Economic Geology, v. 65, pp. 373-408

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

VOL. 65 JUNE–JULY, 1970 NO. 4

Lateral and Vertical Alteration-Mineralization Zoning in Porphyry Ore Deposits

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Abstract

The geologic history of the San Manuel–Kalamazoo deposit has provided an opportunity for the examination of vertical and horizontal zoning relationships in a porphyry copper system. Precambrian Oracle "granite," a Laramide monzonite porphyry, and a Laramide dacite porphyry are hosts to zones of potassic, phyllic, argillic, and propylitic assemblages shown to be coaxially arranged outward from a potassic core through phyllic, argillic, and propylitic zones. Alteration zones at depth comprise an outer chlorite–sericite–epidote–magnetite assemblage yielding to an inner zone of quartz–K-feldspar–sericite–chlorite. Mineralization zones are conformable to the alteration zones, the ore zone (with a 0.5% Cu cutoff) overlapping the potassic and phyllic zones. Occurrence of sulfides changes upward and outward from dissemination at the low-grade core of the deposit through microveinlet to veinlet and finally vein occurrence indicating the progressively increasing effect of structural control.

Several aspects of San Manuel–Kalamazoo geology suggest that it is exemplary of the porphyry copper deposit group. To test that idea and to evolve three-dimensional aspects of these deposits, a table of geologic characteristics of 27 major porphyry deposits is presented. Consideration of the table indicates that the "typical" porphyry copper deposit is emplaced in late Cretaceous sediments and metasediments and is associated with a Laramide (65 m.y.) quartz monzonite stock. Its host intrusive rock is elongate-irregular, 4,000 × 6,000 feet in outcrop, and is progressively differentiated from quartz diorite to quartz monzonite in composition. The host is more like a stock than a dike and is controlled by regional-scale faulting. The orebody is oval to pipelike, with dimensions of 3,500 × 6,000 feet and gradational boundaries. Seventy percent of the 140 million tons of ore occurs in the igneous host rocks, 30 percent in preore rocks. Metal values include 0.45% hypogene Cu with 0.35% supergene Cu, and 0.015% Mo. Alteration is zoned from potassic at the core (and earliest) outward through phyllic (quartz–sericite–pyrite), argillic (quartz–kaolin–montmorillonite), and propylitic (epidote–calcite–chlorite), the propylitic zone extending 2,500 feet beyond the copper ore zone. Over the same interval, sulfide species vary from chalcopyrite–molybdenite–pyrite through successive assemblages to an assemblage of galena–sphalerite with minor gold and silver values in solid solution, as metals, and as sulfosalts. Occurrence characteristics shift from disseminations through respective zones of microveinlets (crackle fillings), veinlets, veins, and finally to individual structures on the periphery which may contain high-grade mineralization. Breccia pipes with attendant crackle zones are common.

Expression of zoning is affected by exposure, structural and compositional homogeneity, and postore faulting or intrusive activity. Vertical dimensions can reach 10,000 feet, with the upper reaches of the porphyry environment perhaps only at subvolcanic depths of a few thousand feet. The vertical and lateral zoning described is repeated with sufficient constancy that depths of exposure at many deposits can be cited against the model of San Manuel–Kalamazoo.

Several lines of evidence suggest relatively shallow depths of formation and significant variations in water content in the porphyry environment. Shallow emplacement is consistent with the appearance of breccia pipes associated with ring and radial diking and with vertically telescoped zoning. Models of the source of altering-mineralizing fluids are considered.

Contents

Introduction

Exploration of the Kalamazoo portion of the San Manuel–Kalamazoo district, Pinal County, Arizona, has presented an unparalleled opportunity for the study of a porphyry copper deposit in three dimensions. The coaxial symmetry of alteration and mineralization zones which was the basis of the exploration model has been verified in the exploratory drilling (Lowell, 1968) of the Kalamazoo portion of the district and in exploitation of the San Manuel portion. As exploration proceeded, it became increasingly apparent that many elements of mineralogy, occurrence, and geometry of other porphyry copper deposits were explicitly represented at San Manuel–Kalamazoo. Zoning patterns there can be considered a refined base for the study of mineralization and alteration relationships in other porphyry copper deposits, and this is the subject of the study reported here, with compilation of data from 27 major porphyry copper and molybdenum deposits in North and South America. Most significant is the emergence from the many descriptions of a more generally applicable unifying theme of large-scale alteration-mineralization zoning in these large deposits than has generally been recognized. Stringham (1953, p. 990) stated that "a review of hydrothermal studies of porphyry copper deposits shows as many dissimilarities as similarities to the hydrothermal features at Bingham Canyon." We now take the opposite position that there are many characteristics which link Bingham Canyon and many other deposits to the general porphyry copper deposit type. There appears to have been little published effort specifically to compare and contrast the porphyry deposits as a group.

The first portion of this paper describes both lateral and vertical alteration-mineralization relationships at San Manuel–Kalamazoo. The exploration model included and substantiated approximately 70 degrees of postmineralization tilting. Thus this geologic system provides information concerning both vertical and horizontal axes of a porphyry deposit. A three-dimensional synthesis is given of hydrothermal alteration mineralogy and assemblages, of the distribution and quantitative aspects of sulfides, and of the structural occurrence of sulfide and oxide minerals. Vertical treatment of alteration and mineralization geometry is still tentative, but some vertical zoning changes can be identified.

Comparison of other major porphyry base-metal deposits to San Manuel–Kalamazoo by means of published data assembled in Table 1 permits development of a generalized lateral and vertical zonation model for the deposit group. Finally, that model is used to examine the genesis and environment of formation of the porphyry deposits. The data suggest that it is sometimes possible to estimate the position of the present erosion surfaces of other porphyry deposits with respect to their original columns of mineralization. Depth parameters have been assigned to nine deposits, and it is hoped that both scientific and explorational use can be made of three-dimensional alteration-mineralization zoning.

The porphyry copper and molybdenum deposits, hereafter called "porphyries," must first be defined. A necessarily flexible definition emerges from consideration of many deposits and descriptions of a "typical" one.

A porphyry deposit is here defined as a copper and/or molybdenum sulfide deposit consisting of disseminated and stockwork veinlet sulfide mineralization emplaced in various host rocks that have been altered by hydrothermal solutions into roughly concentric zonal patterns. The deposit is generally large, on the scale of several thousands of feet, although smaller occurrences are recognized. The relatively homogeneous and commonly roughly equidimensional deposit is associated with a complex, passively emplaced stock of intermediate composition including porphyry units. It contains significant amounts of pyrite, chalcopyrite, molybdenite, quartz, and sericite associated with other alteration, gangue, and ore minerals and metals including minor lead, zinc, gold, and silver. Mineralization and alteration suggest a late magmatic-mesothermal temperature range. The deposit is generally associated with breccia pipes, usually with a large crackle breccia-tion zone, and is surrounded by peripheral mineral deposits suggestive of lower temperature mineralization.

The grade of primary mineralization in typical porphyry copper deposits ranges up to 0.8% Cu and 0.02% Mo, and porphyry deposits in which molybdenite is the chief economic mineral have grades ranging up to 0.6% Mo and 0.05% Cu. All porphyry copper deposits contain at least traces of molybdenite, and all porphyry molybdenum deposits contain some chalcopyrite. Many deposits contain recoverable quantities of both minerals, either in separate orebodies or in ore with approximately equal copper and molybdenum dollar values. Although typical porphyry copper deposits differ from typical molybdenum deposits in some respects, the existence of gradational characteristics in metallization suggests a common origin.

This definition is somewhat generalized because it must permit consideration of many deposits whose local geologic circumstances vary as expressed by their geometries and physical characteristics. We believe the porphyry deposits to be a petrological-mineralizational class, and individual porphyry deposits are best interpreted as greater or lesser departures from the unifying model of the above definition as elaborated upon below.

Genetic Models of Porphyry Deposits

Several genetic models have been proposed to relate the characteristics of porphyry copper and molybdenum deposits. All of the models recognize the important involvement of porphyritic intrusive rocks with ore deposition, and all are fundamentally magmatic-hydrothermal, differing in the sequences of events, depths of intrusion, the timing of derivation of fluids, and the source of fluids. The models considered here are the orthomagmatic model, Fournier's model of intrusion of a water undersaturated melt, and the White model of multilevel circulation of brines adjacent to a heat source.

The orthomagmatic model has been best described in the recent writings of Burnham (1967) and Nielsen (1968). It is the genetic model tacitly adopted in most deposit descriptions, as for example, those described in Titley and Hicks (1966). It sometimes involves penetration of the source to levels as shallow at 1,500 feet (Nielsen, 1968), but more commonly to depths apparently on the order of 3,000–5,000 feet. The model depends on a melt derived at some greater depth, probably near the mantle-crust boundary, which becomes saturated with water as it approaches the upper surface. Release of that water may occur when internal vapor pressure developed by supersaturation exceeds the lithostatic load pressure or when the intrusive system is rent by external stresses. Crystallization then proceeds presumably along the lines of Emmons' (1933) cupola or R. H. Sales's sub-hood cupola development.

As described by Nielsen (1968), the sequence of events can be paraphrased as intrusion, early marginal crystallization which produces a solid shell, and rupture of that shell to produce porphyritic-aphanitic textures in subsequently crystallized rocks. Volatiles released by the quenching migrate outward through crackle, stockwork, and brecciated zones in the cooler margins where, augmented by diffusion effects, alteration and mineralization occur in response to gradients "from near magmatic temperatures at the center of the stock to relatively cool temperatures in the wall rocks" (p. 37). Silicate sulfide reactions of the type described by Hemley and Jones (1964) prevail. Other authors would not necessarily limit the separation of volatiles to the period of quenching, but rather would consider evolution of the hydrothermal fraction a quasi-continuous separation of volatiles in response to the many variables related to temperature and pressure. The loss of volatiles from near-surface portions of a melt may permit the upward and outward replenishment of mineralizers from greater depths.

Fournier (1968) suggests that the initial deep porphyry copper melt was unsaturated with water at one to three percent, that it was intruded to depths of less than about 4,500 feet, and that rupture by faulting would cause sudden, even explosive loss of water and supercooling of the silicate melt. Crystallization would then abruptly halt the upward progress of the now dry melt. Subsequent "extensive argillic alteration shown by most porphyry copper deposits is probably due to a superimposed circulating hot-spring system, fed mainly by meteoric and connate water" (p. 101).

White (1968) in a particularly stimulating paper suggests that circulation of sulfur-deficient Na–Ca–Cl brines, with salt contents generally equivalent to 5% to 40% NaCl, are responsible for many base-metal deposits. Such brines may be produced in porphyry systems by deuteric reaction of residual liquids with earlier formed plagioclase and ferromagnesian minerals to achieve high contents of calcium and base metals. Although White in his paper does not develop a specific space-time model for the porphyry deposits, he implicitly develops a model involving multilevel circulation of deuterically metal-enriched or connate-meteoric sulfur-deficient metallizing solutions under the influence of thermal gradients established by an adjacent or subjacent magmatic heat source. The model differs importantly from the orthomagmatic model in that the source of the solutions, and perhaps the metals, is almost completely external to the magmatic system, with convective overturn of circulating solutions producing alteration-mineralization envelopes and zones.

Geology of the San Manuel-Kalamazoo Deposit

The San Manuel–Kalamazoo deposit (Lowell, 1968), located in Pinal County, Arizona, is here accepted as the type porphyry copper deposit, and its geology and other characteristics are presented for comparison and contrast with others (Table 1).

Precambrian quartz monzonite of the Oracle Granite batholith in the San Manuel area was intruded in Laramide time by swarms of monzonite porphyry dikes and irregular masses of monzonite porphyry, more properly termed biotite latite porphyries, although long-established "monzonite porphyry" terminology will be followed here. Closely related in time and space to the activity was a porphyry copper mineralization event that produced the San Manuel–Kalamazoo orebody and its associated concentric alteration zones. The hydrothermal system appears to have been centered in the middle of the monzonite porphyry dike swarm, and metallization is almost equally distributed between the monzonite porphyry and the Oracle Granite host rocks (Fig. 1).

Following hydrothermal mineralization and alteration (Fig. 1a), the whole district was tilted to the northeast, and the block including the San Manuel–Kalamazoo orebody was probably relatively elevated. Erosion of this block exposed the top of the orebody, and supergene activity formed a thin chalcocite enrichment blanket. At this time, the long axis of the orebody may have plunged at about 65°SW. Shortly thereafter, terrestrial sediments began to cover the deposit.

Further tilting, perhaps 15°, followed deposition of the lowermost Cloudburst Conglomerate. An erosion surface formed on the Cloudburst sediments was later covered by the Gila Conglomerate. A third-stage tilt of about 30° gave the Gila Conglomerate its present inclination and brought the originally vertical axis of the San Manuel–Kalamazoo orebody into a 20° southwest-plunging attitude. The San Manuel fault then diagonally offset the original, nearly cylindrical orebody into two roughly equal-sized pieces, the San Manuel and the Kalamazoo portions. The upper Kalamazoo portion moved about 8,000 feet in a down-dip, S55°W direction.

Small, high-angle, northwest-trending normal faults later displaced both halves of the original orebody, and erosion stripped most of the Gila Conglomerate from the east end of the present San Manuel orebody (Fig. 1b).

The original, unfaulted orebody, as defined by a 0.5% copper limit, formed a slightly flattened or elliptical cylinder which was at least 7,700 feet long and from 2,500 to 5,000 feet in diameter. The top of the cylinder, at the east end after tilting, may have been rounded, with the bottom, at the west, having an irregular shape. The center of the orebody is poorly metallized, so that ore actually forms a hollow cylinder or cylindrical shell. The shell surrounding the low-grade center varies from about 100 to 1,000 feet in thickness. Mineralization and alteration zones are approximately coaxial.

The alteration assemblages in the San Manuel–Kalamazoo deposit form regular, smoothly bounded zones, which, as in most porphyries, are locally gradational and difficult to place within a hundred feet, although they are well defined on a broad scale. The boundaries are more clearly defined than they are in most porphyry deposits, presumably because the mineralizing fluids affected intrusive, essentially homogeneous, isotropic plutonic and hypabyssal host rocks of intermediate composition. These rocks responded to the indicated alkali chemistry without important gains or losses. No marginal sediments, compositionally contrasting intrusive rocks, planar rock fabrics, or prominent tectonic elements produced steep physical or chemical gradients to influence the uniform zoning and symmetry.

Mineralogic zoning at Kalamazoo and elsewhere suggests that at least four alteration assemblages are easily discernible in the porphyry copper and molybdenum deposits. The terms potassic, phyllic, argillic, and propylitic have been adapted or adopted from the literature (Burnham, 1962; Creasey, 1966; Meyer and Hemley, 1968) to describe the four principal assemblages. The terms "argillic" and "propylitic" are well known and widely accepted, broadly describing quartz-kaolin-montmorillonite-chlorite-biotite and chlorite-calcite-epidote-adularia-albite alteration assemblages, respectively. "Phyllic" is here applied to the assemblage quartz-sericite-pyrite with less than 5% kaolin, biotite, or K-feldspar, and "potassic" is suggested (Guilbert and Lowell, 1968) to include introduced or recrystallized K-feldspar and biotite, with minor sericite and highly variable but persistent and generally minor amounts of anhydrite. Each of these assemblages will be more fully described below, especially as they occur at San Manuel–Kalamazoo. Other assemblages

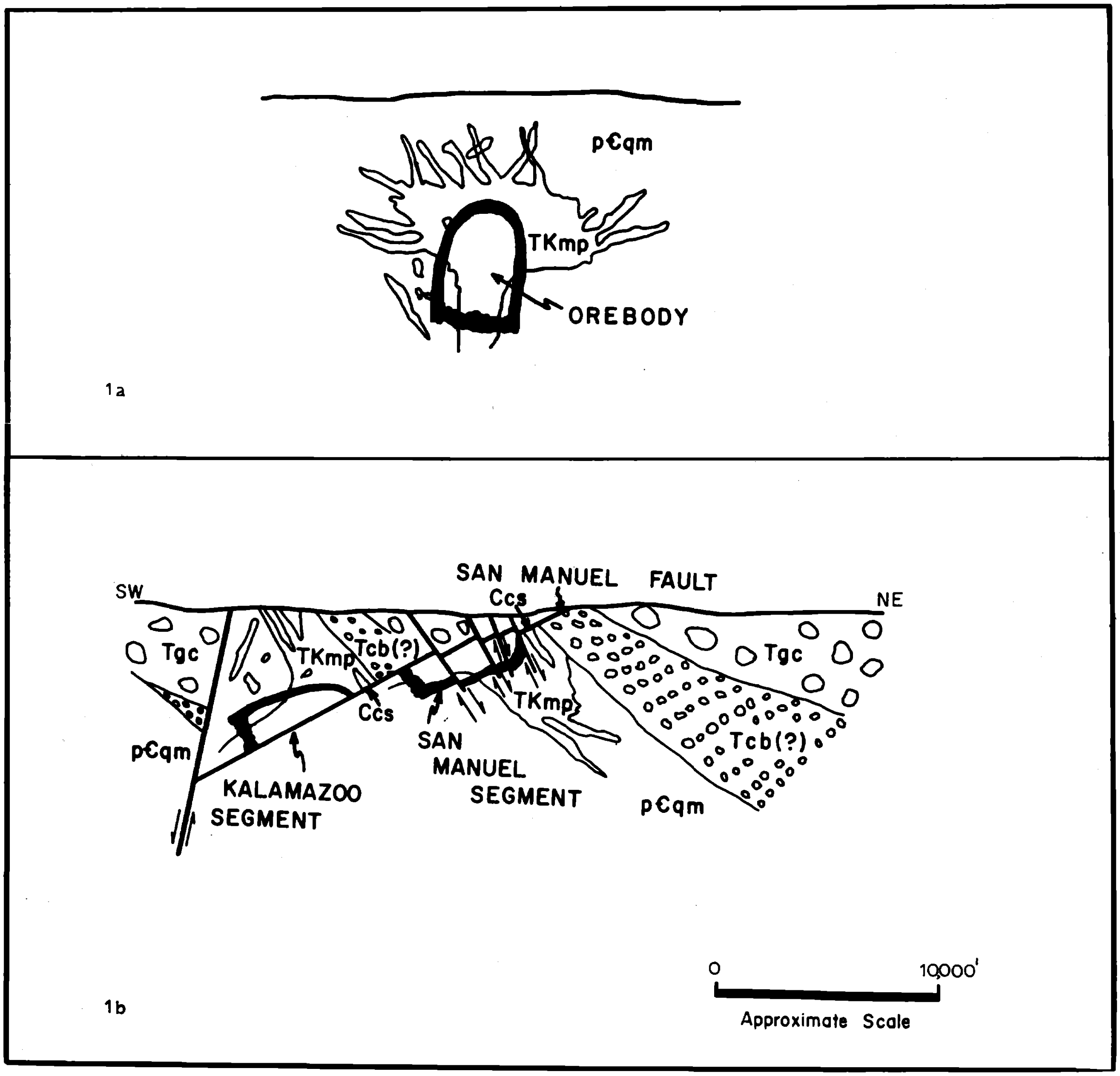
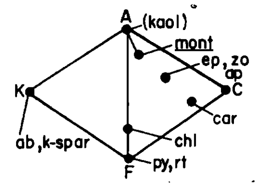
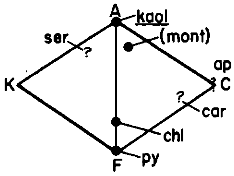
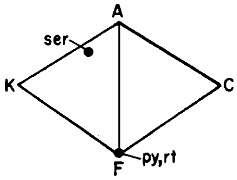
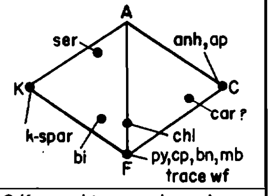


FIG. 1. Schematic drawing of structural history of San Manuel–Kalamazoo deposit. (a) at time of emplacement and (b) at present. Note the umbrella-like flare of dike swarm and the chalcocite enrichment zone (CCa). pꞒqm = Oracle Granite, TKmp = monzonite porphyry, Tcb = Cloudburst Formation, Tgc = Gila Conglomerate.

rarely encountered in the porphyry environment are the advanced argillic (Meyer and Hemley, 1968) and pegmatoid, respectively involving quartz and pyrophyllite, with traces of dickite or kaolinite, topaz, and zunyite, and quartz–coarse sericite–K-feldspar, with or without carbonate, anhydrite, and apatite.

Hydrothermal alteration assemblages in the San Manuel–Kalamazoo deposit are summarized in Figure 2, which shows alteration changes mineral by mineral and assemblages on AKF–ACF diagrams. Supergene activity is limited to a 200-foot thick zone near the top of the deposit.

The alteration zones were separated during Kalamazoo exploration as follows. The inner limit of the propylitic zone was placed where the total quartz–montmorillonite, quartz–kaolin, or quartz–sericite content in plagioclase sites exceeds the total of chlorite and epidote replacing mafic minerals; here the color usually changes from green to light gray. The argillic zone, in which kaolin or montmorillonite predominates in plagioclase sites and chlorite replaces biotite, was not generally mapped separately and is least significant quantitatively. The inner limit of propylitic alteration is locally the outer

SHALLOW-MODERATE DEPTH ASSEMBLAGES				
FRESH QM, PORPHYRIES	**PROPYLITIC ZONE**	**ARGILLIC ZONE**	**PHYLLIC ZONE**	**POTASSIC ZONE**
Quartz	No Change	Augmented	Augmented	Augmented
Orthoclase–Microcline	No Change	Flecked with Sericite	Sericitized	Recrystallized, in part replaced by alteration K-feldspar–quartz
Plagioclase (An_{35-45})	Tr. Mont, flecks & granules ep, zois, car, chlorite, kaol.	Montmorillonite → Kaolin	Sericitized	Fresh to completely replaced by brn-grn alt'n biotite, K-spar, ser.
Biotite	Chlor, zois, car, leucoxene	Chloritized, + leucoxene, qtz	Sericite, pyrite, rutile	Fresh or recrystallized to sucrose brn-grn granules, ± chlorite
Hornblende	Ep, car, mont, chlor (2 types)	Chloritized	Sericite, pyrite, rutile(?)	Biotite, ± chlorite, rutile
Magnetite	trace pyrite	Pyritized	Pyritized	Pyritized
A–K–C–F A = Al K = K, Na C = Ca salts F = Fe, Mg				
Veinlet Fillings	Q-cal- K-spar-chlor-rare ab–rt	Q–ser–py–chlor	Q–ser–py	Q-K-spar–bi–ser–anhy–cal–ap

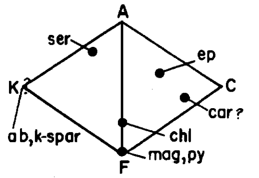
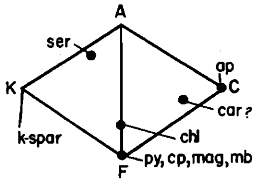
DEEP-LEVEL ASSEMBLAGES		
	OUTER	**INNER**
Quartz	Slightly Augmented	Augmented
Orthoclase-Microcline	Dusted with trace sericite	Alteration K-spar with sericite, relicts common, minor quartz
Plagioclase (An_{35-45})	Dusted with sericite, chlorite, epidote	Sericitized, with alteration K-spar-quartz, relicts uncommon
Biotite	Largely chloritized, minor epidote mag added	Chloritized, rare primary relicts
Hornblende	Chlorite + Epidote + Carbonate	Chloritized; trace carbonate
Magnetite	Augmented	Mostly pyritized
A–K–C–F A = Al K = K, Na C = Ca salts F = Fe, Mg		
Veinlet Fillings	Q–mag–py ± Q–ser–cal envelopes	Q–K-spar–ser–chl, tr mag, py, cp, mb

FIG. 2. Summary of hydrothermal alteration assemblages at San Manuel–Kalamazoo.

limit of either the argillic or the phyllic zone of pervasive conversion to quartz, sericite, and pyrite. The inner limit of the phyllic zone is the outer limit of the first continuous section of secondary K-feldspar and secondary biotite, even though the total quartz and sericite content here ordinarily exceeds the total K-feldspar plus biotite content. The zoning patterns and intercepts can be projected remarkably well from hole to hole. Subsequent petrographic study has contributed to these descriptions of the zones, and subsequent publications by J. M. Guilbert describing the chemical and structural mineralogy and physical geochemistry of the alteration-mineralization processes are planned.

In the following sections, the fresh rocks at San Manuel–Kalamazoo are first discussed and alteration zones exposed on a horizontal plane at moderate depth are described successively outward from the center. Alteration and mineralization changes with depth are discussed last and are summarized schematically in Figure 3a.

Fresh Rocks

The unaltered rocks at San Manuel–Kalamazoo include Precambrian Oracle porphyritic quartz monzonite and two varieties of much younger biotite porphyries. The Oracle "granite" is coarse grained (Fig. 4) with anhedral subrounded quartz units about a centimeter across and commonly tangential to their nearest neighbors, rectangular to irregular plagioclase tablets (An_{35-45}), and interstitial quartz and K-feldspar. K-feldspar species include microcline, orthoclase, and microperthite. Several authors, especially Banerjee (1959) have considered the rock palingenic, although many other workers accept its orthomagmatic origin. Accessory minerals include biotite and hornblende, with trace amounts of zircon, apatite, sphene, magnetite, and very sparse monazite.

The porphyries are of at least two types. One (here called Type A) is a quartz monzonite porphyry distinguished by its zoned and twinned oligoclase-andesine phenocrysts which average about 5 mm and range up to 15 mm across (Fig. 5), its quartz–K-feldspar groundmass commonly containing

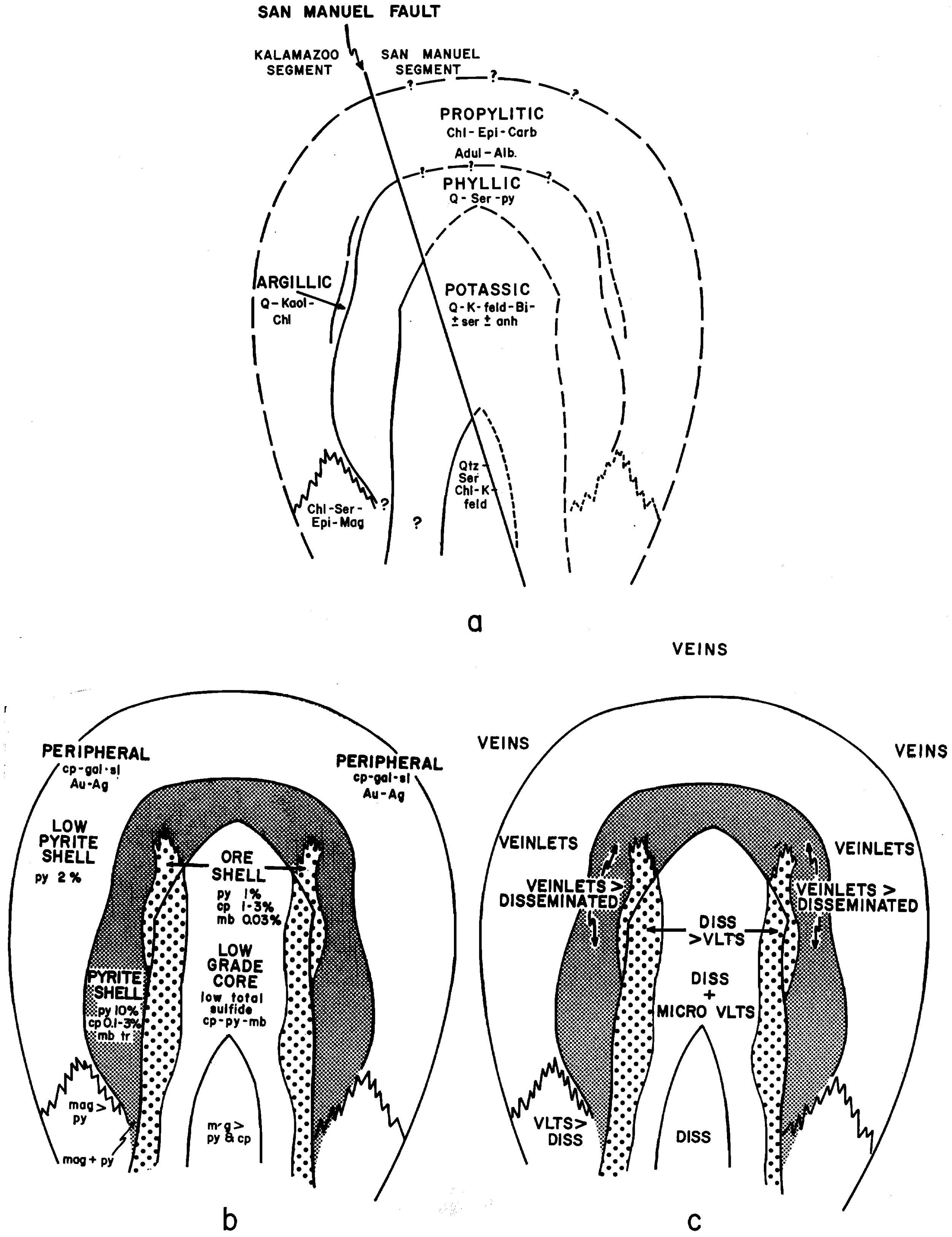


FIG. 3. Concentric alteration-mineralization zones at San Manuel–Kalamazoo. (a) schematic drawing of alteration zones. Broken lines on Kalamazoo side indicate uncertain continuity or location and on San Manuel side extrapolation from Kalamazoo. (b) schematic drawing of mineralization zones. (c) schematic drawing of the occurrence of sulfides.

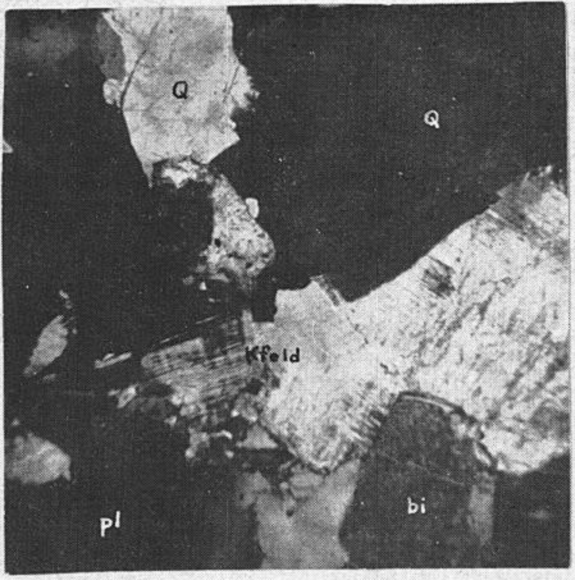


Figure 4

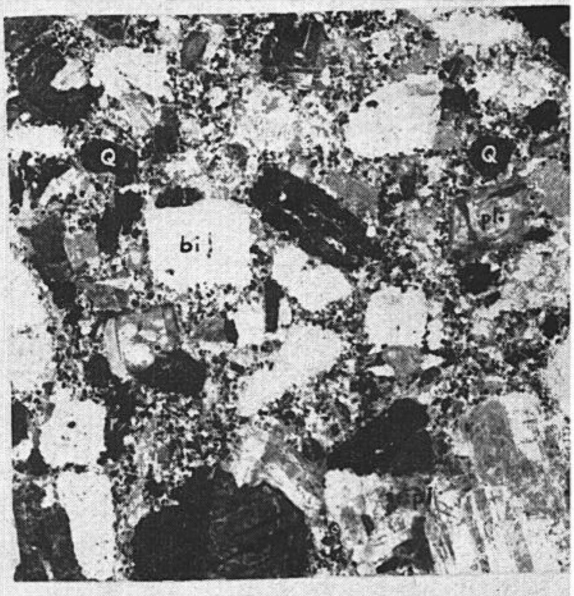


Figure 5

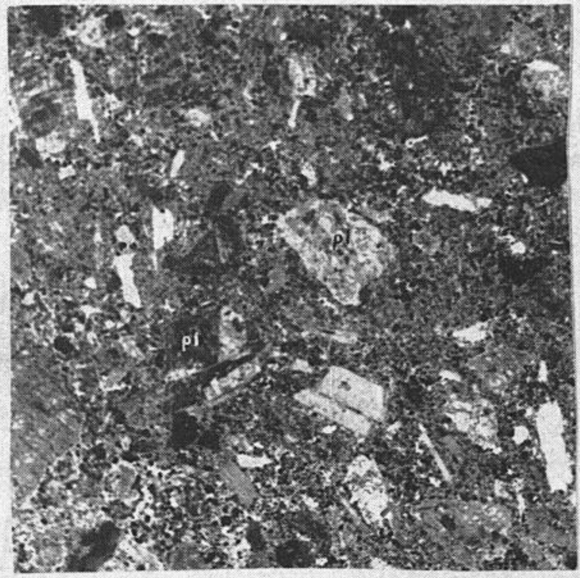


Figure 6

Fig. 4. Fresh Oracle quartz monzonite. Quartz grains along top, microcline across center, and biotite at lower right. Andesine unit at extinction at left. Both feldspars mottled but essentially fresh. Crossed nicols, 15 ×.

Fig. 5. Fresh Type A monzonite porphyry. The stippled sucrose quartz-K-feldspar groundmass is studded with compound rectangular twinned plagioclase phenocrysts. The white rectangular unit is a biotite phenocryst and the black blebs immediately above and to the left are quartz "eyes." Negative photograph, crossed nicols, 3.2 ×.

Fig. 6. Fresh Type B biotite dacite porphyry. Plagioclase phenocrysts are square, trapezoidal, or rectangular. They are twinned but generally unzoned. Negative photograph, crossed nicols, 3.2 ×.

fine-grained, embayed quartz "eyes" with stippled overgrowth rims. Few quartz eyes exceed 1 mm in diameter. Accessory biotite, hornblende, apatite, rutile, zircon, and minor magnetite are generally euhedral, the first two reaching 5 mm in length. No K-feldspar phenocrysts were observed. The groundmass is that of the widespread quartz latite porphyry and quartz monzonite porphyry of the porphyry deposits. Its grain size averages 0.1 mm and its texture is granular sucrose. Though locally variable, it averages 55 percent quartz and 45 percent K-feldspar, so that the overall whole rock feldspar composition averages about 35 percent plagioclase and 25 percent K-feldspar. The K-feldspars are anhedral, granular, and mutually intergrown with quartz; granular, often euhedral apatite and rutile and shreds of mafic minerals are sparse.

A second porphyry (here called Type B) is a biotite dacite. Plagioclase phenocrysts in Type B are generally roughly square to rectangular or even trapezoidal in cross section (Fig. 6) rather than compound and zoned as in Type A. Rarely do they exceed 5 mm on a side. Biotite phenocrysts up to 3–5 mm are prominent. Quartz phenocrysts are absent, and the biotite-to-amphibole ratio is slightly greater than that of Type A. The groundmass is composed of intergrown microcrystals of sparsely twinned plagioclase with quartz, apparently slightly later, and sparse K-feldspar. Rutile and apatite accessory minerals are rare.

It is difficult to estimate from drill core the relative abundances of the two varieties of porphyry. Type A predominates along the core of the San Manuel–Kalamazoo system. Porphyry units form an umbrella or mushroom-shaped outward expansion of diking at higher levels (Fig. 1a). Although porphyry-quartz monzonite contacts are predominantly sharp, they may in some cases appear gradational in diamond drill core, and the porphyry "dikes" must be highly sinuous and variable in attitude, especially at greater depths. Indeed, an approach to wholesale mobilization of porphyry concurrent with the potassic alteration is suggested by coarsely vermicular and diffuse contacts between quartz monzonite and porphyry seen in drill core from deep within the orebody.

Alteration Zones

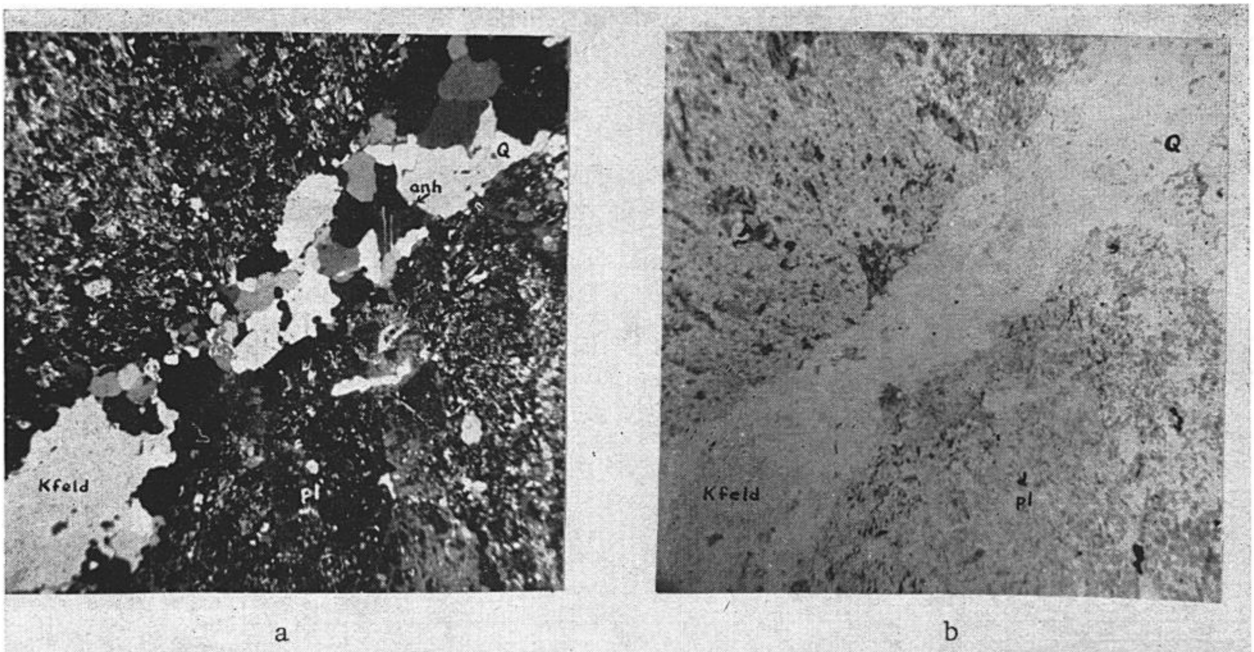
Alteration zone boundaries are not affected by rock type interfaces, at least at the scale of study to date. Systematic comparisons of fresh and altered rocks on either side of a particular contact have not yet been made, but the various starting material compositions, structural characteristics, and fabrics seem to have responded nearly identically to alteration processes.

Potassic Zone.—Several authors, especially Hemley and Jones (1964), Creasey (1966), and Meyer and Hemley (1968), have discussed the potassic alteration environment. Hemley and Jones have delimited an environmental interface between K-feldspar and sericite stabilities, the latter with higher HCl/KCl ratios at a given temperature, an environment consistent with late magmatic or early hydrothermal conditions in the K-feldspar–sericite–kaolin (pyrophyllite) system. Inclusion of iron and magnesium should bring biotite or chlorite into consideration with K-feldspar, sericite, and quartz, an assemblage increasingly noted in porphyry copper deposits (Creasey, 1966) and assignable to a late magmatic-early hydrothermal "deuteric" environment. Such a biotite–K-feldspar alteration assemblage with quartz, sericite, anhydrite, pyrite, chalcopyrite, molybdenite, and traces of bornite generally constitutes the low-grade center and part of the ore shell of the Kalamazoo deposit (Figs. 7, 8, 9).

This innermost alteration zone (Fig. 3a) involves pervasive and veinlet replacement of primary minerals by secondary biotite, K-feldspar, quartz, sericite, and to a lesser extent anhydrite (Fig. 9). K-feldspar occurs with quartz as microveinlet fillings that heal minute stockwork-like fractures in the primary rocks and also replace original feldspars to varying degrees. "Rock" orthoclase is flesh colored when fresh, turning slightly orange where extensively replaced by alteration K-feldspar. Typically, quartz heals quartz grains, and K-feldspar heals orthoclase, with K-feldspar also commonly replacing andesine plagioclase extensively, either by rimming or by advance along twin planes. K-feldspar also locally replaces plagioclase in the porphyry groundmass. No albitization has been found, although preliminary examination of alteration K-feldspar indicates it to be more sodic than the primary orthoclase.

Alteration biotite occurs in four important modes: (1) as hairline veinlet fillings along with chalcopyrite, alteration silicates, and anhydrite; (2) as sparse to massive replacement of plagioclase phenocrysts; (3) as bright black euhedral units megascopically nearly identical to primary rock biotite; and (4) as locally pervasive replacements of groundmass feldspars (Fig. 8). Alteration biotite is recognizable both by its fine-grained, sucrose, subhedral to euhedral form and by the coexistence of two distinctive color variants, one a light tan to brown which mostly predominates, the other a light apple green. Shagreen is not present, and birefringence is slightly lower than that of the rock biotite. Chlorite intergrown with biotite is common.

The altered rocks, especially the porphyries, are distinctively pigmented by groundmass biotitization. Porphyries megascopically showing the smoky gray



a

b

Figure 7

Figure 8

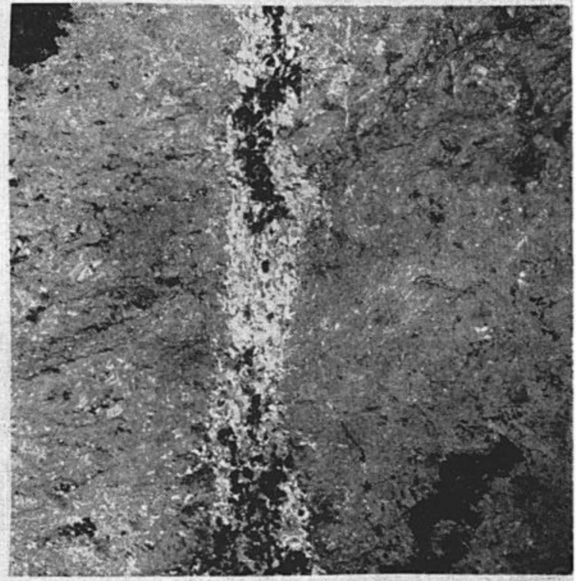


Figure 9

FIG. 7. A $\frac{1}{16}''$ veinlet of mosaic quartz, K-feldspar, anhydrite, and biotite in potassic alteration assemblage. (a) K-feldspar (stippled, lower left corner) and anhydrite (vertically twinned) in veinlet. The white stippled tablet to right of center in lower half of photo is a K-feldspathized-biotitized plagioclase phenocryst in Type A porphyry. Crossed nicols, 15 ×. (b) The same field in plane light, showing shreddy brown biotite pervading the potassic assemblage and replacing the plagioclase tablet described above. Plane light, 15 ×.

FIG. 8. A veinlet of quartz, K-feldspar cutting Type A porphyry in the potassic alteration zone. Note rivulet replacement of plagioclase by alteration K-feldspar at upper center adjacent to veinlet. Groundmass is biotitized. Crossed nicols, 15 ×.

FIG. 9. A veinlet of dominant calcite, anhydrite, K-feldspar, and opaque minerals (pyrite-chalcopyrite) in a pervasively biotitized Type B porphyry. The finely shreddy groundmass is composed of fine biotite with scattered chalcopyrite (black). Crossed nicols, 3.2 ×.

color normally found with advanced potassic alteration generally also carry significant base metal values. Such rocks also show K-feldspar-rich veinlets up to ¼ inch wide (Fig. 9).

The potassic alteration assemblage generally involves sparse to trace amounts of anhydrite, carbonates, and apatite. Rutile and wolframite have been observed in several veinlets. Anhydrite, not previously reported as a widespread alteration mineral, commonly forms granules in the quartz–K-feldspar-rich gash veinlets and in microveinlets which cut individual rock feldspar grains. Unlike biotite, it is not generally a replacement mineral. It is widespread but rarely abundant. Carbonates occur both in veinlets and as bits and shreds dispersed through the entire rock. Apatite, though not yet well studied, occurs both as a veinlet mineral and as minor but pervasively distributed anhedral units.

Phyllic Zone.—Surrounding and to some extent overlapping the biotite–K-feldspar zone is a zone in which alteration minerals include quartz, sericite, pyrite, hydromica, minor chlorite, and traces of rutile. This zone (Figs. 3a and 3b) generally includes part of the ore zone and all of the marginally mineralized and pyritic zones and is nearly coextensive with strong pyrite mineralization. Sericite predominates in the inner part of this zone, clay minerals and hydromica in the outer margins. The most distinctive assemblage, both megascopically and petrographically (Fig. 10), is that of complete sericitization of all silicates except quartz. Original rock plagioclase and orthoclase are both pervasively replaced by a felted mat of fine-grained muscovite with abundant ultrafine granular quartz. Vestiges of cleavage, zoning, and twin planes of plagioclase are retained in most instances in preferred orientations of sericite flecks. Original biotite sites can be identified by relatively well-oriented alteration sericite flecks, by less abundant alteration quartz, and by either anhedral or sagenitic rutile or leucoxene, presumably representing titanium from the original biotite. Primary quartz is unaffected but generally overgrown.

K-feldspar is totally sericitized in the innermost phyllic zone, but shreds and scraps of K-feldspar persist in the outer part. Pyrite is abundant; chalcopyrite is variable, generally occurring as disseminated grains, commonly in sericitized sites. Pyrite forms veinlets and generally granular disseminations in the pervasively phyllic-altered material. Pyrite content ranges from 2–30 percent by weight, averaging 5–10 percent. Apatite and rutile again appear to have been recrystallized and redistributed. Silicification well beyond that expected from the breakdown of feldspars to sericite plus quartz plus alkali ion appears common. Neither carbonates nor anhydrite were identified in the phyllic zone assemblage.

The phyllic assemblage at San Manuel–Kalamazoo closely resembles the quartz-sericite-pyrite alteration at Butte (Sales and Meyer, 1951), at Morenci (Moolick and Durek, 1966), and at many other southwestern North American porphyry deposits.

Contacts of the phyllic zone with the potassic zone have been described above; they are generally gradational over a hundred feet or so. Contacts of the phyllic zone with the next outer most, argillic zone are less definite.

Argillic Zone.—The argillic zone at San Manuel–Kalamazoo is least well understood at this stage, both mineralogically and distributionally. It is the least well developed and is the most likely to be absent in any given penetration of the ore deposit symmetry. It is characterized by the conversion of plagioclase to either kaolin nearer the orebody or montmorillonite farther away from the orebody center (Fig. 11). Kaolin is the more common reaction product, grading outward to sparse outlying montmorillonite. Pyrite is common but much less abundant than in the phyllic zone. It is generally distinctly veinlet controlled rather than disseminated. Primary biotite may be essentially unaffected, persisting as shiny black megascopic flecks in a white, earthy rock, or it may be in part converted along cleavage to chlorite. The compositional characteristics of this chlorite have not yet been compared with those of the chlorite of the potassic and deep zones. K-feldspar shows minor flecking with sericite and dusting with kaolin, but it is generally not extensively affected.

Propylitic Zone.—This zone contains the most widely distributed and least distinctive of the alteration assemblages. Plagioclase generally remains fresh (Fig. 12), although it is locally ribbed with either montmorillonite, kaolin, or an apparent mixture of the two minerals. Amorphous mineraloid clouding the plagioclases was not conclusively identified but is suspected in small amounts. Biotite is replaced along cleavage by both chlorite and carbonate, which generally decrease in abundance outwardly. Epidote and calcite are common as fine granules in plagioclase and as coarser aggregates with montmorillonite in amphibole sites. Both albite and veinlet K-feldspar with minor carbonate, quartz, and epidote are rare. Rock quartz is unaffected. Chalcopyrite is rare, but pyrite constitutes one to three percent by volume of the rock. The propylitic assemblage grades into argillic or phyllic phases at the inner side over an interval of from 10 to 100 feet and is presumed to fade over perhaps thousands of feet in the outer reaches, although this has not been proved.

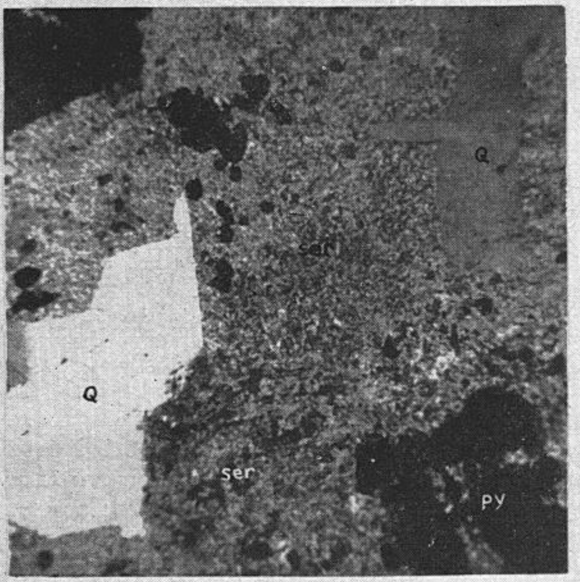


Figure 10

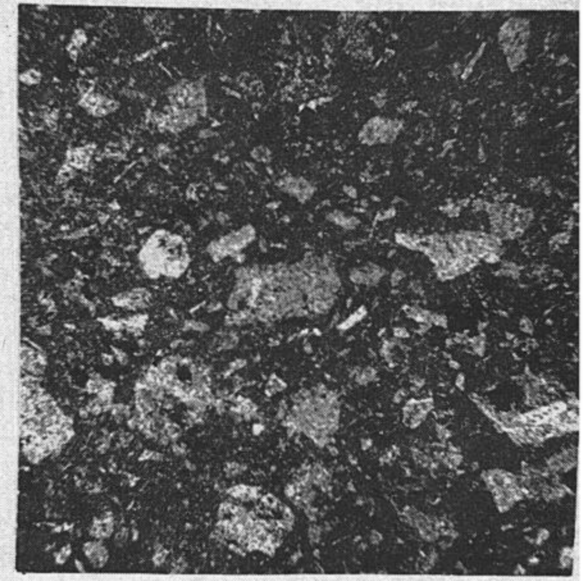


Figure 11

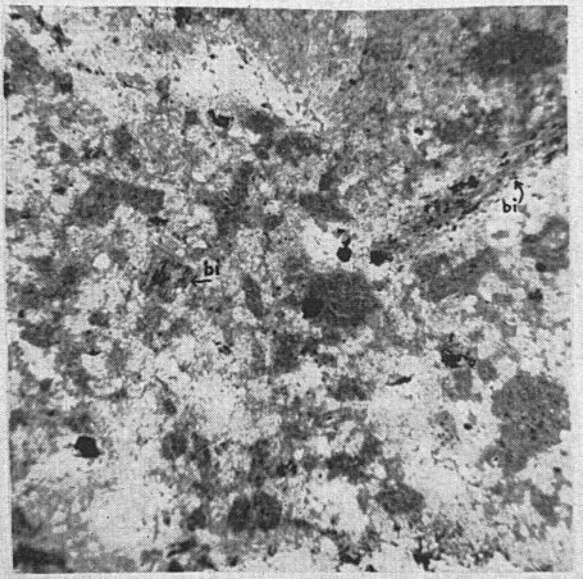


Figure 12

Fig. 10. Phyllic alteration of Oracle quartz monzonite. The white and gray quartz units are embedded in plagioclase and orthoclase units, which have been completely converted to sericite, quartz, and pyrite (black). Perceptible orientation of sericite and pyrite at bottom left denotes sericitized biotite. Crossed nicols, 15 ×.

Fig. 11. Argillized Type B porphyry. Plagioclase in both phenocrysts and groundmass has been converted to weakly birefringent kaolin, which contains scattered shreds of sericite or hydromica. See Fig. 6. Sparse pyrite, principally in plagioclase phenocryst sites, is black. Crossed nicols, 15 ×.

Fig. 12. Propylitized Type B porphyry. See Figs. 6 and 11. Plagoiclase units are predominantly chloritized with shreds of epidote and calcite (visible as stipplings in unit at lower right). Biotite blade at upper right and book at left center are chloritized and pyritized. Plane light, 15 ×.

Deep Zones.—The deep zones at San Manuel–Kalamazoo cannot be described with certainty. Our findings are based on only a few drill intercepts and may be modified in detail by further work and better exposures. The gross relationships are shown schematically in Figure 2. A slight uncertainty, especially with respect to chlorite–biotite relationships, is introduced by the nearness of the post-Laramide San Manuel fault and its possible effects.

As shown in Figure 2, the propylitic assemblage which rims the deposit at moderate depths grades downward from propylitized Oracle quartz monzonite into a zone in which both rock feldspars are dusted with sericite. Biotite is largely chloritized, and chlorite and epidote replace amphibole. Quartz–magnetite–minor pyrite veinlets up to ½ inch wide are common and generally have narrow quartz–sericite–chlorite selvages. The rocks are greenish and free of alteration K-feldspar and biotite.

The phyllic zone is widest, possibly with some repetition by steep faulting just below the midpoint of the orebody on the Kalamazoo side, but is virtually absent from the deepest levels (Fig. 2). Moving laterally toward the center of the deposit at depth (Fig. 3a), sericite content in altered plagioclase sites increases; magnetite content of the zone in veinlets and as disseminations diminishes but does not disappear. Narrow veinlets of chalcopyrite and pyrite occur which lack anhydrite but have selvages of nearly normal potassic alteration but without biotite. Neither typical argillic nor phyllic assemblages are discernible. The deepest penetration into the core zone shows an assemblage in which K-feldspar and sericite dust both primary plagioclase and orthoclase; in which veinlets of quartz–K-feldspar are flanked and intergrown with selvages of sericite after biotite and plagioclase; and in which magnetite, chalcopyrite, pyrite, and trace molybdenite occur as disseminations and microveinlets. This deep-level aspect of the symmetry and character of the Kalamazoo assemblage resembles that at Butte where alteration envelopes flanking Main Stage veins decrease in width at deepest levels with increasingly common quartz–K-feldspar–sericite assemblages and with chlorite replacing biotite (Meyer et al., 1969). No real argillization is present in this deep zone at San Manuel–Kalamazoo.

Mineralization Zones

Concentric mineralization zones are coaxial with the alteration zones as shown in Figures 3a and 3b. A plane normal to the axis of the deposit at a moderate depth shows the following zones of mineralization.

Potassic Zone.—An inner zone entirely within the potassic alteration zone averages about 2,600 feet in diameter and contains about 0.3% Cu almost totally as chalcopyrite. Total sulfide content is low and pyrite-to-chalcopyrite ratio is about 1:2; magnetite is rare or absent. Most sulfides are disseminated grains. Surrounding this zone (Fig. 3b) is the ore shell as defined by a 0.5% Cu cutoff lying in the potassic zone but also overlapping into the phyllic zone. This ore shell averages about 600 feet in thickness and ranges from 0.5%–1.0% Cu in grade with a pyrite-to-chalcopyrite ratio of 1:1. Pyrite generally forms stockwork veinlets; chalcopyrite occurs in disseminated grains.

Phyllic and Argillic Zones.—There are three rather distinct types of "ore" mineralization in the phyllic alteration zone. The outer portion of the ore shell, as just mentioned, lies in the phyllic zone. Surrounding the ore shell and entirely within the phyllic zone is a zone about 200 feet thick in which copper mineralization ranges from 0.1%–0.5% Cu, with a pyrite-to-chalcopyrite ratio of about 10:1. Most of both the pyrite and chalcopyrite forms veinlets. Surrounding this zone of marginal mineralization but still entirely within the phyllic and argillic zones is a zone of pyrite mineralization which ranges from 1,000–1,500 feet in width and contains 6%–25% pyrite by weight. Pyrite occurs with quartz in veinlets ranging up to ½ inch thick.

Propylitic Zone.—Mineralization in the propylitic zone consists of a few small, high-grade silver, gold, chalcopyrite veins, and pervasive pyrite in veinlets which constitutes 2%–6% by weight of the rock. Since the outer edge of the propylitic zone does not crop out it is uncertain whether disseminated pyrite is coextensive with propylitic alteration. The area of pervasive pyrite veinlets contains 100–500 ppm copper which is apparently included in the pyrite since discrete primary copper minerals have not been found in this material.

Vertical Changes in Mineralization.—Total sulfide content and copper content in the low-grade portion of the phyllic zone decrease with depth. The character of the mineralization appears also to change with depth from finer grained disseminated grains to coarser grained blebs. In the ore shell, there is remarkably little change in copper grade with depth, but the chalcopyrite again changes downward to a predominant bleb-type disseminated occurrence. As shown on Figure 3b, a progressively greater portion of the ore shell occurs in the potassic alteration zone as depth increases. Little change with depth is noted in the marginal zone except that magnetite substitutes for much of the pyrite near the bottom of the orebody. Similarly, magnetite substitutes for most of the pyrite in the zone of peripheral pyrite mineralization near the bottom of the orebody. These relationships are also shown in Figure 3a.

Molybdenite and Bornite Distribution.—Molybdenum shows a tendency to be concentrated in the middle two thirds of the ore shell (Fig. 3b) with lower grade zones at the upper and lower portions of the ore shell. Within the 0.5% Cu zone, molybdenum grade in individual drill intercepts tends to increase with copper grade and with thickness of the ore shell. Higher grade molybdenum occurs in both the potassic and phyllic zones and does not seem to be controlled by lateral alteration zoning, but from the standpoint of vertical zoning, molybdenum content drops off at about the same level that deep alteration assemblages become important (Fig. 3a).

Although only a dozen or so bornite identifications were recorded in drill hole logging, bornite also tends to occur in a short vertical column less than half the total length of the column of copper mineralization and nearly centered between top and bottom of the ore-grade copper interval. Most bornite is found with potassic alteration but it occasionally occurs also in phyllic and propylitic zones.

Comparison of Porphyry Deposits

The authors have used the San Manuel–Kalamazoo lateral and vertical zoning data as a framework into which information on zoning in other porphry deposits might be fit. Table 1 is a comparison of the geologic characteristics of 27 major North and South American porphyry deposits for which detailed information is available. The table summarizes the descriptions as well as possible, although careful interpretation was required simply in selecting the appropriate column in which to enter information. Factual information, widely known but not necessarily in print, has also been judiciously included. Entries for most deposits have been reviewed by the geologists most familiar with them. Abbreviations used are listed on the page preceding the table.

The table first compares preore controls and geologic setting of the deposits—age, shape-size, composition, sequence of intrusion, and mode of emplacement of the igneous host rock. Orebodies are considered in terms of shape, nature of external boundaries, percent of ore in ore-stage igneous rocks and preore rocks, dimensions, tonnage and grade. More significant, however, are the sections on hypogene alteration, hypogene mineralization, and sulfide occurrence.

The problem was approached with a model in mind, but without assumptions concerning its correctness. This model assumed that the porphyry deposit environment is one of coincident alteration and mineralization involving silicate–sulfide–oxide equilibria in a large, significantly three-dimensional petrologic-mineralogic system. These assumptions appear confirmed by the consistency of combined deposit descriptions.

We adopt the four alteration assemblage names earlier defined. Twenty-five of the 27 deposits described contain a phyllic zone, so it serves as a reference point in constructing the table. Other alteration types were entered wherever they fell with respect to that quartz–sericite–pyrite zone according to the descriptions.

At least 17 porphyries approach the form of a steep-walled cylinder. Another seven, including three molybdenum deposits, show elements of stubby cylindrical or inverted flatly conical form. The chiefly cylindrical deposits are the most distinctly zoned. The innermost (or deepest and/or generally earliest zone) is typically potassic; the next outward zone is phyllic. Beyond that is the commonly thinner and less well developed argillic zone, and the outermost zone is propylitic. Ore mineral distribution and sulfide occurrence proved to be consistently related to alteration. A summary, column by column, of the data entered in Table 1 is presented.

Deposit (Column 1)

This column gives the names and locations of the deposits.

Preore Host Rock (Column 2)

This column cites rock types and ages into which the igneous host rocks of the respective deposits have been intruded. These preore rocks may be mineralized, as at Bingham and Safford, or the preore wall rocks may be too remote, as at Butte. An appraisal of the importance of preore rocks with respect to ore control is given in Columns 14 and 15 under "Orebody." It is apparent that igneous host rocks most closely related to ore in time and space are emplaced generally high in the geologic column. Of the 26 deposits for which preore wall rock ages are available, 9 deposits have penetrated into late Cretaceous preore materials, 5 are in older Mesozoic sections, 4 are in Paleozoic rocks, and 7 occur in Precambrian rocks only. In several deposits, the younger sections of the geologic column can be projected over them without adding more than a few thousand feet of capping above the top of the porphyry deposit. Probably mineralization in most of the porphyry deposits extended upward to within a few thousand feet of the surface.

Igneous Host Rock (Columns 3–11)

The third major section of Table 1 describes the igneous host rocks of the porphyry deposits. The names of Column 3 apply to the intrusive units most intimately associated with the orebodies in both space and time. Ages cited in Column 4 apply to the intrusive hosts rather than to the ore deposits

TABLE 1. Geologic Characteristics of 27 Major Porphyry Copper and Molybdenum Deposits

ABBREVIATIONS–TABLE 1

Minerals

ab	albite
Ag	silver & silver minerals
anh	anhydrite
ank	ankerite
ap	apatite
Au	gold & gold minerals
bar	barite
bi	biotite
bn	bornite
cal	calcite
car	carbonate
cc	chalcocite
cp	chalcopyrite
chl	chlorite
clzo	clinozoisite
cs	cassiterite
cup	cuprite
cv	covellite
dck	dickite
dg	digenite
dol	dolomite
en	enargite
ep	epidote
feld	feldspar
fl	fluorite
fm	famatinite
gal	galena
gr	garnet
gyp	gypsum
hbl	hornblende
hm	hematite
hn	huebnerite
ill	illite
kaol	kaolin
mag	magnetite
mal	malachite
mb	molybdenite
mc	marcasite
mn	manganese minerals
mont	montmorillonite
py	pyrite
prp	pyrophyllite
pyx	pyroxene
Q	quartz
rc	rhodochrosite
rd	rhodonite
rt	rutile
ser	sericite
sl	sphalerite
spec	specularite
stb	stibnite
tm	tourmaline
tn	tennantite
trem	tremolite
tt	topaz
V	vanadium minerals
wf	wolframite
zo	zoisite

Rocks

alsk	alaskite
And	andesite
apl	aplite
Dac	dacite
Db	diabase
Dio	diorite
gn	gneiss
G	granite
Gd	granodiorite
lph	lamprophyre
L	latite
ls	limestone
M	monzonite
p	porphyry
peg	pegmatite
Qd	quartz diorite
Ql	quartz latite
Qm	quartz monzonite
Qmp	quartz monzonite porphyry
'Qp'	'quartz porphyry'
qtzt	quartzite
Rhy	rhyolite
sch	schist
seds	sediments
sh	shale
ss	sandstone
volc	volcanics

Geologic Time

Lar	Laramide
T	Tertiary
K	Cretaceous
Trias	Triassic
Meso	Mesozoic
Perm	Permian
Penn	Pennsylvanian
Pal	Paleozoic
p€	Precambrian

Alteration

Arg	Argillic
Phyl	Phyllic
Pot	Potassic
Prop	Propylitic

Miscellaneous

adv	advanced
bx	breccia
Cu	copper
diss	disseminated
flt	fault
irreg	irregular
μvlt	microveinlet
Mo	molybdenum
mod	moderate
ND	no data
repl	replacement
sul	sulfide
text	texture
tr	trace
vn	vein
vlt	veinlet
%	weight percent

DEPOSIT (1)	PREORE HOST ROCK (2)	IGNEOUS HOST ROCK			
		Name (3)	Age (m.y.) (4)	Controlling Structures (5)	Shape (6)
Ajo Arizona	p€ gn; Meso(?) Qm; K And, tuff	Cornelia quartz monzonite	63	steep NW fault possible control	elongate NW irregular
Bagdad Arizona	p€ volcs, sch & G	Bagdad stock	71	N 70 E & N 30 W flts	irregular lenticular
Bethlehem British Columbia	Triassic volcanics	Guichon Qd & Bethlehem Qd	200	N–N 25 E flts	irregular multiple plugs
Bingham Utah	Penn qtzt > limestone	Bingham stock	37	NE & NW flts	irregular, pipelike, steep
Bisbee Arizona	p€ sch; Pal ls, shale, sandstone	Sacramento stock	163	steep NW flt; NE flts	irregular elongate NW
Braden Chile	K–T And & seds	brecciated Dac p stock, Qd	mid–T (?)	N–S & N 55 E flts	circular & elongate dikes
Butte Montana	Pal ls, sh, ss; K And	Boulder Batholith	72	NW & EW flts	batholith elongate NE
Cananea Sonora	Pal seds; Lar volcs & intrusive rocks	La Colorada 'Qp'	59	N & NW flts	irregular stocks, plugs
Castle Dome Arizona	p€ sch & p€ G	Lost Gulch Qm, granite porphyry	64	N 40 E flts	irregular stock
Chuquicamata Chile	metaseds & volcs	Chuquicamata Mp	Lar	N & N 10 E flts	narrow, semicontinuous N 15 E belt
Climax Colorado	p€ sch	Climax rhyolite porphyry	30	N–S anticline possible control	circular, pipelike
Copper Cities Arizona	p€ sch & p€ granite	Lost Gulch Qm, granite porphyry	60	N 50 E	stock elongate NE
El Salvador Chile	K And, rhyolite	El Salvador stock	Lar(?)	NE & NW flts	elongate NE
Ely Nevada	Pal ls, ss, sh	Ely stock	109	E–W flts	irregular elongate E–W
Endako British Columbia	early Meso seds & volcanics	Topley Qm, alsk & granite	139–143	NW & ENE flts	irregular elongate NW
Esperanza Arizona	K fragmental & welded tuff & qtzt	Esperanza stock	62	NE, NW & N–S flts	irregular large stock
Inspiration Arizona	p€ sch, G, qtzt & Db	Schultze quartz monzonite	60	N 50 E flt	irregular large stock
Mineral Park Arizona	p€ metaseds & metavolcs, gneiss	Ithaca Peak stock	72	NW & NE folds, NW best	elliptical, pipelike NNW
Mission–Pima Arizona	Pal, K, Eocene sediments		60	not recognized	sill-like, tabular
Morenci Arizona	p€ G, Pal–Meso ls, ss, sh	Morenci stock	Lar	p€ NE; K NW	elongate NE
Questa New Mexico	Miocene(?) And, latite, rhyolite	Questa mine aplite porphyry	30	N, NW flts	very irregular domical
Ray Arizona	p€ seds, metaseds, Db; Pal limestone	Granite Mt. Qm	63	ENE schistosity NNW flts	irregular masses in NE belt
Safford Arizona	K Qm, Qd, Rhy, Ql, L, Dac dikes & plugs	Weber Peak dike swarm	58	NW flts & NE shears	dike swarm elongate NE
San Manuel–Kalamazoo Arizona	p€ quartz monzonite	San Manuel Mp	67	NE & NW flts	irregular, mushroom-shaped stock
Santa Rita New Mexico	Pal–Meso (K) seds	Santa Rita stock	63	NNW & NE flts	complex, elongate NW, domical
Silver Bell Arizona	Pal & K seds	Silver Bell stock	63	NNW flt	stock elongate NW
Toquepala Peru	late K(?) Rhy, And, Dio	dacite porphyry	59	none recognized	irregular stock elongate N–S
Typical Porphyry Copper	p€–late K seds & metasediments	Qm stock	65	NE & NW flts	elongate irregular

IGNEOUS HOST ROCK—*Continued*

Size (feet) (7)	Mode of Emplacement (8)	Stock–Dike (9)	Sequence of Intrusion (10)	Rock Types Mineralized (11)
3000 x 10,000	passive	stock	Dio → Gd → Qm → Qmp → vfg Qm	all
3000 x 6000	passive	stock	Rhy → Gd → Q Dio p → Dio p → Qmp	all
± 12,000 x 5000	probably passive	stock > dike	Qd → Gd → Dac p → Lp → Rhy	all
6000 x 9000	passive > active	stock > dike	Qd → Gd; Lp, Qlp	all + seds
5000 x 5000	passive > active	stock	‘Qp’ → ‘feld Qp’ (both altered)	all + seds
4000 x 4000	passive > active	stock > dikes	Qd → Dac p → Lp → Iph	And, Qd, Dac p, Lp
150,000 x 350,000	passive	batholith	Qm (apl, peg) → Qmp	all
8000 x 25,000 cluster	passive > active	stock > dike	Dio, Gd, sy, G → ‘Qp,’ Db	all + seds
5000NE x 6500NW	passive	stock > dike	Gd → Qm → Qmp → G → Gp → Db	Qm, Gp & Db
2500 x 1,000,000+	passive > active(?)	stock > dike	soda Gd → Qd → Dio → Qm → G → apl Gd → Mp	all(?)
± 3000 x 3000	active	stock > dike	Rhy p → apl p → Gp	all
5000NW x 13,000NE	passive	stock	Qm → apl → alsk p → Db → Gp	all
5000 x 15,000	passive	stock > dikes, sills	Gd → Gdp → ‘Qp’	all
large, elongate EW	passive	stock > dikes, sills	M, Qmp complex	all + seds
180,000 x 1,000,000	active(?)	stock > dike	Qm → G → alsk → Q feld p	all
45,000 x 60,000	passive	stock > dike	Qm → Dio → Qmp → And p	all + seds & volcs
30,000 x 60,000	passive	stock > dike	Db → Gd → G → Gp	all + metaseds
2000 x 4000	passive	stock	Qd → Qmp → ‘Qp’ → ‘Qp’+ Q	Qmp - ‘Qp’ - ‘Qp’ + Q
± 4000 x 4000	passive	sill > stock	Qmp	all + seds
± 10,000 x 50,000	passive–doming	stock; sill, dikes in wall	Dio p → Qmp → Gp → Db	Qmp + seds
15,000 x 90,000	passive	stock > dike	Mp, Gp, bio G → apl, apl p, Rhy p	all + volcs
8000 x 15,000	passive	stocks > dikes	Qd → Db → Qmp → And → Qmp → Qdp	all + metaseds
2000 x 4000	passive	dike swarm	Qlp, Rhy, Dac, Qd, Gd → Dac → Ql, L, Rhy	all + volcs
4000 x 7000(?)	passive	stock > dike	Mp → Qmp → Db	all
4000 x 7000	passive	stock > dike	Dio → Qd + hbl Gd & bi Gd → Qmp	Qd, Gd + seds
> 10,000NE x 30,000NW	passive	stock > sill > dike	alsk → Dac p → And p → Qmp	all + seds
1500 x 2500	active	bx pipe ≫ dike	Dac p	all + bx & volcs
4000 x 6000	passive	stock > dikes	Dio → Qm → Qmp → ‘Qp’	all + seds

DEPOSIT	OREBODY			
	Outward Shape (12)	Boundaries (13)	Percent in Igneous Host (14)	Percent in Preore Rocks (15)
Ajo Arizona	oval, elongate NW	original & faults	80?	20?
Bagdad Arizona	elongate oval	original	± 90	± 10
Bethlehem British Columbia	steep, elliptical cylinder	original	± 50	± 50
Bingham Utah	pear-shaped, elongate WSW	original	75	25
Bisbee Arizona	elongate EW, oval	original & faults	± 30	± 70 (incl. bx)
Braden Chile	hollow circular cylinder	original & postore breccia pipe	25	75
Butte Montana	crudely domical	original	100	0
Cananea Sonora	pipelike	original breccia pipe	± 90	± 10
Castle Dome Arizona	oval, elongate NE	original & NW fault	100	0
Chuquicamata Chile	wedge, broad end NE n	original & fault(?)	95(?)	5(?)
Climax Colorado	nested, inverted cones	original	40(?)	60(?)
Copper Cities Arizona	oval, elongate NW	original & NE & NW faults	100	0
El Salvador Chile	oval pipe, lower grade center	original	70(?)	30(?)
Ely Nevada	?flat cylinder	original with faults above & below	80	20
Endako British Columbia	elongate oval	original	100	0
Esperanza Arizona	elongate NW oval	original	60(?)	40(?)
Inspiration Arizona	flat cylinder	original & fault	50	50
Mineral Park Arizona	crescent, convex SW		± 100	± 0
Mission–Pima Arizona	oval	original & fault	± 10	± 90
Morenci Arizona	oval	original + fault	± 70	± 30
Questa New Mexico	irregular	original	70(?)	30(?)
Ray Arizona	irregular oval, elongate EW	original & fault	20	80
Safford Arizona	oval, dipping pipe	original	20	80
San Manuel–Kalamazoo Arizona	hollow oval cylinder	original	50	50
Santa Rita New Mexico	oval, elongate NW	original	± 70	± 30
Silver Bell Arizona	elongate oval mineral belt	original	70	30
Toquepala Peru	oval, elongate NW	original: breccia pipe	70 (bx & Dac p)	30 (walls pipe: Dio & volcs)
Typical Porphyry Copper	oval, pipelike	original & postore faults	70	30

OREBODY – *Continued*

Dimensions (feet) (16)	Total Ore Tonnage (million) (17)	Grade Hypogene + Supergene (18)	Grade Hypogene Only (19)
4000 x 7000	< 500	0.75% Cu	0.75% Cu
1000 x 5000	< 100	0.76% Cu ± 0.025% Mo	± 0.5% Cu ± 0.025% Mo
2000 x 3000 (Jersey)	< 100	0.6% Cu	0.6% Cu
5000 x 7000 WSW	> 500	0.75% Cu 0.05% Mo	0.75% Cu 0.05% Mo
2000 x 2000	< 100	0.81% Cu	± 0.55% Cu
± 5000 x 5000 hollow cylinder	> 500	2.25% Cu 0.05% Mo	1.00% Cu 0.05% MO
5000 x 10,000 EW	> 500	0.8% Cu	0.2% Cu
250 x 1200 ring-shaped	> 500 (district)	0.8% Cu	0.5% Cu
± 1500 x 3000	< 100	± 0.70% Cu	± 0.5% Cu (?)
2500 x 10,000	> 500	± 1.7%	± 1.2% Cu
4000 x 4000	> 500	± 0.24% Mo	± 0.24% Mo
1500 x 2000	< 100	± 0.60% Cu	± 0.4% Cu
3000 x 4000	> 500	± 1.5% Cu	ND
± 1000 x 3000 x 10–20,000	< 500	± 0.9% Cu (1–2% common)	± 0.1% Cu (0.4% common)
1200 x 6000	> 100	± 0.09% Mo	± 0.09% Mo
2300 x 4200	< 100	0.51% Cu 0.028% Mo	± 0.3% Cu 0.028% Mo
2500 x 8300	< 500	0.90% Cu	0.15–1.20% Cu 0.007% Mo
2200 x 3400	< 100	0.5% Cu 0.04% Mo	0.1–0.15% Cu 0.04% Mo
5000 NW x 7000 NE	> 500	0.8% Cu	0.8% Cu
6000 x 13,000	> 500	0.88% Cu	0.1–0.15% Cu 0.007% Mo
7000 x 7000	> 500?	0.15–0.18% Mo	0.15–0.18% Mo
3000 NS x 10,000 EW	< 500	0.80% Cu	0.10–0.80% Cu
± 4000 x 5000	> 500	0.50% Cu	± 0.2% Cu
cross section: 2500 x 5000 x ± 8000 high	> 500	± 0.75% Cu 0.015% Mo	± 0.75% Cu
5000 x 7000 NNW	< 500	0.97% Cu	0.1–0.2% Cu (intr) 0.8% Cu (tactite)
2000 x 2500 & 1500 x 2500	< 100	0.75% Cu	0.3–0.4% Cu (intr) 0.8% Cu (tactite)
4000 WNW x 5000 NNE	> 500	0.9% Cu	0.3% Cu
3500 x 6000	150	0.80% Cu 0.015% Mo	0.45% Cu 0.015% Mo

DEPOSIT	HYPOGENE ALTERATION			
	Known Extent Beyond Ore (ft) (20)	Peripheral Zone (21)	Outer Zone (22)	Intermediate Zone (23)
Ajo Arizona	+ 5000		?chl, ab, zo, ser, Q, ank	
Bagdad Arizona	500 +	ND	not reported	not reported
Bethlehem British Columbia	+ 300	ND	Q, chl, ep	Q, kaol, mont
Bingham Utah	3000 +	chl, talc, kaol, ep, gr, mag, pyx	Q, chl, kaol, cal, ep	
Bisbee Arizona	7000?		chl, ep, zo, cal, ser ?	kaol, ser(?)
Braden Chile	+ 5000	chl, mag, ep, hm, tm	ep, tm, mag, spec, cal	Arg – Phyl, minor
Butte Montana	1000 +		Q, chl, ep, cal	Q, mont, kaol
Cananea Sonora	5000		chl, ep	Q, ser, kaol
Castle Dome Arizona	3000		chl, ep, py, ser, cal & clzo	mont
Chuquicamata Chile	few hundred		chl, ep, cal, spec, hm, TiOx	kaol > ser
Climax Colorado	2000?		Q, chl(?), ep(?)	Q, py, ser
Copper Cities Arizona	5000 +		ep, cal, clzo, ser	mont, Q
El Salvador Chile	1000 +		py, chl	Argillic
Ely Nevada	2000		"propylitic"	
Endako British Columbia	2000 + (?)		kaol weak, Q, cal	kaol moderate, Q, chl
Esperanza Arizona	ND		not reported	Q, kaol, mont
Inspiration Arizona	1500 +		chl, ep	Q, ser, kaol
Mineral Park Arizona	10,000	chl, ep, clzo, (latest)	Q, ser, 'clay' (Argillic)	Q
Mission–Pima Arizona	up to 5000		skarn, tactite, hornfels	present
Morenci Arizona	> 5000	skarn on SE	chl, ep	Q, mont
Questa New Mexico	2000 + (?)	ser, car, kaol, ep, chl	ser, Q, py ± cal, kaol, ill, fl	ser, Q, py ± cal, kaol, ill
Ray Arizona	1000–15,000		chl, ep, ab, cal, mont to 20,000 x 30,000	
Safford Arizona	± 12,000		ep, chl	"chloritic"
San Manuel–Kalamazoo Arizona	3000–5000		Q, chl, ep, cal	Q, kaol, chl
Santa Rita New Mexico	± 5000	tactite	tactite	chl, ep (Argillic)
Silver Bell Arizona	± 32,000 x 5000 alteration zone		chl, cal, ser, mont tactite	Q, ser, kaol tactite
Toquepala Peru	minor; < 1000			mont
Typical Porphyry Copper	2500	chl, ep, kaol, (skarn)	chl, ep, cal	Q, kaol, ser, mont

DEPOSIT	HYPOGENE MINERALIZATION			
	Peripheral Alteration Zone (28)	Outer Alteration Zone (29)	Intermediate Alteration Zone (30)	Inner Alteration Zone (31)
Ajo Arizona	spec, bar		cp, py, bn, mb, mag, hm py:cp < 1	py:cp = 1:4; py, cp
Bagdad Arizona	Au, sl, Ag, cp			py > cp > mb
Bethlehem British Columbia	cp, Ag, Au	py > cp, bn	cp > py > bn	bn > cp > py
Bingham Utah	en, fm, gal, sl, tt	py		py, cp, mb
Bisbee Arizona	sl, gal, py, cp	ND	ND	py, cp, bn, cc, mb, sl py:cp = 10:1
Braden Chile	gal, sl, Ag, stb, py	py		py > cp > bn > mb > en mb > en
Butte Montana	Mn, Ag	rc, sl, gal, rd	py, bn, cp, tn	py, cc, en, bn
Cananea Sonora	gal, sl, tt, Ag		py, cp, bn, mb, sl, gal	py, cp, bn, mb
Castle Dome Arizona	sl, gal, py, cp, mb, V, Ag, spec	py	py > cp > mb	py > cp > mb
Chuquicamata Chile	minor sl, gal, spec	py, cp	en, cp, cc, bn, py(?)	en, cp, cc, py, bn(?), mb
Climax Colorado	gal, sl, Ag(?)		py, tz, fl, hn, cs	mb, cp
Copper Cities Arizona	sl, gal, Ag	py	py > cp > mb	py > cp > mb
El Salvador Chile	gal, sl, Ag	py, spec	ND	py - cp
Ely Nevada	Au & base metals in seds			py, cp, high total sul py:cp = 5–10:1
Endako British Columbia	sl, gal, Ag	spec, cal < .05% py	mag, py, mb, < 0.15% py	py, mb, mag .5–1.0% py
Esperanza Arizona	gal, sl, Ag	py	py > cp > mb	py > cp > mb
Inspiration Arizona	cp, gal, sl, mb, V, Mn	py > cp(?)	py > cp	py > cp > mb
Mineral Park Arizona	Au, Ag, gal, sl	py, cp, sl, gal	py, cp	py, cp, mb
Mission–Pima Arizona	gal, sl, Ag	'heavy minerals'	?	py, cp, mb
Morenci Arizona	gal, sl, Au, Ag	py	py:cp = high; high total sul; py, cp	py 3–8%; cp 9.3–0.5%; py, cp, mb, sl
Questa New Mexico	py, mb, gal, sl	py, mb, cp–gal–sl	py, mb	mb, py, cp, hn
Ray Arizona	gal, sl	py, cp, bn	py, cp, bn	py, cp, bn, mb
Safford Arizona	Ag, cp	Au, cp	ND	py, cp, mag, tt, gal, sl py 4–8%; cp ± 0.4% py:cp = 10–20:1
San Manuel–Kalamazoo Arizona	cp, gal, sl, Au, Ag	py (2%)	py (2%)	py (10%); cp (0,1–3%) mb(0–0,05%)
Santa Rita New Mexico	sl, gal, Ag, spec, cp, mc		py 4–8%; cp < 0.4% py:cp = 40:1	py 1–4%; cp 0.4–1%; mb; py:cp = 3:1
Silver Bell Arizona	Ag, gal, sl	Ag, gal, sl(?)	py:cp = 6:1	py:cp = 1:1
Toquepala Peru	minor cp, bar	no py halo	mod py:cp low total sul	low py:cp; higher total sul; py, cp, bn, sl, mb
Typical Porphyry Copper	gal, sl, Ag, Au	py, gal, sl	py ≫ cp > bn; mod total sul; py: cp= 23:1	py > cp > mb > bn; high (10%) tot sul; py:cp = 13:1

HYPOGENE ALTERATION – *Continued*

Inner Zone (24)	Innermost Zone (25)	Zoning Sequence from Center (26)	Vertical Sequence from Bottom (27)
(Q, ser, py)?	Q, K feld, chl (anh)	partial overlap Pot – Phyl – Prop	
Q, ser, K feld	bi, ab, Q, K feld	Pot – Phyl	
Q, ser		Phyl – Arg – Prop	
Q, ser, K feld ± clays, chl	Q, K feld, bi, ser	Pot – Phyl – Prop	
'Qp', Q, dck, prp; "feld Qp" = Q, ser		adv. Arg & Phyl – Arg – Prop	
Q, ser, bi, anh	Q, ser, bi, anh	Pot & Phyl – Arg – Prop	Pot – Phyl
Q, ser, py; Q, dck, prp	Q, K spar, bi, ser (anh)	Por – Phyl – Arg – Prop	Pot – Phyl – Arg – Prop
Q, ser	Q, mb, bi, tm(?)	Phyl – Arg	
Q, ser, hydromica, K feld		Phyl – Arg – Prop	
Q, K feld, ser		Phyl – Arg – Prop	ND
K feld, Q, bi, fl	Q (nesting)	Q – K feld – Q, py, ser – chl, ep	Q – K feld – Q, py, ser
Q, ser, py, hydromica		Phyl – Arg – Prop	
py, Q, ser ± tm	Q → Q, K feld; anh, general bi	Pot – Phyl(?) – Arg(?) – Prop	Pot – Phyl(?) – Arg – Prop
"sericitic"	"potassic"		granitoid -p texture; ser – bi – clay
Q, ser, py, kaol	Q, K feld, bi	Pot – Phyl – Arg	ND
Q, K feld	Q, ser, K feld, bi (anh) (innermost)	Pot – Phyl – Arg(?)	not reported
Q, ser, kaol	K feld, bi, ser	Pot – Phyl – Prop	ND
Q, ser, py	Q, K feld (earliest)	Pot – Phyl – Arg – Prop	not reported
Q, ser, clay(?); skarn	Q, K feld, ser, bi; skarn	Pot – Phyl – Arg – skarn	
Q, ser, py	ND	Phyl – Arg – Prop	not reported
Q, K feld, bi ± cal, kaol, ill	Q, K feld (anh)		
Q, ser to kaol 10,000 x 16,000?	bi, Q, ser, K feld 8000 x 8000	Pot – Phyl – Arg – Prop	ND
Q, ser, py	K feld, bi, Q, ser	Pot – Phyl – Arg – Prop	
Q, ser, py	Q, K feld, bi, anh	Pot – Phyl – Arg – Prop	Pot – Phyl(?)
Q, ser, py, tactite	Q, K feld, bi, plag, kaol, mont (anh)	Pot – Arg – Phyl – Prop	
Q, ser, tactite	Q, K feld, ser, hydromica	Pot – Phyl – Arg – Prop	ND
Q, ser, py	Q, tm, bi, K feld	poorly developed	anhydrite at depth
Q, ser, py	Q, K feld, bi, ser (anh)	Pot – Phyl – Arg – Prop	Pot – Phyl(?)

HYPOGENE MINERALIZATION—*Continued*

Innermost Alteration Zone (32)	Overall Abundance Major Ore Minerals (33)	Zoning Sequence from Center (34)	Vertical Sequence from Bottom (35)
mag; cp; py, bn; low total sul	cp> py>bn>mb(?)	mb → cp → py → spec	cp:bn decreases
cp>py>mb	py>cp >mb	cp → py	ND
	cp>py>bn>mb	bn → cp → py	ND
cp, bn, mb	py>cp>bn>mb	mb → bn → cp → py → (gal, sl, Ag, Mn)	Cu to Pb–Zn in veins
	py>cp>bn>cc	not reported	less py upward
py>cp>bn>mb>en	py>cp>bn>mb>en	(cp, py, bn, mb) → (py, cp) → (gal, sl, Ag)	(bn, cp, mb) → (cp,bn, py, mb) → (py, cp, mb, bn)
cp, py, mb	py>cc>en>bn>cp	mb→cp→py→cc→en→ cp→tn→rd→Ag	mb→cp→py→cc→en→ cp→tn→rd→Ag
py, cp, bn, mb	py, cp>bn, sl, gal	not reported	ND
	py>cp>mb	cp→py→(sl, gal, Ag)	cp→py(?)
en, py, cp, cc, bn(?), mb	py>en>cp>bn>mb	py→cp→py(?)	ND
minor mb	py - mb	mb→py→hn	three cycles mb-py-hn
	py>cp>mb	cp→py→(sl, gal, Ag)	py→cp(?)
cp - py? - bn - mb	py>cp>bn>mb	(cp, bn, mb)→(cp, py)→ py→spec(?)	cp, bn, mb→cp, py→ py→spec(?)
py, cp, bn, mb py:cp>1:1	py>cp≫bn, mb	(cp, bn, mb)→py→ (Au, gal, sl)	ND
mag, mb, py <.15 py	mag>py>mb>cp	mag→(py, mag, mb)→ (mb, cp py)→py→spec	ND
py>cp>mb(?)	py>cp>mb	cp, mb→py	ND
cp>py>mb(?)	py>cp>mb	(cp, mb)→py	ND
py, mb, wf	py>cp>mb	cp→mb→py→(gal, sl, Ag,Au)→(Au, Ag)	ND
py, cp, mb	py>cp>bn>mb>sl	(cp, py, mb)→(skarn, gal, sl)	ND
cp:py low, high py? py, cp, mb, sl	py>cp>sl>mb	(cp, sl, mb)→py→ (sl, gal, Ag, Au)	not reported
mb, py, cp, hn	py>mb≫cp, gal, sl	mb→(cp, py)→(gal, sl, mb)	not recognized 1000 ft
py, cp, bn, mb	py>cp>bn>mb	cp→py→(gal, sl)	ND
cp, py, bn, mb,mag, tt, gal, sl; py 0.2-1%, cp 1-2% py:cp= 0.1-1:1	py>cp>bn>mb	(cp, mb)→py→Au	mb at depth
py (1%); cp (1-3%) mb (0.01-0.05%)	py>cp>mb	cp→py→(gal, sl, Au, Ag)	cp→py
low total sul; py<1%; py:cp= 10:1	py>cp>mb>bn	low-grade center→annular ore zone & (cp, mb)→py→ (Ag, gal, sl)	py zone contracts & py:mag increases
py, cp, bn, tt, mb, sl	py>cp>mb>bn>sl	cp→py→(Ag, gal, sl)	ND
Q, tm+minor sul	py ±= cp≫bn, mb	(Q, tm)→cp→py	not observed anhydrite at depth
py>cp>mb>bn; low (3%) tot sul; py:cp =3:1	py>cp>mb>bn	(cp, mb)→py→(gal, sl, Ag, Au)	(cp, mb)→py

DEPOSITS	OCCURRENCE OF SULFIDES			
	Peripheral Alteration Zone (36)	Outer Alteration Zone (37)	Intermediate Alteration Zone (38)	Inner Alteration Zone (39)
Ajo Arizona	veinlets	diss > μvlts		diss > μvlts
Bagdad Arizona	vns & massive replacement	vlts > diss		diss > vlts
Bethlehem British Columbia	veins	veinlets	veinlets	veinlets
Bingham Utah	veins & replacement	vns, vlts, diss	vlts, diss	diss ≫ vlts
Bisbee Arizona	vns, vlts, mass. repl.	ND	ND	vns, vlts, diss
Braden Chile	veins	patches & vlts	vlts & patches	vlts > patches
Butte Montana	vn, vlt	vn, vlt	vn, vlt	vlt, vn, diss
Cananea Sonora	vein	veinlets	vlts, diss, mass.	vlts, diss
Castle Dome Arizona	veins	veinlets	diss > vlts	diss > vlts
Chuquicamata Chile	veins	vns & vlts	vlts > diss	vlts > diss
Climax Colorado	vns & dikes		vlts ≫ diss	vlts ≫ diss
Copper Cities Arizona	veins	veinlets	diss > vlts	diss > vlts
El Salvador Chile	veins	μvlts, vlts ?	μvlts, vlts ?	diss, μvlts
Ely Nevada			diss ≫ vlt	diss ≫ vlt
Endako British Columbia		vlt > diss	vlt > diss	vlt ± = vlt
Esperanza Arizona	veins	vns & vlts	vlts	diss > vlts
Inspiration Arizona	veins	vns & vlts	vlts > diss	vlts > diss
Mineral Park Arizona	veins	vlts, vns, stkwk 3–6" spacing	vlts, vns, stkwk 3–6" spacing	vlts, vns, stkwk 3–6" spacing
Mission–Pima Arizona	vn & vlt			vlt, diss & massive
Morenci Arizona	vns, ls repl.	vlts > diss	ND	vns, vlts, diss
Questa New Mexico	veins	paint	vlts	vns & vlts
Ray Arizona	veins	vns, vlts, diss	vns, vlts, diss	vlts, diss, vns
Safford Arizona	veins	in shears, vns, dikes	in shears, vns, dikes	in veins, vlts, diss
San Manuel–Kalamazoo Arizona	veins	vlts	vlts > diss	vlts > diss
Santa Rita New Mexico	veins	vns & vlts	vns & vlts	vlts, μvlts, diss
Silver Bell Arizona	vns & tactite	vns & tactite	vlts > diss	vlts > diss
Toquepala Peru	veins		diss > vlts bx vug fillings	diss > vlts bx vug fillings
Typical Porphyry Copper	veins	vns & vlts	veinlets	vnlts > diss

OCCURRENCE OF SULFIDES—*Continued*			
Innermost Alteration Zone (40)	Breccia Pipes (41)	Crackle Zones (42)	SUPERGENE SULFIDES (43)
diss > µvlts	not reported	beyond ore limit	minor cc, cv
diss > vlts	present & mineralized	2000 x 6000 ft	cc
vlts > diss	present & mineralized	slightly larger than orebody	none
diss ≫ vlts	in gal, sl zone peripheral	extends beyond gal, sl	cc, cv
	important; 2 stages	NE horsetail zone	cc
vlts > patches	postore with min. frag.	present	cc ≫ cv
diss > vlt	none	horsetail zone	cc, cv, dg
vlts, diss	numerous & mineralized	present	cc, cv
	present?	present	cc, cv
vlts > diss	large central pipe	horsetail zone	cc, cv
irregular clots	minor breccia, dikes	present	none
	present	present	cc, cv
diss, µvlts	deep, central, mineralized	present	cc ≫ cv
diss ≫ vlt	present	present	cc, cv
diss > vlt	not reported	present	none
diss > vlt	present	present	cv, cc
vlts > diss (?)	not reported	present	cc
vlts, vns, stockwork 3–6" spacing	none	present	cc
vlt, diss & massive	ore N–S dike; cp, gal, sl, tt	poorly developed	cc, thin zone
	breccia zones, in pit	extensive	cc, cv
vns & vlts	present, important	extensive	none
vlts, diss, vns	present & mineralized	present	cc, cv
vns, vlts, diss	present & mineralized	present	cc, cv
diss > vlts	not reported	± 5000 ft diameter	cc
vlts, µvlts, diss	one 500 x 2500 ft pipe, mineralized	same area as intrusive	cc ≫ cv
ND	none	NW horsetail zone	cc
breccia fillings & diss	large multiple & many small mineralized	present beyond breccia	cc
diss > µvlts	present & mineralized	present	cc > cv

associated with them, but evidence shows that ore deposition was essentially contemporaneous with intrusion within the precision of the K–Ar technique. Age dating of the Laramide–mid-Tertiary interval in the Southwest reported by Damon and Mauger (1966) has indicated two distinct pulses, one of Laramide plutonic activity between 50 and 75 million years ago and one of dominantly extrusive activity during mid-Tertiary time approximately 30 million years ago.

Table 1 includes ages for deposits in British Columbia and South America as well as southwestern North America. Six of 27 deposits are of mid-Tertiary age at 30–37 million years, 17 are probably in the Laramide range of 59 to 72 million years, 3 are in the Jurassic range of 122–143 million years, and 1 deposit has a 200 million year Triassic date. Of the Southwest deposits included in Table 1, all are of Laramide age except three mid-Tertiary deposits (Climax, Questa, and Bingham) and two Jurassic deposits (Bisbee and Ely), two of the mid-Tertiary ones being porphyry molybdenum deposits.

The pattern for porphyry dates emerging in British Columbia seems to be one in which parallel, overlapping, northwest-trending belts of mineralization increase in age from west to east. The single numerical age for a South American deposit in Table 1 is for Toquepala, Peru, at 59 million years. However, geologic relationships and recent dating by Chilean geologists indicate that many of the South American deposits are of mid-Tertiary age.

Controlling Structures (*Column 5*).—Column 5 lists attitudes of regional-scale structures thought to have controlled the emplacement of the stocks and batholiths and hence the porphyry deposits themselves. Consideration was given to local structure shown on published mine and district maps in preparing Column 5, but many bounding faults shown on these maps are of postore age or of multiple age such that their preore importance cannot be determined. Greater reliance was therefore placed upon direct text statements than upon maps. Several authors comment that the specifics of controlling structures were obliterated by the intrusions which they guided.

Shape and Size (*Columns 6 and 7*).—The shapes of intrusions (Column 6), like determinations of their size (Column 7), are difficult to establish meaningfully, since both have been affected by internal and external variables. Exposure of a pluton is certainly affected by original depth and by post-intrusion tectonic and erosional history. The Boulder batholith has been exposed for tens of miles, and a large southern Arizona batholith (Ettlinger, 1928) has been inferred from the distribution of cupolas. The shape and size of porphyry host intrusions seem to be related to contemporaneous and younger faulting and uplift. Table 1 shows that most of the host igneous bodies are somewhat elongate and that districts with strong structural control tend to include pronouncedly elongate stocks.

Column 7 lists the size of igneous host rock outcrops for each district, the numbers having been taken from texts or measured from geologic maps. These dimensions are in part subject to the same uncertainties as the descriptions in Column 6. The dimensions indicate that the porphyry copper deposit environment was commonly developed in stocks or cupolas with cross sections of well under a square mile at the elevation of ore deposition. There appear to be two host-rock size populations, one group less than a mile square and another smaller group of very large dimensions.

Mode of Emplacement (*Column 8*).—These entries adopt the terminology and tend to confirm the conclusions of Stringham (1966) regarding mode of emplacement. Stringham's criteria are extended to include the additional porphyry copper deposits described here. Emplacement of the porphyry copper deposit host rocks is shown to be almost totally passive. This passivity suggests that replacement, stoping, and assimilation were more important processes than shouldering aside or other manifestations of forceful intrusion, and it also suggests the likelihood that both lateral and vertical petrologic zoning might be more common than has been recognized. Comparison of Column 8 with Columns 41 and 42, the latter reporting brecciation and shattering specifically within the orebodies, reveals that brecciation or shattering are associated with ore deposition in every porphyry deposit, even where emplacement of the host stocks is passive. This disparity suggests that brecciation and shattering are themselves "passive," and that they can commonly be expected to be "blind," as they are at many southwestern North American porphyry deposits and prospects. Forceful intrusion and active, even explosive brecciation as at Toquepala and Braden are apparently rare. Extensive magmatic stoping, assimilation, and metasomatism appear mechanically and kinetically inconsistent with extremely shallow emplacement, but moderately shallow environments may be indicated.

Porphyry molybdenum deposits seem to show more evidence of forceful emplacement than do porphyry coppers in general. This evidence consists of ring and radial dikes and doming of the layered rocks which sometimes overlie the deposits.

Stock–Dike (*Column 9*).—Column 9 indicates that stocks and stocks with subordinate associated dikes are far more typical of porphyry copper deposits than are dikes, dike swarms, or breccias alone. This same relationship was indicated in Column 6 where porphyry deposits were shown to be equidimensional to oval rather than tabular or linear bodies. Twenty-four of the 27 deposits involve important stock development and a high ratio of stock to dike forms.

Sequence of Intrusions and Rock Types Mineralized (Columns 10 and 11).—The sequences of intrusion shown in Column 10 reinforce early observations (Buddington, 1933) of the association of copper deposits with intermediate to felsic igneous rocks. Except for generally late diabase dikes, no rocks more mafic than diorite occur in the intrusions associated with porphyry copper deposits. Granodiorite and quartz monzonite and their aphanitic and hypabyssal equivalents occur in almost all of the porphyry copper deposits, with more felsic variants common to the porphyry molybdenum deposits. Most papers consulted in preparing Table 1 give specific sequences of intrusive events and igneous rock compositions, but uncertain field relationships coupled with paucity of radiometric age determinations seldom permit unequivocal identification of the beginning and ending of the magmatic episode that involved ore mineralization. Much older and much younger rocks, as described in the appropriate references, are excluded. Column 11 shows that all of the intrusive rocks of Column 10 are mineralized in 22 of the 27 deposits tabulated and the youngest intrusive unit is mineralized in 2 of the remaining 5.

Columns 10 and 11 show that the sequence is generally from dioritic to monzonitic rocks, commonly with late latitic to rhyolitic or "quartz porphyry" intrusions. Typically, all of these are mineralized, showing that mineralization either accompanied or briefly succeeded the emplacement of intrusive rocks. The association of porphyry copper deposits with intermediate plutonic rocks is impressive but not as consistent as the association with porphyry in all 27 districts listed. There has been discussion in recent years as to whether the name "porphyry copper" is appropriate for the group of deposits described in this paper. The writers believe that this association is genetic rather than coincidental and feel that "porphyry copper" is an excellent descriptive name for this unique and important group of ore deposits.

The lamprophyre or "late diabase" event is less common in the porphyry coppers than has been previously thought (Spurr, 1925). Late diabase has been reported in only 5 of the 27 districts. The general trend, clearly, is from dioritic plutonic toward more felsic hypabyssal rocks with all rock types usually mineralized. The degree to which the shift from dioritic through granodioritic to monzonitic rocks may reflect K-feldspar enrichment by means of potassic alteration (Peters et al., 1966) will be considered below. Dioritic rocks commonly occur at intrusion margins, as at Ajo and Mineral Park, with progressively more K-feldspathic rocks inward, a relationship not apparent in the table. This distribution is consistent with apparent felsic-component enrichment accompanying potassic alteration near the central portions of some porphyry copper deposits.

Orebody (Columns 12–19)

Outward Shape (Column 12).—The porphyry copper deposits almost all have circular or oval cross sections. At least four deposits have clearly defined low-grade centers producing a ringlike orebody in plan. The vertical dimensions of hypogene mineralization in most deposits are unknown; however, the tabulated hypogene mineral bodies seem to fall into three general configurations.

1. Seventeen deposits have a steep-walled cylindrical shape. Two deposits (Cananea and Toquepala) approximately coincide with breccia pipes.
2. Seven deposits have stubby cylindrical or flat, conical forms, as do all three of the porphyry molybdenum deposits.
3. Three deposits (Inspiration, Ely, and Safford) have a gently dipping, tabular shape, perhaps representing a deposit similar to (2) following a preore structure or postore displacement, or they may represent a separate type.

Boundaries (Column 13).—In all of the deposits studied, the orebody boundaries are at least in part gradational or "assay wall" boundaries. All have been intersected by a postore erosion surface. Eleven are bounded by at least one postore fault. Two coincide closely with breccia pipes which are preore or contemporaneous with ore, and one deposit (Braden) forms a crude cylindrical shell surrounding a postore breccia pipe.

Percent in Igneous Host and Preore Rocks (Columns 14 and 15).—In several deposits, 100 percent of the ore mineralization is in igneous host rocks (Butte, Castle Dome, Copper Cities, Endako, and Mineral Park). All contain some ore in igneous host rocks, but most ore at Bisbee, Braden, Mission, and Ray is in wall rocks. Something like 30 percent of all ore mineralization associated with porphyries occurs in wall rocks, again suggesting cupola or at least high-level environment for the porphyry deposition.

Dimensions (Column 16).—Horizontal dimensions of the tabulated deposits range from 250 × 1,200 feet for the La Colorada pipe at Cananea to 6,000 × 13,000 feet for the Morenci deposit. Fringes of the difficult-to-limit Butte district may reach to dimensions on the order of 20,000 × 50,000 feet (only the "porphyry equivalent" for Butte is cited in Column

16). The average deposit size deduced from published descriptions and maps is a perhaps surprisingly small 3,500 × 5,000 feet.

Total Ore Tonnage and Grade (Columns 17, 18, and 19.)—Of the 27 deposits tabulated, 13 are estimated to contain over 500,000,000 tons of ore, 6 fall between 100,000,000 and 500,000,000 tons, and 8 contain less than 100,000,000 tons. These tonnage estimates must be considered only approximate.

Included in these figures are several deposits whose ore grade depends on secondary chalcocite enrichment. Average grade of copper ore is 0.80% Cu, and average grade of hypogene mineralization, where this information is available, is 0.45% Cu. Twelve copper deposits contain at least 0.5% Cu in hypogene mineralization and 10 contain less than 0.5% Cu. Molybdenum deposits average 0.17% Mo in grade.

Hypogene Alteration (Columns 20–27)

The next three sections, Hypogene Alteration (Columns 20 through 27), Hypogene Mineralization (Columns 28 through 35), and Occurrence of Sulfides (Columns 36 through 42), have parallel organization so that the columns for each zone in a given deposit have identical headings. For example, the innermost alteration zone at San Manuel–Kalamazoo consists of quartz, K-feldspar, biotite, and minor anhydrite (Column 25), and the ore minerals (with amounts) are pyrite, chalcopyrite, molybdenite, and trace bornite (Column 32). The sulfides occur more commonly as disseminations than as veinlets (Column 40).

It should be restated here that the table is based as completely as possible upon published descriptions, and these are hardly uniform in approach, detail, or even terminology. Several deposit descriptions were based on temporal rather than spatial relationships; these deposits were entered as earliest equals innermost, and so on outward. Several deposit descriptions involved separate and poorly related descriptions of alteration, mineralization, and occurrence. We have made every effort to match appropriate spatial and mineralogical data. Question marks in the table generally denote uncertainty of placement of the information rather than uncertainty in the data.

The problem of distinguishing between supergene and hypogene effects is important. Hemley and Jones (1964) curves indicate sericite stability only at moderately high K^+/H^+ ratios at low temperatures, an environment consistent with (but not requiring) high pH. The extremely low pH presumed for active supergene enrichment zones argues against important development of supergene sericite and indicate the kaolin minerals to be stable supergene silicate alteration phases. Nonetheless, supergene sericite has been reported. Supergene effects have been eliminated from Table 1 wherever original authors provided descriptions which would permit it.

Known Extent Beyond Ore (Column 20).—Column 20 records the stated or mapped extent of alteration beyond the outer boundary of the orebody itself. These distances are somewhat uncertain since different observers drew the outer line on differing criteria. External alteration is narrow around the Bethlehem, B. C., deposit, a characteristic of many of the Canadian porphyry deposits. Other deposits show alteration extending thousands of feet, averaging approximately 2,500 feet. The higher numbers probably represent merging of hydrothermal with low-rank regional metamorphic effects, the two being distinguished only with difficulty. Significantly, detectable alteration extends laterally an average of half a mile beyond the orebodies, perhaps more, since some authors drew the outer limit on the basis of "bleaching" and the presence of sericite, phenomena that probably do not mark the true outer limit.

Peripheral Zone (Column 21).—Alteration is described in this zone for only five deposits. It is generally along well-developed structures and is seldom well described with respect to associated mineralization. Where alteration mineralogy is given it is of mixed affinity, dominantly propylitic, with sericite mentioned at Questa. Skarn is described in this zone at Morenci and Santa Rita. Skarn or tactite development is not as well reported in the literature as are hydrous silicate alteration assemblages. It is well known that skarn zones project into and apparently distort more normal zoning relationships, and that many porphyry deposits might also be described as contact-metamorphic deposits. Skarn can also apparently persist to the centers of orebodies.

Outer Zone (Column 22).—Mineralogic notation is given for 20 of the 27 deposits, with "propylitic" cited for Ely, Nevada. Of these, 18 include chlorite, 17 epidote, and 13 a carbonate (calcite in 11). Quartz is cited 7 times, sericite 6, zoisite–clinozoisite 5, kaolin 3, specularite 2, montmorillonite 2, and albite, hematite, magnetite, tourmaline, and rutile(?) once each. By far the most common assemblage is chlorite–epidote–calcite. Mention is seldom made of the replaced minerals, but the chief ones are amphibole, biotite, and plagioclase (Fig. 12). This assemblage has affected by far the largest volume of rock. The chlorite–epidote–calcite propylitic assemblage is always outside the ore zone and beyond the phyllic and argillic zones where these are present. Sericite is commonly reported even in outermost alteration assemblages. Whether this mineral varies importantly in composition, and hence in stability field and distribution, is yet to be shown. It has been observed, however, in amounts ranging from trace to moderate, and chiefly replacing plagioclase, in some outer zones not reported in Table 1. The distribution with respect to vertical zoning will be discussed below.

Intermediate Zone (Column 23).—This column describes predominantly argillic assemblages. Silicification is clearly more important here than in the outer zone, and the dominant minerals are quartz, kaolin, montmorillonite, and sericite. Argillic assemblages are discernible in 22 of the 27 deposits, if quartz–sericite–kaolinite (4 occurrences) be included as argillic. Quartz is cited first in most assemblages. Kaolin is cited singly or before montmorillonite in 17 of the 22 assemblages for which data are given. Three deposits have montmorillonite zonally beyond kaolin, and 7 involve sericite. No argillic assemblage is reported in 5 deposits.

Inner Zone (Column 24).—Most of the quartz–sericite (and pyrite) assemblages, the chief ore bearers of the porphyry copper deposits, fall in this inner zone column. The zone is reported unequivocally to have a pervasive quartz–sericite assemblage at 19 porphyry districts, a quartz–major sericite–minor K-feldspar array at 3 more, and a quartz–major sericite–minor kaolin assemblage at 3 more. At Braden a quartz–sericite–biotite–anhydrite inner-zone assemblage grades into stronger secondary biotite in the innermost zone. Only at Esperanza is a quartz–K-feldspar pair reported zonally outside of an unusual quartz–K-feldspar–biotite assemblage. Creasey (1966) indicates that K-feldspar can be part of his quartz–muscovite assemblage found at Bagdad, Bingham, and Chuquicamata. Creasey states (1966, p. 62) "quartz–sericite–pyrite without either a clay mineral or K-feldspar associated is a common assemblage that does not fit into any of the three previously described alteration types. If clay were present [as at Endako, Inspiration, and Mission–Pima, where kaolin is reported], the assemblage would belong to the argillic alteration, and if K-feldspar were present [as at Bagdad, Bingham, and Chuquicamata], it would belong to the potassic." Since the assemblage appears by far most commonly as quartz–sericite–pyrite, the term "phyllic" is herein urged as a specific term. Advanced argillic alteration, involving chiefly pyrophyllite, dickite, and topaz (Meyer and Hemley, 1968), is associated with phyllic assemblages at Butte and Bisbee. It is not reported elsewhere but may have escaped detection.

The phyllic assemblage of Column 24 is the innermost exposed alteration assemblage in at least six districts.

Innermost Zone (Column 25).—This column is perhaps the most surprising of the hypogene alteration data block. Potassic alteration, though relatively subordinate in the literature, occurs at most of the porphyry deposits as either an early or an innermost assemblage or both. It is reported as simple quartz, K-feldspar, and biotite(?) only at Endako; as quartz, K-feldspar, biotite, and sericite at 7 deposits, and as quartz, K-feldspar, biotite with chlorite, albite, fluorite, anhydrite, or tourmaline at 8 more. Quartz, K-feldspar, and sericite are reported at Silver Bell, and quartz with only K-feldspar occurs at Mineral Park and Questa. Quartz, phlogopite, and tourmaline occur at Cananea, but the zone may not be innermost there. Quartz, sericite, biotite, and anhydrite occur at Braden. Anhydrite at several locales is given in parentheses in Table 1 where it has not been described in print. Specimens of anhydrite from Esperanza, Questa, San Manuel–Kalamazoo, and Santa Rita have been observed to swell the published occurrences at Butte, El Salvador, Toquepala, Ajo, and Braden.

The common occurrence of anhydrite in the potassic zone indicates that (1) redox potentials are considerably higher in the late magmatic-deuteric fluids than the prevalence of unoxidized sulfur species would indicate; (2) a high percentage of the total sulfur in the porphyry system may be present as sulfate; and (3) high-temperature hydrothermal reactions involving silicates, oxides, and sulfides must concern themselves with equilibria involving higher total sulfur than the net sulfide contents would indicate. It is also noteworthy that the conclusion of Lutton (1959) concerning depositional continuum from pegmatoid into "porphyry" conditions are supported and that the elements grouped by Ringwood (1955) as "complex formers" of high ionic potential are precisely those found in major and trace minerals in the porphyry base-metal deposits, especially in the potassic alteration zone.

Other characteristics of the potassic zone are briefly described by Meyer and Hemley (1963) and Guilbert and Lowell (1968). Ore commonly occurs at the interface between potassic and phyllic alteration zones. The potassic zone is generally central or deepest, or if a time sequence is discernible, it is earliest.

Zoning Sequence from Center and Bottom (Columns 26 and 27).—The upward zoning and outward zoning of alteration assemblages are seldom reported as such, but their systematic entry by description or from map or diagram reveals a significant sequence.

Seven, possibly eight (the position of phyllic alteration at El Salvador is uncertain), of the deposits show alteration assemblages in the same outward sequence: potassic, phyllic, argillic, and propylitic. Even where certain assemblages are not reported, the remaining assemblages fall in the same order. Two deposits, possibly three, show only potassic and phyllic zones, four lack only argillic, and six start with phyllic and include argillic and propylitic. For a few deposits the sequence is unknown.

Vertical sequence of zonation is generally much less well known, so assignments can be made in Column 27 only for Butte, Climax, El Salvador, and San Manuel–Kalamazoo. Except for uncertainty at El Salvador, the order is consistent with lateral zoning. Outward and upward zoning of the 27 deposits is most consistent with the sequence of potassic, phyllic, argillic, and propylitic assemblages.

An alteration assemblage has been noted in several localities which consists of K-feldspar, biotite, coarse sericite, chlorite, and albite, accompanied by moderate pyrite and chalcopyrite mineralization. This group does not readily fit the classification outlined in Table 1, nor do the deposits generally reach ore grade. The writers are of the opinion that this represents a deep assemblage whose relationship to the main porphyry system has not been exposed for study because of the geometry and large vertical dimensions involved.

Hypogene Mineralization (Columns 28–35)

As has long been known, hypogene sulfide-oxide mineral assemblages are closely related in time and space with silicate alteration mineral assemblages in porphyry deposits. The designation of pyrite and magnetite as ore minerals rather than alteration minerals, for example, appears to be largely arbitrary.

In Table 1, sulfide-oxide mineral assemblages have been described in Columns 28–35 with reference to the same alteration zones as are described in Columns 20–27. The consistent sequence through each zone and from one assemblage to another outward from the center is again significant.

Peripheral Alteration Zone (Column 28).—This column describes metal occurrences that form a discontinuous ring normally near the outer edge of the propylitic zone. The deposits tend to be small to medium size, although large lead-zinc deposits with or without precious metals occur in this zone at Santa Rita, Bingham, and Butte. At least minor peripheral mineralization is found in all 27 deposits studied. Arcuate clusters of mines or prospects surround 23 deposits. Minerals common in this zone are sphalerite, galena, silver, chalcopyrite, gold, and pyrite, and less commonly, specularite, enargite, famatinite, tetrahedrite, barite, various sulfosalts, and manganese and vanadium minerals.

Outer Alteration Zone (Column 29).—This zone generally corresponds to the propylitic alteration zone, and mineralization is generally restricted to pyrite, although sparse chalcopyrite is generally present along with variable amounts of bornite, molybdenite, magnetite, specularite, rhodochrosite, sphalerite, galena, and rhodonite.

Intermediate Alteration Zone (Column 30).—This corresponds roughly to the argillic alteration zone, and the bulk of mineralization is usually pyrite with high pyrite-to-chalcopyrite ratios which average 23:1 in deposits for which figures are available. Variable amounts of bornite, molybdenite, tennantite, sphalerite, galena, enargite, chalcocite, and huebnerite have been found in this zone. Hypogene ore-grade mineralization may overlap into this zone, but generally this zone is outside the orebody.

Inner Alteration Zone (Column 31).—This zone commonly corresponds to the phyllic alteration zone and typically contains abundant pyrite and high total sulfides together with pervasive sericitization. Pyrite content is not reported quantitatively for most deposits but it appears to average about 10 percent by weight for the 27 deposits, or about 16 percent, excluding the porphyry molybdenum group, which are relatively low in pyrite. Pyrite-to-chalcopyrite ratios average 12.5:1. This zone commonly constitutes the ore zone, especially in those deposits in which chalcocite enrichment has occurred. The principal "ore" mineral is pyrite, which occurs with chalcopyrite, molybdenite, and variable but generally small amounts of bornite, chalcocite, sphalerite, enargite, and magnetite.

Innermost Alteration Zone (Column 32).—This zone is generally equivalent to the potassic alteration zone and is usually the central zone. Total sulfide content is low to moderate with an average pyrite content of about one percent and a pyrite-to-chalcopyrite ratio of 3:1 in the deposits tabulated. This zone may reach ore grade and probably accounts for most ore in solely hypogene ore deposits. It also forms the "low-grade center" in five deposits. The sulfide mineral assemblage is chalcopyrite, pyrite, and molybdenite.

Overall Abundance of Major Ore Minerals (Column 33).—In the porphyry coppers, pyrite is by far the most common sulfide, followed in order by chalcopyrite, bornite, enargite, and molybdenite. Molybdenite is present in all 27 deposits, a fact not previously recognized.

Zoning Sequence from Center (Column 34) and from Bottom (Column 35).—Grading outward from the center of the deposit, the typical lateral mineralization sequence appears to be the assemblages (1) chalcopyrite, pyrite, bornite, molybdenite; (2) pyrite, chalcopyrite, molybdenite, bornite; (3) pyrite, chalcopyrite; and (4) sphalerite, galena, silver, gold. Apparent reversals were noted in only three camps.

Information as to vertical zoning is extremely limited. Most deposits have been explored by mine openings or drill holes only to depths which are shallow as compared with the probable original vertical dimensions. Tentative evidence from 13 deposits suggests that typically a pyrite–chalcopyrite–molybdenite assemblage grades upward into pyrite. An apparent reversal of this order has been reported in two deposits.

Occurrence of Sulfides (Columns 36–42)

Hypogene sulfides in porphyry deposits typically form veinlets or disseminated grains. This habit is probably related to the fact that crackle brecciation is present throughout the volume of mineralization. Broadly, the porphyries seem to be masses of homogeneous rock penetrated by reticulate fractures and mineralized by fluids which soaked the mass rather than being constricted to tabular masses or replacements.

Occurrence of Sulfides by Zones (Columns 36–40).—A progressive gradation in sulfide distribution is noted in almost every deposit tabulated. This sequence progresses from veins in the peripheral zone to veinlets in the outer zone, veinlets and minor disseminated grains in the intermediate zone, veinlets approximately equal to disseminations in the inner zone, and predominant disseminations in the innermost zone. The tendency for the increasing importance of dissemination towards the core may result from metasomatism or recrystallization of the rock and healing of veinlets. The absence of prominent veins in most alteration zones may indicate that a crackle brecciation zone behaves as an incompetent mass which can not support through-going fissures and veins.

Breccia Pipes and Crackle Zones (Columns 41 and 42).—Breccia pipes are present in 20 and are mineralized in 18 deposits. Toquepala and Cananea are mineralized breccia pipes in which ore limits are nearly coextensive with the pipes. Toquepala, in particular, shows evidence that the surrounding alteration zones have been telescoped into a relatively thin halo, and alteration assemblages within the orebody overlap. The Braden orebody apparently consists of a vertical cylindrical deposit which has been penetrated along its vertical axis by a postore breccia pipe.

A well-developed crackle zone is present in 26 deposits but is largely absent in the skarn of the Mission–Pima orebody. Crackle zones are usually circular in outline and are always larger than the orebodies, typically fading out in the zone of propylitic alteration. Crackle texture is often less distinct near the center, particularly if a potassic alteration zone is present.

Supergene Sulfides (Column 43)

Twenty-three deposits contain supergene sulfides, and secondary enrichment was required to reach marginal ore grade in 10. Supergene chalcocite (and probably also secondary digenite and djurleite) is present wherever secondary sulfides occur and always constitutes the chief enrichment mineral. Covellite is reported in 12 deposits, generally low in the enrichment blanket.

Porphyry Deposit Genesis

The data of Table 1 and the inferences drawn from them, from the field, and from the detailed geology of the San Manuel–Kalamazoo deposit appear to support the orthomagmatic model described earlier, although the nature of the data and the scale factors are not such that the problems can be conclusively resolved. The formational model which appears most generally applicable is one of a differentiation continuum as suggested many years ago by W. H. Emmons (1933) in his description of cupola formation. Near-surface intrusion of a melt which produces rocks of intermediate granitoid composition is either a passive intrusion as at Butte, Santa Rita, and Ajo, or a dike swarm as at San Manuel–Kalamazoo and Safford. Response of wall rocks to this intrusion depends upon their composition, their structural fabric, and the nature of the intrusive melt. Cooling begins from the surface downward, and gentle thermal gradients are established from higher temperatures at depth to slightly lower ones nearer to the surface and outward. Mineralization and alteration chemistries are established with respect to these gradients, chemistries that reflect essentially deuteric to late magmatic conditions, with potassic alteration yielding upward and outward through the phyllic zones (or the "zone of feldspar destruction," Robertson, 1962) into the zones of more typical hydrothermal alteration responses. These gentle gradients presumably have a direct bearing on the large dimensions of the porphyries and the coarsely gradational alteration-mineralization boundaries which they show.

We thus reaffirm on the basis of the published record that the porphyry copper deposits are the results of a physical-geochemical continuum from low-temperature magmatic to "conventional" hydrothermal conditions. The gradients are reached as a result of cooling in an intrusive mass, and the alteration-mineralization zonal boundary interfaces appear to have been established as standing forms rather than as upward and outward advancing mega envelopes. Application of the Hemley-Jones model of potassium silicate stabilities and alteration, as modified by Fournier (1967) and Meyer and Hemley (1968), permits passage from essentially magmatic conditions at depth to areas of higher hydrogen ion concentration and lower K^+/H^+ and lower temperatures either with time at a given point deep in the system or through space upward and outward at a given time. It is important to note, however, that an inner zone need not have been preceded by the mineralogy and assemblages of an outer zone in a system of decline, of lowering temperatures, or of shallow upward gradients. Variation in the differentiation index of the intrusion may well dictate whether copper or molybdenum predominates in the ultimate deposit, molybdenite tending to be associated with more silicic variants.

Conclusions

The foregoing summary forcefully demonstrates that the porphyry copper-molybdenum deposits display important unifying geologic characteristics including various lateral and vertical zones. The fact of zoning is not new, but several important aspects, such as sulfide species, detailed alteration assemblages, and the characteristic occurrences of the sulfides, is far more widespread than has previously been realized. Indeed, a "typical" porphyry copper deposit can be hypothesized from Table 1 and is included along the bottom of the table.

It is especially noteworthy that many, and perhaps most, porphyry deposits have coaxially cylindrical alteration zones. Factors that limit the development of discernible symmetry in porphyry deposits include the following:

1. Regional or local structural fabric that may produce asymmetry in alteration and mineral ore zones.
2. Heterogeneous and contrasting composition of preore rocks, especially the presence of sedimentary "screens."
3. Dislocations of the original geometry by fault displacement or by postore intrusions.
4. Exposure of the porphyry system laterally and at depth.

The vertical dimension interpreted for the San Manuel–Kalamazoo system is on the order of 8,000–10,000 feet. No definite evidence suggests that this vertical dimension is either typical or normal, but the mineral assemblages typical of different vertical zones in San Manuel–Kalamazoo appear to be useful in estimating the depth of formation of several deposits. These "depth levels" of present exposure surfaces for several porphyry copper deposits are shown in Figure 13. Morenci is placed high in the hypothetical vertical section because of the wide exposure of the phyllic zone without exposure of potassic assemblages. Several aspects of Morenci geology—breccia zones, the broad-scale alteration symmetry, and the occurrence and distribution of sulfides—suggest that potassic alteration will be encountered at depth under the existing open pit.

It is also noteworthy here that phyllic zone alteration assemblages, with their high pyrite content and their profusion of veinlets and microveinlets, are chiefly responsible for the extensive development of supergene oxidation, leaching, and enrichment of southwestern North American deposits. This high level of exposure appears to be the most common, especially in supergene-enriched deposits.

Recent publications on the Chino deposit at Santa Rita, New Mexico, show that an island of low-grade material is being left in the center of the northern portion of the pit area. This island of low grade is symmetrically and centrally disposed with respect to secondary K-feldspar, chalcopyrite, and pyrite distribution as reported by Nielson (1968, Figs. 6, 7, and 9). This "low grade island" may represent the cropping out of a low-grade barren zone analogous to the central core at San Manuel–Kalamazoo. Lastly, Gilluly's (1946) description of the Ajo deposit involves much the same K-feldspar–biotite–chlorite–sericite and magnetite–chalcopyrite assemblages and zonal characteristics as those encountered at depth in San Manuel–Kalamazoo. It appears possible, therefore, to assign a third dimension to at least several deposits, and many others may be assigned depth parameters as further information develops. For example, brecciation and ring diking may have significance in regard to depth of formation.

It also appears significant that the major porphyry deposits of British Columbia (for example, the Bethlehem and Lornex deposits) occur in quartz diorite, and the K-feldspathic rock types reported at Ajo yield outward to a quartz diorite composition (Wadsworth, 1968). The evidence concerning large-scale metasomatism of rocks, generally with attendant enrichment in K-feldspar and quartz as described at Bingham Canyon by Stringham (1956), may well prove to be more general than is now realized. The alteration assemblages, mineralization characteristics, and occurrence of sulfides at Bethlehem and Lornex are consistent with deep exposure, and we may see now exposed a relatively deep-seated porphyry environment. The fact that these deposits also involve quartz diorites rather than granodiorite or quartz monzonites may be another manifestation of the vertical dimension in porphyry deposit genesis.

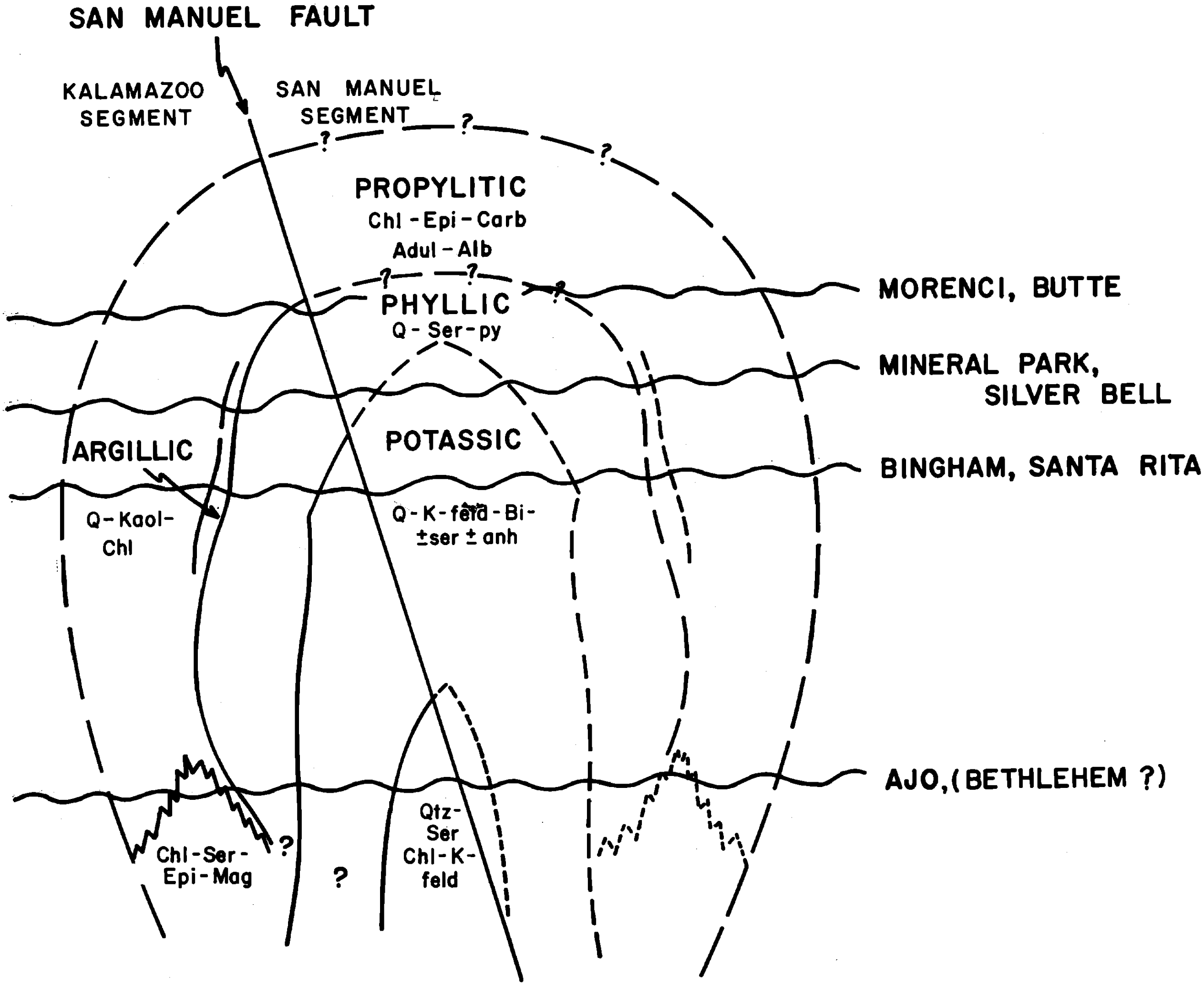


FIG. 13. Schematic drawing of San Manuel–Kalamazoo showing exposure levels of several porphyry copper deposits. Other deposits could be added, but these few serve to show a vertically developed dimension.

A growing body of data indicates that the porphyry deposit minerals may form at depths as shallow as 5,000–10,000 feet. Facts supporting this conclusion are (1) the occurrence of porphyry rocks in all 27 deposits of Table 1; (2) the cutting of all deposits by postore erosion surfaces; (3) the widespread occurrence of brecciation (even though the host intrusions are usually passively emplaced); (4) the location of 14 deposits in Cretaceous or younger preore rocks while the intrusions themselves are of late Cretaceous or younger age; (5) regional structural-stratigraphic considerations; and (6) the common occurrence of porphyry-ore-forming environments in cupola-like stocks less than one square mile in area at the ore-forming elevation.

Deposits seem to range from "wet" types having high pyrite-to-chalcopyrite ratios and surrounded by enormous halos of pyrite–sericite–quartz hydrothermal alteration to "dry" deposits with relatively low sericite–pyrite content. Although perhaps the terms are too casual, "wet" and "dry" refer to the net apparent abundance, involvement, and permeation of a mineralizing-altering fluid. Concentric zoning is also present in "dry" deposits, but it is telescoped laterally into a small fraction of the halo thickness of the "wet" type. The "wet" type is represented by most of the Southwest deposits, such as Bingham and Morenci, and includes most of the large porphyry copper deposits. The "dry" type is represented by many of the British Columbia deposits, such as Bethlehem, and includes many of the hypogene ore-grade porphyry coppers.

The most distinctive feature of the porphyry deposits is simply their huge size as compared with other hydrothermal ore deposits. Including ore-grade mineralization and surrounding alteration and mineralization, they assume dimensions more commonly associated with stocks than with ore deposits.

The bulk shape of porphyry deposits reflects large-scale structural control of mineralization and may also be related to the original depth of formation. Flat-tabular, cone, and flat-dipping tube-type deposits may represent relatively shallow depth of formation where steep environmental gradients prevail. Steep, columnar deposits with long vertical dimensions and little brecciation seem to indicate relatively great depth of formation and gentle environmental gradients.

Breccia pipe deposits, such as Toquepala, with only thin alteration halos and with evidence of violent emplacement, are clearly representative of a different genesis in which the mineralizers may have evolved suddenly in a more or less open vent with relatively steep pressure gradients. Examples of blind mineralized breccia pipes at Cananea, Pilares, and elsewhere indicate, however, that mineralized breccia pipes need not necessarily be either open to the surface or emplaced at shallow depth.

Porphyry deposits tend to have either elongate, vertical, columnar shapes (San Manuel–Kalamazoo and Bingham) or foreshortened columnar, almost discoid shapes (Climax or Ray). These shapes suggest that migration of hydrothermal fluids was controlled by nearly vertical gradients and that fluids, however derived, migrated upward across large areas, up to tens of thousands of feet in diameter. It appears likely that the mineralizers originated as a separation of fluids at the point of crystallization of the "host intrusive body." It should be noted that the "overhang" effect or beet shape of San Manuel–Kalamazoo could also be consistent with an influx of deeply circulating, externally derived, perhaps cooler water, although both the depth and wall rocks involved make this explanation seem unlikely.

Many characteristics described in Table 1 and systematized in Figure 13 are consistent with one another. Variations in the character of sulfide occurrence, for example, appear best explained by considering that dissemination textures are compatible with a model involving crystallization of rock-forming silicates (i.e., the potassic zone) such that the sulfides, which are really igneous accessory minerals, are deposited either as truly included minerals or in fractures and microfractures in newly competent rocks which are subsequently healed by local crystallization.

The San Manuel–Kalamazoo deposit thus appears to be typical and illustrative of porphyry copper and molybdenum deposits. We suggest in conclusion that the integrated model of vertical and lateral silicate-oxide alteration, sulfide mineralization, and sulfide occurrence characteristics in the porphyry deposits may be useful to economic geologists both explorationally and scientifically.

Acknowledgments

The writers wish to express their appreciation to their many colleagues whose discussion and comments have contributed to this paper, to L. B. Gustafson, James Gilluly, and T. W. Mitcham who reviewed the manuscript, and to H. R. Hauck, M. T. Wolf, and B. Townsend for their assistance in preparing the manuscript and illustrations.

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