-green zircon occasionally coats the fractures. The deposits of caldasite are generally interpreted (e.g. Ellert, 1978) as due either to the hydrothermal remobilization of Zr (and trace U) from zircon, eudialyte, astrophyllite and other minerals that are accessory in the host alkaline rocks, or to an exclusively supergene remobilization during lateritization. A combination of both processes is most likely to be the case.

In the presently exploited Cercado and Agostinho camps, Poços de Caldas complex, a low-grade U-Mo mineralization is superimposed on nepheline syenite and phonolite as well as the volcaniclastics and sediments in their roof. Maroon fluorite, zircon, uranothorianite, pyrite, coffinite, pitchblende, torbernite, jordisite and ilsemanite are disseminated or form impregnations in hydrothermal breccias, stockworks and veins, fringed by argillized and silicified hosts (Cavalcante et al., 1979).

In the Magnet Cove alkaline complex, Arkansas, thompsonite (zeolite) veins enriched in Be (up to 0.02% Be) have been reported (Ericson and Blade, 1963). At the Magnet Cove rutile deposit,

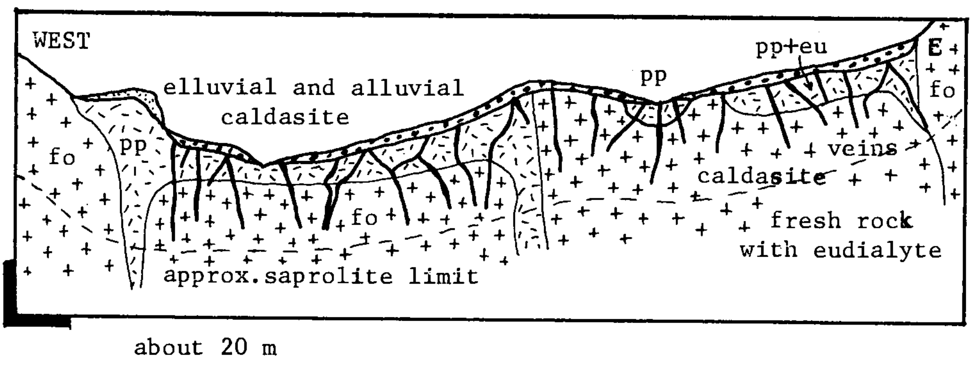


Fig. 33-21. Cross-section of the Serrote caldasite mine, Poços de Caldas Plateau, M.G., Brazil. pp=porphyritic phonolite; fo=foyaite (fine crystalline nepheline syenite); pp+eu=phonolite with eudialyte. Modified after Guimarães (1948).

feldspar, carbonate, rutile veins and masses occur in brecciated and altered phonolite. There is about 8 Mt of 3% TiO_2 ore (Fryklund and Holbrook, 1950), too low-grade to be profitable to mine, except in the soft saprolite. The rutile concentrate contains 2.2% Nb and 0.6% V. Another small Ti-oxide and Mo occurrence in the Magnet Cove complex is in microcline, albite, apatite, brookite, sphene, pyrite and molybdenite veins. The veins are up to 170 cm wide and 13 m long, N.W.-trending and hosted by a jacupirangite dike (Holbrook, 1948).

(b) Unaffiliated veins

The high-grade but thin Ag,Au, minor Pb,Zn fissure veins in the Horn Silver mine in southern British Columbia (Currie, 1974), are hosted by the alkaline intrusive rocks of the Kruger Mountain Pluton. The character of the veins, however, suggests that they are members of the hydrothermal aureole of the adjacent calc-alkaline batholiths.

6. MINERALIZATIONS IN THE EXOCONTACT OF ALKALINE INTRUSIONS

There is a considerable variety in the alkaline exocontacts and metallic mineralizations they contain. Empirically, it seems appropriate to subdivide the contact aureoles into (a) those that show distinct effects of the alkaline alteration or metasomatism (fenitization) and (b) those lacking fenites and showing no contact effects at all, or containing a variety of products due to isochemical contact (thermal) metamorphism.

(a) Fenitized exocontacts

Fenitization is an alkaline metasomatism, during which substantial amounts of Na or K and often Al and Fe are added to the original wallrocks from the alkaline intrusion, and silica is removed. Most varieties of alkaline intrusions (described in Sections 33-5,6,8,10) cause fenitization. The dominantly carbonatic Fen alkaline complex in southern Norway is the type area, and the memoir by von Eckermann (1948) describing the Swedish Alnö Island alkaline complex, is considered a classical paper on the subject. Von Eckermann demonstrated the zoned nature of fenites in Alnö, and his zones overprinted on Precambrian metamorphics are frequently quoted, mostly in the European literature (from outside towards the alkaline intrusion): (1) thermal shock zone, a shattered zone showing the effects of thermal metamorphism and minor metasomatism and comprised of feldspar, alkaline amphibole and pyroxene, carbonate, etc. fracture and breccia fillings; (2) a zone marked by spreading of the same minerals inward from fractures into their wallrocks and breccia fragments. Relic textures and quartz in the partly replaced rocks may still persist; (3) inner zone form, composed of microcline-aegirine, albite-riebeckite, or similar assemblage devoid of quartz. Original rock structures are often obliterated, and a massive rock of syenitic appearance forms in their place. The latter metasomatites are often indistinguishable from magmatic alkaline rocks.

The petrography of a fenite is strongly influenced by the character of the rocks intruded by the alkaline complex. The fenitization envelope around the Callander Bay alkaline complex, Ontario (Currie, 1974) superimposed on early Precambrian granitic rocks, starts to be noticeable about 650 m from the complex, and its zoning is close to the Alnö model. Gabbroic host rocks intruded by nepheline-dominated complexes are usually altered into rocks of ijolitic (=nepheline and pyroxene) composition, as around the Lackner Lake complex, Ontario; Parsons (1961). A considerable amount of iron seems to have been set in motion during fenitization of mafic precursors and Ti-magnetite is commonly found as disseminations, anastomosing veins, masses, etc. in ijolites (e.g. near Nemegos, Ontario).

Intensive fenitization tends to obscure the boundary between the truly magmatic crystallizates of the core alkaline suite, and fenitic metasomatites. Some practically indistinguishable syenites occur on both sides of the contact. Thin screens or slices of alkaline magmatites, moreover, frequently occur in many fenitized exocontacts. Fenitized remnants of former roofs to alkaline complexes may also occur within circular intrusions, where their metasomatic nature is often unrecognizable.

Although the majority of fenites described in the literature are situated around a known intrusion in the centre, several occurrences of fenites where such intrusion is missing have been recently described (e.g. from the Sudbury area, Ontario; Siemiatkowska and Martin, 1975). Presumably, the source of the alkaline fluids and probably the intrusion is at a depth and not yet unroofed. Metallic mineralizations in fenitized aureoles have the form of (i) anomalous metal enrichment or disseminated (scattered) ore minerals or (ii) hydrothermal ore veins in fenitized aureoles. Examples of mineralizations:

Zr enrichment

Ordovician shales at the contact with agpaitic syenite and phonolite at Mount St.-Hilaire, Quebec (Currie, 1974) have been sericitized in the inner contact zone, and converted to a Zr and Ti-enriched granular aggregate of albite, arfvedsonite and narssarsukite in the outer zone. A portion of the fenite aureole of the Lovozero complex is enriched in Zr, accumulated in accessory vlasovite (Vlasov et al., 1959).

Ti-enrichment

Many fenites are enriched in titanium, usually in the form of disseminations, lenses, veins and veinlets of rutile (e.g. Siemiatkowska and Martin, 1975). The analytically determined whole rock TiO_2 content is usually low, far from approaching the economically interesting threshold. In tropical areas, however, such rutile can be residually enriched in saprolite or reworked into placers. Rutile from fenites has usually high Nb and V trace content.

V enrichment

In Wilson Springs, Arkansas (Hollingsworth, 1967; D.R. Owens, guided tour, 1978), a major mine is producing vanadium from the fenitized exocontact of the Cretaceous Potash Sulfur Springs nepheline syenite intrusion. The Ordovician host rocks originally of chert, sandstone and impure carbonate composition, have been extensively fractured and converted into diopside, hedenbergite, lesser aegirine contact pyroxenite (alkaline skarn), to wollastonite tactite and metaquartzite. The latter is locally potash feldspathized. Argillic alteration is widespread on the fringe. Several alnöite dikes (alkaline lamprophyre) intrude the exocontact.

The vanadium ore (about 4.5 Mt ore with 1% V_2O_5) contains no megascopically recognizable minerals. In the unoxidized ore, vanadium is bound in rutile and in a variety of submicroscopic V minerals. There is a high scandium content. White, granular and veinlet apatite serves as a megascopic indicator of the V ore, that is richest in the calc-silicate hosts. A considerable proportion of V is contained in saprolite, in which it is believed to be bound in montmorillonite and goethite (also possibly montroseite).

Nb-U enrichment

In the Manitou Island alkaline complex, Ontario (Lumbers, 1971), a 568 m.y. alkaline syenite and pyroxenite intrusion is emplaced in fenitized Precambrian granitic gneisses. The inner zone of fenitization is composed of coarse K-feldspar and aegirine rock, intruded by thin crescentic carbonatite seams, and containing abundant thin feldspar-calcite veinlets. The carbonatite and in places the adjacent granite contain disseminated uranian pyrochlore.

Hydrothermal ore veins in fenitized aureoles

Thin but persistent fissure veins with a variety of mineral fillings (albite, hematite, aegirine, K-feldspar, calcite, quartz, bastnaesite, monazite, etc.) are common in the exocontact along the N.E. side of the Ilímaussaq intrusion (Hansen, 1968). Some veins carry from 60 to 4,500 ppm Th and 17 to 1,500 ppm U. U and Th-bearing veins have also been recorded along the western contact of the Poços de Caldas complex. In the aureole of the Magnet Cove complex, numerous but small quartz, brookite, lesser rutile and taenolite veins are well known, particularly to the mineral collectors.

Siemiatkowska and Martin (1975) described an uneconomic ankerite vein with scattered sphalerite from the fenitized breccia at Kusk Lake near Sudbury.

(b) Exocontacts lacking fenitization

Cordierite-andalusite, mica, hornblende-diopside, and biotite hornfelses, are developed along the contact of Devonian sediments and volcanics and the Lovozero alkaline pluton (Semenov, 1974). Small bodies of massive pyrrhotite were mined in a similar association along the Khibiny massif contacts.

In exocontacts of alkaline complexes rimmed by gabbro and emplaced into "greenstone belts", veins, veinlets and stringers of chalcopyrite are fairly common (e.g. Herman Lake, Ontario; Currie, 1974). Near Chipman Lake, Ontario, chalcopyrite is relatively common in gabbros rimming a syenite core. The copper has most probably been derived from the mafics. Veins of massive pyrite and pyrrhotite with erratic galena, sphalerite, chalcopyrite and arsenopyrite, are abundant in the aureole of the deformed and metamorphosed Ice River Complex, British Columbia (Currie, 1974).

7. DEFORMED AND METAMORPHOSED ALKALINE COMPLEXES

Several such complexes have been described in the literature (the nepheline syenite gneisses in high-grade metamorphic terrains have been reviewed in Chapter 29 and Volume 2, and are not consiedered here). The Paleozoic Ice River alkaline complex in the Rocky Mountains, British Columbia, was deformed by several events between 392 and 220 m.y. ago. The complex, however, acted as a rigid kernel, around which were wrapped much more intensively deformed metasediments (Currie, 1974).

In the Red Wine-Letitia alkaline association in Labrador described in greater detail in Volume 2 (Currie, 1974), remnants of a 1.5 b.y. old central complex comparable with Ilímaussaq, remnants of smaller intrusions, dikes and fenites, have been dismembered, penetratively deformed and metamorphosed. Patches of ore minerals common in undisturbed alkaline complexes (e.g. eudialyte, neptunite, pyrochlore, Be-silicates) occur throughout the area. The most striking feature appears to be a post-magmatic, syntectonic and syn-metamorphic recurrence of alkaline metasomatism, that overprint and/or replace earlier alkaline and non-alkaline rocks.

Syenitic metasomatites in the North Red Wine complex contain eudialyte and often larger amounts of joaquinite $Ba_2Na,Ce_2Fe(Ti,Nb)_2Si_8O_{26}(OH,F)_2$. At the Mann-1 locality, a probable meta-fenite lacking an associated intrusion, Be minerals occur in metasomatic pegmatites and in their vicinity (Evans and Dujardin, 1961).

8. WEATHERING-GENERATED RESIDUAL METAL AND MINERAL CONCENTRATIONS

Deep tropical weathering superimposed on bedrock mineralizations in alkaline complexes containing relatively stable ore minerals, results in their separation and isolation in the soft saprolite or laterite, from which they can be easily recovered. The alluvial caldasite deposits of Brazil are perhaps the best known example. Elsewhere, rhabdophane and bastnaesite have been detected in small amounts in a relic regolith over an alkaline massif located in the Yenisei Range, Siberia (Semenov, 1974). The regolith probably dates from the Cretaceous period.

Residual bauxite deposits frequently form over nepheline syenite and phonolite, and examples include the bauxites topping the Los alkaline complex near Conakry, Guinea; bauxites formed on phonolites and nepheline syenites in the Poços de Caldas complex, Brazil (reserves 200 Mt ore with 56% Al_2O_3; Fig. 33-22); bauxites resting on Cretaceous nepheline syenite, Lavrinhas municipio, Brazil (450 Tt ore with 56-58% Al_2O_3; Fonseca et al., 1979) and others. The Eocene bauxites over Cretaceous nepheline syenite in Arkansas (Gordon et al., 1958) have a high trace Nb content.

Small accumulations of earthy Mn-oxides sometimes cut by infiltration psilomelane veins, formed locally (e.g. near Cercado in the Pocos de Caldas complex; 2 Mt of 35-40% MnO_2 ore; Cavalcante et al.,1979).

9. MINERALIZATIONS RESULTING FROM SEDIMENTOGENIC REWORKING

All the residual commodities listed above also have proximally redeposited equivalents. The residual caldasite is reworked into proximal colluvial and alluvial placers, and the fragments become rounded ("favas"). Dissolution and reprecipitation of caldasite in soil or alluvial profiles results in "refinement". Almost pure, microcrystalline baddeleyite nuggets form.

Other resistate minerals from alkaline rocks sometimes accumulate in alluvial placers. Semenov (1974) mentioned pyrochlore and zircon, contributed to several Uralian streams by the Miask and Vishnevogorsk alkaline complexes. Resedimented bauxite is prominent in the Eocene sediments of Arkansas.

33.5.4. Examples of nepheline syenite-dominated complexes

The three examples of complexes described below, the Ilímaussaq, Lovozero and Poços de Caldas, illustrate two principal varieties, the layered and the non-layered ones. Table 33-7 contains a brief listing of additional examples of mineralized complexes.

ILÍMAUSSAQ, SOUTHERN GREENLAND

The Ilímaussaq intrusive complex is a member of the Gardar alkaline province and was emplaced 1,020 m.y. ago in early Precambrian basement granites under a roof of late Proterozoic lavas and sandstones. Although Proterozoic, it is described in this volume because of its unprecedented example value. The intrusion (Ferguson, 1964; Figures 33-23, 33-24) covers an area of approximately 150 km^2. A dicontinuous margin of chilled augite syenite was the earliest igneous member to crystallize, and it probably represents an example of rocks that compositionally are the closest to the parent magma for the rest of the intrusion.

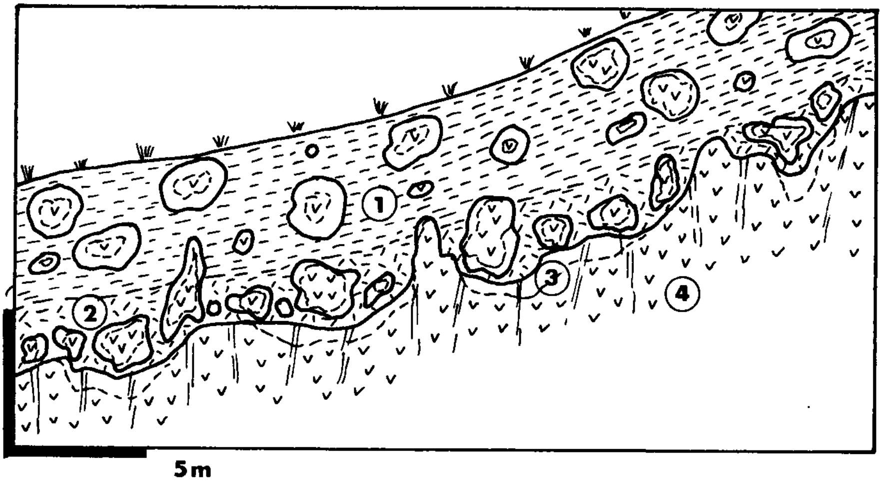


Fig. 33-22. "In situ" and colluvial lateritic bauxite on steep slopes N.W. of Poços de Caldas (city), formed over Cr phonolite. (1) Downslope transported red laterite with saprolitic and fresh allochthonous phonolite boulders; (2) in situ red and yellow mottled bauxite, local patches and coatings of black Mn oxides. In situ phonolite blocks; (3) leached phonolite; (4) fresh phonolite. From LITHOTHEQUE.

The augite syenite was followed by a central stratified series, composed of several saucer-shaped units. These include naujaite (= a poikilitic sodalite-nepheline syenite), sodalite foyaite (=intergranular-textured nepheline syenite) and a heterogeneous syenite believed to have formed by crystallization from the roof downward (Engell et al., 1971). Kakortokite which have already been discussed, have formed contemporaneously with the naujaite by bottom crystal accumulation. Lujavrites (trachytoid nepheline syenites) were subsequently intruded between the naujaite and the kakortokite, and their emplacement caused widespread metasomatism, hydrothermal alteration and epigenetic vein formation in the earlier rocks. The complex is cut by two N.E.-trending normal faults, that expose the intrusion at three progressively deeper crustal levels (Upton, 1974).

The Ilímaussaq complex is an outstanding geochemical and metallogenic anomaly, greatly enriched in Zr,REE,Nb,Ta,Th,U and Be. To call some of these anomalies "ore deposits", however, would require a considerable increase in the demand for Zr,REE and Nb, the most abundant metals there, to offset the logistic problems resulting from their remote location. In the economic geologic literature, Ilímaussaq is noted mainly for its explored low-grade uranium potential which, on the global scale, is only a moderate accumulation (43 Tt U). The spectacularly banded sequence of kakortokites which is

Table 33-7. Phanerozoic alkaline igneous provinces and complexes dominated by nepheline syenite

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Lake Nipissing Prov. Ontario, Canada	560 m.y. 5 nearly circular centr. compl. 3 km diam.; nephel.syenite minor carbonatite screens, lamprophyre dikes; empl.into fenitized PCm granite gneiss	U-pyrochlore dissem. in carbonatite; Manitou Island 25,540 t Nb/0.48-0.6%, 1,050 t U/0.035%	Lumbers (1971)
Monteregian Hills Prov., Quebec, Canada	190 km E.-W. string of small intrus., 110 m.y.; nephelinite, gabbro, nephel.syen., minor carbonatite	acces.pyrochl., enigmatite and rare minerals dissem.in neph. syen. and gabbros; economic only in carb.(see Oka)	Currie (1974)
Magnet Cove and Potash Sulfur Springs compl., Arkansas	Cr (95 m.y.); ring-dike compl.emplaced into PZ sedim.(shale, chert); 800 m wide fenitiz. aureole; ijolite and carb.core envel. by trach., phonol., neph.syen., neph. pyroxenite; dike rocks	qtz.-brookite + Mo veins in exocont.; feldsp., carb., fluor. Nb-rutile veins in endocont. (54Tt Ti, 2.2Tt Nb, 600t V); V at contact (Wilson Springs) parent rocks to Ark.bauxite	Erickson and Blade (1963)
Wind Mountain, Otero Co., S.E. New Mexico U.S.A.	circul.dome, laccol.of neph.syen. intr. into Pe limest., shale; dikes of melanosyen., nephel.syen. pegmatite	up to 20% eudial.in nephel. syen.dikes; Zr silic.with egirine, riebeckite, analc.at dike contacts; erratic Be enrichement	Warner et al. (1959)
Khibiny Massif, Kola Peninsula, N.W. U.S.S.R.	1,327 km^2, 290 m.y., 40 km diam. ring, 7 distinct intrus.phases; system of overlapping rings, domin. by aegirine and nephel. syen.empl.into Arch.gneisses; minor ijolite, alkal.dikes	large apatite and sphene dep. peneconc.with ign.layer., has high eudial.content; 2.7Bt of mater.with 18% P_2O_5, 0.4% REE_2O_3 (=935Tt REE); Yukspor Mt., W.N.W., up to 200 m long REE, Ta-Nb, Th lovchor.vein set	Gerasimovsky et al.(1974) Afanasyev (1937)

Lovozero Massif, Kola Peninsula, N.W. U.S.S.R.	659 km^2, 266 m.y. circular composite intrusion emplaced into Arch. granite-gneiss; layered, concentrically zoned, dominated by varieties of neph. syenite; dike and vein rocks	1) layered eudialyte neph. syen. 150-500m thick, aver. 1.36% ZrO_2; 2) eudialytite layers cont. aver. 5.8% Zr; 0.5% Ta+Nb; 1.1% REE and estim. resource of 50Tt Ta, 500Tt Nb, 500Tt REE, 20Mt Zr; 3) layered loparite urtite cont. about 0.03% Ta, 0.3% Nb, 1.25% REE, 0.03% Th (est. res. 5Mt REE, 30Tt Ta, 6.5Mt Nb; additional REE, Nb, Th, Ta is in steenstrup. rocks	Vlasov et al. (1959)
The Urals alkaline prov. (e.g. Vishnevogorsk, Miask) U.S.S.R.	several massifs usually conformable with struct. grain of enclosing PZ metam.; 268 m.y.; neph. syen., broad hybrid aureoles	widespr. zircon, pyrochl., sphene, britholite in albitized and carbonatized neph. syen. and fenite; Nb, REE, Th produced	Semenov (1974)
Eastern (Soviet) and Mongolian Tuva alk. prov. (e.g. Sangilen, Botogol', Numurgin, Udzhigin complexes)	D_3-MZ, several tens of small intrus.: neph. syen., urtite, phonol., alk. syen., peralk. granite, rare carbonatite; fenite aureoles	Zr, REE, Nb, Ta, Th dissem. in eudialyte rocks; minor pyrochlore in carbonatite; Be asoc. with peralk. granites	Kuznetsov (1967)
Poços de Caldas Complex, M.G., Brazil	almost circular complex domin. by phonol. and subvolc. nephel. syen. (Cr) empl. into PCm gneiss basem. Several intrus. phases but compos. monotonous; local potassic rocks	Zr "caldasite" veins, resid. and placers cont. about 100Tt Zr and 391t U; Th and REE in Ti-magn. stockw. have 255Tt REE and 30Tt Th; U-Mo veins and stockw. in altered complex roof cont. about 8Tt U, 1Tt Mo, 1.5Tt Th; residual bauxite and Mn ox. on neph. s., phonol.	Cavalcante et al. (1979)

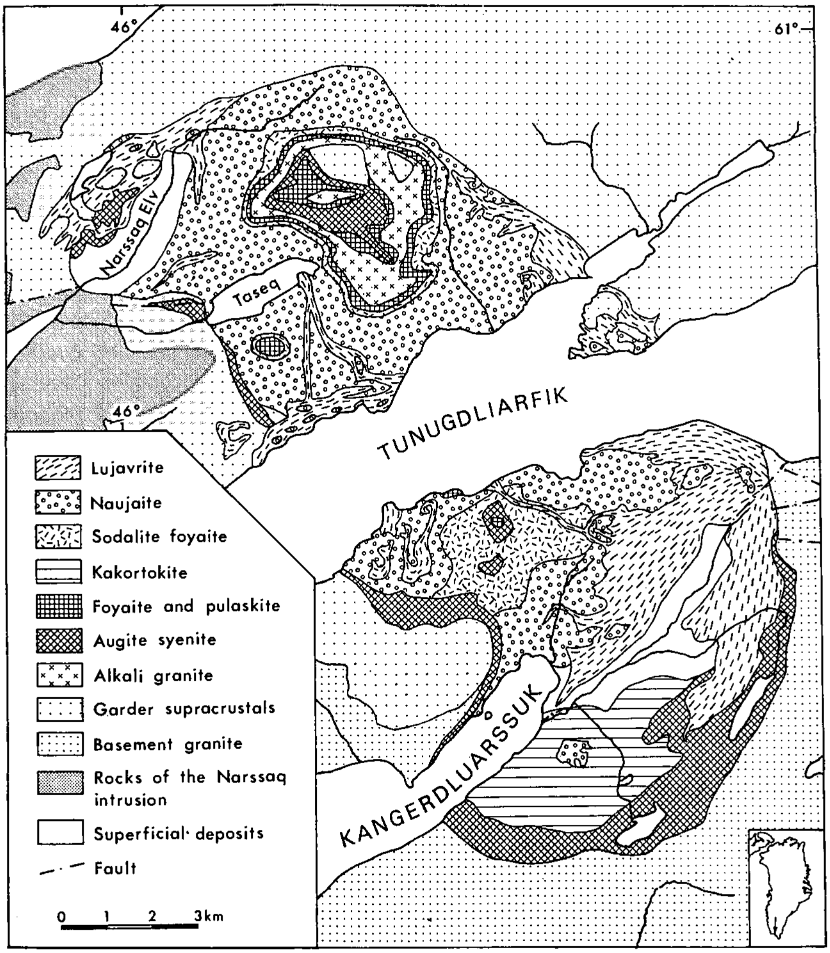


Fig. 33-23. Simplified geological map of the 1.02-1.18 b.y. Ilímaussaq alkaline complex, southern Greenland. After Ferguson, from Nielsen (1973). Courtesy of the Geological Survey of Greenland.

over 400 m thick, represents the most outstanding metal-bearing unit containing some 38.2 Mt Zr and 3.78 Mt Nb, that are uneconomic to work at the present time. Additional Zr+Nb resources exist in a thick layer of a marginal pegmatite.

The lujavrites, as a whole, are enriched in REE,Nb,Ta,Th and U concentrated in a variety of complex accessory minerals (pyrochlore, epistolite, steenstrupine, monazite, thorite, etc.) and host the uranium ore zone at Kvanefjeld. Additional concentration of the same metals is associated with the late stage hydrothermal activity that produced numerous albite, analcite, and zeolites-dominated

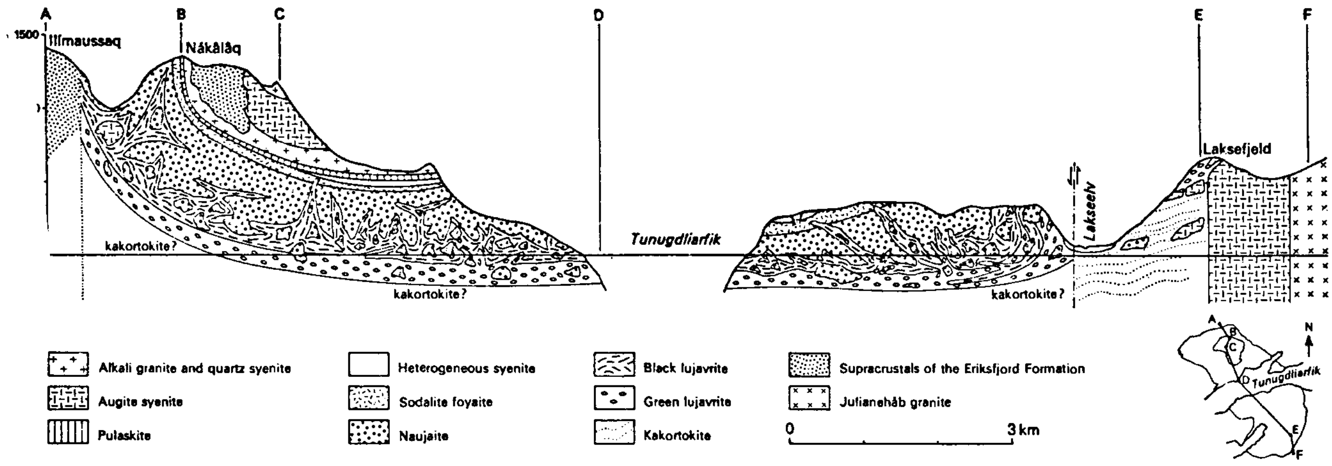


Fig. 33-24. N.N.W-S.E. section across the Ilímaussaq alkaline complex, southern Greenland. After Ferguson, from Allaart (1973). Courtesy of the Geological Survey of Greenland.

metasomatites and veins (Alaart, 1973). Beryllium is irregularly accumulated in several types of hydrothermal veins and metasomatites containing chkalovite, tugtupite, epididymite and other minerals. A mere 180 t BeO is contained in the only outlined deposit (Taseq slope) in the N.W. portion of the complex (Engell et al., 1971).

LOVOZERO ALKALINE COMPLEX

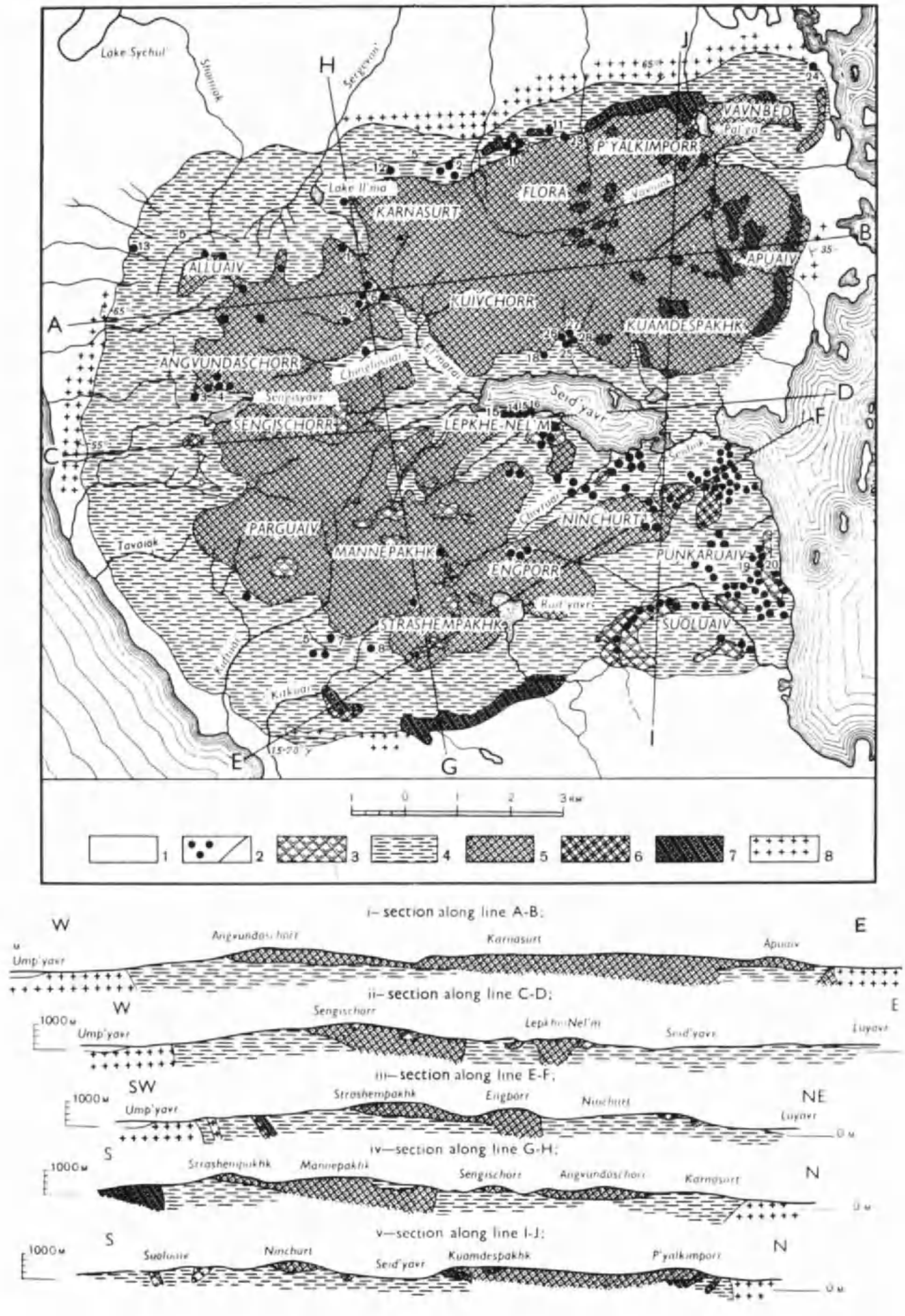
Lovozero is a member of the Kola Peninsula alkaline province, north-western U.S.S.R. It is a large (650 km^2) composite intrusion dating from the Carboniferous age (266 m.y.; Fig. 33-25), emplaced into the surrounding Archean granite-gneiss terrain (Vlasov et al., 1959; Gerasimovsky et al., 1974). The intrusion has sharp contacts, a stock-like shape in depth and it is concentrically zoned. The upper part of the complex consists of a laccolith-like differentiated body.

The complex is a product of four successive magmatic phases. Rocks of the first phase (metamorphosed and metasomatized nepheline syenites) are preserved mostly as rafts and xenoliths. Phase 2 is represented by a rhythmically layered sequence with repetitive stratigraphy (from bottom to top: urtite, foyaite, lujavrite). The rocks of Phase 3 comprise coarsely crystalline layered lujavrites with a prominent zone of eudialyte lujavrite in the central part of the massif. Phase 4 consists of alkaline dikes (monchiquite, camptonite, tinguaite).

Rocks of the Lovozero complex are extremely agpaitic (the $Na_2O+K_2O:Al_2O_3$ ratio is 1.4), dominantly sodic, and anomalously enriched in Zr (0.48% ZrO_2 is the whole complex average). The typical rare-metal minerals in the Lovozero complex are members of the eudialyte and lomonosovite groups, loparite, REE-apatite and minor lovozerite, ramsayite, lamprophyllite, murmanite. They are present either as regularly distributed accessories in the layered rocks (0.01-0.5%), or as locally accumulated minor minerals (up to 5%). Eudialyte forms almost monomineralic rocks locally.

Although Rundkvist, ed. (1978) suggested that the Complex may contain some 25% of the world's reserves (or resources) of Ta and 12% of the world's Nb, it is not clear what type of ore is actually being mined or prepared for production. The most likely industrial candidates are sections with a high content of eudialyte, loparite-rich urtite horizons or steenstrupine and lovozerite-bearing lujavrites. Lovozero appears to be a prime candidate for a large-scale, complex production of multiple commodities.

Fig. 33-25. Lovozero alkaline complex, geology. 1=Q sediments; 2=pegmatites; 3=poikilitic syenites; 4=rocks of the differentiated complex; 5=rocks of the eudialytic and porphyritic lujavrite complex; 6=nepheline syenite fenites; 7=D, augite porphyries, tuff, quartzite, sandstone; 8=gneiss and granite gneiss. From Vlasov et al. (1959). Courtesy of Oliver and Boyd, Edinburgh.


Lake Sychul'
H
J
VAVNBED
P'YALKIMPORR
FLORA
KARNASURT
Lake Il'ma
ALLUAIV
APUAIV
KUIVCHORR
KUAMDESPAKHK
ANGVUNDASCHORR
SENGISCHORR
LEPKHE-NEL'M
Seid'yavr
NINCHURT
PARGUAIV
MANNEPAKHK
ENGPORR
PUNKARUAIV
STRASHEMPAKHK
SUOLUAIV
Tavaiok
A
B
C
D
E
F
G
I
1
2
3
4
5
6
7
8
i– section along line A-B;
W
E
Ump'yavr
Angvundaschorr
Karnasurt
ii– section along line C-D;
1000 м
Ump'yavr
Sengischorr
iii– section along line E-F;
SW
NE
Ump'yavr
Strashempakhk
Ninchurt
0 м
iv–section along line G-H;
S
N
Strashempakhk
Mannepakhk
Angvundaschorr
Karnasurt
v–section along line I-J;
Ninchurt
Seid'yavr
Kuamdespakhk
P'yalkimporr

Agpaitic pegmatites, hydrothermal veins, and fenite-hosted mineralization, although of considerable variety and scientific importance, treated in detail in the book of Vlasov et al. (1959), appear to have little practical value at present.

POÇOS DE CALDAS COMPLEX, MINAS GERAIS, BRAZIL

This complex (Fig. 33-26) forms, geomorphologically, a dissected plateau with a medium altitude of about 1,200 m, surrounded by an almost circular range of hills reaching 1,500-1,600 m. It is situated 250 km from São Paulo in the Cretaceous alkaline province on the fringe of the Paraná Basin, and has an area of about 800 km^2 (Cavalcante et al., 1979). The complex was emplaced in a Precambrian gneiss basement presumably under a thin roof of its own ejecta (tuffs, breccias, ankaratritic lavas) and associated sediments some 87-60 m.y. ago. The earliest phase produced ankaratrites, the following phases generated phonolites and intrusive hypabyssal nepheline syenites (foyaites, tinguaites).

Compositionally, the Complex is quite monotonous and nepheline syenite-phonolite account for 90% of the rocks. No distinct intrusive layering is present, and the phonolites are locally potassic. A pseudoleucite-rich facies occurs in places. Zircon and eudialyte appear to be widespread accessory minerals, but are mostly "invisible" because of the fine grain of most rocks and a deep weathering crust. Coarse eudialyte syenites and pegmatites are locally developed along the northern rim of the complex.

The Poços de Caldas district contains quite a variety of Zr,Th,U,REE,Al and Mn ores. These have all arisen as a result of local accumulation of the originally rock-forming trace and major elements by a variety of superimposed agents. Probably the best known example and a unique case is the "caldasite" vein, residual and placer mineralization. It is widespread (containing close to 100 separate workings) and represents some 230 Tt of 50-75% ZrO_2 and 0.2% U_3O_8 concentrate mined in the past and present in known reserves (Tolbert, 1966; Cavalcante et al., 1979). The Morro de Ferro, a magnetite vein and stockwork with superimposed Th and REE, contains some 30 Tt Th and 255 Tt REE.

The U-Mo veins, stockworks, and disseminations in hydrothermally altered nepheline syenites and roof rocks at Agostinho and Cercado, represent the first and only exploited and complexly treated Brazilian uranium deposit existing at present. The measured and inferred reserves are about 7,939 t U, 1,500 t Th, 1,000 t Mo and 64 Tt Zr (Ramos and Fraenkel, 1974).

Good quality bauxite is widespread, occurring in numerous small deposits formed, in situ, over nepheline syenite and phonolite or transported clays. The reserves are estimated at between 70 and 200 Mt and they support an operating smelter. Manganese oxides are sometimes recovered from lateritic profiles as a by-product of bauxite mining. The Mn deposit near Cercado contains about 480 Tt Mn in a

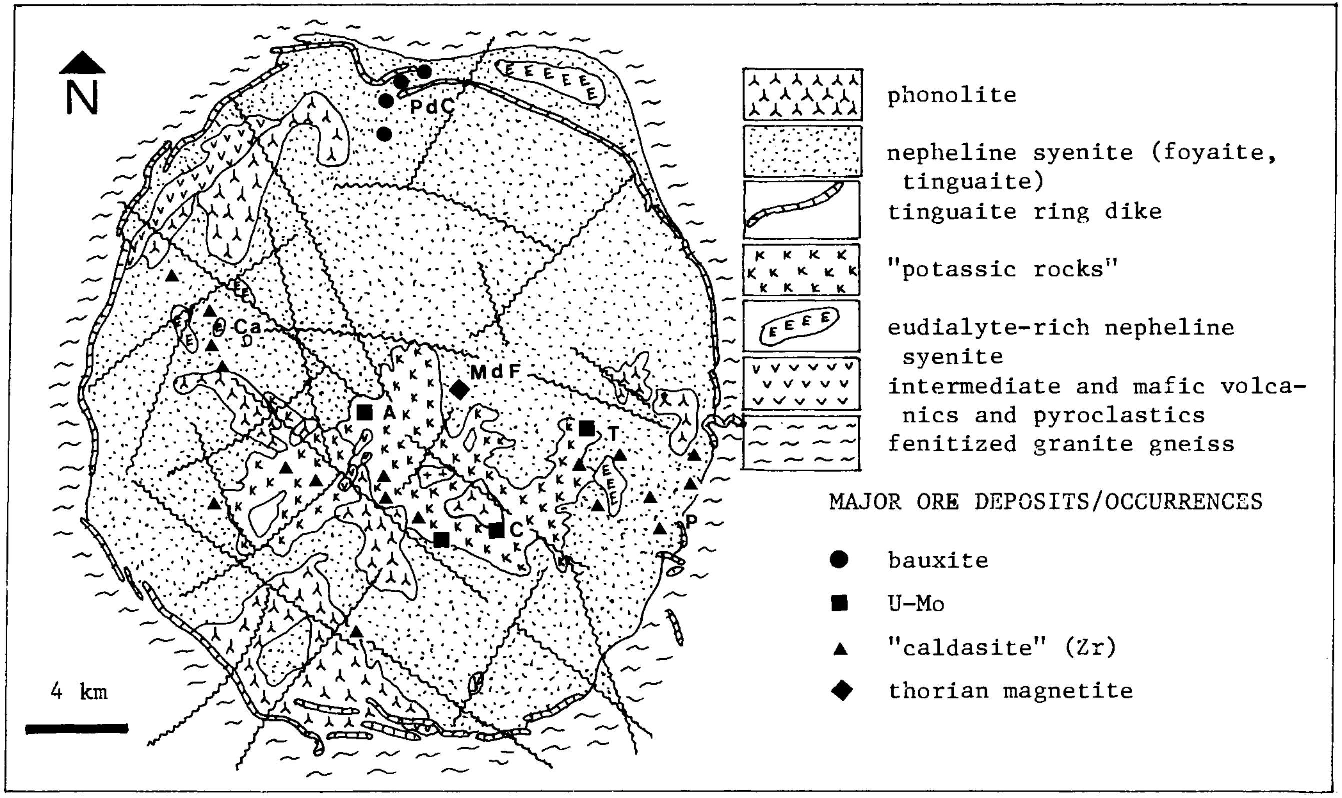


Fig. 33-26. Poços de Caldas alkaline complex, Minas Gerais, Brazil, showing locations of major ore occurrences. PdC=Poços de Caldas; Ca=Cascata; MdF=Morro de Ferro; T=Taquarí; P=Pocinhos; A=Agostinho; C=Cercado. The "potassic rocks" are phonolites with pseudoleucite and also probably remnants of fenitized roof rocks. From LITHOTHEQUE, compiled from published maps.

horizon 0.5-1 m thick, grading around 24% Mn.

33.6. ALKALINE-ULTRAMAFIC ASSOCIATION

33.6.1. General

Alkaline-ultramafic association is widely recognized in the U.S.S.R. (e.g. Rundkvist, ed.,1978) and it usually includes peridotite, pyroxenite, alkaline gabbros, alkaline syenites, carbonatite and kimberlite. In this section, only those complexes actually composed of major peridotite or pyroxenite units, are treated. Carbonatites or kimberlites may be present, but the dominantly carbonatite complexes are treated in Section 33.8., and the kimberlites in Section 33.9.

The mode of occurrence of alkaline-ultramafic intrusions is comparable with that of the nepheline syenite-dominated complexes, except that layered intrusions comparable with Ilímaussaq or Lovozero are not known. Circular or elliptical zoned intrusions are most characteristic and the fully developed ones have usually a dunite or peridotite core, fringed by pyroxenite, alkaline gabbroids and alkaline syenites. The fringe syenites and a variety of associated or substituting rock types (norites, "aplites", etc.) are genetically controversial and are currently interpreted as orthomagmatic differentiates by some and metasomatites by others. In the latter interpretation, the syenites would coincide with the most proximal zone of fenitization.

33.6.2. Metal geochemistry and metallogeny

Dunites and peridotites lacking alkalies are petrochemically neutral and common to alkaline as well as tholeiitic and calc-alkaline families. As a consequence, the ultrabasics considered alone display predictable trace metal anomalies (Cr, Ni, platinoids) and ore occurrences influenced by such anomalies. The nickel laterites represent an example. However, pyroxenites (e.g. jacupirangite; Upton, 1967) and in particular gabbros, show distinctly alkaline tendencies, although non-alkaline pyroxenites and gabbros also occur. The alkaline mafic rocks are enriched in the rare metals characteristic of alkaline complexes (REE,Zr,Nb,Th), but are depleted in Ni,Cu and S, the elements that normally combine to form a plethora of mineralizations in tholeiitic and calc-alkali mafic suites. Cu and Ni occurrences are consequently rare in alkaline gabbros.

Iron and titanium, however, had been mobile in several phases of development of alkaline pyroxenites and gabbros, and these rocks host a variety of Ti-magnetite, Ti-oxides, ilmenite, perowskite, etc. mineralizations that sometimes constitute important mineralized provinces (e.g. at least 1.4 Bt Fe, 15 Mt Ti, by-product apatite, vermiculite, REE,Ta,etc. in the Caledonian alkaline province of the Kola Peninsula).

33.6.3. Major mineralization styles (Fig. 33-27, Tables 33-8, 33-9)

EARLY MAGMATIC MINERALIZATIONS

These are hosted by magmatic rocks and believed to have formed during the process of original magmatic crystallization as cumulate crystals or as a solidified intercumulus phase. Minerals accumulated in the form of schlieren, disseminations, etc. in inclusion-rich zones may have formed as the result of magma contamination. In the overall balance, magmatic "syngenetic" ores in alkaline-ultramafic rocks (except carbonatites) are of limited economic importance.

Dunites often have high trace Ni content (e.g. 0.29% NiO in the fresh dunite from the Santa Fé massif, Iporá Group, Brazil), but this is a silicate-bound nickel and Ni sulphides have rarely been reported. The dunite core of the Inagly Massif in Siberia (Rundkvist, ed., 1978; Fig. 33-28) contains Pt metals in Pt-Fe and Pt-Ir alloys, cooperite and laurite, associated with chrome spinelides. These minerals are enriched in nests, lenses and schlieren in the central part of the dunite core and, so far, only the secondary placer deposits seem to have been of interest from an economic point of view.

Pyroxenites usually carry high accessory contents of Ti-magnetite, perowskite and sometimes (as in Africanda, Kola Peninsula) knopite (cerian perowskite). They are also the most common hosts to the large Ti-magnetite and apatite deposits, but most such deposits are metasomatites or epigenetic bodies emplaced after the pyroxenite solidification. The most notable exception where an industrial Fe-Ti deposit appears to have formed by a "syngenetic" magmatic crystallization from an immiscible liquid, is the mineralized jacupirangite (=alkaline pyroxenite) dike in Kodal, Norway (Bergstøl, 1972). Here, the Permian jacupirangite forms a dike 2 km long and 20 m wide emplaced in augite monzonite. Portions of the dike consist of dense intergrowths of Ti-magnetite (40%), apatite (18%) and ilmenite (8%) with aegirine, minor biotite, and amphibole. The textures are typical of magmatic crystallization.

Gabbros. Low-grade schlieren and disseminations of Ti-magnetite and ilmenite are common in the middle Proterozoic (1.8 b.y.) alkaline-ultramafic intrusions in Kola and Karelia (north-western U.S.S.R.; Yudin and Zak, 1970). In addition to these lean ores, high-grade densely disseminated to massive ilmenite and Ti-magnetite ores form layers and lens-like seams up to 100 m long, conformable with igneous layering. In addition discordant vein-like bodies of massive ores are formed. Such ore is interpreted as being late magmatic (hysteromagmatic) injection, but the possibility of metamorphogenic upgrading of lower-grade magmatic ores cannot be excluded.

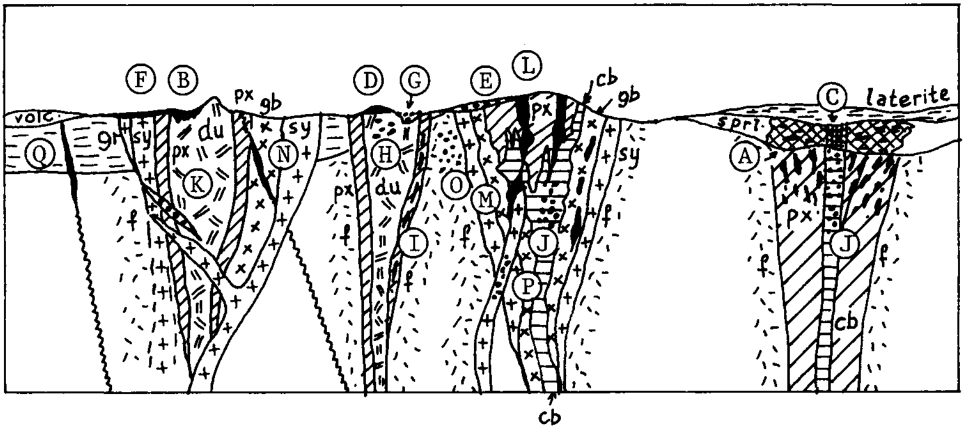


Fig. 33-27. Principal lithologic sub-associations, rock types and mineralization styles in alkaline ultramafic complexes (see Table 33-8 for an explanation of letter codes). gb=Gabbro (alkaline); px=alkaline pyroxenite; du=dunite; sy=syenite (magmatic and metasomatic); gr=granite; cb=carbonatite; f=fenitization; sprl=saprolite.

Pegmatites. Alkaline pyroxenites and gabbros commonly contain coarse ("pegmatitic") facies that are mineralogically identical with the rest of the host rock. Light (syenitic) pegmatites, usually corresponding in composition to nepheline syenites, often transect the mafic magmatic rocks. In the Inagli intrusion and elsewhere, such dikes carry small anounts of Zr,Nb, and REE minerals. Many pegmatites react with the mafic or ultramafic wallrocks and phlogopite or vermiculite is usually the only economically important product (as in Afrikanda, Kola Peninsula). Ti-magnetite, perowskite, chalcopyrite and other minerals may be present in small quantities and recovered as a by-product.

EPIGENETIC METASOMATITES AND VEINS SUPERIMPOSED ON ALKALINE PYROXENITES AND GABBROS

Most alkaline-ultrabasic complexes are polyphase, and the most volatile components (residual liquids, hydrothermal fluids) of the younger magmatic phases reacted with the older, solidified and usually fractured phases to produce a series of hybrids, metasomatites and hydrothermally-filled veins. The latter often carry important ore accumulations. The most common hosts to such ores are alkaline pyroxenites and the usual phases contemporary with the mineralization are nepheline syenites and carbonatites. The most common mappable hybrid rocks correspond petrographically to ijolites and urtites (nepheline-pyroxene rocks), to carbonate-pyroxene and to other

Table 33-8. Principal mineralization styles in alkaline-ultramafic intrusive complexes

	WEATHERING CRUSTS
(A)	Partly modified residual minerals (magnetite, ilmenite, anatase, leucoxene); about 20 Mt Ti (Tapira)
(B)	Residual and infiltration oxide and silicate Ni in laterite, saprolite (about 500 Tt Ni)
(C)	Residual apatite, francolite, enriched in REE, Th, etc.
(D)	Residual minerals in silicified ultramafics (birbirite); Pt
	PRODUCTS OF SEDIMENTOGENIC REWORKING
(E)	Fragmental ore and ore boulders in glacial drift (X Mt Fe)
(F)	Redeposited ferruginous (locally bauxitic) laterite
(G)	Alluvial placers (X0 t Pt)
	MAGMATIC "SYNGENETIC" MINERALIZATION
(H)	Scattered Pt metals in dunite
(I)	Magmatic "syngenetic" disseminations of Ti-magnetite, ilmenite, perovskite, apatite, etc. in pyroxenites and alkaline gabbros (X0 Mt Fe, X Mt Ti)
(J)	Disseminated Nb,REE,Th, etc. minerals in minor carbonatite bodies and screens
(K)	Mineralized pegmatites and their contacts (Zr,Nb,REE)
	EPIGENETIC METASOMATITES AND VEINS SUPERIMPOSED ON ALKALINE PYROXENITES AND GABBROS
(L)	Ti-magnetite, perowskite, apatite, etc. masses, veins, lenses in pyroxenite and alk. gabbro (Kovdora; 1.4 Bt Fe, 15 Mt Ti)
(M)	High-temperature silicate metasomatites (skarns)
(N)	Fracture filling hydrothermal veins
	ORES IN INTRUSIVE EXOCONTACTS
(O)	Fe,Ti,Nb, apatite, etc. disseminations, replacements in fenites
(P)	Radioactive syenite porphyry dikes (X Tt Th)
(Q)	Hydrothermal fissure veins (X0 Tt Th)

silicates mixtures. The common ore minerals are Ti-magnetite, ilmenite and perowskite. Apatite, phlogopite and vermiculite are the usual nonmetallic commodities.

In the Kovdora massif, Kola Peninsula, steeply dipping replacement veins or lenses of massive Ti-magnetite enveloped by an apatite-forsterite rock were emplaced in ijolite-urtite and pyroxenite (Borovikov and L'vova, 1962; Fig. 33-29). These, in turn, were intruded by a younger carbonatite, resulting in a mineralization strongly reminescent of Palabora, South Africa. By-product betafite, baddeleyite and minor copper, is recovered at Kovdora.

Similar mineralization but spreading over a smaller area is hosted

Table 33-9. Alkaline-ultramafic complexes, selected examples

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Libby, Montana U.S.A.	Cr? composite intrusion into Pt_{2-3} sediments; core of biotite pyroxenite with coarse-grained biot. and xenoliths of ultram.surround.by magnet.pyrox. ring dike;neph.syen.,phon.,dks.	perowskite conc. in vermiculite; magnet.pyrox. contains 15-21% Fe 0.13% V_2O_5; locally scattered accessory sphalerite	Boettcher (1967)
Powderhorn Complex S.W. Colorado U.S.A.	Cm; about 30 km^2 pear-shaped, multiphase compl. Pyrox.intrud. or replac.by nephel. or melil. rocks and carbonatite; intrud. into PCm gran.,fenitiz.aureole	vermicul.,Ti-magn.,perowsk. and apatite form dikes and irreg. lenses in pyrox.; 100 Mt ore with 6.5% TiO_2 and 11.7% Fe. Nb in carbonatite; Th widespr.in carb.,pyrox.,altered dikes, exocont. veins	Temple and Grogan (1965)
Gem Park complex Wind Mts.,Colorado U.S.A.	Cm; small funnel-shaped compos. intrus.;pyrox.,gabbro,minor lamproph.,neph.syen.,carbonatite,intr.PCm metam. Fenite envel. Believed underl.by large carb.	vermicul.,magn.;pyrochl.in carb. dikes; Nb,REE,Th miner.dissem. in fenite and anastomosing carbonatite dikelets	Parker and Sharp (1970)
Iporá Group, Paraná Basin fringe,S.W. Goiás, Brazil	Cr_3; 73 small intrus.,10 larger massifs; circul.to ellipt.intr. comp.of dunite nuclei surr.by pyrox.,alk.gabbro,neph.syen., syen. Some have Na-amphib.rich fenitiz.margin; intr.to PCm metam. and D_1 sandstones	Ni later.on dunite (100Mt ore with 1.5% Ni; largest Santa Fe massif, 21.14 Mt ore with 1.5% Ni	Danni (1976) Pena and Figueiredo (1972)

Tapira, Paraná Basin fringe, M.G. Brazil	Cr, elipt.intr.6 km diam., pyroxenite and perid.with small carbonatite, empl.into fenitiz. PCm metamorphics	dissem.primary apat., anatase, magn., phlogop.and perowsk., irregul.bodies and veins in pyrox. Actual prod.is from up to 100 m thick saprolite; 200Mt ore with 22% TiO_2 in pyrox., 113Mt ore with 1% Nb_2O_5 in carbonatite	Herz (1976) de Tarso, oral comm. (1980)
Kola Penins.early PZ alkal.ultram.pr. N.W. U.S.S.R.	14 plutons, 340-590 m.y., early dunite, pyrox., foll.by ijolite, melteigite, nephel.rocks	stock-shaped bodies of dissem. perowsk. and Ti-magn., high rare elements content	Yudin and Zak (1970)
Kovdora massif (member of above province)	D_2; concentr.zoned intr.with pyrox. and dunite core surr.by melil.rocks, outer ijol.zone and fenites; intr.by silic.carbont. Widespr.hybrid rocks	steep vertic.replac.veins and lenses of Ti-magn., apat., phlog. 1,300 m long in ijolite and pyroxenite; 708Mt ore with 35% Fe; 6.6% P_2O_5; 0.3% Zr; about 0.2% Nb and 0.01% Ta	Borovikov and L'vova (1962) Rundkvist, ed., (1978)
Afrikanda massif (member of above province)	pipe-like 400 m long body, peridot.core with erupt.dunite brec. transected by nephel-pyrox.pegm.	Ti-magnet. and Ce-perowskite, phlogop.veins, veinl.and metas. in pyrox.near pegmat.dikes; 626Mt ore with 13% TiO_2	Sokolov and Grigor'yev (1974)
Kodal, Oslo Igneous Province, Norway	Pe, 1.9 km long, 10-35m wide jacupirangite (alkal.pyrox.) dike empl. into augite monzon.	densely intergrown apat., Ti-mag. ilm.in pyrox., dissem.in monzon. 70Mt ore with 46% Fe oxides, 8.48% TiO_2, 7.98% P_2O_5	Notholt (1979)
Maimecha-Kotui Prov., N.Siberian Shield, U.S.S.R. largest: Gulya plut. (2,000 km^2)	Pe_2-T_1 central intrus.complexes; dunite, perid., pyrox.core envel. by ijolite-melteigite, carbonat., nephel.syen., syenite	several apatite and Ti-magnet. deposits cont. several billion t Fe; baddeleyite, pyrochlore, francolite in some pipes.	Rundkvist, ed. (1978) Epshteyn and Anikeyeva (1963)

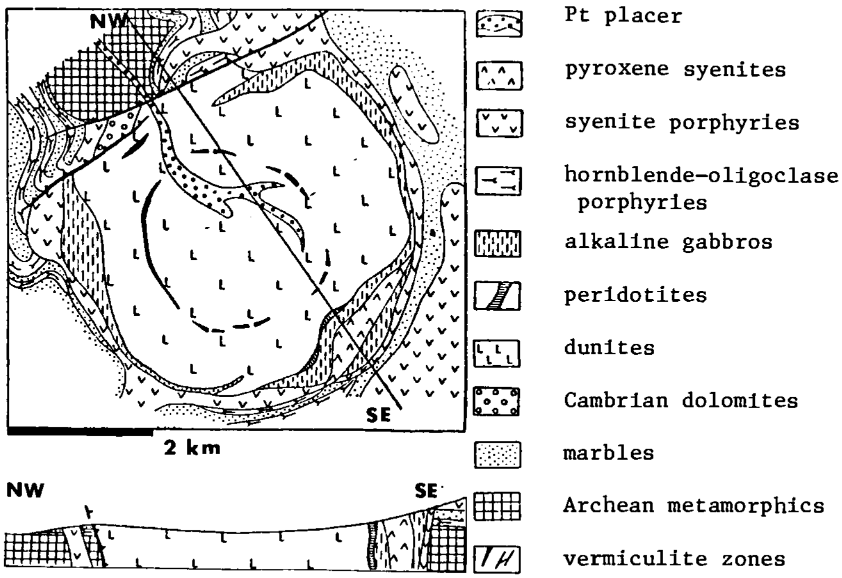


Fig. 33-28. Inagly alkaline ultramafic massif, N. Aldan Shield, Siberia. After Rozhkov and others, from Kazanskii (1972).

by pyroxenite and ijolite at Iron Hill, in the Powderhorn complex, Colorado (Temple and Grogan, 1965). There, the perowskite is locally rich in thorium.

In Tapira, M.G., Brazil, irregular bodies, veins, veinlets and scattered magnetite, perowskite, anatase together with apatite, phlogopite and vermiculite, replace pyroxenite (A. de Tarso, oral commun., 1980). All the minerals and particularly perowskite and anatase, have a high Nb content. The bulk of the ore mined in Tapira comes from the deeply weathered surficial portion.

High-temperature metasomatites comparable with skarns (garnet, alkaline pyroxenes, etc. rocks) are members of a hybrid rock suite formed along the centres of carbonate-rich pyroxenites, silicate carbonatites and urtite-melteigites in the Turiy Peninsula complex, Kola (Samoylov and Afanas'yev, 1978). Magnetite replacements occur in the vicinity, but are not directly hosted by the skarns.

Fracture-filling hydrothermal veins composed of analcite, natrolite, carbonates, etc. are widespread in the alkaline-ultramafic complexes, but no significant associated mineralization has been reported.

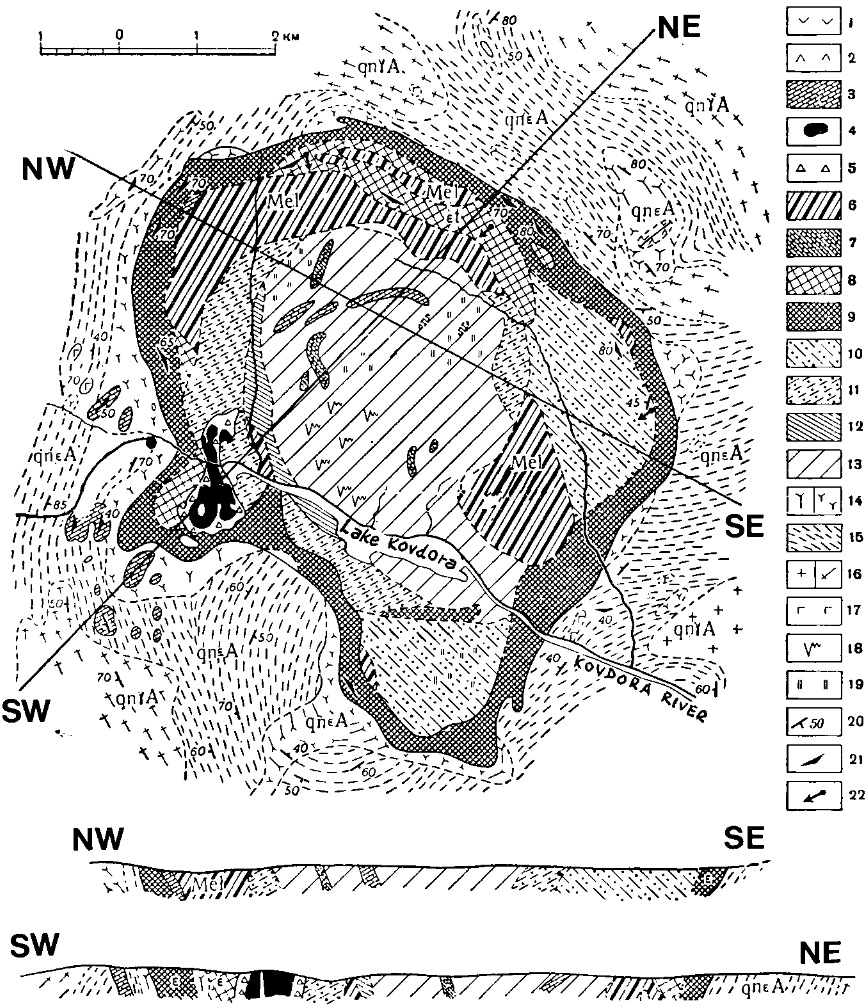


Fig. 33-29. Kovdora alkaline ultramafic massif, Kola Peninsula, U.S.S.R. PZ intrusive complex: 1=poikilitic and trachytic nepheline syenites; 2=trachytoid ijolites; 3=carbonatites; 4=magnetite; 5=apatite, forsterite, phlogopite rocks; 6=turyaites, melilitites, monticellite-melilite rocks; 7=vein ijolites; 8=coarse ijolites; 9=fine ijolites to melteigites; 10=nepheline pyroxenites, partly melteigites; 11=pyroxenites; 12=peridotites; 13=olivinites. Archean crystalline rocks: 14=fenitized gneisses, granite gneisses; 15=ditto, weakly fenitized; 17=amphibolites; 18=zones of sungulitized olivinites; 19=intensive phlogopite and vermiculite metasomatism; 20=schistosity; 21=banding in alkaline rocks; 22=lineation. From Borovikov and L'vova (1962).

MINERALIZATION IN INTRUSIVE EXOCONTACTS

Exocontacts of alkaline-ultramafic complexes are usually fenitized, and the fenitized zones are the same as those described in the previous sections. Certain ores normally formed in the intrusive endocontacts are, in some cases, found in fenitized exocontacts as well. Rundkvist, ed. (1978) reported the existence of apatite-bearing metasomatites which formed in altered quartzites in the exocontact of the Magan Intrusion (Meimecha-Kotui alkaline province, N. Siberia). Apatites normally have high trace contents of rare earth elements.

Parker and Sharp (1970) described a body of fenitized alkaline gabbro located within an alkaline-ultramafic intrusion in the the Gem Park Complex, Colorado. The fenite carries high Nb and V values which the authors attribute to a buried carbonatite body.

In the contact aureole of the Powderhorn complex, Colorado (within an alkaline metasomatic rim several hundred meters wide and beyond this, Th mineralization is widely distributed (Hedlund and Olson, 1961). Pink to red, fine grained trachyte porphyry dikes are radioactive, although no visible radioactive minerals have been detected. About 100 dikes have been mapped and the radioactivity is attributed to fine residual thorogummite, dispersed in earthy hematite pseudomorphs after pyrite. In addition to the dikes, 217 Th-bearing radioactive veins emplaced in Precambrian basement metamorphics have been recorded. The thin veins are most abundant in the proximity of outlying (metasomatic) syenite bodies. They follow shears and breccia zones, and carry scattered thorite crystals in quartz, orthoclase, barite, specularite, carbonate, fluorite, biotite, etc. gangue. The wallrocks are often feldspathized (microcline) and this results in conspicuous pink or red rims.

METAMORPHOSED ALKALINE-ULTRAMAFIC COMPLEXES

Schorscher et al. (1982) interpreted as being meta-jacupirangite several Proterozoic mafic meta-intrusives, located 120 km N. of Morro do Pilar, M.G., Brazil. This rock forms an elongated body, several hundred metres long and emplaced in the metamorphics of the basement complex and itself deformed and metamorphosed in the upper greenschist facies. Hedenbergite, sphene, apatite, carbonate and quartz are the major constituents, and there are anomalous contents of Th (0.21%), Y (0.13%) and other metals. Thorium is bound in orangite and yttrium in apatite.

WEATHERING-MODIFIED OR GENERATED ORES

In Tapira, Brazil (Herz, 1976), a weathering crust which formed in situ over the primary magnetite, ilmenite, perowskite and anatase ore in pyroxenites, is up to 100 m. thick. Within it, ilmenite and perowskite have been converted to "leucoxene" and the anatase was partly leached. The residual ore is slightly enriched in Ti due to removal of Ca,Fe and Nb and it is cheap to mine. The reserves are 132 Mt ore with 21.6% TiO_2. Residual, powdery niobian apatite ore (15% of apatite) has been preserved in the saprolite, but diluted or even dissolved in the topping red laterite.

Francolite (carbonate apatite) is a common alteration product of apatite hosted by or close to carbonatite. It is an inconspicuous, whitish mineral widespread, for example, in the apatite-ijolite and apatite-carbonatite breccias in the Magan complex (N. Siberia; Rundkvist, ed., 1978). Francolite usually has a high trace content of rare earths.

Lateritic weathering superimposed on nickel-rich dunites and peridotites may result in the formation of the usual style of Ni laterite and saprolite, already reviewed in Chapters 7 and 23. Numerous occurrences are known in the Cretaceous Iporá Group belt of alkaline-ultramafic intrusions, located on the fringe of the Paraná Basin, Brazil. The largest and best studied deposit is located in the Santa Fé massif (de Oliveira and Trescases, 1980). There, the following zones of the lateritic profile have been recognized. Running from top to bottom these are as follows: red laterite, yellow laterite, fine saprolite, coarse saprolite, bleached dunite, fresh dunite. The Ni-enrichment is most significant in the yellow laterite and saprolite (max. 7.25% NiO), and it consists of dispersions and, lower in the profile, infiltration veinlets (boxworks) of Ni-kerolite, pimelite and silica. The lateritization is Tertiary and the ore reserves at Santa Fe are estimated to be about 21.14 Mt of ore with 1.5% Ni.

Silcrete present in tropical regions is considered to be a negative development, because it masks the bedrock (compare Chapter 23). It is rarely mineralized. In the Yubdo ultramafic body, Ethiopia (considered by Rundkvist, ed., 1978, to be comparable with the Inagli massif, Siberia), silicified surficial portions of ultramafics ("birbirites") locally contain residual particles of platinum. Relict, residual jasper (ferruginous silica chert) locally present in the surficial portion of the Th-bearing veins near the Powderhorn complex, is radioactive (Hedlund and Olson, 1961). The radioactivity is probably due to finely dispersed secondary Th minerals.

ORES RESULTING FROM SEDIMENTARY REWORKING

The numerous Ti-magnetite deposits (Kovdor, Afrikanda) that crop-out in the recently glaciated regions, are often enveloped by glacial drift rich in ore boulders. Some such boulders have been recovered as an ore in the initial stages of mining of the bedrock deposits.

The Pt scattered in the Inagly and Yubdo peridotites has been reworked into alluvial placers. Those in Inagly are very proximal, directly overlying the source dunite.

33.7. POTASSIC ALKALINE ROCKS

The "most normal" alkaline rocks, such as nepheline syenites and phonolites, contain an excess of sodium over potassium (e.g. 8.46% Na_2O and 5.77% K_2O in an average nepheline syenite; Table 3 in Sørensen, 1974). Exceptions, however, are common and the nepheline syenites from Stjernøy and Vishnevogorsk (same table) have a slight excess of K_2O over Na_2O. Some alkaline rocks contain a large excess of K_2O (e.g. phonolite from Shonkin Sag, Montana; same table; 6.45% K_2O, 1.85% Na_2O) and have been included in a separate class of potassium-rich alkaline rocks. In addition to several distinctly potassic alkaline igneous provinces (e.g. the Highwood Mountains of Montana; Hurlbut et al., 1941), high-K rocks usually marked by abundant pseudoleucite have a patchy distribution within or along the margin of sodic alkaline complexes (e.g. Poços de Caldas). Many are probably metasomatites (fenites).

The class of potassic alkaline rocks is, however, considered unique by petrologists and it has a specialized literature (e.g. Sahama, 1974; Gupta and Yagi, 1980), but its metallogeny is indistinct. This may be due to the general rarity of this association. Geochemical enrichment in U and Th has been reported most commonly and it is interesting that isolated occurrences of K-alkaline rocks coincide spatially (although not genetically) with "granitic" tin provinces (e.g. Loučná in the Erzgebirge; Karagwe-Ankolean Province, E. Africa). The U-Mo mineralization in the Poços de Caldas complex (Section 33.5) is contained partly in potash-rich rocks and so are the hydrothermal veins with brannerite and thorite in an unnamed leucite and kaliophilite-rich late Proterozoic massif in Siberia (Semenov, 1974).

In the Rome and Tuscany Pleistocene volcanic provinces of Italy (von Backström, 1974), potassic alkaline rocks have high trace U and Th contents (25-50 ppm U, 130-240 ppm Th). A variety of low-grade reprecipitated orebodies in volcaniclastics have already been mentioned in Section 33.2.

In the sanidine-rich Cretaceous Crowsnest volcanics, S. Alberta, Canada (Currie, 1974), small Cu and Mo showings are hosted by their high-level intrusive equivalents.

33.8. CARBONATITES

33.8.1. Introduction

Carbonatites are very rare rocks that constitute no more than 0.00X% (by volume) of the alkaline rock suite, yet they are blessed with a copious volume of literature. Every known occurrence of carbonatite has probably been recorded in print and described and a high proportion of such descriptions have been abstracted in the international literature. New occurrences of carbonatites are being added as the result of continuing discoveries as well as genetic reinterpretation of known carbonate occurrences. There is, also, an abundance of petrologic and ore petrologic literature on carbonatites, and two widely available reference volumes exist in English (Heinrich, 1966; Tuttle and Gittins, eds., 1966). This makes carbonatites probably the best covered category of mineralized rocks in the English literature.

To some extent this is economically justifiable. Carbonatites are decidedly the most consistently and most frequently mineralized alkaline rocks, and they hold a disproportionate share of the world's production and reserves of niobium (about 30 Mt Nb) and rare earths (about 35 Mt REE). They also represent a case history of a fundamental scientific recognition and elegant re-interpretation of a formerly controversial rock assemblage. Once an attractive model of the magmatic origin of carbonatites from deep subcrustal sources had been generated, everyone rushed to contribute his or hers data.

While the genetic affiliation of carbonatites to some form of alkaline magmatic activity is not in dispute, not all occurrences are simple stocks or flows of a solidified carbonate magma. It is becoming increasingly evident that, as in the case of feldspathites, carbonatites could form as orthomagmatic crystallizates, as products of hybridization (mixing) of earlier magmatic rocks with carbonatitic magmas, as products of solidification of magmatically remobilized non-magmatic carbonates or as products of alteration metasomatism of earlier rocks by a variety of hydrothermal fluids and gases. Other alternatives are also possible. All these possibilities may host the characteristic rare metal mineralization.

Most "typical" carbonatite complexes have, by now, probably been discovered, described and evaluated economically. Not all are mined, however. There is a limited market for both Nb and REE and two single carbonatite localities alone (Araxá, Brazil and Mountain Pass, California) are capable of supplying most of the Western World's needs with respect to these metals. "Atypical" carbonatites and situations marginally linked to carbonatite activity and its interaction with a variety of environments, however, present a continuous challenge to an exploration geologist. It is likely that unknown "types" of mineral deposits (not only of Nb and REE) will be found in the future.

This section departs from the practice followed in the earlier sections, and treats carbonatites at all levels of emplacement: volcanic, subvolcanic and plutonic. Because of the easily available and comprehensive compilation literature, locality descriptions have been reduced and substituted by an abbreviated data summary in Table 33-10 and Figure 33-30.

Terminological remarks

The name carbonatite implies magmatogene (orthomagmatic) origin, particularly to non-specialists. This need not always be true. Smith (1956) defined carbonatites more sensibly, stressing their common lithologic association: "Carbonatites are carbonates that appear to behave as intrusive rocks and are closely associated with alkaline igneous rocks". This definition, on the other hand, neglected the existence of the empirically proven volcanic equivalents. The logic

Table 33-10. Selected occurrences of mineralized Phanerozoic carbonatites

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Oka complex, W.of Montréal, Québec	Cr_1 double Ca-carb.ring dike and Si-carb. stocks,surr.by melillite rocks,alk.pyrox.,melteig.,urtite; empl.into Pt_{2-3} cryst.basement	magn.,pyrochl.,perowsk.,niocalite in streaky disseminations; 735Tt Nb/0.35%; 267Tt REE/0.127%	Gold (1969)
Lake Nipissing Ontario,Canada	560 m.y. plut.ring dike compl., Ca-carb. lenses in fenite envel. adj.to alk.pyrox.,gabbro in Archean metamorphics	dissem. pyrochlore in carbonatite; 20.3Tt Nb/0.371%	Currie (1974)
Iron Hill, Powderhorn compl.,Colorado, U.S.A.	Cm pyrox.,ijol.,neph.syen.compl., late dolom.carb.stocks,dikes empl.into fenitiz. PCm metam. basement	high trace Th; dissem.Ti-magn., pyrochl.,bastnaes.; endocont. martite,apatite veins; 2.435Mt REE/0.34%; 288Tt Nb/0.04%; 26.2Tt Th/36 ppm	Armbrustmacher (1980)
Seis Lagoas,Guiana Shield,Amazonas, Brazil	circular carbonatite ring dikes and stocks empl. into Archean metamorphics; fenite; lateritically weathered	residual pyrochlore (pandaite) in saprolite; 110Tt REE/1.27%; 14.7Tt Nb; 5.5Tt Th	Bonow and Issler (1980)
Catalão, Goiás, Brazil	Cr_1 central Ca-carb.stock in fenitized PCm gneiss	dissem. pandaite, gorceixite, apat.,goeth.,magnet.,anatase in saprolite; 1.33Mt REE/1.7%; 863Tt Nb/0.6%; 102Mt Ti; 128Tt Th; 45Tt U/aver.180 ppm	Loureiro (1980)
Araxá (Barreiro), M.G., Brazil	Cr_1 Ca- and biot.carbonatite stock in fenitiz. Pt_2 m-quartzite and schist; 200 m thick regolith	pyrochl.,monaz.,apatite dissem. in biot.-rich xenolithic and brecc.carb.cem.by calc. All ore mined comes from saprolite; 18Mt Nb;34Mt REE;660Tt Th;	Grossi Sad and Torres (1978)

Jacupiranga, S.P., Brazil	J_3-Cr_1 Ca-carb.stock in centre of a compos.ellipt.massif (pyrox., perid.,alk.gabbro,neph.syen.) empl.to PCm micasch.,granodior. Lateritically weathered	residual apatite,magnetite, ilmenite with access.pyrochlore, baddeleyite; 26% Fe_2O_3 in residual soil	Melcher (1966)
Fen near Ulefoss, Telemark, southern Norway	600-413 m.y. multiphase Ca and dol.carb.empl.with alk.gabbro and pyrox. into fenitized Pt gneiss	1) dissem.magn.,pyrochl.,koppite,columb.,apatite in dike-shaped bodies of brecc.carb.; 2) Th and REE-bearing N.-S. hemat.veins; 56Tt Nb/0.35%	Vokes ed., (1960)
Alnö near Sundsvall,N.E. Sweden	563 m.y.cone sheet and ring dike compl.of Ca- and dol.,ank.-carb., syen.,kimberlite empl.to fenitized Arch. granitic gneiss	dissem. Th-rich pyrochl. and dysanalyte in Ca-carb.;fluorite, perowskite; miner. occurr. of Nb,REE,Th,U minerals	v.Eckermann (1966)
Sokli, northern Finland	334-378 m.y. zoned multist.silic., Ca-, dolom. carb. stock 18 km^2 emplac. into fenitiz. Archean gneiss and amphibolite; regolith	apatite/francolite relict regolith with minor dissem. pyrochl. baddel.,rhabdophane; 100Mt 19% P_2O_5	Vartiainen and Paarma (1979)
Turiy Peninsula, Kola Pen.,U.S.S.R.	PZ_2 small carb. core envel. by pyroxenite,skarn,analc.-calcite lamproph.,empl.into fenitiz. PCm granodiorite	steeply dipp.small magnet.lodes in phlog.,diops.,amphib.carbont. lens at cont.of pyrox. and ijol.	Samoylov and Afanas'yev (1978)
Kaiserstuhl N.W. of Freiburg, West Germany	Mi_2 subvolc.Ca and dol.,ank.carb. flanked by phonol.and alkal.basalt lavas, empl.into T,MZ sedim. Light fenitization	dissem.pyrochlore, koppite, dysanalite, magnet.,apatite; 4.9Tt Nb/0.23%	Wimmenauer (1966)
Odikhinch Massif, Meimecha-Kotui prov.,N. Siberia	Pe-J concentric zoned intrus., Ca-,dolom.,anker.carb.,alk.pyrox., neph.syenite in fenitized PZ seds.	pyrochlore dissem. in Ca-carb.; monaz. in dolom. carb.	Heinrich (1966)

Table 33-10 (continued). Selected occurrences of mineralized Phanerozoic carbonatites

LOCALITY	GEOLOGY	MINERALIZATION	REFERENCES
Mushugay-Kuduk, southern Mongolia	J_3 volc.-subv.alk.complex; trachyte,nephelin.lavas,pyrocl.,syenite,vent breccias,nephel.syen. carbonatite	stockw.of apat.,Ti-magnet.veins in trachyrhyol.vent breccia; dissem.magn.,fluor.,apat.,celestite in fine-gr.explos.breccia	Vakrushev and Vladykin (1979)
Khanneshin carbonatite volcano, S. Afghanistan	Pl-Q anker.carb.,carb.breccias, lavas,tuffs;dissected compos. volcano resting on T sedim.	bastnaes. and burbankite in hydr.alter.zones; U oxides in exocont.veins;dissem.and repl. magnetite in breccia	Alkhazov et al.(1977)
Yin-Shan Range, Inner Mongolia, China	probable vein/dike carbonatites empl. into Pt and PZ limestone, chrt,biot.schist,iron formation as large tabular bodies (Wula-Shan and Paiyunopo)	dissem.magn.,hemat.,fluor.,aegirine,aeschynite, beiyinite; 40-65% Fe, 2-7.2% REE_2O_3	Lee (1970)
Mrima Hill near Mombasa, Kenya	MZ-T high level Ca- and dolom. carb.plug and breccia; deeply tropically weathered	residual dissem.pandaite,Ba-gorceixite,earthy monaz.; resid. psilom.,pyrolus.,hausmann., ocher; 400Tt Nb/0.5%; 255Tt REE 1.275%; 100Tt Mn	Deans (1966)
Ruri,E.shore Lake Victoria, Kenya	5-11 m.y. circ. intrus.of Ca-carb. accomp.by phonol.,nephel. syen. into fenitiz. PCm metabasalt; regolithic	magnet.,monaz.,bastnaesite in dike-like late ferrug.carb.; minim. 21Tt REE, 16.5Tt Th	Jaffé and Collins (1969)
Mbeya (Panda Hill) S.W. Tanzania	MZ Ca- and Ca-dolom.carbon. stock empl.to fenitiz. PCm metamorphics	pyrochlore dissem.in Ca-carb. and biot. fenite; 283Tt Nb/ 0.553%;	Deans (1966)

S.E.Uganda carb. group (Tororo,Bu-kusu,Sukulu)	T_2, volc.-subvolc. Ca-,dolom., anker.,silic.carb. with pho-nol.,nephelinite,neph.syen., pyrox.,etc. empl.to fenitiz. PCm basement	dissem.pyrochl.,baddeleyite, apatite, Ti-magnetite; Sukulu: 200Mt 13% P_2O_5, 30Mt Fe, 182Tt Nb/0.175%	Deans (1966)
Lueshe, Kivu Prov., Zaïre	zoned ellipt. Ca-,silic.,dolom. carb. compl. assoc. with cancrin. syenite, in fenitiz. PCm basem. schists	dissem. pyrochl. in Ca-carb. saprolite; 282Tt Nb/0.94%	Deans (1966) Gittins (1966)
Longonjo, Benguela Plateau, Angola	J carb.and syenite ring complex in fenitized PCm basement; regolithic	dissem.pyrochlore in saprolite 10.8Tt Nb; 36.8Tt Th	de Kun (1965)
Ondurakoruwe, Namibia	J? Ca- and dolom.carb.,circular plug 1.2 km diam.,in fenitized Pt schists; carbonatite dikes	strontian.,monaz.,pyrochlore, cerianite,columbite,zircon in dolom. carb. dikes; 2.55% REE, 0.002% U_3O_8	Verwoerd (1967)
Kalkfeld, C.Namibia	J? Ca-carb.pipe grading to volc. brecc.in fenitiz.Pt metasedim.	finely divided Th in replac.mas-ses of Mn-rich hematite	Verwoerd (1967)
Chilwa Island, S.Malawi	J_3-Cr_1 4 compos.centres in a ring compl.;Ca-,dol.,ank.,sider. carb. with phonol.,nephel.,alnö-ite in feldsp.and fenitiz.brecc. Pt basement metamorphics	pyrochl. dissem. in Ca-carb.; Th,REE,gal.,fluor.,in late qtz.-calcite veins; Th dispers. in hydroth.metas.sider.carb. 4,550 t Nb/0.7%; 300Tt Mn	Garson (1966)
Kangankunde, southern Malawi	J_3-Cr_1 elong.stock of strontia-nite-rich carb.,ank.,sider.carb. carb.agglom. and brecc. in feni-tiz.,feldsp..brecc.PCm gneiss	impregn.and rich veins of monaz. florencite,bastnäs. in carb.; replac.masses of stront.-monaz. min.54Tt REE; Th;	Garson (1966)
Tundulu complex, southern Malawi	J_3-Cr_1 Ca- and sider.carb.vents, ring,agglom.in Pt syen.,gran.,gn.	sider.,bastnaes. carb. dikes; apatite, pyrochl. in Ca-carb.	Garson (1966)

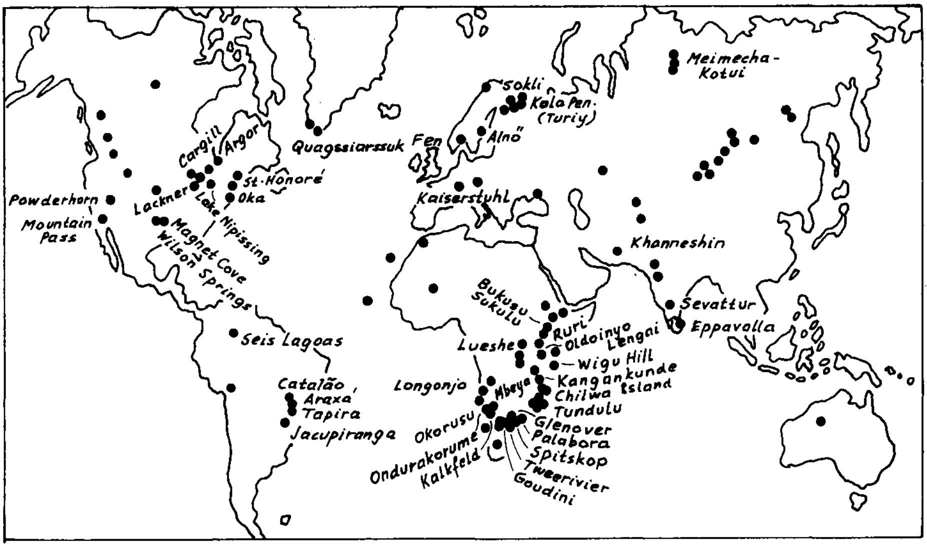


Fig. 33-30. Index map of major occurrences of the carbonatites listed in Table 33-10.

of carbonatite definitions was further reviewed by Moore (1973).

Rather unfortunately, we have inherited a list of petrographic variety names of carbonatites introduced into the literature throughout 50 years of study. Of these, the original Brøgger's terms for the two most widespread mineralogical varieties of intrusive carbonatites: "sövite" (calcite carbonatite) and "rauhaugite" (dolomite carbonatite) are widely used, and so is the von Eckermann's term "beforsite" for a hypabyssal, usually dike-forming dolomite carbonatite. In this book, carbonatites are uniformly identified with the help of a compositional prefix (calcite carbonatite or CC and dolomite carbonatite or DC). Other terms frequently used in the literature are silicate carbonatite or silicocarbonatite (SC) for rocks containing considerable proportions of silicate minerals (biotite or phlogopite, wollastonite, diopside, etc.).

Verwoerd (1967) proposed the use of the term "metacarbonatite" for all "secondary" carbonatites, formed by a hydrothermal reconstitution of earlier "magmatic" carbonatites. This term has been avoided here because of its possible confusion with regionally metamorphosed carbonatites.

33.8.2. Carbonatite complexes and emplacement levels

The outcrop appearance of a carbonatite complex is essentially governed by the erosional level, by the style (pattern) of emplacement and by the nature of the associated non-carbonate rocks. Idealized sections (models) showing the way in which the nature of a carbonatite complex changes with depth, have been presented by Garson (1966), Verwoerd (1967; his Fig. 19), Smirnov, ed. (1968; their Fig. 86) and Moore (1973; his Fig. 1). These models differ in detail, and all apply to zoned central complexes in which the carbonatite is situated in the centre ("normally zoned" carbonatite complexes; Smirnov, ed., 1968; Fig. 33-31). The "normally zoned" complexes are believed to have projected on the surface as central volcanoes (some, however, never vented) and the following levels can be recognized (Fig. 33-32):

(a) Volcanic cone level. This is the topmost level, preserved only in recently active volcanoes (e.g. Oldoinyo Lengai and Kerimasi in northern Tanzania). Oldoinyo Lengai (Dawson, 1966; Fig. 33-33) is a steep, cone-shaped composite volcano approximately 8 km in diameter, standing about 2,100 m above the surrounding plains. The summit is occupied by two craters, and the cone is dissected by radial gullies and interrupted by small parasitic cones, explosion craters and tuff rings. The majority of its lavas and pyroclastics are nephelinitic in composition. Some are ijolitic. Carbonatite volcanism is marked by periodic (approximately every 7 years) extrusions of Na-Ca carbonatite lavas, initially black but rapidly turning gray (composed of nyerereite) and explosions of soda ash. Soda is soluble in water so it is rapidly leached out by rains and carried into the adjacent Lake Natron (a playa lake), where it precipitates as an evaporite. The deeper levels of the volcano are not accessible for observation, but can be interpreted thanks to the exotic ejecta present in the pyroclastics. These include fenitized gneiss, urtite, ijolite, alkaline pyroxenes and alkaline gabbros.

(b) Intermediate volcanic level has been exposed in the late Tertiary alkaline volcanoes in the south-eastern corner of Uganda (Elgon, Napak, Toror, and others; King and Sutherland, 1966). Napak is a remnant of a volcanic cone with an original diameter of 32 km, deeply eroded in its central part. Remnants of the stratovolcano are composed predominantly of pyroclastics (chiefly agglomerates) and minor nephelinite lavas. The central intrusive complex contains a variety of alkaline pyroxenites, gabbros, nepheline syenites and members transitional to carbonatites. Ijolites, frequently present in a very coarse, pegmatitic form, are particularly abundant. Carbonatite constitutes a small hill in the centre (400 m diameter) and also forms a number of dikes intersecting the ijolite. The main mass shows a concentric vertical banding. The central intrusive is surrounded by shattered, sheared and fenitized metamorphics of the Precambrian basement complex.

(c) Subvolcanic level is well illustrated by the late Jurassic-early Cretaceous carbonatite complexes in southern Malawi (Tundulu, Chilwa Island, Kangankunde) described by Garson (1966). Here, the centre of the complex is filled by a variety of carbonatites (calcite, calcite-ankerite, siderite carbonatites), emplaced sequentially. The

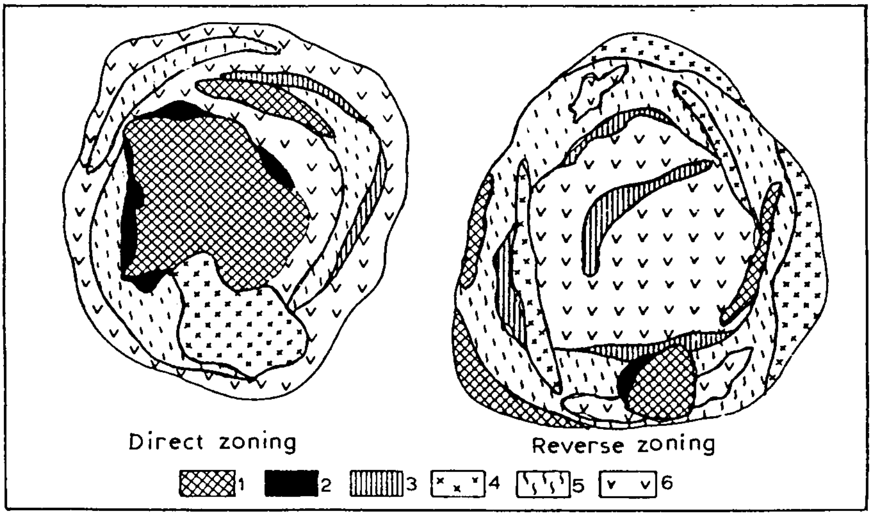


Fig. 33-31. "Normal" and "reverse" zoning in alkaline ultramafic complexes. 1=carbonatites; 2=forsterite, apatite, magnetite rock; 3=silicate metasomatites; 4=syenites; 5=ijolite melteigites; 6=ultramafics. From Smirnov, ed. (1968).

centre is surrounded by feldspathic breccia and agglomerate saturated by a carbonate matrix along the inner contact, and grading into a brecciated and fenitized Precambrian gneiss. The fenitization is predominantly potassic. Trachytic lava and pyroclastics form the remnants of a volcanic cone and there are dikes, plugs, and/or cone sheets of nepheline syenite rocks.

(d) Upper plutonic level of zoned central complexes is exemplified by numerous examples of Mesozoic and Paleozoic carbonatites in Africa (Dorowa, Shawa in Zimbabwe; Spitskop in South Africa; Kalkfeld in Namibia) and elsewhere. The central core of carbonatite is enveloped by alkaline pyroxenites, gabbros and syenites, grading to predominantly sodic fenites. Dikes are moderate to common.

(e) Deep plutonic level is most commonly exposed in Paleozoic and Precambrian carbonatite complexes, e.g. Powderhorn, Palabora (Fig. 33-34), Nemegos, and others. Ultramafics (pyroxenites), alkaline gabbros, syenites, are usually abundant. There is a broad halo of fenitization and widespread metasomatism. Garson (1966) believed that many alkaline pyroxenites are reaction products at the contacts of carbonatite with syenitic fenites.

Heinrich (1966, his Table 10-2) in his classification of carbonatites according to depth levels of emplacement, listed "plutonic catazone" as the deepest level. There, the most conspicuous

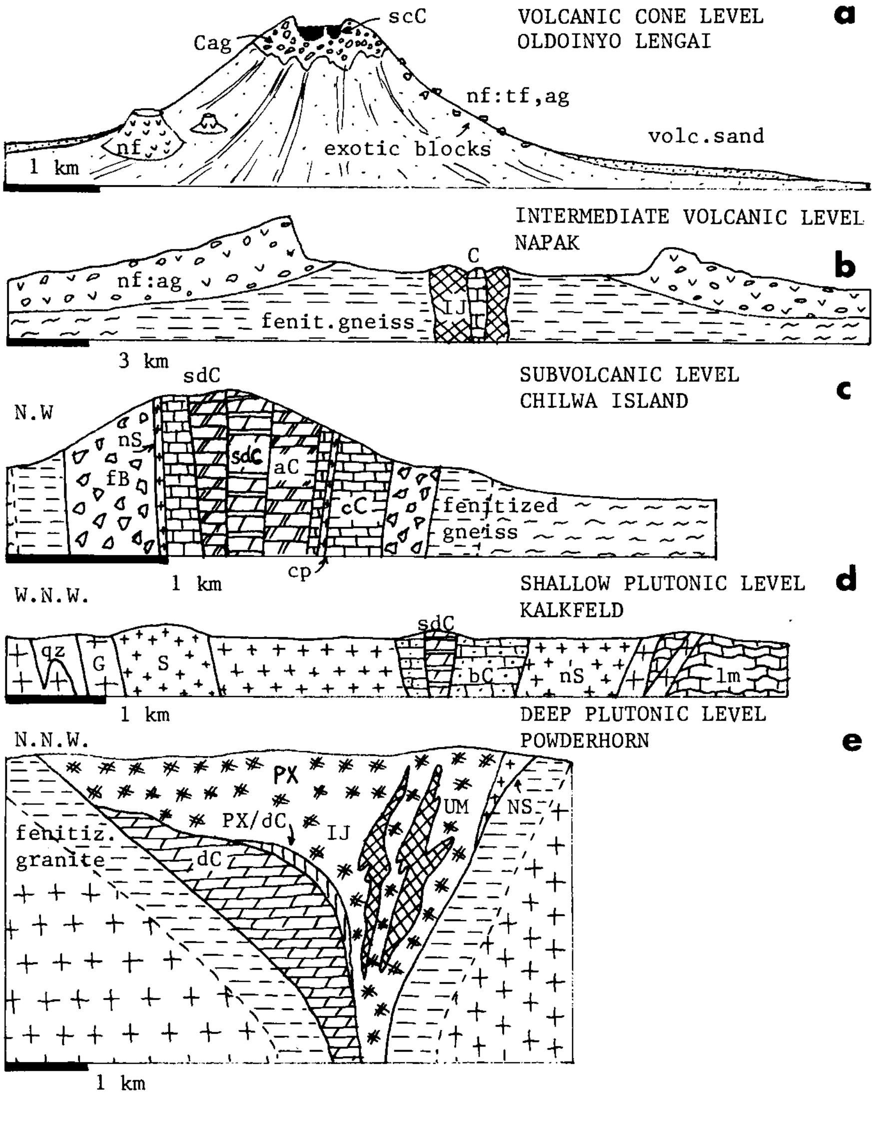


Fig. 33-32. Examples of "normally" zoned carbonatite occurrences arranged according to increasing depth of the erosional level. C=carbonatite; scC=Na-Ca carbonatite; sdC=siderite carbonatite; aC=ankerite carbonatite; cC=calcite carbonatite; bC=biotite containing carbonatite; Cag=carbonatite agglomerate; dC=dolomite carbonatite; G=granite; nf=nephelinite; nf:tf,ag=tuff, agglomerate; IJ=ijolite; UM=uncompaghrite; cp=camptonite; nS=nepheline syenite; fB=feldspathic breccia; lm=crystalline limestone; qz=quartzite; px=pyroxenite. (a) from LITHOTHEQUE; (b) after King and Sutherland (1966); (c) from LITHOTHEQUE, data from Garson (1966); (d) after Martin et al. (1960); (e) from LITHOTHEQUE, modified after Temple and Grogan (1965).

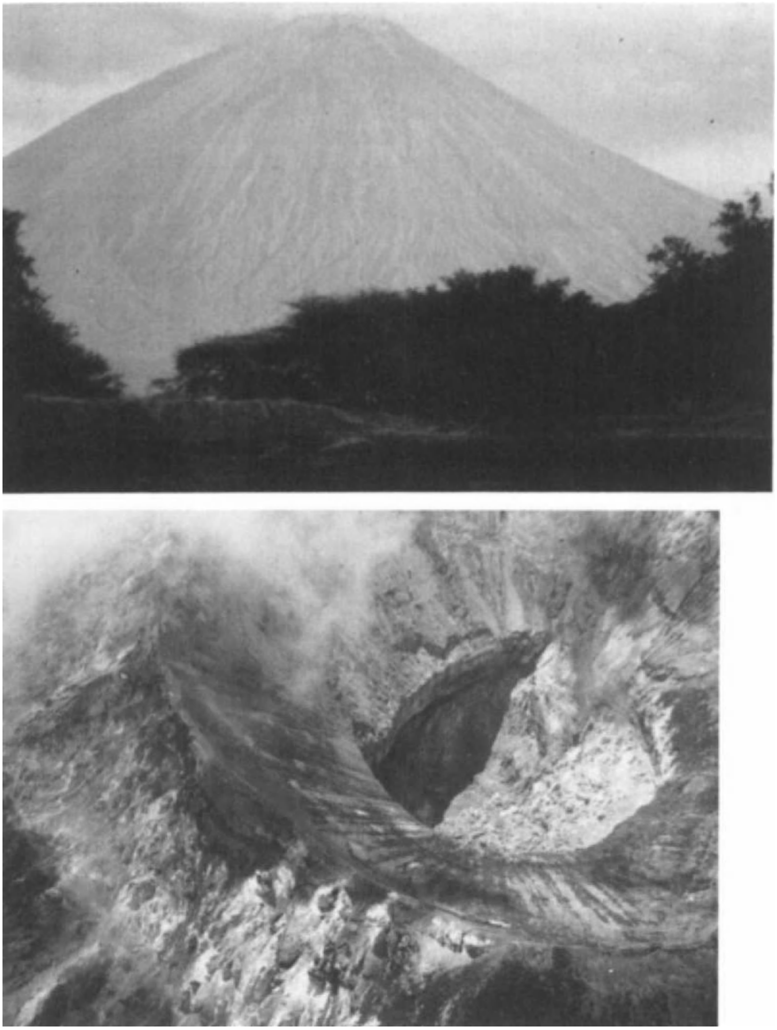


Fig. 33-33. Oldoinyo Lengai nephelinite, carbonatite volcano, northern Tanzania. TOP: general view; BOTTOM: crater; note the white soda and limestone afflorescences on top of the lavas and pyroclastics.

characteristics of the five depth levels treated above, the ring or circular expression and piercement tectonic features, are either not fully developed or are inconspicuous. Instead, "intimate mingling of carbonatitic fluids and various country rocks (including marble) akin to granitic migmatitization" is widespread. Most occurrences, moreover, are genetically controversial.

Although the "normally zoned" alkaline complexes that involve carbonatite are the most conspicuous, they are not the only form of carbonatite occurrence. Their symmetry is often disturbed and the carbonatite occurs eccentrically (e.g. at Iron Hill in the Powderhorn complex), or is substituted by diffuse carbonatite screens alternating with syenite in the zone of fenitization (e.g. Manitou Island, Ontario; Currie, 1974). In the same area (Lake Nipissing, Ontario), carbonatite forms rims at lamprophyre dikes or occurs as dikes in fenites. Carbonatite dikes, ring dikes and cone sheets on the fringe of alkaline ring complexes, occur frequently (Nemegos, Spitskop, Kovdozero, etc.).

Many carbonatite bodies associated with alkaline complexes have a thick sheet-like or irregular form (e.g. Mountain Pass, California)or form dikes, dike swarms, stockworks or sills (e.g. James Bay, Canada; McClure Mt., Colorado). Similar carbonatite bodies sometimes occur in terrains lacking directly affiliated alkaline complexes (Wigu Hill, Tanzania; Turyi Peninsula, U.S.S.R.). Some carbonatites, moreover, lack conspicuous fenite aureoles. The latter are difficult to identify and appear to be more common in mobile belts than within cratons.

In alkaline complexes, carbonatites are associated (1) with ultramafic rocks (dunites, peridotites, pyroxenites); (2) with alkaline pyroxenite and gabbroids, some with a variety of feldspathoids or minerals like melilite, cancrinite (e.g. ijolite, urtite or melteigite) and (3) nepheline syenite and syenite. Verwoerd (1967) pointed out that the above order of decreasing basicity also corresponds to the usual intrusive sequence and the succession of zones from the central carbonatite outward. Calcitic carbonatites are by far the most common, followed by dolomitic, ankeritic and sideritic carbonatites. Carbonatites containing abundant accessory silicates (biotite, alkaline pyroxenes and amphiboles, melilite, wollastonite, etc.) are usually transitional to predominantly silicate rocks, e.g. ijolites.

33.8.3. Multistage development

Few carbonate occurrences formed as a product of the simple crystallization of a single batch of magma. Most are the result of a long-lasting activity, during which carbonatitic (and other) magmas and fluids issued from several centres (or from a single, migrating centre), in several stages. The products issued from adjacent centres reacted with each other and sequentially younger products interfered with, and modified the older products. The result is a great diversity of magmatic, metasomatic and hydrothermal phases in differentiated carbonatite complexes, that exerts an important influence on the mineralization. Table 33-11 documents the sequential development of the Chilwa Island carbonatite ring complex in Malawi (Garson, 1966). Five development stages have been recognized in the Sokli (Finland) carbonatite complex (Vartiainen and Paarma, 1979).

In the Loolekop carbonatite, Palabora, South Africa (Verwoerd,

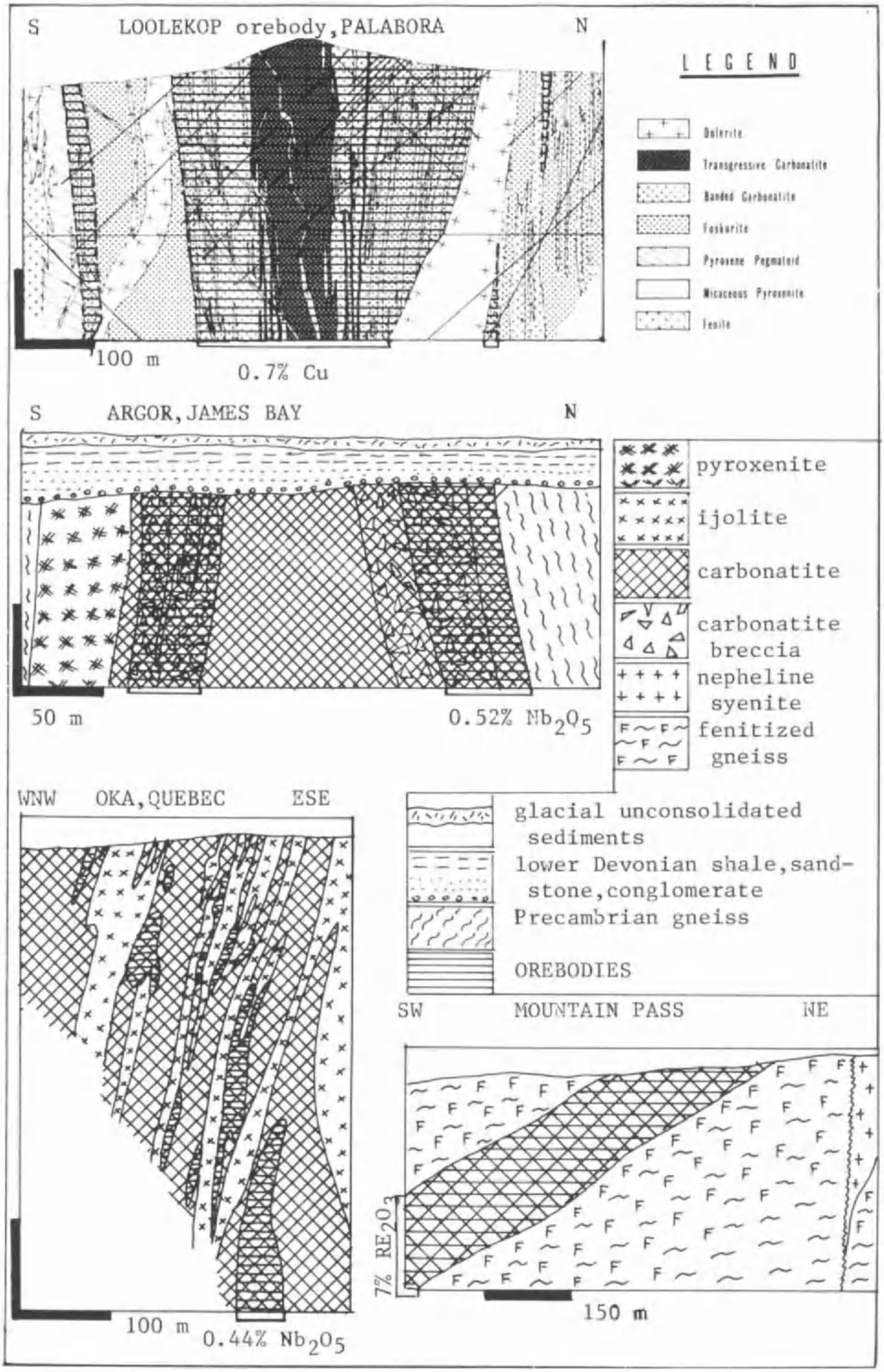

S
LOOLEKOP orebody, PALABORA
N
LEGEND
Dolerite
Transgressive Carbonatite
Banded Carbonatite
Foskorite
Pyroxene Pegmatoid
Micaceous Pyroxenite
Fenite
100 m
0.7% Cu
S
ARGOR, JAMES BAY
N
pyroxenite
ijolite
carbonatite
carbonatite breccia
nepheline syenite
fenitized gneiss
50 m
0.52% Nb2O5
WNW
OKA, QUEBEC
ESE
glacial unconsolidated sediments
lower Devonian shale, sandstone, conglomerate
Precambrian gneiss
OREBODIES
SW
MOUNTAIN PASS
NE
7% RE2O3
150 m
100 m
0.44% Nb2O5

Table 33-11. The sequential development of carbonatites in the Chilwa Island ring complex, Malawi. Slightly modified after Garson (1966)

LATE JURASSIC-EARLY CRETACEOUS CHILWA ALKALINE PROVINCE
CENTRE 4
Faulting and minor overthrusting
Intrusion of lamprophyric plug into Summit Plateau CC
Intrusion of radial dikes of syenite, olivine nephelinite, diabase
Hydrothermal introduction of BaO, ThO_2, Ce_2O_3, PbS, F, late quartz, calcite
Intrusion of manganiferous and sideritic C
Intrusion of ankeritic C and partial replacement of CC by ankerite
Apatite-veining of pressure cracks
CENTRE 3
Intrusion of nepheline syenitic and trachytic dikes and formation of silicate CC
Intrusion of CC with siderite
Intrusion of mobilized feldspathic breccias, brecciation
CENTRE 2
Intrusion of olivine nephelinite, alnöite and pyrochlore-bearing CC into shear planes
Intrusion of cone sheets of phonolite
Intrusion of aegirine-biotite CC into shear planes
Brecciation
CENTRE 1
Intrusion of Marongwe acmite CC
Feldspathization of contact breccia
Brecciation above carbonatite pluton
Intrusion of carbonatite in depth producing aureole of fenitization
UPPER PRECAMBRIAN TO LOWER CAMBRIAN
Quartz syenite and granite intruded into Basement Complex granulite, gneiss, limestone
ABBREVIATION: CC=calcite carbonatite (sövite)

Fig. 33-34. Cross-sections of four mineralized plutonic carbonatites (see text and Table 33-10 for description). Loolekop, after Palabora Staff (1976); approximate outline of the Cu orebody above 0.3% Cu grade added. Argor, after Stockford (1972). Oka, from LITHOTHEQUE, after Gold et al. (1967). Mountain Pass, from LITHOTHEQUE, based on data in Olson et al. (1954) and Molycorp Staff, guided tour, 1982.

1967), three major phases of carbonatite emplacement have been distinguished. There, the dominant "banded carbonatite" is the product of Phase 1. It consists of a relatively coarse calcite carbonatite, conformable with the walls of the feeder conduit. The banding is caused by the parallel arrangement of magnetite-rich layers and parallel lines of crystals of other minerals. Phase 2 produced the "main younger carbonatite", which is a transgressive, irregular body grading into a series of dikes. It was emplaced into the central part of the older carbonatite plug. The younger carbonatite tends to be finer grained than the older one, banding is absent, and the slightly higher magnetite and silicate content is preferentially concentrated in localized lenses. Minor copper mineralization is associated. Phase 3 is represented by the youngest transgressive carbonatite veins and thin sheets, traversing the central mass of Phase 2 carbonatite. It crystallized from hydrothermal solutions and carries the bulk of the Palabora copper ores.

Heinrich (1966), Verwoerd (1967) and other authors described the effects of sequential alterations of older ("syngenetic") carbonatites by younger carbonatitic fluids, resulting in the generation of a "metacarbonatite". Zhabin (1978) discussed the textural features, in particular the crystal habits of calcite, applicable in the interpretation of the metamorphic evolution of carbonatites.

33.8.4. Origin and recognition of carbonatites

Despite the diversity in style, composition and association, carbonatites are a remarkably distinct category of rocks. Their strong tectonic control and association with major continental extensional fault systems (rifts and paleorifts) has been demonstrated many times (see also the review in Heinrich, 1978, also Chapter 30). This together with the experimental evidence points to the subcrustal sources, or at least a subcrustal "initiation" of the carbonatite generation at higher crustal levels. Kapustin (1976) considered the origin of carbonatite independently of that of other alkaline rocks, and placed the site of carbonatite generation into the deep mantle, under the zone of generation of tholeiitic magmas. From there, carbon and hydrogen are carried into a higher chamber, where oxidation takes place to form CO_2. This, then, reaches the crust. Other authors prefer to interpret carbonatite as being a differentiate of a parent alkaline magma. Nephelinite, nepheline-picrite, melilite-basalt, pyroxenite, peridotite, kimberlite, ijolite, etc., have been considered to act as such magmas (compare reviews in Heinrich, 1966, 1978; Sørensen, ed., 1974).

From our practical point of view, however, the criteria for carbonatite recognition in the field and laboratory are more important than the latest genetic story because most carbonatites in hand specimens are megascopically virtually indistinguishable from the much more abundant crystalline carbonates of a less exotic derivation (calcic and dolomitic marbles, hydrothermal veins and replacements, fault impregnations, etc., of any affiliation). The common presence of alkaline silicates (aegirine, melilite, monticellite) or characteristic accessory minerals (apatite, pyrochlore) can help, provided that they can be recognized by the geologist. Biotite, diopside, wollastonite, magnetite, etc. that are common in carbonatites are not diagnostic, because the same minerals occur frequently in many contact- and regionally metamorphosed marbles. By far the most important field criterion is the association with other alkaline rocks (although metasedimentary marbles may be common in the basement as well). The presence of fenite aureole and the intrusive, transgressive nature of most carbonatites are also important criteria.

Geochemically, members of the carbonatite association (that includes not only an orthomagmatic carbonatite but also almost any rock altered, filled or modified by the most mobile carbonatite-related fluids) are characterized by a strong enrichment in one or more of the following elements: Sr,Ba,Nb and REE. These elements (Verwoerd, 1967) are markedly enriched in carbonatites even by comparison with the alkaline silicate rocks, while others (P,F,Zr,Hf,Ti,Th) accumulate in both. The isotopic ratios of $^{13}C/^{12}C$; $^{87}Sr/^{86}Sr$; $^{16}O/^{18}O$ differ from those in limestones and marbles, but are similar to those of basaltic rocks (Heinrich, 1966).

33.8.5. Metal geochemistry and metallogeny

The extraordinary enrichment of carbonatites in certain minor elements has already been mentioned above, and it is further apparent from the comparison of average abundances of trace elements in carbonatites and other rocks (Table 33-12). The minor elements can either be camouflaged in major rock-forming or accessory minerals (e.g. Ba in calcite, Nb in perowskite) or form their own minerals (e.g. barite, pyrochlore). The camouflaged elements show a tendency to accumulate in the early, main (magmatic) stage of carbonatite development, whereas late, usually superimposed processes, tend to collect the camouflaged elements to form their own species (Heinrich, 1966).

Even where the original carbonatite magma was so enriched in the minor elements that they had already formed their own minerals in the early magmatic carbonate (e.g. Nb,REE in pyrochlore, Zr in zircon, REE in monazite), such minerals are widely dispersed and may form only low-grade (but often large tonnage) orebodies. Late-stage carbonatite emplacement and a variety of mobilization processes, on the other hand, tend to redistribute metals bound in the early minerals and concentrate them locally to form usually smaller, but higher-grade orebodies. The mineral species in the late-stage mineralizations may either remain the same (e.g. pyrochlore), or new species may appear (e.g. thorite, bastnaesite, baddeleyite, etc.). Kapustin (1971) prepared a detailed summary of carbonatite mineralogy.

Weathering processes superimposed on mineralized carbonatites are unusually effective metal concentrating agents. Due to the high

Table 33-12. Comparison of average abundance of trace elements in carbonatites and other rocks (in ppm; after Gold, 1963)

	CARBONATITE	AVERAGE IGNEOUS ROCK	LIMESTONE
Sc	10	13	1
Co	17	18	0.1
Ni	8	100	20
Cu	2.5	70	4
Ga	1	26	4
Y	96	20	30
Zr	1,120	170	19
Nb	1,951	20	0.3
Mo	42	1.7	0.4
Sn	4	32	under 1
La	516	40	under 1
Ce	1,505	40	11.5
Cr	48	117	11

solubility of carbonate, relatively small amounts of the insoluble residuum remain after the solution removal of a considerable thickness of the original rock, so that the rare minerals present in insignificant quantities in carbonatite can accumulate in economically significant amounts.

33.8.6. Major mineralization styles (Fig. 33-35, Table 33-13)

MINERALIZED VOLCANIC CARBONATITES

Continental volcanics of any composition rarely contain economic metallic mineralization and the volcanic carbonatites are no exception. Ti-magnetite is an abundant accessory mineral in carbonatite lavas and pyroclastics and it can accumulate in small quantities in streams draining such volcanics (e.g. in the braided ephemeral streams along the base of Oldoinyo Lengai). Perowskite and baddeleyite have been reported as accessory minerals in Kerimasi (Tanzania) lavas and pyroclastics (Gittins, 1966) and they are slightly enriched in the red-brown soil filling the crater floor. Accessory pyrochlore, monazite, allanite and other minerals can usually be detected in small quantities in exotic blocks of carbonatite and silicate alkaline rocks (e.g. ijolite), that occur frequently in vent breccias and in agglomerates (e.g. at Oldoinyo Lengai, in the Laacher Lake area, Germany; Heinrich, 1966).

Carbonatite volcanics have a high trace content of rare elements, for example 800 ppm Nb, 400 ppm La and 34.5 ppm U at Oldoinyo Lengai (Dawson, 1966) and a high but unspecified content of the same metals at Khanneshin (Alkhazov et al., 1977). No information is available regarding the fate of these metals during weathering and sedimentogenic reworking at the first locality, but numerous occurrences of yellow uranium oxides coating the stockworks of fractures in Neogene red sandstones, forming veinlets, sinters and crusts in sandstone and leached carbonatite and associated with chalcedonic crusts in residual clays, have been recorded at Khanneshin. The uranium has presumably been leached from the carbonatite volcanics and redeposited by the action of hot springs as well as supergene agents. REE, Nb, barite, fluorite, magnetite, etc. occurrences at this interesting locality are controlled by hydrothermally altered zones, believed to have formed at the subvolcanic level, postdating the surficial volcanic emplacement of carbonatite.

Mobile metals leached from volcanics (including the areally widespread fine ash) and carried away in solution can accumulate, under favourable conditions, in the sediments of interior basins such as playa lakes (e.g. Lakes Natron and Magadi in the Gregory Rift, Tanzania and Kenya).

ENDOCONTACT MINERALIZATION IN SUBVOLCANIC AND PLUTONIC CARBONATITES

(a) Main mass of carbonatite as a metallic ore.

Siderite (e.g. Chilwa Island, Kalkfeld) or rhodochrosite (Muambe Hill, Mozambique; Gittins, 1966) carbonatite bodies might appear to constitute, respectively, a readily accessible Fe or Mn ore. The highest Fe and Mn contents in the Chilwa siderite carbonatite were found to be only 11.1% Fe_2O_3 and 6.7% MnO_2 (Garson, 1966). The 60% FeO+MnO, mostly hematitic iron ore hosted by the siderite carbonatite of Kalkfeld, Namibia (Verwoerd, 1967), probably formed as a result of a superimposed hydrothermal event.

The Fe- and Mn-rich carbonatites, however, constitute a suitable protore, over which economically important Fe and Mn residual ores can form by tropical weathering (e.g. Mrima Hill, Kenya).

(b) Highly dispersed trace metal content in carbonatite

In the Iron Hill carbonatite stock, Powderhorn complex (Armbrustmacher, 1980), the average content of Th is 36.2 ppm, and it is bound in rather regularly dispersed fine accessory minerals (e.g. pyrochlore). The Th content alone is too low to be economic, but modern complex processing of the entire mass also recovering also REE (0.4% REE_2O_3), Nb (570 ppm Nb_2O_5), accessory apatite, rutile, as well as the rock dolomite, could be profitable. As a consequence, the available Th tonnage figures in Iron Hill are quoted in the literature and this sets this locality apart from numerous similarly (or better) endowed carbonatite localities for which equivalent considerations have not been made or published.

(c) Disseminated (scattered) minerals in carbonatite

Thinly disseminated pyrochlore is present almost universally

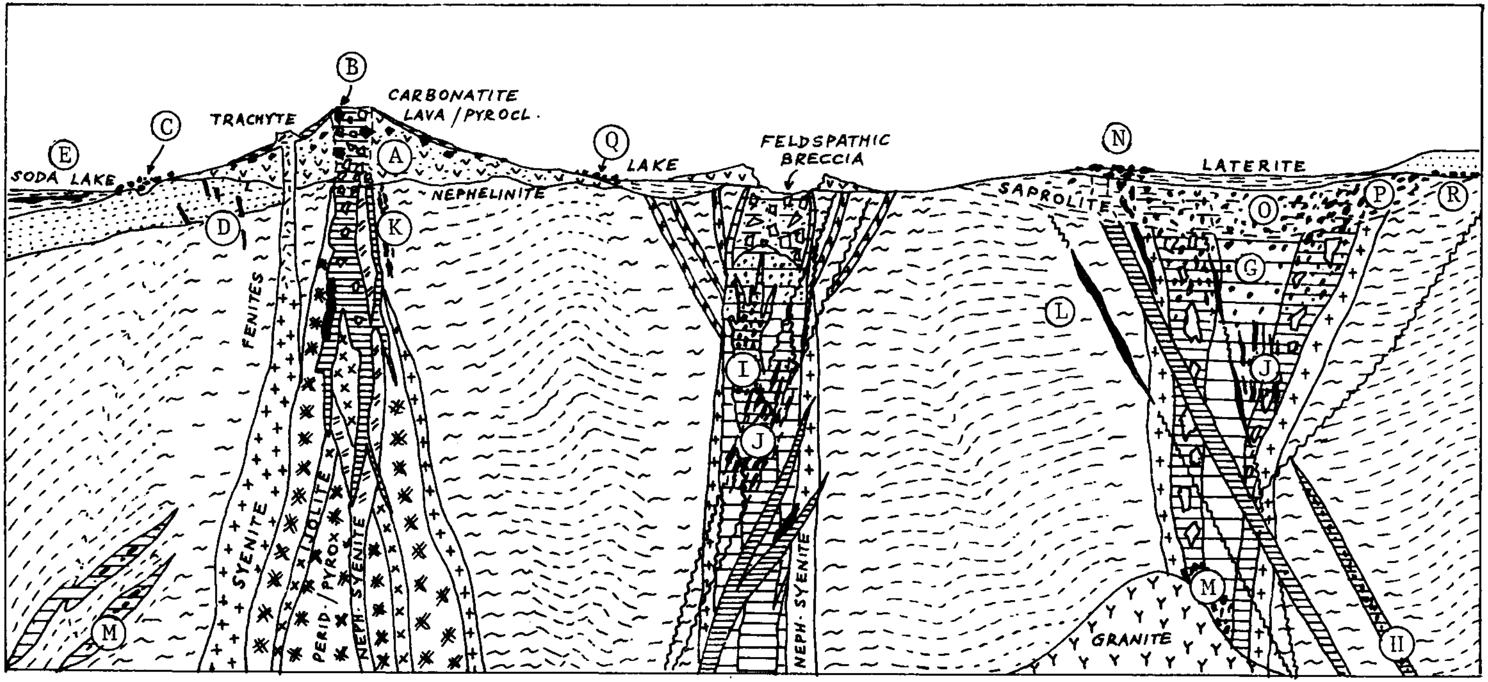


Figure 33-35. Principal patterns, rock types and mineralization styles in carbonatite complexes (see Table 33-13 for explanations of the letter codes). Carbonatites are shown by a horizontal line pattern. The closer the line spacing, the younger the carbonatite phase. From Laznicka (1984).

Table 33-13. Principal mineralization styles in carbonatites

	VOLCANIC CARBONATITES
(A)	High trace metals or accessory metallic minerals (Fe,Ti,U,Nb, REE,etc.)
(B)	Metallic minerals in subvolcanic or plutonic carbonatite inclusions brought from some depth
(C)	Placer Ti-magnetite, etc., in volcanics-derived sand
(D)	Infiltration veinlets of minerals (e.g. U) in volcanics and young associated sediments (X Tt U)
(E)	Metals (e.g. U,Th,REE,etc.) and fluorite in chemical sediments (e.g. playa evaporites)
	SUBVOLCANIC AND PLUTONIC CARBONATITES Recoverable dispersed anomalous trace metal contents (e.g. Nb,REE, Th,U) and disseminated minerals (e.g. pyrochlore), in:
(G)	Early stage (magmatic) carbonatite stocks;
(H)	Carbonatite dikes;
(I)	Late stage (metasomatic, vein) carbonatite;
(J)	Late stage hydrothermal metasomatites, veins and stockworks in carbonatites
(K)	Disseminated and replacement Fe,Ti,REE,Nb,Th ores in fenites
(L)	Mineralized fissure veins in fenites
(M)	Mineralized regionally or contact metamorphosed carbonatites
	WEATHERING CRUSTS
(N)	Surficial ore rubble (magnetite, hematite)
(O)	Residual resistate minerals; minerals formed by alteration of original ores or precipitated from leached components in laterite and saprolite
(P)	Buried mineralized regoliths
	PRODUCTS OF SEDIMENTOGENIC REWORKING
(Q)	Alluvial placers
(R)	Paleoplacers

present in carbonatites (in 0.X to 0.0X vol.% quantities) and so are magnetite, apatite (usually rich in REE), Nb-rutile, baddeleyite, bastnaesite and other minerals. Such disseminations become potentially economic ores when the content of pyrochlore reaches several percent, and that of apatite, magnetite, etc., several tens of percent. This is most common in the late-stage carbonatites. Recoverable amounts of disseminated magnetite have been outlined in the Clay-Howells carbonatite, Ontario (Currie, 1974).

In the mineralized portion of carbonatite in depth at Araxá, Brazil (Fig. 33-36), the ore minerals (pyrochlore, apatite, minor monazite) are hosted by a brown, biotite-rich xenolithic silica carbonatite (glimmerite) in the vicinity of younger phase veins and stringers of

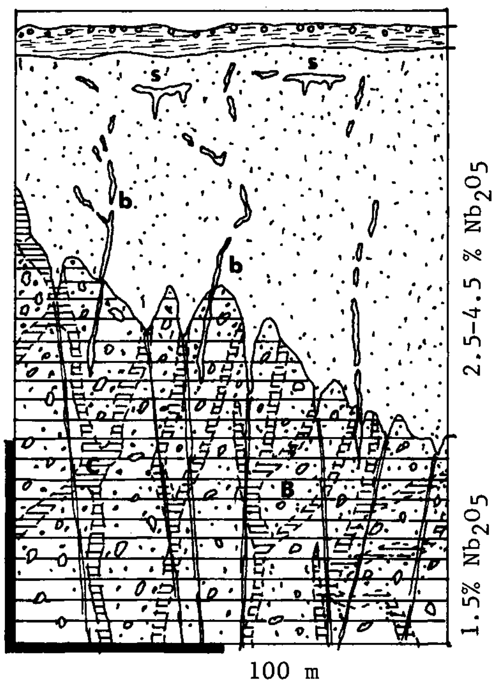


Fig. 33-36. Diagrammatic section across the pyrochlore orebody Barreiro near Araxá, M.G., Brazil. From LITHOTHEQUE, based on W. Betz, oral communication and tour, 1980.

white calcitic carbonatite (W. Betz, oral commun., 1980). In the Kangankunde, Malawi, carbonatite (Garson, 1966; Fig. 33-37) green monazite, pink florencite and pearly flakes of bastnaesite are present in carbonatites of several generations, but the spectacular concentration of monazite with strontianite there is located at the margins of late intrusive carbonatite dikes (Lonrho Staff, oral commun. 1980).

Carbonatite dikes themselves are commonly mineralized, for example at Ondurakorume, Namibia (von Backström, 1974; bastnaesite, strontianite, riebeckite, minor monazite, pyrochlore, cerianite, etc. in a dolomite carbonatite dike) and Mountain Pass, California (high-grade bastnaesite, lesser monazite, parisite, zircon mineralization in dolomite-barite and calcite carbonatite dikes; Molycorp Staff, guided tour, 1982).

Iron and base metal sulphides are relatively rarely disseminated in carbonatite. Widespread pyrrhotite, chalcopyrite and molybdenite are located in carbonatite dikes in the Callander Bay complex, Ontario (Currie, 1974), and minor chalcopyrite usually appears in carbonatites emplaced in mafic basement rocks.

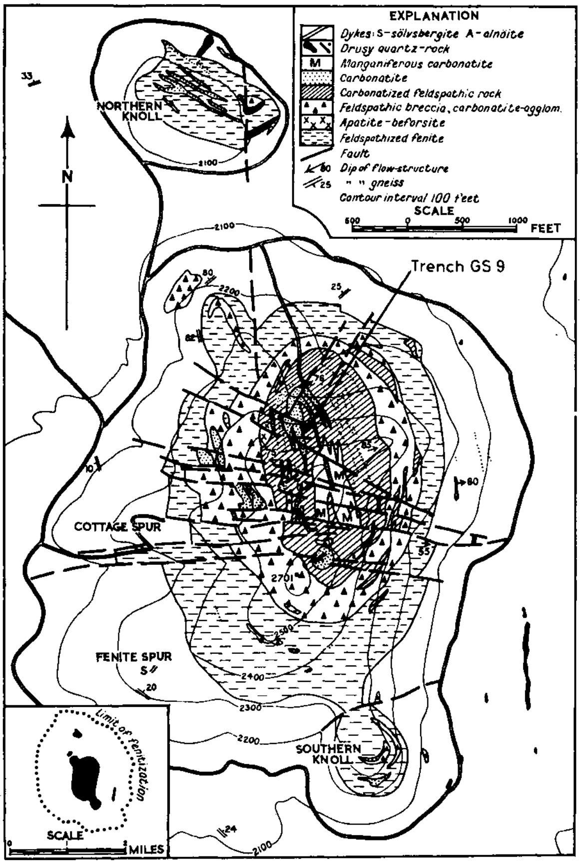


Fig. 33-37. Geology of the Mesozoic Kangankunde carbonatite complex, Malawi. From Garson (1966), courtesy of the Institute of Mining and Metallurgy, London, and the author.

(d) Late stage metasomatites and veins in carbonatites

In multiphase alkaline complexes, the sequentially younger phases, usually rich in volatiles, fill dilations in, or replace older phases. A variety of mineralized metasomatites and open space-filling orebodies (veins, stockworks, breccias) may result. The mineralizations incorporate both newly introduced metals as much as remobilized, earlier introduced metals.

Introduction of silica into earlier carbonatites may result in the formation of skarn-like metasomatites. In the Turiy Peninsula complex, Kola, U.S.S.R., such skarns are composed of diopside, monticellite, phlogopite and Na-pyroxenes. Lenses of replacement Ti-magnetite occur in the adjacent carbonatites (Samoylov and

Afanas'yev, 1978). Incomplete carbonatization of earlier silicate rocks, on the other hand, results in the generation of rocks that correspond compositionally to silica-carbonatites. The "apatite beforsite" dikes at Kangankunde, Malawi (Garson, 1966) contain brucite, portlandite, monticellite, melilite, gehlenite and apatite in a dolomite matrix, and are interpreted as being carbonatized apatite-rich olivine melilite nephelinites. The ore minerals are represented by baddeleyite.

Apatite-dominated breccias in carbonatites are quite common, and they usually have a high rare earths content (e.g. Eppawala, Sri Lanka), or carry a variety of accessory minerals (e.g. monazite in Glenover, South Africa). Magnetite, olivine, apatite rocks ("phoscorites") are frequently developed at the contacts of a carbonatite emplaced in an older pyroxenite, as in Palabora (Transvaal). Some carbonatized breccia zones and faults resemble dikes. The Th-rich "dikes" in Chilwa Island are brecciated zones in sideritic carbonate altered to goethite with interstratified quartz, fluorite and barite. Thoria (up to 2% ThO_2) is dispersed in goethite (Garson, 1966).

Ore-bearing hydrothermal veins and stockworks are common in carbonatites, and Palabora (Transvaal) is certainly the most prominent example. There (Verwoerd, 1967; Palabora Staff, 1976; Fig. 33-34,) a dike-like body of transgressive carbonatite was emplaced in an earlier, banded carbonatite along the intersection of two prominent fracture zones. A stockwork of transgressive carbonatite veinlets crosscut the older rocks along structural trends. This was further fractured and later stage hydrothermal copper sulphides introduced. The result is a large tonnage, low-grade stockwork and disseminated chalcopyrite, bornite, lesser chalcocite, valeriite, cubanite, pyrrhotite, etc. mineralization in carbonatite. In terms of ore distribution this is reminescent of the porphyry copper deposits and almost independent of the early development of the Palabora alkaline complex. Magnetite is widespread and the variety of by-product metals recovered in Palabora comes from two sources: (1) subsidiary metals introduced with the copper ores (Au,Ag,Pt) and (2) metals present in the early stage minerals scattered in carbonatite such as baddeleyite and U-thorianite (Zr,Th,U). A late-stage sulphide mineralization rich in copper, associated with metasomatic carbonatites and reminescent of Palabora, has been described at Bukusu, Uganda (Baldock, 1969).

A few additional examples taken from the large variety of ore-bearing hydrothermal veins in carbonatites, include the following: (a) high-grade (over 10% REE_2O_3) carbonate, bastnaesite, monazite veins from Wigu Hill, E. Tanzania (Deans, 1966) and (b) hematite-calcite veins in red coloured carbonatites, formed along N.W. fissures in the Fen Complex, Norway (Vokes, ed., 1960). These veins have been mined for iron in the past, and they contain high ThO_2 and REE contents (0.2 and 1%, respectively). (c) Veins and replacements of drusy quartz and purple fluorite in the Chilwa Island, Malawi carbonatites (Garson, 1966) carry small quantities of bornite and pyrochlore. (d) At Kangankunde, Malawi (Garson, 1966; Fig. 33-37), ramifying monazite-rich veinlets accompanied by strontianite, ankerite, quartz and barite, grade into spectacular, rounded bodies composed of radiating crystals of barite, strontianite, green monazite and other minerals.

ORES IN FENITIZED AUREOLES AROUND CARBONATITES

In multiphase carbonatite complexes, fenitization is not confined to exocontacts, but often affects its own members (earlier carbonatite and alkaline silicate rocks). In the Mountain Pass REE deposit, California, fenitization impairs spectacular lavender blue colours caused by pervasively distributed riebeckite both to a portion of the carbonatite and to the surrounding granite and syenite. It is related to the latest hydrothermal phase of alkaline magmatism, and not only to the carbonatite.

At some localities, early fenites are extensively carbonatized and so gradually acquire the character of metasomatic carbonatites (e.g. in Kangankunde, Malawi; Garson, 1966). Some such carbonatites are rheomorphically re-emplaced. Carbonatized fenites may carry accessory minerals, identical to those in magmatic carbonatites (apatite, pyrochlore, etc.). In addition to this, they host a variety of mineralized hydrothermal veins, such as: (a) vanadiferous Ti-magnetite veins (Tweerivier, South Africa; Verwoerd, 1967); (b) tabular bodies of Ti-magnetite in K-feldspar fenitized pyroxenite, Okorusu, Namibia (Verwoerd, 1967); (c) calcite, magnetite, pyrrhotite, galena, bastnaesite, apatite, etc. veins with finely dispersed ThO_2 and REE (0.67% and 9.1%, respectively), Itapirapua, Brazil (Gittins, 1966) and (d) quartz veins and stockworks in fenitized quartzite, containing synchisite, Glenover, South Africa (Verwoerd, 1967).

METAMORPHOSED CARBONATITES

Carbonatites affected by regional metamorphism as well as by thermal metamorphism at genetically unrelated contacts (e.g. with granites), have rarely been described. Heinrich (1966, p.376-385) reviewed the "metamorphosed carbonatites" of the Haliburton-Bancroft area, Ontario, located in the high-grade metamorphics of the Grenville province. The origin and interpretaion of these rocks is controversial. They were reviewed in greater detail in Volume 2.

Moore (1973) described greenschist to amphibolite facies metamorphosed carbonatites in the Strangways Range, 100 km N.N.E. of Alice Springs, Central Australia. Several occurrences in the Canadian Cordillera (Ice River, Verity, Lonnie) have been reviewed by Currie (1974). The metacarbonatites are usually inconcpicuous and difficult to distinguish from marbles. Some are discussed in Section 33.10.

WEATHERING-GENERATED RESIDUAL METAL OR MINERAL CONCENTRATIONS OVER CARBONATITES

The fully-developed regoliths over deep tropically weathered mineralized carbonates as in Araxá, contain the following zones running from top to bottom: (a) in situ or transported lateritic residual soil that may contain buckshot concretions, blocks or irregular horizons of ferricrete, or occasionally relict magnetite rubble; (b) powdery (clayous) saprolite, usually of brown or yellowish-brown colour; (c) irregular (pinnacled) top of karsted carbonatite and (d) fresh carbonatite.

Among the ore minerals present in regoliths one can distinguish (1) unaltered relic resistates having the same properties as in the fresh carbonatite (e.g. magnetite, partly pyrochlore, monazite, baddeleyite); (2) altered resistates (e.g. "pandaite", a pyrochlore in which the original Na and Ca were replaced by Ba and Sr in the weathering profile; francolite, etc.) and (3) newly formed compounds pseudomorphing the original minerals, or authigenically precipitated in the weathering profile (e.g. goethite, gibbsite, etc.). Some minerals (e.g. apatite) can occur in all the three modes.

In some apatite-rich carbonatites (e.g. Sokli, Finland; Vartiainen and Paarma, 1979), hard francolithic phosphorite breccia in the upper zones of a relict weathering profile, substitute for ferricrete blocks in the "normal" weathering profile. In Araxá and similarly zoned profiles (e.g. Catalão and Seis Lagoas, Brazil; Mrima Hill, Kenya), the upper lateritic zone is of little economic importance. The main orebody is contained in the brown saprolite. Such saprolite is composed of authigenic goethite, residual magnetite, variable quantities of apatite, residual and secondary pyrochlore ("pandaite") and monazite. Abundant barite forms drusy veins and veinlets.

At Araxá (Fig. 33-36), the reserves of the ochre are estimated to be 450 Mt, having a grade of 2.5% Nb_2O_5, 4% REE_2O_3, 30-40% Fe, 10-20% barite, and a variable grade of ThO_2. The calcite dissolution during weathering caused an improvement of about 160% in the Nb and REE ore grades, and resulted in an orebody that was cheap to mine (W. Betz, oral commun., 1980). This orebody supports the largest and highest grade Nb producer of the world.

At Mrima Hill, Kenya, a residue over carbonatite that is over 200 m deep, contains 40-70% goethite, 10% Mn oxides, barite, gorceixite and "pandaite", that represents an average grade of 30% Fe, 5% Mn, 0.7% Nb_2O_5, and under 5% REE_2O_3 (Deans, 1966). The Mn reserve is 136 Tt Mn.

In Kangankunde, Malawi (Garson and Morgan, 1978; Fig. 33-37), supergene leaching of carbonate from a complex ankerite, strontianite, monazite, bastnaesite carbonatite, resulted in surficial crusts greatly enriched in strontianite. Average grades range up to about 30-40%. The monazite content has also been enhanced, in contrast to bastnaesite which was largely destroyed and removed in solution. In addition to this, there are estimated to be about 100 Tt loose monazite in soils (Deans, 1966). In Glenover, South Africa (Verwoerd, 1967), the residual earth with hematite blocks contains yellow secondary U-Th patches and up to 1.16% Nb_2O_5.

Certain ore-bearing regoliths have not developed directly over carbonatites, but over mineralized fenites. In the Mata Creek section in the Araxá field, a saprolite formed over feldspathized fenite has a high rare earths content, based mostly on goyazite. Monazite, apatite and pandaite are subordinate. The reserves of this material are about 1.3 Mt with 12% REE_2O_3, 2.21% Nb_2O_5, 0.6% ThO_2, 0,05% U and 0.65% PbO (Grossi Sad and Torres, 1978).

Erdosh (1979) described a karst that pobably dates from the lower Cretaceous age, formed over the Proterozoic Cargill carbonatite in Ontario. The sinkholes are now mostly filled by apatite, goethite and clay residue and topped by a crandallite-rich blanket. The rare earths content in crandallite may have some economic significance.

Abundant Ti-magnetite rubble ore rests on the surface of the Bukusu, Uganda, carbonatite (Deans, 1966).

ORES RESULTING FROM PHYSICAL REDEPOSITION

Erdosh (1979) described significant quantities of an almost pure well-sorted apatite sand in Quaternary glacial lake sediments in the vicinity of the Cargill complex, Ontario, formed by reworking of residual apatite capping the carbonatite. The apatite has an enhanced REE content.

ORES RESULTING FROM CHEMICAL REDEPOSITION OF METALS BY GROUND OR METEORIC WATER

Alkhazov et al. (1977) mentioned radioactive stratiform mineralization formed in Quaternary soda lake beds as a result of leaching of uranium from the Quaternary carbonatite volcano Khanneshin in Afghanistan.

33.9. KIMBERLITES AND KIMBERLITIC DIATREMES

33.9.1. General

On a hand specimen scale, kimberlite is defined as "a porphyritic alkalic peridotite containing abundant phenocrysta of olivine and phlogopote and possibly geikielite and chromian pyrope in a fine grained groundmass of calcite and second generation olivine and phlogopite. It has accessory ilmenite, serpentine, chlorite, magnetite and perowskite" (A.G.I. Glossary of Geology, 1981).

When the term "kimberlite" is used to designate a lithologic field unit (for example, a host to diamonds), the term becomes much more complex. With the exception of the relatively deep-seated kimberlite dikes and sills, the "typical" (pipe-like) kimberlite occurrences are rather heterogeneous systems, strongly influenced by the depth of emplacement. A "kimberlite pipe" (or diatreme) as in northern Montana or South Africa (Hearn, 1968; Hawthorne, 1975; Fig. 33-38), starts in depth as a narrow sheet-like peridotite dike. With decreasing depth, it gradually changes into intrusive breccias. Together with the lithologic change, the shape of the intrusion also changes from an initially linear cross-section to an elliptical and ultimately a circular one. The middle and upper part of the kimberlite pipe is filled by a heterogeneous breccia of abundant subrounded to angular rock fragments in a finely crystalline matrix of serpentinite, calcite or dolomite, phlogopite, chlorite, etc.

The fragments are either (1) of subcrustal (mantle) origin and composed of garnet peridotite, lherzolite, eclogite, etc., or (2) of crustal origin, representing wallrocks brought in from great depth, or collected from above the present site and emplaced by gravity slumping and a free fall. The fragments corresponding to category (1) are considered as consanguinous with the kimberlite and are of considerable petrogenetic significance. The fragments coresponding to type (2) frequently represent samples of rock units in which the kimberlite was emplaced, but which have since been eroded away. Usually, the proportion of crustal rocks increases upward.

In the least eroded kimberlite pipes (e.g. Kasama, Mali), the pipe is fringed by a ring of marginal breccia and filled with kimberlitic ejecta and fragments of the wallrock that appear to have been washed into the pipe from the surface. Hawthorne (1975) coined the term "epiclastic kimberlite" for such an association. In outcrop, the kimberlite breccia bears the characteristic appearance of a yellowish or olive-green soft soily saprolite, enclosing less intensively weathered nodular fragments of ultrabasics, as well as hydrated flakes of phlogopite. Further downward, the "yellow soil" changes into a "blue soil".

A characteristic feature of a kimberlite pipe is the lack of thermal and hydrothermal metamorphism and metasomatism in both the endocontact (material within the pipe) and exocontact (the wallrock). Undisturbed fragments of coal and bitumen have been recorded in some African kimberlites.

Lorenz (1975) explained the origin of kimberlite diatremes by a cold emplacement, that followed a hot magmatic emplacement of the deep root dike. The gases and vapours causing fluidization and upward particle transport were geneated either by unmixing of the juvenile gas phase from the ultrabasic magma, or were vapourized local meteoric waters driven by the magmatic heat in the manner described for the phreatomagmatic eruptions. Kimberlites and diatremes (and also maars) may have a causal relationship, but not all diatremes are kimberlites.

Kimberlites are extremely rare rocks and in Africa, where they are most common, they cover an area of less than 100 km^2. There is, however, an extensive literature on the subject (e.g. Vol. 9, 1975, of the Physics and Chemistry of the Earth; several contributions in Wyllie, ed., 1967; Mitchell, 1970; Sobolev, 1977) because of their key scientific significance for providing material for the study of

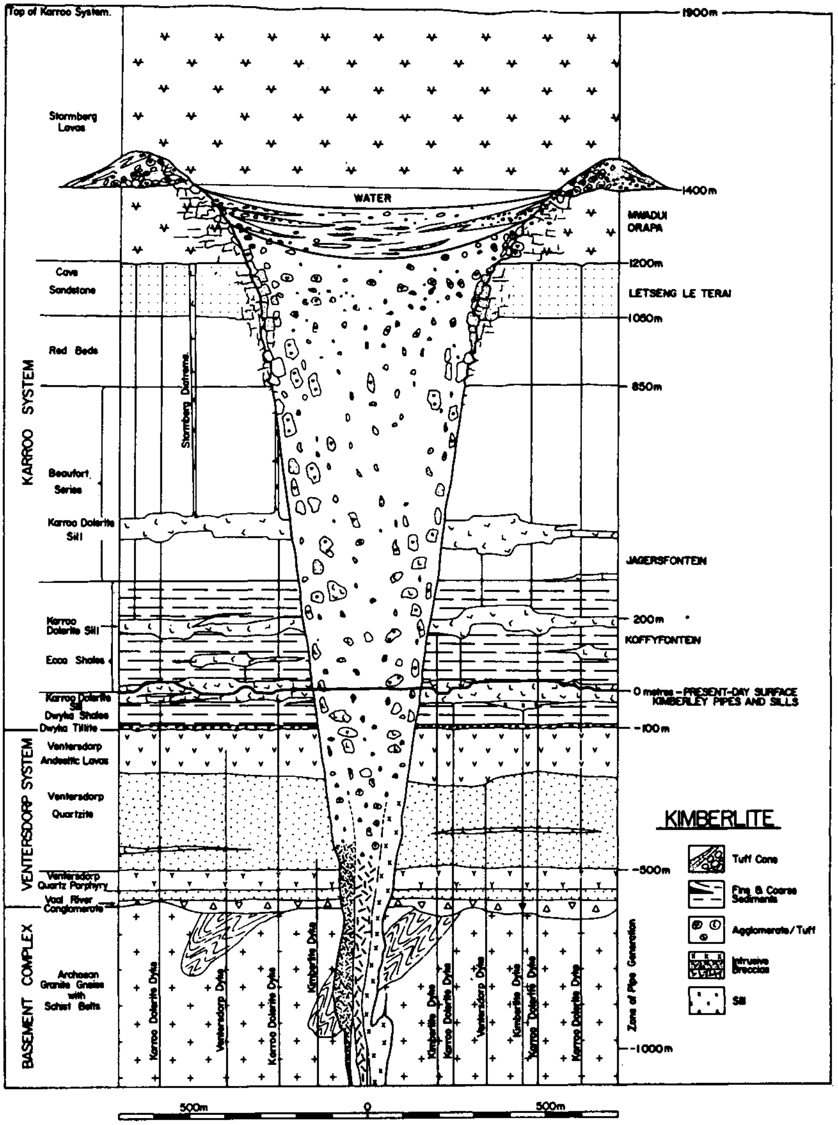


Fig. 33-38. Model of an African kimberlite pipe. From Hawthorne (1975), courtesy of the Pergamon Press.

the deep subcrustal layers of the earth, and because they are the only primary source of diamonds. This book, unfortunately, does not treat diamonds. Although kimberlites do contain a significant trace content of a variety of metals, they hardly represent a viable target for metalliferous exploration. They are too small. For that reason, kimberlites are entitled to only a brief review here.

33.9.2. Metal geochemistry and metallic mineralization

Like other members of the ultramafic-alkaline association, kimberlites are geochemically enriched in both the ultramafic (Ni, 0.13% in the Premier mine kimberlite; Cr, aver. 0.1%; Pt) and alkaline (REE, 300-800 ppm; Zr, 150-300 ppm; Nb, 100-300 ppm) suites of trace elements (Mitchell and Brunfelt, 1974). Kimberlitic breccias contain accessory Ti-magnetite, ilmenite, perowskite and chromite. In the Premier mine in Transvaal, kimberlite contains 2.5% ilmenite with 46-54% TiO_2, recoverable as a by-product of diamond mining. Wagner (1914) referred to the presence of small amounts of Pt metals in some South African kimberlite pipes.

At the Premier mine, the kimberlite breccia is cut by several intrusive magnetite, serpentine, calcite bodies, causing wallrock carbonatization (Robinson, 1975) and formerly interpreted as being carbonatite. Their metal content, however, is low (10-15% Fe oxides, 0.93-1.66% TiO_2 and 0.14% Ni).

Kashtanov (1967) reported several occurrences of redeposited alluvial bauxite, filling kimberlitic diatremes in eastern Siberia.

33.10. MINERALIZATIONS LINKED TO SUBTLE AND QUESTIONABLE ALKALINE INTRUSIVE PARENTS

This is a "convenience type", included in order to notify the exploration geologist of the possible presence of ores (e.g. of Nb,Th,REE,U,Zr) that are normally associated with alkaline complexes in terrains, where such "typical" complexes are not known. Most such terrains are situated in polyphase metamorphosed portions of mobile belts, usually in segments with an old, thick, formerly consolidated continental crust, later affected by retrograde metamorphism, fragmentation, "granitic" plutonism, etc. There is an overlap with the examples treated in Section 29.8.

The majority of the ore occurrences treated are fracture-filling or replacement veins as well as apparently conformable metamorphosed and mineralized rock bands. Some are dominated by feldspar gangue (albite or microcline) so that they resemble pegmatites. Others have quartz-carbonate or barite gangue. Some carbonate "veins" or "marble beds" may be thin carbonatite dikes or sills or metasomatically carbonatitized zones, lacking conspicuous wallrock fenitization, or with fenitization modified or obliterated by metamorphism. In most cases, the evidence for alkaline magmatic affiliation is insufficient or ambiguous. A considerable number of examples comes from the eastern portion of the North American Cordillera. Thorium-bearing veins, the most characteristic mineralization style there, have been reviewed by Staatz (1974).

Lemhi Pass District, Idaho and Montana

Lemhi Pass straddling the border of Idaho and Montana (Staatz, 1979) is underlain by low-grade metamorphosed middle to late Proterozoic schist and quartzite and is adjacent to an outcrop area of mid-Tertiary calc-alkaline volcanics (Challis Volcanics). About 250 Th,REE,Cu and sometimes Au-bearing fissure veins have been identified over a territory of about 130 km^2. The veins are composed of pink microcline, quartz, carbonate (calcite, ankerite, siderite) and sometimes barite. Thorite, in the form of small dark-red to reddish-brown crystals as well as a rarer monazite, are usually scattered within the carbonate. There is no obvious wallrock alteration.

In outcrop, the carbonates are completely leached out, and substituted by a radioactive limonitic residue. The veins are very inconspicuous, resembling pegmatites, and the presence of Th and REE is not megascopically apparent. The largest Last Chance vein is a tabular body, 1.4 km long and up to 13 m thick. The mineralization is mid-Tertiary, postdating the Challis Volcanics. There is a single occurrence of an inconspicuous (and questionable) carbonatite dike in the district, but more similar dikes have been reported by Heinrich (1966) in the nearby Ravalli County in Montana. Lemhi Pass contains a substantial share of the U.S. thorium reserves (242 Tt Th in ores with a grade better than 0.1% ThO_2), as well as 306 Tt REE. Similar veins without known alkaline rocks in the Cordillera have been recorded by Staatz (1974) from Diamond Creek, Idaho; Gold Hill, New Mexico; Quartzsite and Cottonwood, Arizona and Monroe Canyon, Utah.

Monumental Summit, Idaho

Carter (1973) described an occurrence of an earthy, brown to yellowish-brown rhabdophane ($(Ce,La)PO_4.H_2O$) and rare pyrite, rutile, zircon, etc. in association with Fe and Mn oxides and residual clays along a shear in a silicified marble near the contact with Proterozoic metaquartzite. This occurrence is located along the western paleo-caldera rim of the mid-Tertiary Challis Volcanics, and appears to be broadly contemporary with the Lemhi Pass ores. There are about 85 Tt of ore with 0.35% REE.

Iron Hill near Silver Cliff, Colorado

Hildebrand and Conklin (1974) described an interesting breccia dike composed of massive magnetite, apatite, molybdenite, and a variety of other minerals, cementing and replacing fragments of a Tertiary trachyandesite. The apatite contains 3.4-4% rare earths and the occurrence is, to some extent, reminescent of the Morro de Ferro deposit in Brazil. The ore occurrence is of mid-Tertiary age and is located in what is a typical calc-alkaline, epithermal Au-Ag and polymetallic district. Older (Cambrian) alkaline intrusions, however, are known in the Wet Mountains region in this vicinity.

Lonnie Prospect, Manson Creek, British Columbia

The small and uneconomic Lonnie Nb,Th,REE,U showing (Holland, 1955) has been included as an example of a marble band of uncertain origin conformable with foliation of adjacent metamorphics, that carry a low-grade mineralization corresponding compositionally to the alkaline suite. Sparsely scattered ore minerals are contained in a feldspathic marble grading into syenitic to pegmatitic rocks containing conspicuous acmite (columbite, ilmenorutile), and in massive to foliated marble (U-pyrochlore). The gneiss adjacent to the mineralized band contains abundant crossite and acmite, gradually dissapearing with increasing distance from the contact. The most likely genetic interpretation assumes a regionally metamorphosed carbonatite sill partly modified by interaction with a syn-metamorphic pegmatite.

Karonge, Burundi

Van Wambeke (1977) described the small deposit Karonge, consisting of veins and stockworks of monazite, bästnaesite with minor rhabdophane and cerianite in quartz, barite and goethite gangue. The veins are fault-controlled and hosted by Precambrian gneisses and metasediments, cut by pegmatites. About 2,300 t bastnaesite have been produced. Somewhat similar "pegmatite-like" veins with bastnaesite, parisite, chevkinite and monazite near Ifasina, Madagascar (Chantraine and Radelli, 1970) appear to be associated with 550 m.y. old intrusive syenite bodies.

An apatite-uranium mineralized field, U.S.S.R.

This unknown ore field (probably in the Kuznetsk Alatau or Minussinsk Basin region, Siberia) described by Kazansky and Laverov (1974) consists of replacement ore lenses, veins and pipes hosted by argillaceous and tuffaceous Ordovician limestone accompanied by andesite tuffs and porphyritic metabasalts. The orebodies consist of a fine crystalline fluorapatite, arshinovite, pitchblende, and a variety of base metal sulphides and Th,REE minerals. Silicification and albitization are the dominant alterations. The ore is Devonian or later, postdating the main orogeny in the region.

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"A ready reference book is only as good as is its index".

INDICES

GENERAL INDEX

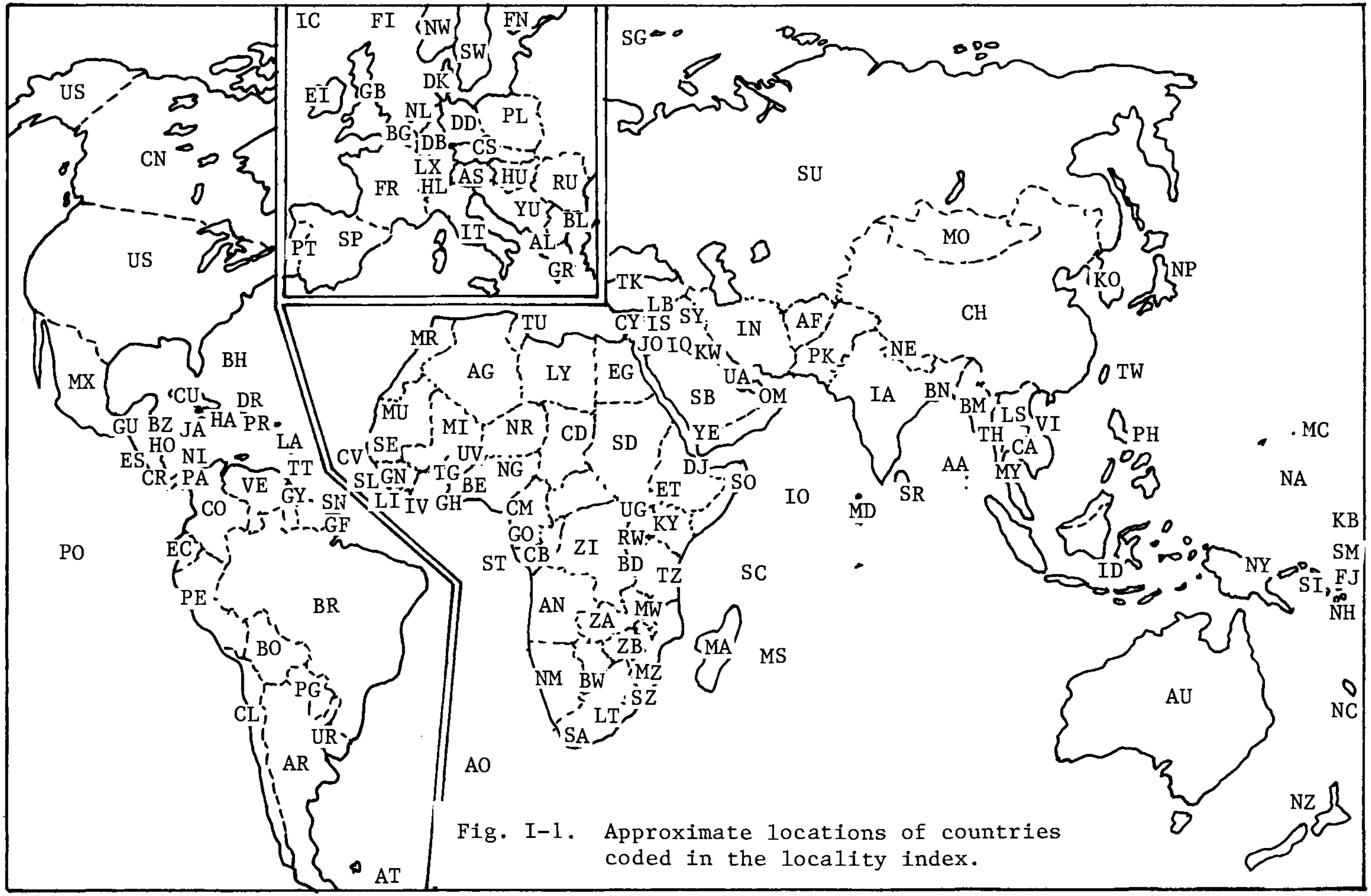


Fig. I-1. Approximate locations of countries coded in the locality index.

LOCALITY INDEX

NOTE: MOST LOCALITIES ARE FOLLOWED BY A COUNTRY:COMMODITY CODE (SEE FIG. I-1 AND TABLE I-1 FOR CODE LOCATIONS AND EXPLANATIONS).

Table I-1. List of country codes used in the locality index.

AA	Andaman-Nicobar	FJ	Fiji	MX	Mexico
	Islands	FN	Finland	MZ	Mozambique
AF	Afghanistan	FR	France	NA	Nauru
AG	Algeria	GB	Great Britain	NC	New Caledonia
AL	Albania	GF	French Guyana	NE	Nepal
AN	Angola	GH	Ghana	NG	Nigeria
AO	Atlantic Ocean	GL	Greenland	NH	New Hebrides
AR	Argentina	GN	Guinea	NI	Nicaragua
AS	Austria	GO	Gabon	NL	Neatherlands
AT	Antarctica	GR	Greece	NM	Namibia
AU	Australia	GU	Guatemala	NP	Japan
BD	Burundi	GY	Guyana	NR	Niger
BE	Benin	HA	Haiti	NW	Norway
BG	Belgium	HL	Switzerland	NY	New Guinea
BH	Bahamas	HO	Honduras	NZ	New Zealand
BL	Bulgaria	HU	Hungary	OM	Oman
BM	Burma	IA	India	PA	Panama
BN	Bangladesh	IC	Iceland	PE	Peru
BO	Bolivia	ID	Indonesia	PG	Paraguay
BR	Brazil	IN	Iran	PH	Philippines
BW	Botswana	IO	Indian Ocean	PK	Pakistan
BZ	Belize	IQ	Iraq	PL	Poland
CA	Cambodia	IS	Israel	PO	Pacific Ocean
CB	Congo-Brazzaville	IT	Italy	PR	Puerto Rico
CD	Chad	IV	Ivory Coast	PT	Portugal
CF	Central African	JA	Jamaica	RU	Rumania
	Republic	JO	Jordan	RW	Rwanda
CH	China	KB	Kiribati	SA	South Africa
CL	Chile	KO	Korea	SB	Saudi Arabia
CM	Cameroon	KY	Kenya	SC	Seychelles
CN	Canada	KW	Kuwait	SD	Soudan
CO	Colombia	LA	Lesser Antilles	SE	Senegambia
CR	Costa Rica	LB	Lebanon	SG	Spitzbergen
CS	Czechoslovakia	LI	Liberia	SI	Solomon Islands
CB	Cuba	LS	Laos	SL	Sierra Leone
CV	Cape Verde Islands	LT	Lesotho	SM	Samoa
CY	Cyprus	LY	Libya	SN	Suriname
DB	West Germany	LX	Luxembourg	SO	Somalia
DD	East Germany	MA	Madagascar	SP	Spain
DJ	Djibouti	MC	Micronesia	SR	Sri Lanka
DK	Denmark	MD	Maldives	ST	São Tome-Príncipe
DR	Dominican Rep.	MI	Mali	SU	U.S.S.R.
EC	Ecuador	MO	Mongolia	SY	Syria
EG	Egypt	MR	Morocco	SW	Sweden
EI	Ireland	MS	Mauritius	SZ	Swaziland
ES	El Salvador	MU	Mauritania	TG	Togo
ET	Ethiopia	MW	Malawi	TH	Thailand
FI	Farøe Islands	MY	Malaysia	TK	Turkey

TG	Togo	TZ	Tanzania	VE	Venezuela
TH	Thailand	UA	United Arab Emir.	VI	Vietnam
TK	Turkey	UG	Uganda	YE	Yemen
TT	Trinidad-Tobago	UR	Uruguay	YU	Yugoslavia
TU	Tunisia	US	United States	ZA	Zambia
TW	Taiwan	UV	Upper Volta	ZB	Zimbabwe
				ZI	Zaïre

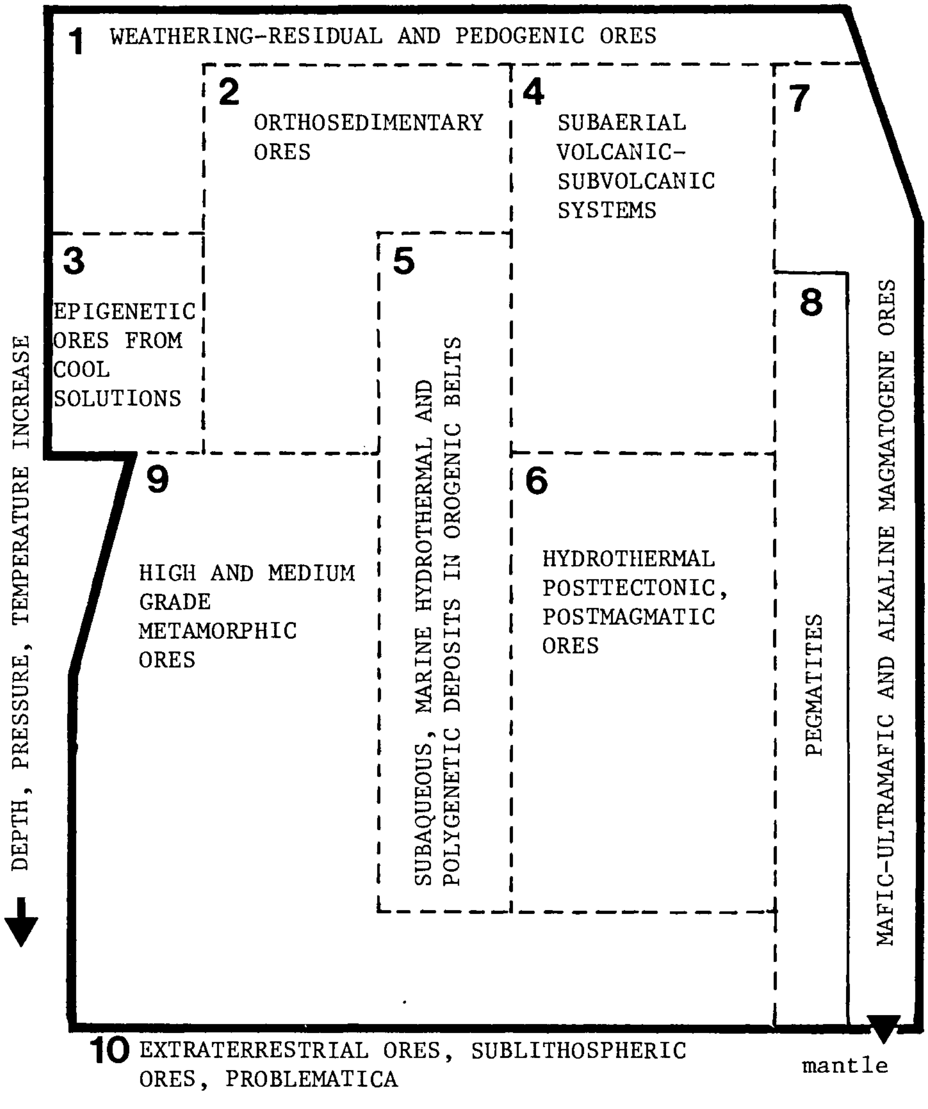


Fig. I-2. Utilitarian organization of metallic deposits (Laznicka, 1984). Most categories are transitional and overlapping.

GENETIC INDICES

A UTILITARIAN ORGANIZATION OF METALLIC DEPOSITS (Laznicka, 1984)

(NOTE: not a classification, because categories overlap and merge)

1. WEATHERING-RESIDUAL AND PEDOGENETIC ORES

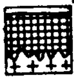
(* denotes fossil ores, buried or recently exhumed)

BOREAL, TEMPERATE

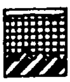
-"limonite" in zoned soil profiles, 682

-gold nuggets, 682-3

HUMID TROPICS



1A: tropical weathering profiles over "rocks"
- -general, 199-205
- -bauxite (Al-laterite), 39, 74-5, 377, 715-8*, 1488, 1432
- -high Fe, Ti laterites, 38-9
- -Sn,Au,Pt,U, 712-3, 1488



1B: enriched zones over metallic "protores"
- -Fe oxides, 703-5
- -Mn oxides, 706-10

1C: relic resistates (eluvial placers), Sn,Au, 692-718

KARSTED CARBONATE BASE

1D: ore lumps in residual clay, 729, 731-3
- -phosphates, 591, 594-5

1E: residual metalliferous clays
- -over carbonate, 596-603
- -over carbonatite, 1576-7

SULPHIDE BASE

1F: gossans (Au), 338,343

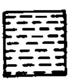
ARID AND SEMI-ARID CLIMATES

1G: calcrete, 566, 719-24, 914

silcrete, 725

2. (ORTHO)SEDIMENTARY ORES (syngenetic and diagenetic, mostly epiclastic derivation, unconsolidated to consolidated)

MOSTLY DETRITAL ORES



2A: clay to silt-size ore sediments
- -Al,Fe,Ti,V, 87, 807-12, 834-35, 1489
- -Mn oxides, 537-41
- -superfine gold, 104, 765

sand-size ore minerals

2B: alluvial, colluvial placers, 91-100, 751-5, 759-67, 205, 209-11, 1532-3

2C: beach placers, 39, 46-7, 76-8, 91, 99, 209

offshore placers, 109-112

dune placers, 86, 795

2BC paloplacers (undifferent.) 209, 244-50, 806-66 525-29, 556-9

2D: granule to block-size ore component
- -ore gravellite, 272, 806
- -Fe beach granules, 100-2
- -glaciers, glac. sediments 744-5, 1551
- -talus, scree, debris flows, 746-7

MOSTLY CHEMICAL PRECIPITATES

2E: bedded floor sediments
- -marine euxinic muds, 115
- -limnic alunite, 792

2E: -ironstones, 530-6, 263
-silic. iron formations, 839-41
-carbonate iron formations, 451-5
-Mn formations, 456-8, 536-41
-bedded dawsonite, 842-4
-stratiform metal. shales Cu: 571-81, 875; PbZn, 313-7, 603-8; U,V: 542-4 pyrite, 455-6


2F: nodular ores
-ocean, sea, lake floor FeMn nodules, 114, 231, 234-5, 424, 537, 541, 784 40, 76, 114-5
-phosphorite nodules, 4, 114, 591, 593, 482-8, 40
-chamosite, 115

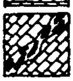

2G: bog, swamp, peat ores, 780-83


2H: cool springs aprons, Fe-Mn, 106, 797

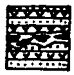
3. EPIGENETIC ORES PRECIPITATED FROM COOL (SUB-HYDROTHERMAL) METEORIC, GROUND, FORMATIONAL, ETC. WATERS.



3A: ore impregn. and cements of non-carbonates (mostly sandstones)
-Pb-Zn: 582-4, 880-4
-Cu: 755-5, 875-80, 885-9
-U-V: 845-871, 993
-Ag: 885
-Sn: 885
-Ni: 887



3B: pore fillings, replacem. in carbonates
-Pb-Zn, MVT: 600-630
-Pb-Zn, APT: 638-54
-Pb-Zn, Irish "type", 631-4
-Mn, 76, 373-5
-Fe,Zn,Mn: 733-4
-calcrete U-V: 722-4

3D: impregn. in coal, bitumen
-U,V,Ge: 828;9822-31
-Hg,U,V: 673-6



3E: infiltr. in contin. volc. and volc. sediments
-Mn oxides: 373-5, 367, 910-11 988-990
-Cu: 889-92
-fluvial deposits, 912, 792-3
-lake beds, 912-3, 792-3
-U in lake beds, 792-3, 912, 993-4


3F: ores infiltrated in basement rocks
-Mn, 260
-U, 1047

4. SUBAERIAL (PALEO)VOLCANIC-SUBVOLCANIC SYSTEMS


4AB: metalliferous lavas and pyroclastics
-magnetite, 58-9, 905-6, 987


4C: fumaroles, fumar. precip. 39, 46-7, 58-61, 9o6-7


4D: hot springs, precipitat. 37, 46-7, 61-74, 238-41, 376, 909, 1484
-volcanic karst, 913
-shallow subaq. ores, 907
-deep metallif. brines, 63


4E: epithermal veins
-general, 914-26
-Pb-Zn, 926-66
-bonanza Ag-Au, 478, 914-66, 980-1, 1267, 1485-8
-Cu, 968-9
-Cd,Zn, 1325
-As,Sb,Hg, 998-1002
-U-Mo, 991-3
-Be, 995
-Mn carbonate, 936
-W, 986-7


4F: miner. stockworks, brecc. 560-2, 968-72, 978-86, 985-6


4H: carbonate replacements,
-Carlin "type" Au, 480-1, 479-81, 566-71, 1319


4I: impregn., repl. in volc.
-bertrandite, 995-7
-alunite, 908-9
-miner. miaroles, 902-3
-volc.-diagenetic ores, 889-91, 909-10


4J: "metalliferous volcanics"
-dispers. trace Au, 903
-ore phenocrysts, 58, 153, 157, 902

5. SUBAQUEOUS, MARINE, HYDROTHERMAL AND POLYGENETIC (TECTONOMAGMATICALLY MOBILIZED) DEPOSITS IN OROGENIC BELTS



5AB:complex ("lens and stockwork") hydr.-sedim. seafloor massive ore deposits
-Cu in metabasalts (Cyprus t.) 255, 186-90
-Cu-Zn in bimodal assoc., 321-347
-Cu in andesites, 305-6, 369-72
-Zn,Pb,Cu in seq. diff. and felsic volc., 295-7, 403-16
-mass.sulph. in sedim., 434-7


5B: "distal" massive ores (stratabound lens only)
-Fe (Lahn-Dill) oxides, 263-6
-siderite, 1292-6
-Mn, 295, 373-5


5C: "lens and stockw.", seiments-hosted
-Zn,Pb,Cu, 451, 459, 469, 1257

5D: stratabd. lens in sedim.
-PbZn, 313-7, 566-8 (remob.)


5E: stratabd. dissem. ores
-Sb, 287
-W,Hg,Sb, remob., 488-500
-Cu, 362-9, 609-10

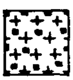

5F: ores control. by deform. (mainly cleavage)
-py, Cu, 301-4
-py, Au, 319-21

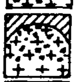

5G: ores in shears
-Au, 281, 277-86, 442-6
-Ni,Cu, 181

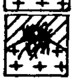

5H: miscell. peneconc. mantos
-nat. Cu, 157, 253-9
-Hg, 552-4

6. HYDROTHERMAL POSTTECTONIC, POSTMAGMATIC ORES

a) close association with granitic intrusions


6A: "metalliferous granites" 1063-66


6B: feldspathized apogranites, 1496-9


6C: dissem.,stockw.,breccia miner. in altered non-carb.
-porph. Cu-Mo, 325-49, 380-8, 968-78, 1018-9, 1088-1144
-stockw. Mo, 43, 1033, 1214-1226
-greisen Sn,W,Be, 1157-62, 1197
-Bolivian "porphyry Sn", 560-2, 978-86
-stockwork Au, 1033, 1275
-Pb-Zn, 1238


6D: fissure fill. and replac. veins, 1072-5
-Sn,W,Be, 560, 562, 985-6, 1157-85, 1197-1206, 1495-6
-Cu, 261, 439, 966-7, 1018-19, 1150-4
-Au, 261, 1035, 1039-43, 1046, 1275-80
-Sb, 1046, 1314-19
-Pb-Zn, 439, 1046, 1238-60
-Mo, 1227
-U, 1046


6E: skarns, 390-93, 1070-1, 1080-84
-Fe, 261-2, 1293-1303

-Cu, 1144-50
-Au, 377, 1280-8
-Sn, 1186-90, 1048
-scheelite, 1208-14
-Mo, 1227-28
-Pb-Zn, 1244-46, 1255, 1263-4


6F: non-skarn carbon. replac.
-Sb, 492-8
-Au, 1288-9
-Pb-Zn, 654-61, 1033, 1244-55, 1254-55, 1261-62
-Sn, 1186-91
-magnetite, 1036-7
-siderite, 1292-6
-U, 1312-14

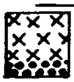
6b) no obvious connection with granitic intrusions


6G: stockworks, disseminations
-Sb, 1319-21, 1071-2
-scheelite, 1071-2, 1206-8, 1312-21
-Au, 1071-2, 1312-21
-Ag, 1264-7


6H: fissure, replac. veins
-Be, 1230-35
-F,Ba, 634-8, 1401-2
-Cu, 1464-5
-Mo, 1227
-Hg, 1321-2, 1401
-Bi, 1322
-Th,REE, 1581-2
-Ni,Co,Bi,Ag,U, 1268-72
-Pb-Zn, 1046, 1399-1400
-Ag, 1264-8, 1268-72
-Sb, 1314-19, 1401
-U, 1046, 1306-12, 1396-8, 1468-9
-Th, 1398-9
-Au, 1400
-Fe, 272, 1290-2


6I: skarns at gabbro contacts
-Fe,Co, 1465-7

7. MAGMATOGENE ORES, a) mafic-ultramafic association

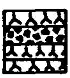
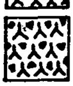

7A: cumulus segregated ores
-Cr,Fe,Pt, 249-50
-platinoids, 244-50, 1543
-Ti-magnetite, 244-50


7B: liquidomagmatic and wallr. interaction, hydrothermal ores
-platinoids, 244-50
-Ti-magnetite, 244-50, 1543


-pyrrh.,pentl.,cp, 255, 1043, 1440, 1455, 1442-6, 1453-4, 1464-9


7C: podiform chromite, 174-5, 178-80

7b) alkaline association


7D: disseminated ore minerals
-in agpaitic suite, 1516-21
-in carbonatite, 1569-73

-in kimberlite, 1577-80


7E: veins and metasomatites 1525-38, 1548-50, 1573-5


7F: mineralized diatremes 1446-7, 1578-9

8. PEGMATITES


8A: granitic pegmatites
-high level, Sn, 1048, 1067-8

-moder. level, hybrid, Be, 1390-4
-rare metal, 1387-92
-deep, 1046, 1385-6


8B: alkaline pegmatites, 1523-25

9. METAMORPHOSED AND METAMORPHOGENIC DEPOSITS IN HIGH-GRADE META MORPHIC AND ULTRAMETAMORPHIC TERRAINS.

10. EXTRATERRESTRIAL ORES, SUBLITHOSPHERIC ORES, PROBLEMATICA

B SOME POPULAR "ORE TYPES" - A RAPID PARTIAL INDEX

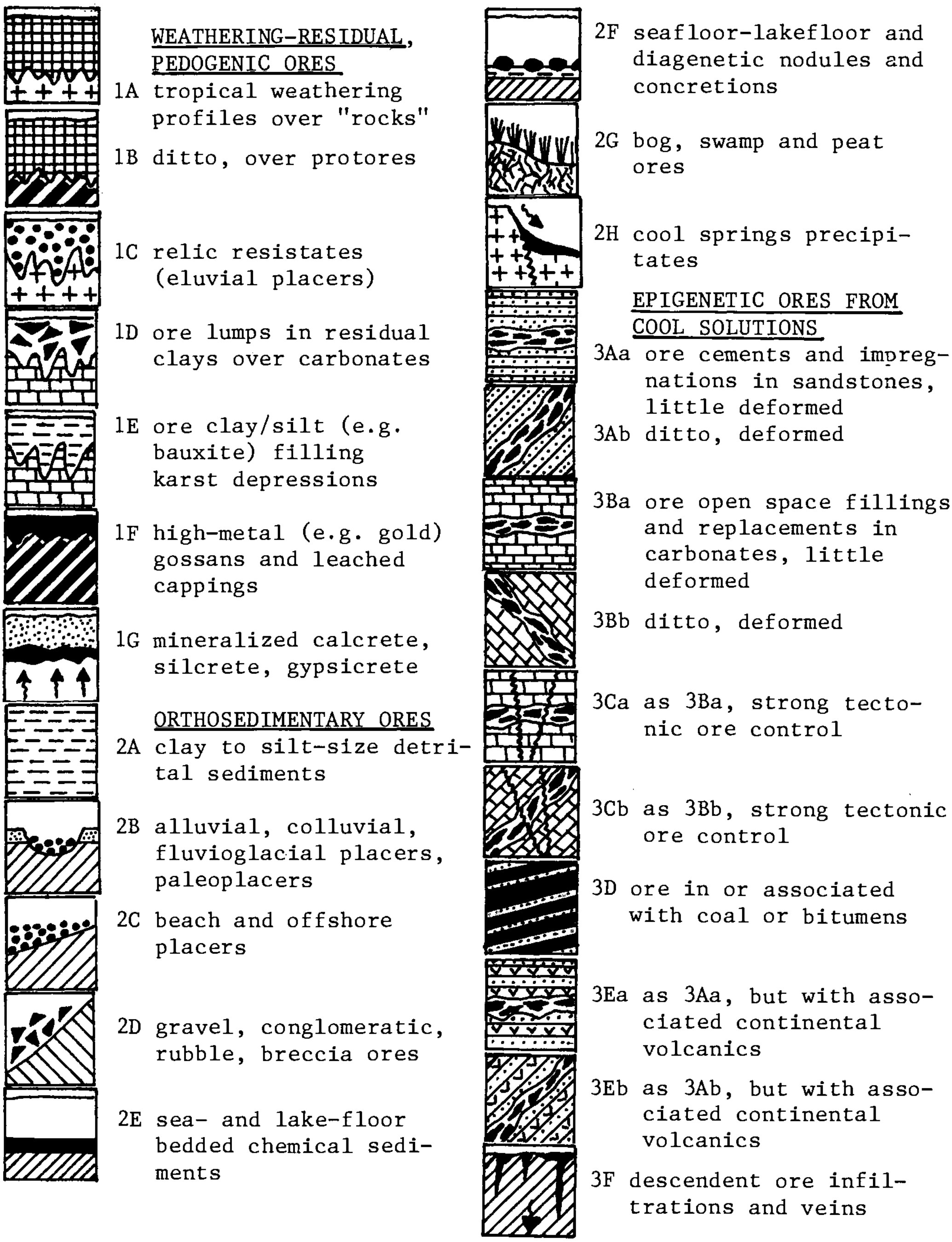
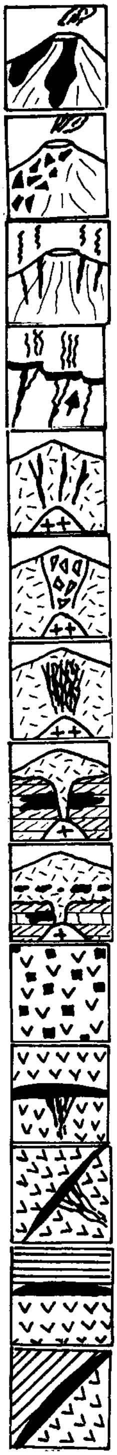


Fig. I-3. Legend to the ore style symbols from Laznicka (1984), used in the genetic and metal index.



SUBAERIAL VOLCANIC-SUBVOLCANIC SYSTEMS

4A metalliferous lavas

4B metalliferous pyroclastics

4C fumarolic mineralizations

4D hot springs, epithermal brines, precipitates

4E epithermal veins

4F high-level hydrothermal ores in breccias

4G high-level hydrothermal stockworks

4H high-level hydrothermal carbonate replacements

4I high-level hydrothermal impregnations in volcanics, miner. basement

4J "metalliferous volcanics", phenocrysts, miaroles

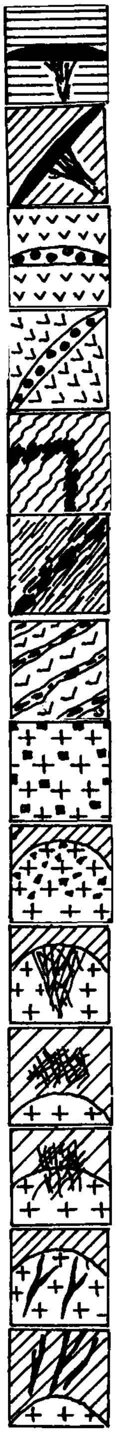
SUBAQUEOUS, MARINE-HYDROTHERMAL AND POLYGENETIC DEPOSITS IN OROGENIC BELTS

5Aa complex (lens-and-stockwork) deposit in volcanics, little disturbed

5Ab ditto, deformed and metamorphosed

5Ba "distal" (lens only) orebody, little deform.

5Bb ditto, deformed and metamorphosed



5Ca as 5Aa, but (meta)sediment hosted

5Cb as 5Ab, but (meta)sediment hosted

5Ea disseminated ore in mantos in (meta)volcanics, little deformed

5Eb ditto, deformed, metamorphosed

5F remobilized and hydrothermal-metamorphics ores

5G ores in shears and high strain zones subparallel with schistosity

5H peneconcordant or discordant ore sheets in (meta) volcanics and sediments.

HYDROTHERMAL-POSTTECTONIC POSTMAGMATIC ORES

6A metalliferous granites

6B disseminated ores in apogranites

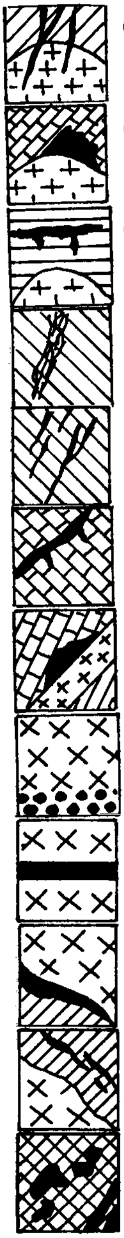
6Ca stockworks and miner. breccias in endocontact

6Cb ditto, in exocontacts

6Cc ditto, along both sides of contacts or undifferentiated

6Da fissure and replacement veins in endocontacts

6Db ditto, in exocontacts



6Dc as 6Db, along both sides of the contact or undifferentiated

6E ores associated with skarns

6F ores in non-skarn carbonate replacements

ORES WITHOUT CLEAR ASSOCIATION WITH GRANITIC ROCKS

6G stockworks, disseminations

6H fissure, replacement veins

6Ia carbonate replacements

6Ib skarns at gabbro-diabase contacts

MAGMATOGENE ORES

a) MAFIC-ULTRAMAFIC

7A cumulus segregated ores

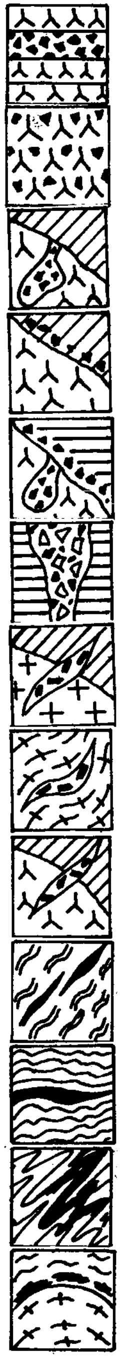
liquidomagmatic or wallrock interaction ores

7Ba within intrusion

7Bb along contacts

7Bc in exocontacts

7C podiform chromite, magnetite in ultramafic tectonites



b) ALKALINE ROCKS

7Da ore disseminations in layered intrusions

7Db ditto, in massive intrusions

7Ea veins, metasomatites, etc. in endocontacts

7Eb ditto, in exocontacts

7Ec ditto, along both sides of the contact or undifferentiated

7F mineralized diatremes

PEGMATITES

8Aa granitic pegmatites of shallow to intermediate depths

8Ab ditto, of great depths

8B alkaline pegmatites

HIGH TO MEDIUM-GRADE METAMORPHIC ORES

9A in high-pressure metamorphics

9B ores in largely statically metamorphosed terrains

9C ores in dynamometamorphic hosts

9D ores in granitized terrains or associated with granitization

Fig. I-3 (continued). Legend to the ore style symbols from Laznicka (1984), used in the genetic and metal index

METALS INDEX

Ag

Al

As

Au

2BC alluvial to beach placers 83, 95, 99, 110-13, 209, 282-3, 376, 444-5, 744-5, 753-7, 759-67, 874, 1046, 1039-41
-deep leads, 745, 767-70
-paleoplacers, 528-9, 805
2E in Kupferschiefer, 115*, 444 5*, 537 77
3D coal, 831*
4D hot springs, 63-67, 241
4E bonanza epithermal veins 1485-8
4F mineralized breccias, 1485-88
4I 376
4J metallif. volcanics, dike 903*, 913*, 1069*
5A 304, 318-21
5B Au mass. sulphide, 416
5D auriferous schists, 281-86
5F axial cleavage, saddle reefs, linear stockworks, 301-6, 435-7, 442-6, 479
5G shear lodes, 198, 277-86, 1039-41
6C stockw., brecc., 1018*, 1275, 1508-11*
6D veins, 184-5, 261, 286-7, 390-3, 444-5, 555, 1035-39 1275-80, 1377
6E skarns, 391
6F carb. replac., 1085, 1288-9, 1508*
6G stockworks, 376-88, 1071-2, 1319-21
6H veins, 1400, 1506
6I Carlin "type", 479-81, 566-71, 1289, 1319
7B 244-5

barite

1D resid. clay, lumps 628, 652, 731
2E black shale, 314-15
2F seafloor concretions, 35
3B anhydr. repl., 317, 665 carb. repl., 628, 631, 634
5B 299
5D 459, 466-7, 471
6H veins, 372, 567, 1401-2

Be

2B arid placers, 1163
3D coal*
4E epithermal veins, 995
4I tuffite repl. by bertrandite, 995-7
4J miaroles, 962
6A Be granite*, 1065
6B apogranites, 1163
6Ca greisen stocks, 1230-35, 1504-6
6D veins, 1231-4, 1506
6E skarn, 1187-8, 1230-4

7E alkal. complexes, 1525-31
8Aa high-level pegm., rare m. pegm.,1230-5, 1387-94
8Ab deep-seated pegmatites, 1385-6

Bi

1D lumps in resid. clay, 718
4C fumaroles, 60
4E epithermal veins, 1322
4G stockworks, 985
6E skarn, 1187-8
6H veins, 1268-72

Cd

in sphalerites (various styles), 1324-5
4E epithermal veins, 945, 1325

Cr

1C eluvial placers, 204-9
2A ochers, 210-14
2BC placers, 205-9, 772-3
2C paleoplacers, 209-11
7A cumulus in ultramafics, 248
7C podiform chromite, 174-80, 234-6, 1041

Co

1A laterites (asbolite), 203-4, 236
2A reworked laterite, 214, 223
2F oceanic nodules, 33-35
3Ba, MVT deposits, 617
3E 367
6H veins, 391, 1268-72
6Ib gabbro contact skarn, 1466-7
7B gabbro contacts, 256

Cu

2A oceanic clays, 32*
2D moraine, talus, ice 741, 746
2E in banded iron formation 839
2F oceanic Fe-Mn nodules, 33-35; Cu nodules, 875
2G swamp, bog, peat 104, 782-3
3A chrysocolla, 755-6, 796-7 sulph., 875-80, 887
3B 631-4, 652, 665
3D coal, 826*, 831*
3E volc. red-beds, 875-80, 885-9, 906-7
4D hot springs, brines, 63
4E enargite, luzonite veins 968-9
4G stockw., 363-5, 380-4, 420-1, 969-72, 1441-2

F

Fe

Ga Ge

Hg

In

Li

Mn

1B Mn oxides, 425-5, 706-10, 1087, 1532, 1540, 1576
1D 604, 731
2A reworked laterite, Mn ox. 214
2E 177, 253, 424-5, 456-8, 537-41, 547, 550-1, 580, 591*, 607-8, 665-6, 840
2F oceanic nodules, 22, 32-5
lake nodules, 784-5
shelf nodules, 114
shales, 231, 441, 541
2G bog ores, 781-3
2H springs, 797
3F descend. veins, 260, 910-1, 988-90

4D hot springs, 798-9
4E epithermal veins, Mn carb. 417, 959
4I 367, 373-5, 919, 989-90
5Ba Red Sea muds, 1414-17
oceanic precip., 24-5
5Bb silic. Mn ores, 177, 187, 191-6, 231, 264, 267, 271-2, 312, 425, 1041
carbonate/felsics, 295
5Db 313-15
6E skarn, 269, 1304
6H veins, 272, 1304
7Db rhodochros., Mn-ankerite in carbonatite, 1569
9B 1346

Mo

2E shale, phosphorite, 482*, 485*, 544*
3Aa sandstone, 856, 868-71
3D lignite, 824-5, 830
3Eb 890
4E wulfenite vein, 1227
4G 985-6

5Aa ocean floor mass. sulph., 22*
6Cc stockworks, granodior. as. 1018-9, 1043, 1222-6
granite assc.,1032-3, 1214-22
peralkal., 1506
6Dc veins, 1227
6E skarns, 1227-8
7Ec nepheline syenite, 1377-8
8Aa pegmatites, 1067-8

Nb

1B resid. over carbonatite, 1576-7
1G silcrete, 725*

6B apogranite, 1496-99 1502
6Ca stockworks, veins, 1504-5

Ni

P

Pb

6E skarn, 1244-6, 1255, 1509-13, 1643-4
6H veins, 475-7, 563-6, 1046 1238-9, 1252-4, 1256-60, 1485, 1509-13

6F mantos, chimneys, 395, 654-62, 1244-55, 1261-2
9C massive sulphides, 1353
9D cordierite-anthophyllite assoc., 1376

Pt

1A birbirite, 205
2B alluv. placers, 209, 244-5 764, 772-3, 1548
2C paleoplacers, 209-10 529
2E Kupferschiefer, 573-7
4J tuff, 1483*

6F replac. pipes, 1142
7A 244-50, 1548
7Bb Noril'sk, 1442-6
7C ultramaf. tectonite, 175, 181

Re

3D coal, 831*

6Cc porphyry Cu-Mo, 420-1

REE

1B 1531, 1576-7
2B floodplain placers, monazite, 765
2C beach plac., 83, 91-100 dune placers, 96 relic pl., shelf, 111-12 paleoplacers, 528, 838
2F 551, 595*, 668
6A allanite granites, 1063-5

6Ca stockw., vein, 1504-5, 1509, 1512
8A pegmatites, 1385-92
9B dissem. in metam., 1342
7Da agpaitic intr., 1517-21
7Db dissem. in carbonatite, 1568-72
7E replac., veins, 1525-8, 1572-4, 1581-2

Sb

1D 733
3Ea 875
4C fumarolic veinlets, 61
4D hot springs, 63, 66, 241
4E epithermal veins, 999-1000

4I 198-9
5Db 287, 489
6G stockworks, dissem., 1072, 1319-21
6H veins, 491, 1046, 1314-19
6Ia mantos, replacements, 492-7, 667

Se

3Ba in roll U deposits, 856
3D in coal, 836
4C fumaroles, 39
4E epithermal veins, 954
6 Se in hydrothermal deposits 1324

Sn

1C eluvial placers, 712-13
1B glaciofl. plac., 744-5
colluvial placers, 729, 758-9
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2C beach placer, 83
offshore, 108-111
? paleoplac., 556-60
2D moraine, talus, 741-2, 746-7
3A mantos, 885
3D in coal, 831*
4C fumaroles, rec., 60*
wood tin, 61
4G stockw., vein, 560-2 979-86
4J cassiterite in miaroles, 903
6Ca endocont. stockw., veins, 1157-74, 1495-9, 1503-4
6Db exocont. vein, stockworks 338, 556-62, 966-7, 1074, 1175-85, 1027-8, 1047-8
6E skarn, 1048, 1186-90
6F carbonate replacements, 1186-91
8A pegmatites, 1067-8, 1387-92
9C 1342-48

Ta

6B apogranites, 1162-64, 1382
6Ca stockworks, 1504-5
7Da layered intrus., 1517-21, 1547, 1549
8A pegmatites, 1381-3, 1387-92

Te

6 hydrothermal deposits, 199, 1324
6Ca stockworks, 1504-5

Th

1B resid. ochers, 1576-7
2C paleoplacers, 528
6A metallif. granites, 1063-4, 1066, 1202
7Bc 1469-70
7Da agpaitic intrusions, 1517, 1521, 1523
7Db carbonatite, 1568-9

6H veins, 1581-2

7E veins, breccias, replac. 1398-9, 1512, 1525-8, 1570-5, 1581-2

Ti

1A 697-8, 1488

1C 711-2, 1341, 1547-8, 1550

1G silcrete, 725*

2A claystone, 835, 1489

2C beach placers, 83, 91-100
dune placers, 86
shelves, 111-2
paleoplacers, 527-8, 805-6, 837, 875

4J 38*

7A Ti-magnetite, 21*, 184, 244-50, 1543-9

7B Ti-magnetite, 1543-9

7D layered compl., 1521

7E alkal. metas., 1547-80

9A rutile in eclogite, 237-8

9BC rutile, ilmen., in metam. 1341

Tl

4D hot springs, brines, 66-63

6 hydroth. dep., general, 1324

6Ia 491, 571, 1000

U

1B 591-5, 713, 729

1E 40

1G silcrete, 275*, gypsicrete, 726-7

2E recent euxinic seds, 115
black shale-schist, 269, 440*, 482-8*, 542-4, 550, 591*, 593*, 602*, 1341, 1413

2F phosp. nodules, 114*

2G peat, 783

3Ab 890

3Ba paleokarst, 653, 735
calcrete, 722-4

3D lignite, 822-5, 828-9
coal, 824-6
bitumens, 675, 843

3Ea 1489

3F infiltr. veins, 1039-41, 1047, 1396-8

4D opalite, 903

4E veins, 991-3

4I 910-11

6B metallif. granite, 1069, 1063-66, 1498-9, 1502

6C stockworks, 1498-9, 1502-4

6H veins, 1046, 1306-14, 1396-8
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7Bc 1468-9

7Da layered intr., 1523

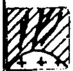

5Aa model, 158-62, Red Sea muds, 1414-7, black smokers, 25; Kuroko, 403-16


5Ab mass. sulphides, 273-76, 297-300, 321-47, 372

5Db 313-17, 458-71


5F cleavage oreb., 434-37


6C stockw., dissem., 1238


6Db, veins, 474-7, 563-6, 1018-9, 1238-44, 1252-4, 1256-60


6E skarns, 1244-6, 1255, 1263-4


6F repl. mantos, chimneys, 395, 654-62, 1244-52, 1254-55, 1261-2


6H veins, 1046

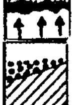

6Ia willemite mantos, 662


9C mass. sulphides, ZnCu, 1352, 1354-7 PbZn, 1353, 1357-9

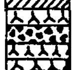
Zr

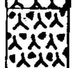

1C caldasite, 1531


1G silcrete, 725*


2C beach plac., 83, 91-100 shelf plac., 111-2 paleoplacers, 527-8


2E phosphorite, 487*


7Da agpaitic intrus., 1516-21


7Db carbonatite, 1569-77


7E 1527-8

Abbreviations: *high trace metal content, low grade technological ore or potential "ores of the future"

m modified, mobilized orebodies