Uranium deposits of the world, excluding Europe

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Description of types of deposits

This paper is an overview of the diverse types of uranium deposits that are recognized in the world, exclusive of Europe, and presents brief descriptions of selected deposits of each major type. Descriptions of geology, mineralogy, genesis and economics of each type of deposit precede summaries of selected occurrences of most types. The locations of described deposits are shown in Fig. 1.

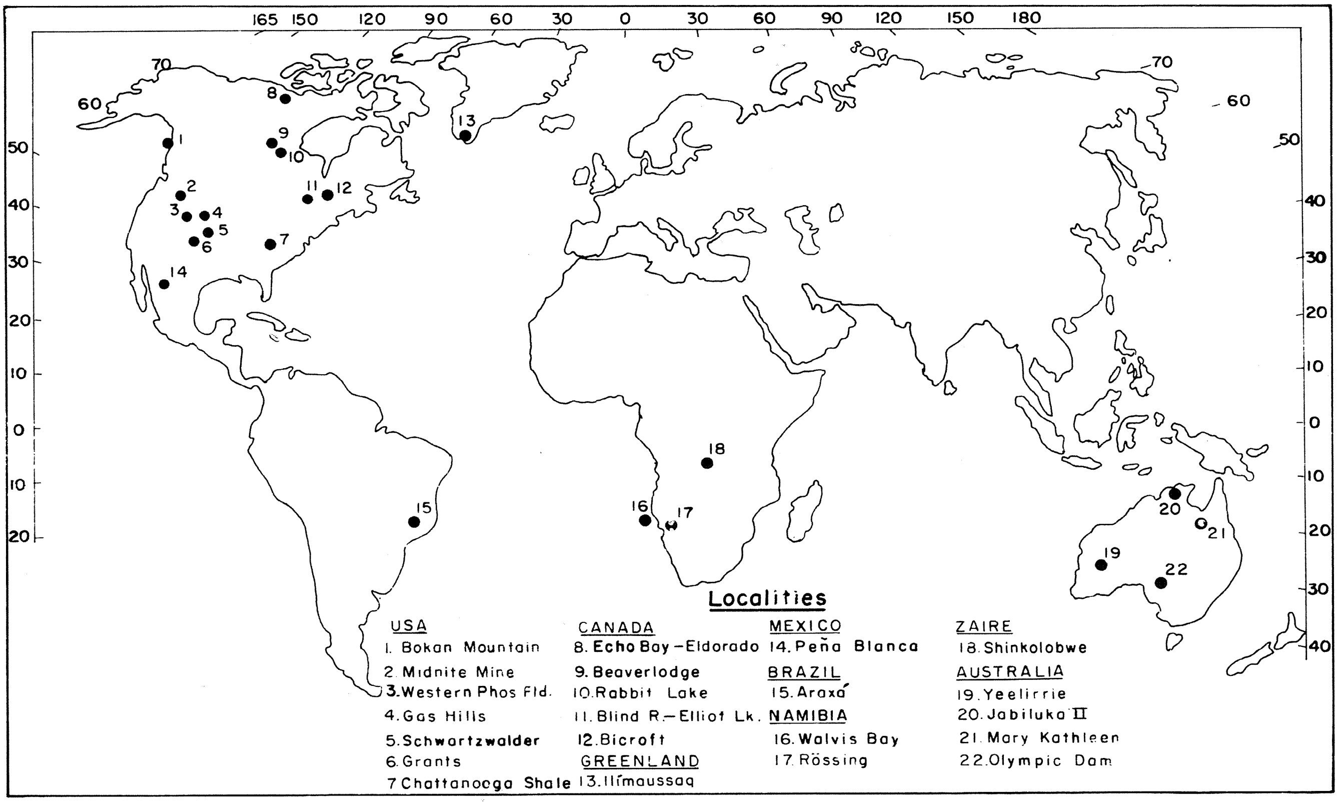

Fig. 1 Location of uranium occurrences described

Uranium is a lithophile element that is enriched in the earth's upper crust, where it has an abundance of about 2 ppm.[25,42] It is enriched in acid igneous rocks, such as granites, to about 4 ppm (occasionally to 20 ppm), whereas basic igneous rocks average 1 ppm. Uranium is known to have formed economic deposits in a great variety of igneous, metamorphic and sedimentary rocks, ranging in age from late Archaean to Holocene. Because of this ubiquitous nature and its habit of forming concentrations in diverse geologic environments, uranium deposits of one or more types are present in nearly every country.

One problem that is created by such a plethora of deposits is the difficulty of placing them in a rigid classification scheme. Many classifications have been proposed, but that used here (Table 1) is modified from that of Dahlkamp[30] and is based on the presumed time relationship of host rock to uranium emplacement. A few of the types of occurrences that are described here are not characterized by currently economic deposits, but they do represent potentially enormous uranium resources. The relative importance of major types of occurrences in relation to current reserves is shown in Fig. 2.

Sedimentary deposits

One of the major categories of uranium occurrences is that of sedimentary deposits. Such deposits are considered secondary occurrences in that they owe their existence to exogenic processes, but in these types the uranium was deposited at the same time as the enclosing sediments. They formed as a consequence of erosion of previous uranium deposits under both oxidizing and reducing conditions. Some formed in late Archaean–early Proterozoic time (2800–2200 m.y. ago) when a non-oxidizing atmosphere favoured mechanical weathering and led to the formation of placer deposits with detrital uranium.[64,93,94] Many other sedimentary uranium deposits formed after the development of an oxidizing atmosphere in mid to late Proterozoic time about 2200 m.y. ago.[103,112,113] From that time chemically liberated uranium has moved in aqueous solution to numerous lithochemical environments in which it has formed secondary concentrations. Sites of reconcentration include (1) the sea, where it has accumulated in muds, organic oozes and phosphates or has remained in solution in brines, (2) terrestrial sediments in intercratonic and intermontane basins, (3) littoral clastic sediments and (4) the weathering crust surface.

Quartz-pebble conglomerates

Quartz-pebble (Oligomictic) conglomerate uranium deposits

B. De Vivo et al. (eds.), *Uranium geochemistry, mineralogy, geology, exploration and resources*

Table 1 Classification of uranium deposits

Mode of origin	Host rock/type deposit	Example
Sedimentary	Quartz-pebble conglomerate	Blind River–Elliot Lake (Canada)
	Black shales	Chattanooga Shale (U.S.A.)
	Muds	Walvis Bay (Namibia)
	Phosphorites	Western U.S.A.
	Bauxites	Arkansas (U.S.A.)
	Placers	Southeastern U.S.A.
	Brines	Sea water
Effusive	Silicic volcanics	Peña Blanca (Mexico)
	Mafic volcanics	Olympic Dam (Australia)
Intrusive	Peralkaline nepheline syenites	Ilímaussaq (Greenland)
	Carbonatites	Araxá (Brazil)
	Anatectics	Rössing (Namibia)
	Pegmatitic alkalitic granites	Bokan Mountain (U.S.A.)
	Granites	Spokane Mountain (U.S.A.)
	Pegmatites	Bancroft (Canada)
	Hydrothermal veins	Schwartzwalder (U.S.A.) Shinkolobwe (Zaire)
Metasomatic	Contact	Mary Kathleen (Australia)
	Sodic	Ukranian Shield (U.S.S.R.)
Metamorphic	Phyllites	Forstau (Austria)
	Schists	Portugal
Uncertain (vein-like)	Unconformity-related	Rabbit Lake (Canada) Jabiluka II (Australia)
	Vein-like in metamorphics	Beaverlodge (Canada) Echo Bay–Eldorado (Canada)
	Vein-like in sediments	Orphan mine (U.S.A.)
Epigenetic	Sandstones	
	Peneconcordant	Grants (U.S.A.)
	Roll-type	Gas Hills (U.S.A.)
	Stack	Franceville Basin (Gabon)
	Calcretes	Yeelirrie (Australia)
	Lignites, coals and carboniferous shales	Williston Basin (U.S.A.)
	Limestones	Todilto LS (U.S.A.)
	Epigenetic phosphates	Baukoma (Zaire)

occur in quartz-pebble conglomerates with a quartzite matrix and abundant pyrite. They contain probable detrital primary uranium minerals (uranite, brannerite, thucholite and uranothorite), and in some districts gold is an accessory. Economic concentrations are apparently restricted to the late Archaean–early Proterozoic (2800–2200 m.y. ago), but other uraniferous pebble conglomerates occur at various horizons in Precambrian shields throughout the world. The economic occurrences represent approximately 15.5% of known uranium reserves.

The origin of these deposits is controversial. They appear to be controlled not only by their proximity to unconformities (i.e. immediately above the post-Archaean unconformity) but also by hydrodynamic processes responsible for the packing density of the quartz pebbles, the abundance of pyrite and its predecessors, and its proximity to a uranium-rich Archaean source terrain. Many of the conglomerates were deposited in fluvial channels, but others appear to have been laid down in lacustrine, littoral marine and deltaic environments. Whether the uranium and other metals in the conglomerates are syngenetic (placer), hydrothermal or redistributed has not been completely resolved, but most recent literature[80, 92, 97] supports a detrital or placer origin. If they are true placers, these Precambrian uranium-bearing conglomerates are unique. The ore minerals, uraninite, brannerite, thucholite, etc., are rarely seen in Upper Proterozoic and Phanerozoic placers because of their instability during weathering and transport in an oxidizing environment.

	SHORT TONS U_3O_8	%
Pebble Conglomerate	380 000	15.54
Volcanic	380 000	15.54
Plutonic — Metamorphic	298 000	12.20
Veinlike	596 000	24.40
Sandstone	700 000	28.64
Other	90 000	3.67

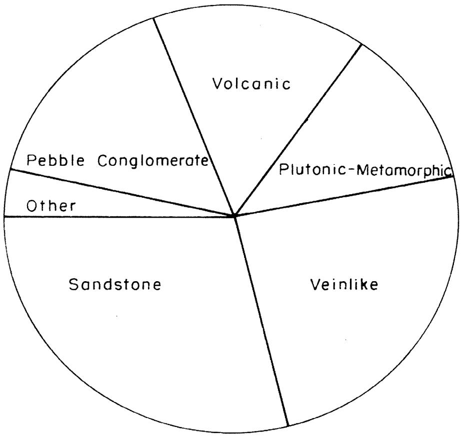

Fig. 2 Distribution of Western world uranium reserves ($30/lb) by host

Their preservation is presumably an indication of an anaerobic environment during late Archaean–early Proterozoic time.

Precambrian quartz-pebble conglomerates are low-grade uranium resources in which uranium may be just a by-product of gold mining with a grade as low as 0.01% U_3O_8, or it may be the major ore mineral with grades from 0.10 to 0.15% U_3O_8. Individual deposits range in size from 5000 to 150 000 ton U_3O_8.

Classic quartz-pebble conglomerate districts are the Blind River–Elliot Lake district, Canada, and the Witwatersrand, South Africa. Similar deposits are known in Australia, Brazil, Finland, Algeria, India, the U.S.S.R. and the U.S.A.

Black shales

Uraniferous black shales are of marine origin and, in addition to colour, are characterized by high sapropelic organic content, abundant pyrite or marcasite in thin lenses, nodules or disseminated particles, and the paucity of calcium and magnesium carbonates. The shales also contain small quantities of such other metals as Mn, Ti, V, Cu, Cr, Mo, P and REE. Most of these metals are dispersed in the shale, but phosphate may also occur as nodules or phosphate-rich layers.[124]

Uraniferous shales are generally relatively thin, widespread units interbedded with other shales, limestones, phosphorites, cherts or bentonites. Some are members of cyclic units that consist of shale, sandstone and limestone, but others are siliceous and may be lateral equivalents of siliceous volcanic rocks. Most black shales are evenly laminated and dense, breaking with conchoidal fracture when fresh.

All black shales contain more uranium than the average sedimentary rock, but to be classified as a uraniferous black shale they must contain more than 0.005% U_3O_8. Uranium content differs from bed to bed, but the grade of a particular bed is remarkably uniform and predictable over large areas. Uranium content seems to be highest in closely laminated beds or those that are the finest grained, and also increases with increase in organic matter. Phosphate nodules are commonly richer in uranium than surrounding shale, but there are exceptions. No uranium minerals have been identified from the shales. It is probably adsorbed in organic or phosphatic molecules or absorbed by clays.

Uraniferous black shales are believed to have been deposited very slowly on or adjacent to tectonically stable continental platforms. Some of the richest and thickest deposits seem to have formed near platform margins. Pre-orogenic stability appears to be a requisite. The uranium seems to have accumulated syngenetically with the sediment. The marine waters may have been greatly enriched in soluble uranium by nearby volcanism or by intense weathering of granitic source terrain under oxidizing conditions. The uranium may have been extracted from the sea water (under reducing conditions), by organic matter, phosphate minerals, pyrite or colloidal clay.

Uranium deposits are typically several feet thick and cover tens, hundreds or thousands of square kilometres. Uranium content ranges from less than 0.001% to more than 0.05% U_3O_8; but, because of the immense volume of black shales, uranium resources are very large. The only near-economic deposit (Ranstad, Sweden) averages about 0.035% U_3O_8[75] and has potentially recoverable resources of about 300 000 ton U_3O_8. Other uraniferous shales have almost an order of magnitude less uranium. Problems common to the development of these deposits are the difficult and costly metallurgy and the enormous environmental impact. Most of the deposits can be mined only by large open-pit operations that must be conducted in moderately populated areas.

All the larger and higher-grade uraniferous black shales are of Palaeozoic age, but some of the smaller deposits in Canada are Precambrian and some in the U.S.A. are of Mesozoic and Caenozoic age. The best known black shales are the Cambrian Külm Shale of Sweden and the Devonian–Mississippian Chattanooga Shale of the U.S.A. Similar shales are present in Brazil, Canada, France, Norway, Portugal, the U.S.S.R. and West Germany.

Muds

Many of the world's large anaerobic water bodies contain relatively thin deposits of Recent mud with a uranium content nearly an order of magnitude larger than that in average marine sediments. The muds range in thickness from 1 to 15 m and consist of planktonic ooze, sapropel and clay. Uranium averages about 25 ppm and most of it seems to be bound to planktonic matter (coccoliths and diatoms). Like black shales, uraniferous muds represent a very large uranium resource—perhaps 10 000 000–20 000 000 ton U_3O_8—but exploitation problems are enormous.

The two largest deposits of uraniferous muds are in the Black Sea (Turkey and U.S.S.R.)[33] and in the Walvis Bay area, South Africa.[78] Similar deposits are known from the Caspian and Baltic Seas and some Norwegian fjords. It thus appears that restricted environments with a trend to euxenic conditions favour uranium accumulation.

Phosphorites

Sedimentary marine phosphorites are composed principally of phosphatic minerals, and many contain significant amounts of disseminated uranium. These phosphorites have been classified as either miogeosynclinal or platform types. Four additional types that are low in uranium and of little economic importance are residual phosphorites, phosphatized rock, river pebble deposits and guano.

Phosphorites that are richest and thickest and contain the most uranium are the miogeosynclinal type deposited on the outer parts of continental shelves where upwelling of deep marine waters has occurred. These waters were saturated with respect to phosphate and were probably the source of the phosphate in the phosphorites. These phosphorites are commonly present in thick miogeosynclinal sequences, where they are associated with carbonates, black shale, chert, carbonaceous mudstone and minor amounts of mudstone.[74] The Phosphoria Formation of the western U.S.A. is an example.

Platform phosphorites are generally nodular, rather than bedded, and are associated with sandstone, limestone and glauconite. Most are low in uranium, but an exception is the Bone Valley Formation of the southeastern U.S.A. This unit has been reworked and enriched by re-exposure to sea water during a subsequent transgression. These phosphorites differ from shelf phosphorites in that they are near-shore sub-tidal and shoreline deposits, and they change facies oceanward to carbonate sediments.

All marine phosphorites consist mostly of microcrystalline apatite (carbonate fluorapatite) in the form of laminae, pellets, oolites, nodules and skeletal or shell debris. Uranium, considered syngenetic, may be present in carbonate fluorapatite as a substitute for calcium. Uranium in sea water was probably incorporated during or shortly after precipitation, and it is usually disseminated rather uniformly throughout a given bed or horizon. Primary uranium minerals are rarely present, but secondary uranium minerals (tyuyamunite, autunite, torbernite) have been identified in a few localities.

Because most of the world's phosphate resources are marine phosphorites, the uranium content of phosphate products is relatively uniform, ranging from 60 to 130 ppm. The phosphate product from the principal phosphate-producing fields of central and southern Florida (U.S.A.), Morocco, Idaho and Utah (U.S.A.), the Western Sahara, Mexico, Jordan, eastern Florida (U.S.A.), Peru and Iraq has a relatively uniform concentration of 100–120 ppm uranium. Other major phosphate-producing areas (North Carolina, Wyoming, Montana, other Florida districts, U.S.A., Australia, Tunisia and Algeria) have a concentration of 60–90 ppm uranium. DeVoto and Stevens[38] estimated that uranium in the 292 727 000 000 ton of the Western world's total estimated recoverable phosphate product is 29 532 000 ton. The U.S.A. has the bulk of these phosphate deposits (223 342 000 000 ton recoverable) with an estimated recoverable resource of 22 459 000 ton uranium. Other countries with sizable resources of uranium in phosphate are Morocco (4 950 000 ton uranium), Western Sahara (555 000 ton uranium), Mexico (415 000 ton uranium) and Jordan (360 000 ton uranium).

Bauxites

It has long been known that most bauxites are moderately radioactive. Assays of bauxite samples from throughout the world show ranges of concentration for the three radioactive elements present—thorium (8–132 ppm), uranium (3–27 ppm) and potassium (0–0.3%).[1] Approximate median values are thorium, 42 ppm; uranium, 8 ppm; and potassium, 0.1%. In general, bauxites developed on mafic igneous rocks are lowest in uranium (averages 4.2 ppm). Those formed on other rock types are higher—shales, 10.5 ppm; carbonates, 12.9 ppm; and acid igneous, 15.9 ppm. There are also indications that Th and U concentrations may reflect the grade of the bauxite ore.

Experiments indicate that much of the thorium and uranium is contained in resistate minerals, such as zircon, and that very little uranium is carried over into commercial alumina and aluminium metal.

In the aluminium industry the most widely used method for the extraction of alumina (Al_2O_3) from bauxite is the Bayer process, in which aluminium and silica are leached from bauxite under pressure with hot caustic soda. The residue is 'red mud', a silt-like mixture of iron oxides, titanium dioxide, silica, caustic and many impurities. Roughly one ton of insoluble residue of red mud is produced for each ton of alumina. The liquors, following appropriate treatment to recover alumina, are recycled. In view of its high solubility in nature, it seems that most of the uranium must also be leached and possibly build up in the leach liquors. Small mills are now recovering this uranium, but analyses of red muds show uranium contents that vary from 12 to 40 ppm uranium, which suggest that it is not all leached.

Present annual world production of bauxite is about 70 000 000 ton, which results in the production of 35 000 000 ton of red mud. Many plants throughout the world have been operating for 40 years or more, and the resulting red mud wastes may exceed 1 000 000 000 ton. Assuming an average of 10 ppm uranium in this mud, the volume of uranium is very large. The bulk of the radioactive bauxites are in Brazil, Cameroon, Surinam and the U.S.A.

Placers

Placer deposits are concentrations of heavy minerals that form in high-energy fluvial and littoral environments. Here currents and waves selectively concentrate high-density mineral grains and winnow out finer and lighter material. Placer minerals are generally dense and resistant to weathering, solution, abrasion and impact. In radioactive placers most radioactivity is from thorium-bearing minerals (i.e. monazite, zircon, thorite and euxenite). These minerals are generally more resistant than uranium to weathering and destruction during transport. Modern placers[32] show a total absence of uraninite, but trace amounts of uranium occur as minor constituents in monazite, xenotime and thorite. Conversely, ancient placers (quartz-pebble conglomerates) commonly contain uraninite and, in places, brannerite.

Radioactive placers consist of minerals derived from the weathering of silicic and alkalic igneous and metamorphic rocks. They are on and peripheral to shields or regions of strongly deformed and intruded rocks. Two types of placers can be recognized on the basis of depositional environment—stream and beach.

Stream placers, because they occur in mountainous high-energy environments, are ephemeral deposits formed close to their source areas. Seldom are they preserved by lithification. Stream placers are known in North Carolina, South Carolina and Idaho in the U.S.A., British Columbia in Canada, India and Japan.

Beach (littoral) placers are generally deposited near base level and are more susceptible to burial and preservation. Thus, they are more common in the geologic record. Included in this group are placers that form either as beaches or various types of bars (longshore, baymouth, shoal, etc.). Unlike stream placers, beach placers may form tens or hundreds of kilometres from their source areas. The greater the distance of transport the greater are the attrition and reduction in grade by abrasion and solution. Generally, only the most resistant minerals (monazite and zircon) survive. The most radioactive placers are those in Upper Cretaceous beach sandstones in the western U.S.A. and those in Holocene sediments in China, Egypt, India, Brazil, Korea, Malagasy Republic, Taiwan and Alaska, and Georgia and Florida in the U.S.A.

Placers are a low- or very low-grade uranium resource and many of their sometimes uraniferous minerals, such as monazite and zircon, are refractory and difficult to process. The low grade and refractory nature tend to make placers unattractive; but, on the other hand, the volume of individual placers may be millions of cubic metres and they may contain hundreds of thousands of tons of heavy mineral concentrate. Uranium may be recovered as a by- or co-product from large placers if they also contain economic concentrations of such minerals as ilmenite, rutile, cassiterite or gold.

Brines

All natural waters, such as surface water, groundwater, hot springs, oilfield brines, sea water and mine and mill waters, contain uranium. None of these is a 'deposit' in the usual sense, because they are not concentrations of crystalline minerals in rocks. Typical values for fresh surface and groundwaters are in the range 0.05–10 ppb uranium.[101] Such values are too low to constitute an economic source of uranium at present. Sea water and mine and mill waters are most likely to yield uranium economically, but some saline and playa lakes may also be profitable on a small scale. Fresh water from some mining districts may contain several hundred to several thousand ppm U. Mine waters of this type have been processed in the Grants mineral belt, U.S.A. Leach solutions at some copper mines and mills average as much as 10 ppm U.[131] At Bingham Canyon copper mine, Utah, by-product uranium is recovered. Sea water contains about 3 ppb U and is present in enormous volume. Pilot plants for its extraction from sea water have been built in Japan. Saline and playa lakes, common to hot dry climates, attain their high salt concentrations through evaporation. Most have concentrations of 5–10 ppb U,[63] but their volume is relatively small.

Effusive igneous deposits

In many localities anomalously high concentrations of uranium of probable hydrothermal origin have been noted in, or associated with, volcanic rocks. Volcanic rocks serve as hosts for important uranium deposits in several countries. Uranium is most commonly associated with highly silicic types of volcanic rocks, but peralkaline and peraluminous variants also can be uraniferous. Some deposits in Australia bear some relation to basaltic eruptives. It is estimated that about 15.5% of the

Western world's reasonably assured uranium reserves are found in volcanic rocks.

Silicic volcanics

It is generally recognized that alkaline rock provinces are anomalously enriched in uranium and other trace elements, such as F, Mo, Be, Li and Hg. Uraniferous alkaline volcanic rocks occur in taphrogenic zones that may flank orogenically uplifted areas or may represent foundered rift systems. Effusive activity within taphrogenes can produce a comagmatic sequence of alkaline volcanic rocks and their associated sediments, constituting a volcanogenic system.

Dewey and Bird,[39] in their model for the subduction of an oceanic plate beneath a continental plate, described the mechanisms and distribution of structural elements and associated rock types resulting from mountain building and subsequent relaxation tectonics. They concluded that igneous rocks become more alkaline and more differentiated with increasing distance on to the continent from the subduction zone. Deep-seated magmas arise from the melted zone of the subducting plate, and the deeper the magma the more time it will have for differentiation.

For a magma to differentiate sufficiently to concentrate elements necessary for the deposition of uranium it must remain undisturbed for considerable time at a relatively shallow depth in an environment such as that of a taphrogene. Any premature release of pressure may permit the escape of volatiles and preclude uranium mineralization.

A great variety of deposit forms and structural settings are found in volcanic uranium deposits[84] and, commonly, several types of deposits occur in the same district. Uranium deposits are associated with rhyolitic plugs and domes at several localities in the western U.S.A.[26, 29, 107, 122] Deposits at Marysvale, Utah, occur in faults cutting hypabyssal intrusives and outflow tuff, probably above an unexposed intrusive.[29] Similar deposits were reported from China and the U.S.S.R.[69] Deposits may occur in volcaniclastic sediments filling caldera moats (McDermitt Caldera, U.S.A.), filling grabens (central Italy) or filling palaeo-valleys. Some uranium deposits occur in, or are associated with, ignimbrites, agglomerates, ash flow tuffs and other outflow (extra-caldera) rocks at Rexspar, Canada, Peña Blanca, Mexico, Maureen, Australia, and Thomas Range, U.S.A.

Most writers have proposed a magmatic source for the principal elements of these deposits (U, F, Be, Hg, Th, Mo, etc.), also postulating elevated temperatures. Solutions with the same elements could, however, be produced by diagenetic or mildly hydrothermal alteration of volcanic sediments. Localization of uranium in some deposits appears to be controlled by carbonaceous material (Maureen, Australia; Anderson mine, U.S.A.), but in others the controls are not understood.

Mineralization style in volcanogenic rocks is variable. Where porosity and permeability changes are rapid, reduction in temperature and pressure may be sufficient to reduce hexavalent uranium and form pitchblende. Where porosity and permeability changes are less abrupt, cooling of the silica-rich uranium-enriched fluids may produce uranosilicates.

Silicic volcanogenic uranium deposits range in size from a few tons to several thousands of tons U_3O_8, and ore grades vary from 0.05 to 0.30% U_3O_8. Reasonably assured reserves for silicic host rocks in the Western world are probably of the order of 5000–10 000 ton U_3O_8.

Mafic volcanics

Mafic volcanic rocks appear to be relatively poor hosts for uranium deposits, but a few occurrences have been described. Most important is that in the McDermitt district of the U.S.A., where mafic flows in a caldera moat contain 8.5 ton at an average grade of 0.05% U_3O_8.[102] In this deposit fine-grained pitchblende and coffinite are associated with abundant pyrite and leucoxene.

It has been suggested that the large Cu–U deposit at Olympic Dam (Roxby Downs), Australia, is in some way related to alteration of associated basaltic flows, but this has not been fully documented.

Intrusive igneous deposits

High concentrations of uranium (> 10 ppm) occur in many types of intrusive igneous rocks. Generally, the uranium content of large igneous bodies does not exceed 20 ppm, but the most differentiated components of these bodies may show extreme enrichment of uranium with respect to the mean value for the entire body.[86] Uranium, along with other incompatible elements, generally enters into the silicate melt and late-stage magmatic fluid or gas phases rather than into the liquidus minerals. In granites the highest uranium concentrations are most commonly in pegmatitic or aplitic portions of plutons. Studies by Rosholt and co-workers[104] and Bohse *et al.*[15] indicated that magmas that have retained their volatiles also have retained uranium, so rocks with high bulk-rock volatile content should have high uranium concentrations in late differentiates. Intrusive igneous and associated metamorphic rocks are host to approximately 12.2% of the Western world's reasonably assured \$30/lb resources.

Peralkaline nepheline syenites

Peralkaline nepheline syenites are alkaline rocks characterized by a chemical composition with a $Na_2O + H_2O/Al_2O_3$ molecular ratio greater than 1.2. Rocks with this composition are termed 'agpaitic' by petrologists. Agpaitic nepheline syenites with unusually high concentrations of U, Th, Nb, Zr and REE occur in many localities: most notable are those of Ilímaussaq, Greenland, Pocas de Caldas, Brazil, Lovozero, U.S.S.R., and Pillanesberg, South Africa. Lesser known examples occur in India and Bolivia and elsewhere in Brazil. These rocks contain very little of the Western world's reasonably assured \$30/lb U_3O_8 resources, but they may contain as much as 70 000 ton of the \$50/lb U_3O_8 resources.

Carbonatites

Carbonatites have been designated as a separate class of igneous rocks because of their unusual composition. They are characterized by an abundance of incompatible elements (U, Nb, etc.) and a large proportion of carbonate minerals, such as calcite, dolomite, ankerite and other rock-forming carbonates.

There are more than 300 known carbonatites, but most cover less than 20 km^2 in area.[87] They have been reported from all continents except Antarctica and commonly show a tendency to cluster into belts or provinces. Some of the more important carbonatite provinces are the East African Rift Zone, the Monteregian province of eastern Canada, the South Atlantic occurrences of southern Brazil, Paraguay, Angola and Namibia, the Finland–Kola Peninsula provinces, southern Peninsular India and the Colorado Rocky Mountain Province in the U.S.A. Other carbonatites are found in Bolivia, Ecuador, Sweden, the Canary Islands, Germany, Greenland, Canada and the U.S.A.

Most carbonatites contain insufficient uranium to constitute a minable uranium deposit, but some are mined for other minerals and uranium is recovered as a co- or by-product. Valuable elements contained in, or associated with, carbonatites include Cu (Palabora, South Africa), REE (Mountain Pass, U.S.A., and Araxá, Brazil), Nb (Araxá, others in Brazil, Africa, Canada and the U.S.A.), Th (Wet Mountains, U.S.A.), Ta (U.S.S.R.) and V (Magnet Cove, U.S.A.).

Non-refractory primary uranium minerals are rare, but uranothorianite has been reported from Palabora[46] and uraninite from Lake Nipissing, Ontario, Canada.[48] Most carbonatite uranium-bearing minerals are refractory phases. Uranium occurs as a minor or trace element in zircon, apatite, baddeleyite, perovskite, monazite, pyrochlore minerals, goyazite, bastnaesite, allanite, anatase, rutile, etc. The secondary mineral autunite occurs in soil covering the Araxá carbonatite.[24]

The average uranium content of carbonatite is about 57 ppm, thorium is about 649 ppm and the Th/U ratio is 11.4.[49] The spread of values is large for both U (0.05–400 ppm) and Th (0.1–2500 ppm), however, as was shown by Nishimori and Powell.[87] It is estimated that carbonatites contain at least 150 000 ton recoverable U_3O_8, most of it in the reasonably assured $50/lb category.

Anatectics

Uranium released from sedimentary and igneous rocks by ultrametamorphic processes may become concentrated in anatectically derived quartzo-feldspathic melts. Liquidus crystallization of such uranium-enriched melts produces anatectic uranium concentrations in pegmatites, alaskites and, occasionally, aplites. Alkali feldspars and quartz are the major mineral components, but small amounts of biotite and altered ferromagnesian minerals are generally present. Muscovite is a common accessory mineral and trace amounts of garnet occur. Anatectic uranium concentrations are found in structurally complex, highly metamorphosed and migmatized terrains formed in deep metazonal and catazonal regions of mobile belts. They are characterized by steeply plunging, tight isoclinal folds.

Euhedral to subhedral primary uranium minerals, primarily uraninite and uranothorite, are finely disseminated throughout anatectic alaskites and pegmatites, but quartz-rich zones and pods may contain localized concentrations of uranium minerals. Secondary uranium minerals may be present in either the palingenetic rocks or host rocks.

Anatectic uranium occurrences are tabular to lenticular quartzo-feldspathic bodies that generally show sharp contacts with the host rocks. Dyke-like pegmatites and alaskites are most generally concordant to foliation, but locally may be discordant along axial folds. The size and grade of anatectic uranium occurrences depend on such factors as uranium content of source rocks, degree of cementation in the palingenetic melt and extent of uranium retention during subsequent crystallization. They range from small sub-economic occurrences to very large low-grade deposits. Grades range from about 0.01 to 0.20% U_3O_8, and the size of deposits ranges from a few to as much as 150 000 ton U_3O_8.

The largest and only currently economic deposit is the Rössing deposit in Namibia, but smaller deposits exist, such as those at Crocker Well, South Australia, Serido Province, Brazil, Saskatchewan and Manitoba Provinces, Canada, Travancore, India, Kenema, Sierra Leone, Wheeler Basin, U.S.A., and localities in Zimbabwe.

Pegmatitic alkalitic granites

Pegmatitic alkalitic (peralkaline) granites are distinct both geologically and chemically from calc-alkaline granites and granodiorites. They generally are holocrystalline and leuco- to mesocratic and consist of 25–40% quartz, about 50% alkali feldspar (microcline, perthite, or late forming albite) and 10–25% accessories (pyroxenes, amphiboles, etc.).

The origin of pegmatitic alkalic granites is somewhat in question. Some writers believe that they are derived from the mantle,[127] but others[7,17] contended that they form through anatexis of lower crustal material. Murphy *et al.*[83] suggested that they can be explained by a combination of genetic models, along with such factors as tectonic setting, crustal contamination and volatile segregations.

Uraniferous peralkaline granites are known in Scotland and in the ring complexes of Niger and Nigeria, but the only such granite with a history of uranium production is the albite–riebeckite granite at Bokan Mountain, Alaska. All these occurrences are characterized by (1) the strongly peralkaline nature of the host granite—a result of extreme chemical differentiation; (2) the concentration of incompatible elements (U, Th, Nb, Zr, Be, Li, etc.) in the volatile stage from the parent magma; (3) high oxygen fugacity, as shown by high Fe^{3+}/Fe^{2+} ratios and normative acmite; (4) reinjection of late-stage fluids either as a deuteric or metasomatic event; (5) additional enrichment of the volatile phase in the form of pegmatites; (6) hydrothermal reinjection of fluids into the host rock along faults; and (7) pervasive albitization of the pluton.

Uranium may occur as deuteric or autometasomatic concentrations in the albitized granite, syngenetic emplacements in pegmatite, epigenetic hydrothermal replacement veins or as epigenetic deposits in the adjacent country rocks. Primary uranium minerals are uranothorite, uranian thorianite and coffinite. Associated minerals include calcite, fluorite, pyrite, galena, hematite, quartz and clays. Grades of uranium mineralization range from 0.01 to 1.00% or more U_3O_8. Peralkaline granites host only a few hundred tons of the Western world's reasonably assured and estimated additional uranium resources.

Granites

In a series of granitic rocks the greatest uranium concentrations generally are in the youngest, most highly differentiated rock unit. Many granites have a bulk concentration of more than 10 ppm, but entire granite plutons with more than 20 ppm are rare.[86] The best examples of uranium-rich granites are the Hercynian massifs of France, but granites and quartz monzonites with 2–15 ppm U are known in Canada (Johan Beetz, Quebec), Australia (Elizabeth Creek, Queensland), the U.S.S.R. (Ognitsk, East Sayan), Ireland (Donegal) and the U.S.A. (Conway, New Hampshire; Granite Mountains, Wyoming; Mount Spokane and Midnite mine, Washington; Bingham Canyon, Utah).

Most high-uranium granites are post-orogenic, epizonal plutons that have not lost their uranium-bearing aqueous fluids during an orogenic episode. Because the uranium content of these granites is uniformly low, it is unlikely that any large syngenetic orebodies exist. In some areas, however, where other metals are present in sufficient quantity the disseminated U may be recovered as a by-product (Bingham copper mine, U.S.A.).

In some localities weathering of uranium-bearing granites may produce concentrations of secondary uranium minerals in vein-like bodies along and adjacent to major fracture systems within the parent pluton. Associated minerals may include sphalerite, pyrite, galena, chalcopyrite, fluorite, limonite and quartz. Fracture and joint systems may be expansion features related to pluton deroofing. Shear intersections are particularly favourable sites for deposition of secondary uranium minerals, so ore zones are generally lenticular to pod-shaped. Deposits are generally small, but may be high-grade: an example is the Daybreak mine, Washington, U.S.A., where uranium occurs as meta-autunite crystals along fractures, microfractures and cleavage traces in pegmatitic and alaskitic phases of a Cretaceous porphyritic quartz monzonite. Similar deposits occur in the Lachaux district of France.

In other areas uranium liberated by weathering from uranium-bearing granites has migrated into low- to medium-grade metamorphic rocks surrounding shallow-seated plutons.

Because potential host rocks must be capable of reducing hexavalent uranium in aqueous solution, ideal host lithologies are carbonaceous slates, graphitic schists and calc-silicate rocks. Uranium transportation may be a continuous process. Pitchblende and coffinite are the principal uranium minerals, but secondary uranium minerals may occur in the near-surface portions of the deposit. Gangue is variably abundant in the form of quartz, carbonates and fluorite. Examples of this type of occurrence are Spokane Mountain, U.S.A., Nisa, Portugal, and Mina Fe, Spain. Average uranium contents vary from 0.05 to 0.3%. Thickness of ore zones ranges from a few centimetres to metres or tens of metres, and lengths range from tens to hundreds of metres. They may extend vertically to depths of 100 to 200 m. Granitic deposits contain about 30 000 ton of reasonably assured $30/lb uranium, but they contain much larger amounts of reasonably assured $50/lb uranium.

Pegmatites

Pegmatitic and aplitic uranium occurrences form from 'pegmatitic' fluids produced by saturation during late-stage magmatic evolution. Uranium, because it does not readily enter into common rock-forming minerals during orthomagmatic crystallization, becomes progressively concentrated in residual melts. Such pegmatitic fluids may become still more concentrated in a second boiling of the magma. For this reason pegmatitic phases of a comagmatic sequence are generally enriched in uranium relative to the main body of a given pluton.

Uraniferous pegmatites differ from non-uraniferous pegmatites primarily in their uranium content, which can be attributed to original uranium content of the parent magma, extent of uranium removal prior to saturation, and degree of concentration in the pegmatitic fluid. Other differences are in their contents of F, Nb, Ta, REE, primary hematite, sodic amphibole and/or sodic pyroxene. In general, the more complex the chemistry the more likely it is that a pegmatite will contain radioactive elements.[2] Uraniferous pegmatites are also characterized by temporal, spatial and probably genetic association with plutons with an anomalously high uranium content. They commonly occur within or at the margins of such plutons, but they may be injected into country rock. In general, their size, number and complexity decrease with increasing distance from the parent pluton.[79]

Pegmatitic uranium concentrations occur in areas of extreme crustal mobility. They occur most frequently in intercratonic mobile belt terrains associated with deep epizonal to mesozonal plutons produced from crustal materials. They are characteristically Precambrian or Devonian–Carboniferous and occur in high-grade metamorphic rocks as well as granitic intrusives. Because of their occurrence in high-grade metamorphic rocks, some writers have classified such pegmatites as ultra-metamorphic or anatectic.

Uraniferous pegmatites are generally granitic, consisting mostly of alkali feldspars and quartz with mica and a few sodic amphiboles and/or pyroxenes. Common accessory minerals are fluorite, topaz, hematite, zircon, garnet and apatite. Uranium and uranium-bearing minerals (uraninite, allanite, uranothorianite, brannerite) are disseminated throughout the dykes, but quartz-segregation blobs may contain higher concentrations. Much of the uranium is tied up in accessory minerals, such as apatite and zircon, but some may be present within or on the surfaces of rock-forming minerals.

Most uraniferous pegmatites occur as tabular discordant dykes, but some are elongate pods. Some are structurally simple, but others are zoned. Regardless of type, radioactive pegmatite minerals rarely occur in sufficient quantities to constitute an economic source of uranium or thorium. Grades range from a trace to more than 0.37% U_3O_8, but average about 0.01%.

Several hundred tons of complex oxide minerals has been produced from pegmatites in Malagasy. In recent years there has been exploration for uranium in both zoned and unzoned pegmatites in Canada. Most important are the unzoned red pegmatites in the Bancroft, Ontario, area, but there are also important unzoned white pegmatites and some zoned pegmatites in other parts of Canada.[65] It is estimated that Bancroft reserves are of the order of 2000 ton U_3O_8 averaging 0.11%.[18] Other uraniferous pegmatites are known in Argentina, Australia, Brazil, Ethiopia, Finland, India, Norway, Sri Lanka, Sweden, the U.S.S.R. and the U.S.A. Total reasonably assured $30/lb resources do not exceed a few thousand tons.

Hydrothermal veins

Hydrothermal (classical) uranium vein deposits are those with predominant structural control that are generally spatially and probably genetically related to uraniferous plutonic hypabyssal and/or pegmatitic bodies. Such deposits occupy relatively simple fault and fracture zones, some extending to depths of 300–500 m in a variety of host rocks, but display many mineralogical and geochemical similarities. Some veins occur in metamorphic rocks, such as in the Beaverlodge and Great Bear Lake districts of Canada, Schwartzwalder mine, U.S.A., Pribram and Freiberg districts of eastern Europe and Shinkolobwe mine, Zaire. Others occur within the parent pluton (intragranitic), such as the well-known deposits in France, Spain and Portugal.

Hydrothermal solutions responsible for these veins are generated during the final stages of magmatic differentiation. Continued magmatic evolution causes progressive increase in volatiles and, ultimately, a separate, very hydrous phase that may contain a wide variety of dissolved constituents. High oxygen fugacity causes oxidation of uranium, but not vanadium, bringing about an effective fractionation of the two elements. When hydrothermal solutions are released from the magma chamber it is by way of permeable channelways, such as fault and fracture zones that have been active for long periods. Such systems are of considerable length and depth and provide the most favourable sites of deposition. Here reductants for the hexavalent uranium are generally absent, but the mechanically induced decrease in oxygen fugacity of the system as the temperature, pressure and pH of the hydrothermal fluid change with upward migration into dilatant zones may result in reduction.[79]

Two types of vein deposits are recognized: (1) monometallic veins of pitchblende and (2) polymetallic veins of U with (Co, Ni, Bi, Ag) or (Ni, Co and Cu). Both types of deposits generally occur in brecciated veins and vein systems, and multiple stages of brecciation are common. The breccias normally consist of fragments of the enclosing wallrock. Quartz, both massive and cryptocrystalline, composes the bulk of the vein material. Associated minerals include Fe, Zn and Pb sulphides, barite, purple fluorite and carbonate minerals. (Cu, Ni, Ag and Bi) or (Ni, Co and Cu) enrichments are present in some veins as the result of telescoping of multiple primary mineralizations.[30] The major uranium mineral is uraninite, which may occur as finely disseminated euhedra, intergranular coatings, fracture fillings or as a replacement product. Ore-grade concentrations are intermittent along the veins, but grade tends to be highest along zones of maximum dilatancy. Grades of these deposits range from less than 0.10% to more than 1.0% U_3O_8. Hydrothermal vein deposits contain about 50 000 ton of the Western world's reasonably assured $30/lb uranium resources.

Metasomatic deposits

Contact-metasomatic occurrences

Contact-metasomatic uranium occurrences form by replacement reactions between magmatic emanations and pre-existing rocks during the late stages of magmatic evolution. Most commonly, metasomatism occurs as a halo in older metamorphic and igneous rocks intruded by the magma, but in places it occurs in outer zones of the pluton and in cataclastic rocks of shear zones bordering the pluton.

Some uranium and part or all of the uranium-transporting fluids that form contact-metasomatic deposits may be derived from the host rock, but uranium can also be introduced into the host rock as magmatic emanations. Berezina and coworkers[13] recognized a systematic increase in uranium content from the outer portions toward the centre of a 'metasomatizing column'. Uranium becomes progressively more concentrated along microfractures, cleavages and crystal defects, especially in ferromagnesian minerals. Distances of uranium transport in metasomatizing fluids and the sites of deposition are primarily governed by the temperature gradient and the effective porosity, permeability and composition of the host rock.

There seem to be two major types of metasomatic uranium occurrences: (1) carbonate-metasomatic and (2) alkaline or sodic-metasomatic (albititic), characterized by pervasive albitization of host rocks. Carbonate-metasomatic uranium deposits are normally found in middle- to high-rank dynamically metamorphosed rocks adjacent to silicic uraniferous plutonic and/or pegmatitic rocks in mobile belt terrains. The high-rank host rocks may indicate a deep-seated environment for evolution of the magma that would enable uraniferous fluids to permeate the country rock rather than escape along fractures. Common host rocks include ferruginous quartzites (taconite), iron ore, mafic and calc-silicate schist, gneisses and impure marbles. Primary uranium and uranium-bearing minerals (usually uraninite and thorianite) are finely disseminated in the host rocks, and some uranium may be within rock-forming minerals. Uraninite is the dominant uranium mineral, but uranium may occur in monazite, zircon, aegirine, riebeckite and biotite. Albitization, carbonatization and chloritization are the most common forms of alteration in these occurrences. Size and grade of the pod-shaped orebodies vary greatly. Most ore is low-grade, but secondary enrichment may make them economically viable. The most important occurrence is Mary Kathleen, Australia, but other deposits are known at many localities in Brazil, Canada and the U.S.S.R.

Contact-metasomatic uranium deposits contain only a few thousand tons of the Western world's reasonably assured $30 uranium resources. Grades range up to about 0.15% U_3O_8, but associated metals, such as REE, tend to make them more economic.

Sodic-metasomatic occurrences

The sodic-metasomatic (albititic) uranium occurrences are largely confined to the Ukranian Shield of the U.S.S.R.,[59] but similar occurrences may be found in association with the mantled gneiss domes of North America. Uraniferous sodic-metasomatic deposits occur in tectonic-metasomatic zones developed along large faults in ultra-metamorphic rock terrains. The faults are associated with fold structures of the basement and with exo-contacts of major (hundreds to thousands of km^2) abyssal granitoid massifs.[59] The uraniferous albitites replace interlayered granites, gneisses and pegmatites (migmatites?) near the fault contacts, as well as cataclastites and mylonites at the fault contacts. Most albitites have cataclastic textures that have been inherited largely from epidote–chlorite cataclastites formed prior to the sodic metasomatism. The ore minerals (uranotitanate, nenadkevite, brannerite, pitchblende, coffinite, uranophane, beta-uranophane and others) are evenly distributed in the albitites, where they impregnate and partly replace the fine-grained matrix and form discontinuous seams of micro-breccia. Orebodies are both vein type and disseminated. Both the uranium deposits and the host rocks have a similar age (~1800–2000 m.y.). They formed at shallow depth and are considered medium-temperature hydrothermal.

Vein-like type deposits

Much of the world's currently minable uranium is found in vein-like deposits of uncertain origin. They consist of three general types of unequal importance. Most important are unconformity-related deposits and vein-like deposits in metamorphic rocks. Least important and probably of different origin are vein-like deposits in sedimentary rocks. The origin of all three types is a matter of much conjecture. Major unsolved genetic questions are the source of the uranium and its mode of transport, the source of the mineralizing solutions, the nature and role of reductants and the control exerted on uranium deposition by structural and lithologic features of the host rocks. Unconformity-related deposits and vein-like deposits in metamorphics commonly occur in brecciated and foliated metamorphic rocks in stable Precambrian Shield areas. They contain about 24.4% of the Western world's reasonably assured $30 uranium resources.

Deposits of all three types are associated with faults and/or shear zones, but unconformity-related deposits are also closely associated with major regional unconformities where coarse terrestrial clastics overlie metamorphosed basement rocks. Unconformity-related deposits and vein-like deposits in metamorphic rocks are all of Precambrian age, whereas vein-like deposits in sedimentary rocks are found only in strata of Palaeozoic and Mesozoic age.

Unconformity-related deposits

Unconformity-related deposits are large moderately high-grade deposits consisting of epigenetic concentrations of primary uranium minerals in veins and strata-bound deposits spatially associated with major regional Middle Proterozoic unconformities. In Northern Territory, Australia, they are associated with the pre-Carpentarian unconformity and in northern Saskatchewan, Canada, with the Palaeohelikian unconformity.

Most unconformity-related deposits occur near the erosional edge of terrestrial units that overlie the unconformities. These terrestrial units are mostly unmetamorphosed Middle Proterozoic buff to red orthoquartzitic to feldspathic fluvial sandstones that may contain lenses of polymictic conglomerate near the unconformable contact and lenses of shale and siltstone higher in the sequence.

Metamorphosed sedimentary and igneous rocks of Early Proterozoic age underlie the unconformities and host most of the uranium deposits. Grade of metamorphism and degree of structural complexity of the host rocks show no correlation with uranium content, but most such uranium deposits are confined to, or are concentrated below, reducing horizons within metasedimentary host rocks. Graphite- and chlorite-bearing schists are the most common host lithologies. Quartzites, sericite schists, chloritic gneisses, calc-silicate rocks and marbles are present, but generally contain less uranium.

Uranium occurs as concentrations of pitchblende with some coffinite in veinlets along faults, in brecciated zones and in satellite structures associated with the major structure. These minerals may occur also as fine disseminations in selected horizons in the host rocks. Secondary uranium minerals are locally abundant, especially in near-surface portions of deposits. Small amounts of quartz and carbonates are the gangue minerals. Associated minerals vary in type and abundance and determine whether a deposit is classified as monometallic or polymetallic. The latter may contain a wide variety of associated minerals, including sulphides. Hematitization and chloritization are the most common forms of alteration present. Hematitization generally precedes uranium mineralization, and higher-grade uranium concentrations commonly coincide with the most intense alteration.

Mineralization straddles the unconformity in some deposits, but is mostly restricted to the metamorphic rocks. Most occur at the erosional edge or a short distance in front of it. Ojakangas[89] discussed the probability of their presence underneath the terrestrial sediments. The uranium deposits vary in size and shape, their geometry depending on whether lithology or structure is the dominant factor in localization. They rarely extend more than 100 m below the unconformity, and they may extend horizontally for considerable distances. Structurally controlled deposits tend to be elongate, whereas those which are stratigraphically controlled are commonly amoeboid. Grades range from 0.01% to more than 50.0% U_3O_8.

The origin of these deposits is unknown, but any genetic hypothesis must explain (1) their presence in or near sequences of metamorphic rocks formed from marginal marine sedimentary units, (2) their proximity to Archaean granite–gneiss complexes with reactivated migmatite fringes, (3) ore occurrences in repeatedly faulted and chloritized zones and (4) their proximity to Middle Palaeozoic unconformities.[62]

Unconformity-related deposits are known only from Northern Territory, Australia (Rum Jungle, South Alligator Valley and Alligator River regions), and Saskatchewan, Canada (Athabasca Basin). They include many of the world's largest and richest deposits, such as Koongara, Ranger I, Ranger II and Jabiluka II in Australia and Rabbit Lake, Key Lake and Midwest Lake in Canada.

Vein-like deposits in metamorphic rocks

Vein-like deposits in metamorphic rocks also occur in Precambrian Shield areas, but they differ from unconformity-related uranium deposits in that they are not associated with major regional unconformities, the geometries of orebodies are different and they extend to greater depths. Vein-like deposits are closely associated with steeply dipping, brecciated major fault systems. Uranium minerals (pitchblende with some coffinite and brannerite) occur as open fracture fillings and as fine disseminations adjacent to the fractures in Proterozoic meta-igneous and metasedimentary rocks. Common associated minerals are chlorite, hematite and pyrite.

These uranium deposits are generally elongate and steeply dipping. They have very long strike lengths in comparison with their thickness, and they may extend to depths of several hundreds of metres. Some deposits are in anastamosing vein systems associated with cymoid structures related to the major fault systems. Other deposits may occur as individual veins or as a series of complex anastamosing veins and veinlets with a width up to 50 m. The long, deep major fractures may have been active over long periods of time[9] and may have served as passageways for hypogene or supergene mineralizing solutions.

Favourable host rocks are carbonaceous slates, chloritized schists and gneisses, graphitic units, metacarbonates and metavolcanics. All these rocks are characterized by retrogressive chloritization that predates uranium mineralization. Hematite haloes are common around ore, and carbonatization and chloritization are also normal features of the deposits. Both monometallic and polymetallic types of deposits are recognized.[6] Pitchblende is the principal uranium mineral in both types of deposits, and Ag, Ni, Cu and Co form accessory minerals (sulphides and arsenides) in the polymetallic deposits. Mineral assemblages, wallrock alteration types and mineral formation temperatures suggest that these deposits form from medium- to low-temperature hydrothermal solutions.

Vein-like deposits in sedimentary rocks

Vein-like deposits of uranium in sedimentary rocks are epigenetic deposits in brecciated, tabular bodies and pipe-like structures orientated transverse to stratification in Palaeozoic and Mesozoic rocks.[58] They occur in areas of thick sedimentary sequences and of moderate structural deformation.

Pipe-like structures are generally cone-shaped, and they become progressively narrower with depth. They range up to a hundred metres or more in diameter, but rarely attain a depth of more than 200 or 300 m. They consist of an inner core of brecciated downdropped blocks surrounded by a steep inward-dipping circular fault system. They occur at intersections of fracture systems in structurally stable areas and are underlain by massive carbonate and/or evaporite units. The pipe-like structures may terminate in these carbonates or evaporites, suggesting that they are produced by solution collapse. They may have acquired their uranium from remobilization of uranium in uranium-bearing strata cut by the pipe-like structure. Other suggested origins are cryptovolcanic explosions or pipe-drilling by gases from an underlying magma.

The types of rocks that comprise a collapse structure depend on the types of rock that are cut by the structure, the amount of underlying material removed by solution and rock units overlying the structure at the time of development. Blocks of sandstone, siltstone, shale and carbonates may be found in the collapse. Sandstone and some siltstones are the common uranium hosts. Well-known pipe-like bodies include Woodrow Pipe, New Mexico, Orphan mine, Arizona, and Temple Mountain, Utah, all in the U.S.A.

Tabular vein-like deposits may be associated with regional fractures, shear systems and/or growth faults. Breccia fragments within these deposits are generally limited to blocks of the host rock.[51]

Pitchblende is the dominant uranium mineral in all these vein-like deposits in sedimentary rocks. It occurs as small veinlets along fractures within and surrounding the structures and as finely disseminated crystals in porous breccia fragments within the structures. Pitchblende concentrations may be distributed zonally within the ore, and in some deposits may be concentrated in the upper levels of the structure. Associated minerals may include sulphides and sulpharsenides. Calcite and quartz are the most common gangue. Types of alteration include bleaching of red sediments, silicification, carbonatization and argillization.

Vein-like deposits in sedimentary rocks are generally quite small and relatively low-grade, ranging from a few to several hundred tons of U_3O_8 at grades of 0.05–0.25% U_3O_8. They represent less than 1000 ton of the Western world's reasonably assured $30 uranium resources.

Epigenetic uranium deposits

Epigenetic uranium deposits are similar to sedimentary uranium deposits in that they occur in sedimentary rocks and they owe their existence to exogenic processes. They differ, however, in that the sediments formed prior to introduction of uranium. Epigenetic deposits form by precipitation of uranium from solutions moving through previously deposited sediment or pre-existing rocks. Uranium-bearing solutions include hydrothermal solutions, connate and meteoric waters. Uranium in these oxidized groundwaters may be reduced and precipitated by organic matter in sandstone, limestone, lignite, coal and carbonaceous shale. Evaporites may contain secondary uranium minerals that precipitate on the outcrop or in pore spaces, solution cavities and fractures within the oxidized zone.

The largest and highest-grade epigenetic deposits are those in sandstone, but other types are important in a few areas. Epigenetic uranium deposits contain about 32% of the Western world's reasonably assured $30 uranium resources.

Sandstone

Sandstone-type uranium deposits occur primarily in sandstone, but may be found in silty and conglomeratic rocks as well. The host rock may be quartzose, feldspathic to arkosic, and tuffaceous to volcaniclastic. The most common hosts are medium- to coarse-grained, poorly sorted, quartzose and arkosic fluvial sandstones. The normally red or brown host sandstones are typically reduced (bleached) to grey, green or tan in the vicinity of uranium deposits. Most sandstones also contain iron sulphides that, together with the bleaching, reflect the reducing environment required for deposition and preservation of epigenetic uranium.

Host sandstones are of fluvial, lacustrine, eolian, deltaic, paludal and marginal marine origin, but deposits in fluvial sandstones are most common. Finch[45] calculated that, of 4600 sandstone deposits other than vein-like, 97% are in continental, 2% are in mixed continental and marine and 1% are in marine (marginal marine) rocks. Fluvial sandstones are most favourable because they are interbedded with mudstones and they commonly contain disseminated plant debris. Eolian sandstones are poor hosts because they lack mudstone partings and plant debris. Marginal marine sandstones are fair hosts because they may contain organic matter and are interbedded with carbonaceous marine, deltaic and lagoonal muds. Mudstones and shaly interbeds are important because they impede or stop groundwater movement.

Organic material in the sandstone and interbeds commonly acts as a reducing agent. A reducing environment is necessary to precipitate hexavalent uranium from solution to form insoluble tetravalent uranium (when vanadium is present it can cause uranium to precipitate in an oxidizing environment). The reductant may be a complex organic acid or it may be H_2S produced or introduced from one or more of these sources: anaerobic destruction of organic material in the sediment, oil and gas, or oxidation of pyrite. Most epigenetic uranium deposits in continental sandstones are Devonian or younger because of the absence of land plants prior to that period. Occurrences in marine sandstones as old as Precambrian are possible because of the earlier presence of marine organisms.

Uranium in epigenetic sandstone deposits is believed to have come from such varied sources as weathering of granitic rocks, siliceous tuffs or other uraniferous rocks in the source area for the sandstone; devitrification of tuffaceous sediment in or interbedded with the sandstone; hydrothermal solutions from nearby magmas; and recycling and redistribution of earlier-formed uranium deposits.

Three types of epigenetic uranium deposits in sandstone are recognized on the basis of their relationship to bedding or structure—peneconcordant, roll-type and tecto-lithologic (stack). Uraninite and coffinite are typical minerals of unoxidized portions of all three types of sandstone uranium deposits. They replace organic material, coat mineral grains and fill interstices in the host rock. Oxidation produces such secondary minerals as tyuyamunite, carnotite and uranophane. Cu, V, Cr, Mo and Se are common accessory elements in both economic and subeconomic occurrences. Grades in sandstone deposits range from less than 0.01 to more than 1.0% U_3O_8. Deposits range in size up to 45 000 ton U_3O_8. Most of the U.S.A., Argentina and Niger production is from sandstone uranium deposits. About 28.6% of the Western world's reasonably assured \$30 resources is in sandstone deposits.

Peneconcordant deposits

Peneconcordant uranium deposits are those that generally lie parallel to bedding in nearly flat-lying sandstones, but in detail they are locally discordant. In cross-section they may be tabular, lenticular or irregular; in plan they are equidimensional to amoeboid (blanket-like) or elongate in one direction (trend). Thicknesses range up to 10 m and lengths may reach several thousands of metres.

Dominant ore minerals in the reduced zone are pitchblende and coffinite and, in some deposits, associated primary vanadium oxides—for example, montroseite. In oxidized zones the important uranium minerals are the uranyl vanadates (carnotite, tyuyamunite or francevillite). Accessory elements include Mo, Se and Cu. Average uranium content ranges from 0.01 to 0.40% U_3O_8.

Peneconcordant uranium deposits occur primarily in Permo-Carboniferous, Triassic, Jurassic and Tertiary sediments. Principal ore districts are the Colorado Plateau and Grants Mineral Belt, U.S.A., Agadès region, Niger, sub-Andean zone, Argentina, and Lake Frome, Australia. Lesser deposits occur in Algeria, Brazil, China, Egypt, Gabon, India, Italy, Japan, Mexico, New Zealand, Pakistan, Spain, Turkey, the U.S.S.R. and other areas in the U.S.A.

Roll-type deposits

Roll-type uranium occurrences were first noted in mines on the Colorado Plateau, but they are best developed in the Wyoming, U.S.A., deposits. In vertical section these deposits are *C*- or *S*-shaped and cut sharply across bedding. They form at the boundary between altered and unaltered sandstone. This boundary or 'solution front' is the result of oxidizing uraniferous groundwater moving progressively through a body of reduced (unaltered) sandstone bounded by shale partings.[8, 128] The roll front, which represents the farthest downdip or outer penetration front of the oxidizing waters, may extend in sinuous fashion across a broad front or may be elongate in one direction. In some areas rolls are closely associated with or gradational into stratiform peneconcordant ore deposits.

Roll-type orebodies are generally crescent-shaped in vertical section, the sharp concave margin facing the alteration. The highest-grade ore generally occurs near the contact with the altered sandstone, and the grade diminishes away from the alteration. Low-grade mineralization (protore) may extend for up to 100 m away from the roll front in unaltered rock. Modifications of the crescent shape are common and may produce *S*-shapes, compound crescents and other forms. Crescent horns are commonly elongated and are generally confined by less permeable strata above and below. Orebodies are elongate parallel to the roll front. They may be as much as 30 m wide and 2 km long and may be up to 10 m thick. Many deposits are less than 5 m wide and 3 m thick. The main ore minerals are pitchblende and coffinite. Selenium may be enriched on the convex side and molybdenum and calcite on the concave side. Grade of mineralization ranges from 0.01 to >0.50% U_3O_8.

Roll-type uranium deposits occur in intracratonic sedimentary basins in the U.S.A. Best known are those in Tertiary strata of Wyoming (Powder River, Shirley and Wind River basins) and the Texas Gulf Coast. Smaller deposits are present in Jurassic rocks of the Colorado Plateau.

Stack deposits

The term 'stack deposit' was first used to describe uranium ore deposits associated with peneconcordant deposits in the Grants Mineral Belt, New Mexico. Stack deposits are also called 'tecto-lithologic', 'redistributed' or 'post-fault' ore because they represent uranium that was mobilized from earlier peneconcordant or roll-type occurrences and redeposited in near-vertical bodies. The geometry of stack deposits commonly is controlled by faults or fractures that post-date the formation of the other uranium deposits. Stack deposits generally have greater thicknesses than the associated peneconcordant or roll-type deposits, but their shape is irregular.

In most cases red sandstone with hematite staining is closely associated with stack deposits, which indicates that oxidized groundwater invaded the environment and redistributed the uranium. It is now concentrated as pitchblende and some coffinite along permeable fault zones with linguiform impregnation of the adjacent sandstone. Uranyl vanadates may be present in the oxidized zone. Thicknesses of ore range from a few tens of centimetres to more than 10 m. Lateral dimensions may be 100 m or more. Grades average from 0.10 to 0.40% U_3O_8.

The best-known deposits are those in the Precambrian Franceville Basin, Gabon, and in the Jurassic of the Grants Mineral Belt, U.S.A. Other occurrences are in the Miocene–Pliocene of Pakistan, the Miocene of Japan, the Permian of Europe, the Karoo Formation of South Africa and the Proterozoic of Canada.

Calcretes

Calcrete, dolocrete and gypcrete uranium deposits in arid Western Australia and the Namib Desert of Namibia contain uranium derived by weathering of granitoid rocks and transported laterally as uranyl carbonate complex ions in vadose and phreatic waters within the regolith.[22, 23] Carnotite, the only uranium mineral present in most deposits, is deposited with authigenic carbonate (occasionally gypcrete or dolocrete) in trunk subsurface drainages and calcrete deltas. Mineralization occurs in areas of constricted flow or where waters are forced close to the surface. Carnotite is precipitated in, adjacent to, and commonly just below a valley calcrete mass, close to the water-table and in an oxidizing environment. It fills cavities and fractures in the calcrete and gypcrete and associated sediments.

Calcrete host rocks are crudely lenticular masses of alluvium and soil cemented by calcium or calcium–magnesium carbonates into masses that are up to tens of metres thick, several hundred metres to a few kilometres wide, and tens of kilometres long in the axial portions of palaeo or modern drainages in arid regions. In Australia these 'valley calcretes' cement and replace detritus derived primarily from the kaolinitic portions of lateritized granitic rocks. The calcretes are fine-grained to earthy, but are highly permeable because of shrinkage cracks and collapse structures, particularly within mound-like masses. In Namibia the uraniferous valley calcrete cements coarse to fine alluvium, and in areas near the ocean they are commonly overlain by gypcrete that can also contain uranium.

Because of their ephemeral nature there are no known uraniferous calcretes older than about 300 000 years.[23] The known deposits contain, however, about 2.4% of the Western world's reasonably assured $30 uranium resources. The largest and best-known are those at Yeelirrie, Western Australia (believed to contain about 50 000 ton U_3O_8), and Langer Heinrich, Namibia. Other occurrences are in these countries as well as in Angola, Botswana, Mauritania and Somalia.

Lignites, coals and carbonaceous shales

Lignite, coal and non-marine carbonaceous shale are among the least uraniferous sediments when deposited, but they may become sufficiently enriched locally by later processes to constitute a low-grade resource. Among the coaly rocks, high-ash lignite and sub-bituminous coal are the best hosts. Most beds of uraniferous coaly rocks are relatively thin, ranging from a few centimetres to a metre or more. The mineralized zone in the host rock is also thin, ranging from 1 to 25 cm. Thin beds may be completely mineralized, but in thicker units only the top is mineralized. Identifiable uranium minerals are sparse or absent. The uranium is probably present in organic ionic compounds similar to humic acids (uranyl humates). Some secondary minerals (meta-autunite and meta-tyuyamunite) may occur in higher-grade deposits.

Most uraniferous coaly rocks were deposited in structural basins, and many are interstratified with acid tuffs or tuffaceous sedimentary rocks. Others are within the drainage basin of rocks known to contain uranium (granite, uraniferous sandstone, etc.). Uraniferous coaly rocks appear to have been mineralized by uranium-bearing groundwaters that leached uranium from overlying tuffs or tuffaceous sediments and transported it to the reducing environment created by plant debris of the host rocks. Some uranium may have been leached from vein occurrences or marine black shale.

Uranium in uraniferous coaly rocks ranges from 0.005 to as much as 0.8% U_3O_8. Deposits range in size from less than 1 km^2 to more than 250 km^2 and contain from 100 to 10 000 ton U_3O_8. They are low-grade, relatively small and localized and most can be upgraded by burning or retorting. Most of the uranium remains in the ash along with small amounts of Ti, Ni, Co, Mo, Sn, V and REE. These deposits do not represent a sizable portion of the Western world's reasonably assured $30 resources. Best known of the uraniferous coals are those of the Williston Basin.[34]

Limestones

Limestone is not a favourable host for syngenetic uranium deposits. Both tetravalent and hexavalent uranium are highly soluble in the presence of concentrations of carbonate or bicarbonate ions; thus, in carbonate-forming environments most uranium will remain in solution. If any syngenetic uranium is present, it will be associated with such impurities as heavy mineral resistates, marine apatite, fluorite and some kinds of organic material.[12] The only favourable carbonate rocks are those which are capable of serving as hosts for epigenetic uranium. There are three types of epigenetic uranium deposits in limestone—peneconcordant, efflorescent and karstic. Most important are the *peneconcordant deposits*—tabular, lenticular or irregular masses concordant with gross sedimentary structures of the host rock. Best examples are the Todilto Limestone, U.S.A., and the Buda Limestone, Mexico. Others are known in Canada and the U.S.A.

Efflorescent deposits are unimportant powdery encrustations formed on rock surfaces by evaporation of uranium-bearing waters. Minerals such as tyuyamunite, carnotite and uranophane occur in cavities, on fractures and on exposed rock surfaces.

Karstic deposits are those in which secondary uranium minerals occur in large caverns, cave breccias and in bedded cave-fill deposits of clay and silt in karstified limestone. Best known of these deposits are Tyuya-Muyum, U.S.S.R., and Pryor Mountains, U.S.A. Tyuyamunite is the principal uranium mineral at both localities. These deposits are also of minor importance and contribute little to the $30 uranium resources.

Epigenetic phosphates

Most uraniferous phosphates are classified as syngenetic types because they acquired their uranium at the time of deposition. One exception appears to be the occurrence at Baukoma, Zaire, where uranium occurs in an Eocene phosphatic clay beneath a shallow lake. The phosphatic clay, with an average content of 3000 ppm uranium, rests on a limestone and in places on a sandstone that overlies the limestone.[70]

Tetravalent uranium replaces calcium in the apatite structure. Hexavalent minerals (autunite, meta-autunite and torbernite) are also present. Reserves are estimated at 10 000 ton uranium. The origin of this occurrence is uncertain, so an exploration model for this type deposit has not been constructed.

Examples of important types of deposits

Quartz-pebble conglomerates

Blind River–Elliot Lake district, Ontario, Canada

The Blind River–Elliot Lake district is on the north shore of Lake Huron, about 400 km northwest of Toronto. Uranium occurs here in lowermost Proterozoic fluvial conglomerates at the base of the Huronian Supergroup. The Huronian consists of a thick sequence of quartzite, conglomerate, argillite, arkose and siltstone. Deposition of the supergroup (Fig. 3) was cyclic, each cycle beginning with a conglomerate. The Matinenda Formation, at the base of the sequence, contains the oldest Huronian conglomerates, the ore-bearing quartz-pebble conglomerates. The lower part of the Matinenda consists of greenish arkose and conglomerate. The upper part is grey quartzite, and it is overlain by grey argillite of the McKim Formation. The two formations constitute a fining-upward transgressive sequence that onlaps Archaean basement rocks progressively toward the north.

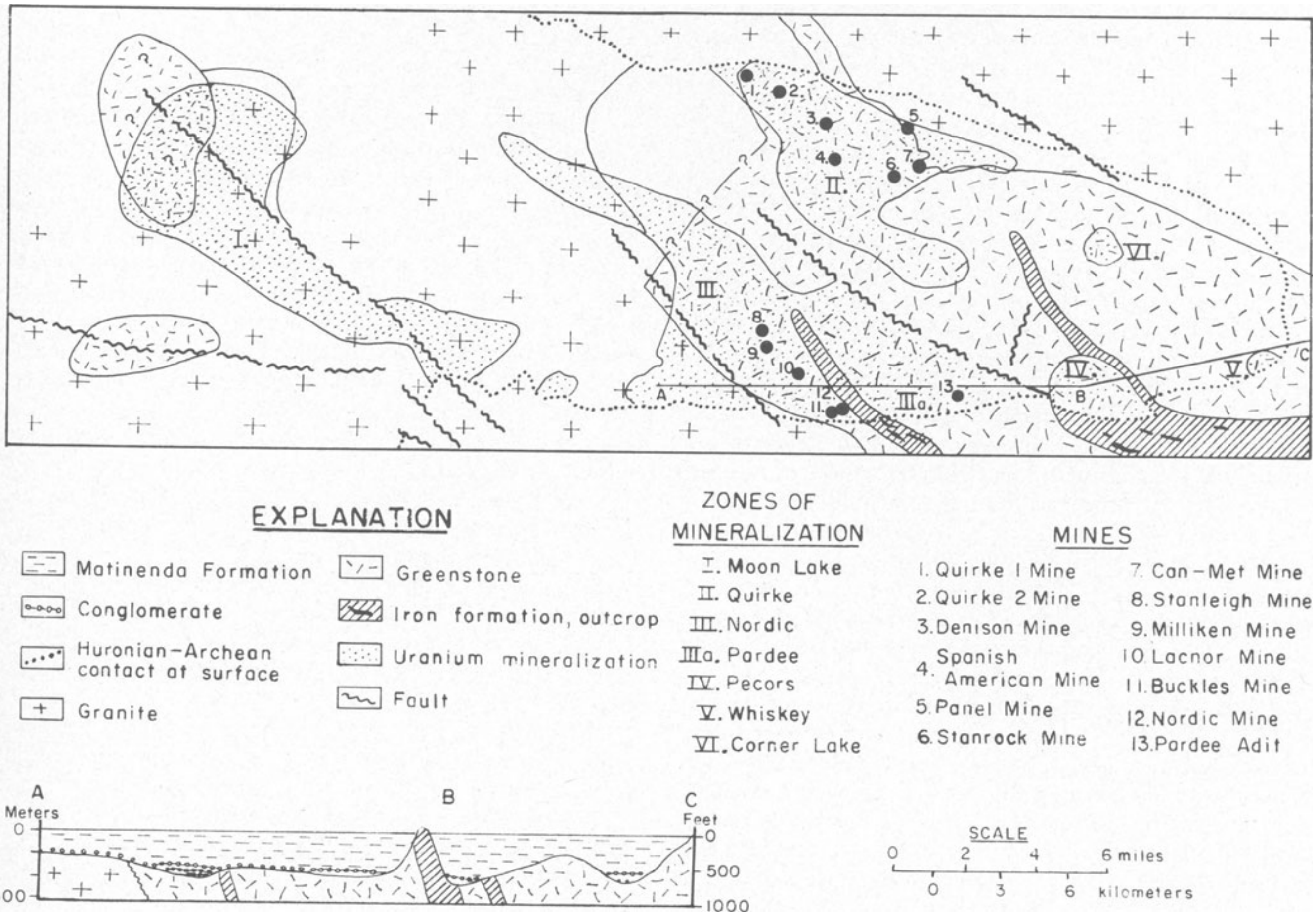

Fig. 3 Uranium deposits in Quirke syncline. Modified from Robertson[98]

The Matinenda ranges in thickness from zero to about 213 m in the south, but thickness varies because of basement irregularities. Ore-bearing conglomerates are generally at or near the base of the Matinenda, but may be as much as 45 m above the base. The pebble conglomerates are lenticular and range from a few centimetres to 6 m in thickness. Large-scale trough cross bedding is the most prominent sedimentary structure. It is probable that the conglomerates were deposited in anastamosing or braided stream channels, lateral migration coalescing the channels into broad thin sheets or reefs.[97] Cross bedding and pebble orientation indicate a northwest source; but, locally, currents were influenced by basement topography. Uraniferous conglomerates are best developed above old valleys on the basement surface that are underlain by greenstone. The courses of some palaeostreams may have been controlled by tholeiitic basalt flows that occur locally in the Matinenda.

Typical ore-bearing conglomerates consist of well-rounded, well-sorted quartz pebbles in a matrix of abraded quartz, feldspar, sericite and pyrite grains. Pyrite content ranges from 10 to 12% and occurs as rounded to subhedral grains or in massive form. Rarely does it replace or fill fractures in the quartz pebbles. Arnold[5] postulated that the pyrite was formed by sulphidization of detrital magnetite, and he reported grains with cores rich in leucoxene, believed to have formed from ilmenite exsolved from the original magnetite. The ore minerals (brannerite, uraninite and monazite) are in the matrix. Thucholite is present both in ore and as post-ore secondary material in fractures. Gummite (soddyite and uranophane), uranothorite and coffinite have also been reported. A great variety of minerals, especially heavy minerals, have been described from the conglomerates, but their quantity is very small.[32]

Brannerite occurs typically as ovoid, reddish-brown to black grains, which suggests that it is detrital.[36] Ferris and Rudd[44] stated that brannerite is a low-temperature diagenetic mineral formed when uranium replaced iron in decomposing ilmenite. They also believed that the released iron combined with volcanic sulphur to form the pyrite in the matrix.[16, 96]

Uraninite generally occurs as black subhedral to rounded grains about 1 mm in diameter. Again the rounding indicates a detrital origin. Derry[36] noted that the 5–6% ThO_2 content of the uraninite is more typical of pegmatitic uraninite than hydrothermal types, thus supporting a detrital origin, but J. Patchett[97] suggested that uraninite may have resulted from leaching of brannerite by hydrothermal solutions. Carbon sometimes partly replaces uraninite and fills microfractures in uraninite grains. Some uranium appears to have dissolved locally and reprecipitated as pitchblende with carbonaceous material (thucholite).

The origin of the Blind River–Elliot Lake uranium minerals is uncertain and controversial, but most workers favour a detrital beginning. McDowell[72] suggested that the source area was an area of low-grade uraniferous pegmatites and late Precambrian pitchblende occurrences some 210–400 km to the northwest. Robertson[98] favoured a source in bodies of red quartz monzonite and associated pegmatites (eroded) that occur in Archaean terrain just north of the Elliot Lake area. These monzonites contain anomalously high concentrations of uranium and are readily detected by airborne gamma-spectrometry surveys.[31, 95]

The uranium deposits occur in three different southeast-striking channel systems or zones of mineralization controlled by topography.[36] They are, from west to east, the Moon Lake, Quirke and Nordic zones. The Quirke ore zone is 13 000 m long and 1800–5500 m wide, whereas the Nordic zone is 19 500 m long and 1400–8000 m wide. In the Quirke zone some eight orebodies or reefs are known. They range in thickness from 1.8 to 6 m and are separated by 3.6–30 m of quartzite. In the Nordic zone three or four reefs that vary in thickness from 1.5 to 3 m are being exploited.

Grade of ore is generally higher where conglomerate thickness and degree of pebble packing (least matrix) are greatest. Locally, conglomerate beds may contain as much as 1.0% U, but in mining widths of 2.7–9 m the average grade is 0.1–0.15% U_3O_8. Between 1955 and 1973 the Blind River–Elliot Lake district produced uranium valued as $1500 000 000 from ore averaging 0.10% U_3O_8. Robertson[98] estimated that identified and partly identified uranium resources in the district were at least 400 000 ton recoverable U_3O_8. Other geologists place the figure nearer 300 000 ton.

Black shales

Chattanooga Shale, eastern U.S.A.

The Devonian–Mississippian Chattanooga Shale of Kentucky, Alabama and central Tennessee is a massive, siliceous, pyritic shale lying unconformably on the Ordovician Leipers Limestone.[60] It averages about 9 m in thickness and is divisible into two members—the Dowelltown Member at the base and the Gassaway Member at the top. The Dowelltown is about 4.5 m thick and carries low uranium values (28 ppm in the lower 1.5-m 'A' unit and 11 ppm in the upper 3-m 'B' unit). The Gassaway is also about 4.5 m thick and is divided into three units. The lower ('C') unit is about 2 m thick, the middle ('D') unit is about 1 m thick and the upper ('E') unit varies from 1.5 to 2.5 m in thickness. The uranium content of the Gassaway ranges from 55 to 70 ppm and is generally greatest in the 'E' unit, which also contains phosphate nodules in its upper part in some areas.[82]

Carbonized plant material is abundant in the Chattanooga. It consists mostly of macerated and unidentifiable fragments that constitute about 20% of the shale by weight. The remains are those of land plants that drifted into the sea and indigenous planktonic marine algae. Oil yield by pyrolitic destruction of organic matter in the Gassaway Member is as much as 8 gal/ton.[27]

The Chattanooga shales were deposited at the southern end of a shallow sea, bordered on the southeast, south and west by a stable, nearly peneplained lowland formed on carbonates. Uranium was probably deposited syngenetically with the clay, silt and organic material that constitute the shale. The uranium is more or less evenly distributed throughout the shale, and was probably adsorbed from sea water on plant debris and clay particles.[123]

The Chattanooga constitutes a very large low-grade uranium resource.[124] The richer black shales of the Gassaway Member underlie an area of 10 000 km^2 and contain an estimated 30 000 000 ton U_3O_8 plus large amounts of V, Mo, petroleum and other potentially valuable by-products.

Muds

Walvis Bay area, Namibia

The Walvis Bay area, as used here, refers to an area of some 40 000 km^2 off the coast of Namibia between latitudes 19°S and 25°30′S. Water depths in this area range from 40 to 160 m. Investigations have revealed four depositional 'basins', the largest lying between 21° and 24°S.[78] Diatomaceous mud covers an area of about 19 000 km^2 within the basins and reaches a maximum thickness of 15 m. The diatomaceous ooze is underlain in most places by a layer of shells that, in turn, rests on hard grey siltstone, uncompacted silt, grey medium-grained sandstone, viscous grey clay, fine breccia or calcarenite.

The mud, dated as Eocene, is relatively homogeneous with an average solid content of 7% by weight in the upper part and 23% by weight in the lower part of the unit. It is greenish-grey to dark grey and emits H_2S odour. The mud is very fine-grained, 70–80% by weight of the grains being smaller than 6.3 μm and 15–25% between 6.3 and 20 μm. Most of the mud consists of disc-shaped diatoms, but some foraminifera, ostracods, pteropods, gastropods, lamellibranchs and a few shark teeth are present.

Uranium, which seems to occur in an amorphous state, has not been directly correlated with organic content. It occurs both in the mud and the underlying sediments. It varies in concentration from 7 to 70 ppm (average, ~21 ppm). Other average metal contents include Mo (112 ppm) and V (112 ppm). Based on the average of 21 ppm, it is estimated that the 19 000 km^2 of diatomaceous sediments contain 4 000 000–5 000 000 ton U_3O_8.

Phosphates

Western U.S.A. phosphate field

Phosphates in the western U.S.A. phosphate field occur in the Permian Phosphoria Formation in an area of 350 000 km^2 in southeastern Idaho, northeastern Utah, western Wyoming and southwestern Montana. The Phosphoria consists of two transgressive–regressive marine cycles, each cycle composed of a lower carbonaceous phosphatic shale member overlain by a chert or carbonate member. The phosphatic shale member is a complex of black carbonaceous shales, pelletal phosphorites and phosphatic shales. Phosphorite and mudstone are the lithologic end-members of the phosphatic shales. The lower phosphorite–chert couplet (Meade Peak Phosphatic Shale Member and Rex Chert Member) is thickest in southeast Idaho, where it ranges up to 396 m. The upper couplet (Retort Phosphatic Shale Member and Tosi Chert Member) is thickest in northwestern Wyoming and southwestern Montana, where it may be as much as 91 m thick.[74] Most of the phosphorite mining has been in the thick lower phosphatic shale member. Eastward in Wyoming the phosphatic shale and chert members change facies to carbonate rocks that, in turn, change facies still farther east in Wyoming to evaporites and red beds.

The phosphorites consist of carbonate–fluorapatite mixed with varying amounts of quartz silt, clay minerals, calcite, dolomite, chert and carbonaceous matter. Most of the phosphate occurs as pellets with amounts of oolites, intraclasts, scales, phosphatic shells and replaced skeletal grains. The pellets are cemented with dolomite, calcite, phosphate or, rarely, chert. Some phosphorite beds are composed of phosphate mud. There is a general decrease in size and abundance of intraclast fragments and an increase in carbonaceous content in the phosphorite beds toward the west. These characteristics, plus the close association of phosphorites with cherts and carbonaceous shales and their shoreward facies change to carbonate rocks, suggest that the Phosphoria accumulated on a moderately shallow shelf edge with prolific planktonic life or in an anoxic basin with restricted circulation.

Where fresh and unweathered, phosphorite beds are hard and dark brown or black, and interbedded mudstones are pyritic. Weathered phosphorites are friable and brown to grey, and they are commonly enriched in phosphate and depleted in uranium. Phosphatic shale members are most phosphatic at both top and bottom or at the bottom only. In southeast Idaho the Meade Peak averages 11–12% P_2O_5, but beds 1–3 m thick near the base and at the top assay 25–33% P_2O_5. Nearly all phosphorites and phosphatic beds contain U, but content varies from 0.001 to 0.65%. Uranium content generally increases with increase in P_2O_5, and both uranium and P_2O_5 increase westward. McKelvey and Carswell[73] determined that phosphate beds of minable thickness (1 m +) that contain more than 31% P_2O_5 generally contain 0.01–0.02% U. It is estimated that this phosphate field has reserves of 202 324 000 000 ton of recoverable phosphate product (about 30% P_2O_5) containing 20 783 000 ton U.

Brines

Uranium in sea water

Uranium concentration in sea water ranges from 1 to 4 ppb,[101] except in inland seas, such as the Caspian Sea, where uranium content ranges from 3 to 10 ppb. The total amount dissolved in the oceans is estimated at 5000 000 000 ton uranium.[131] Research on extraction has been conducted by several countries, including Japan, the United Kingdom, the U.S.A. and West Germany.

Methods considered for uranium extraction include desalination-uranium plants, pumped-water plants, tidal-powered plants and masses of floating logs. Although all these methods can recover uranium from sea water, a profitable method of recovery has yet to be devised. The major difficulty with most processes is the problem of ensuring large and constant volumes of untreated sea water and to prevent processed water from being recycled through the plant. Llewelyn[66] estimated that to obtain 1000 ton uranium per year would require the processing of one trillion ton of sea water.

Silicic volcanics

Sierra Peña Blanca district, Chihuahua, Mexico

The Peña Blanca uranium district is about 50 km northeast of Chihuahua, Mexico, on the east side of a large Basin and Range horst block and near the eastern edge of the Caenozoic Sierra Madre Occidental volcanic province. The bulk of the uranium deposits, which total about 5000 ton of reasonably assured U_3O_8 resource, occur in extracaldera ash-flow tuffs overlying Cretaceous limestones.[50] The source of the tuffs is unknown, but some appear to be related to a large caldera south of Chihuahua. Other tuffs appear to have a western source.

The volcanic sequence at Peña Blanca consists of about 200 m of limestone conglomerate and welded, unwelded and epiclastic tuffs. The volcanics were laid down on a surface of considerable relief. A Cretaceous rudistid reef complex was being exhumed with the formation of local limestone conglomerates prior to deposition of the oldest volcanics.

Uranium occurs in at least five different environments in the district.

(1) Mineralized step faults in welded members: jointing or faulting of the brittle massive ignimbrite provided pathways for solutions and sites for precipitation. Deposits average 300–500 ton U_3O_8 at grades of 0.30–0.40% U_3O_8. Examples are Nopal nos. 1, 3 and 5 deposits.

(2) Mineralization within the more porous and permeable units, such as lapilli tuff: porosity was provided by pumice and lithic fragments.

(3) Mineralization in altered vitrophyre at the base of a welded tuff: larger lower-grade deposits, such as the Margaritas, are of this type. It is about 2 km long, 100–200 m wide and several metres thick, and it contains about 4000 ton U_3O_8 at an average grade of 0.20%. Uranium occurs mostly as uranophane with some carnotite and autunite. Alteration is characterized by the formation of hematite and montmorillonite. The position of this deposit adjacent to a slightly petroliferous rudistid reef complex suggests possible palaeo-hydrologic and organic-reductant influences on mineralizing fluids.

(4) Mineralization of a pumice zone below an ignimbrite, as at Margaritas.

(5) Mineralization in underlying rudistid limestones: uranium occurs in faults, solution cavities, palaeo-karsts and other zones in fetid limestone beneath volcanics at Domatilla mine.

Mafic volcanics

Olympic Dam, South Australia

An important discovery of uranium, apparently related in part to mafic volcanic rocks, is the very large Cu–U orebody in probable Proterozoic rocks at Olympic Dam (Roxby Downs), South Australia. This blind orebody, covered by 350 m of unmineralized rock,[84] was discovered by utilizing the concept that continental basaltic rocks release Cu during alteration.[54]

Uranium occurs here in hematitic granitic breccia or arkose about 800 m thick overlain by more than 100 m of hematite-sericite-altered volcanic rocks and 100 m of shale. Pitchblende, brannerite and davidite occur with chalcopyrite, cobaltite and gold. REE are also abundant. Gangue is hematite, barite, fluorite, magnetite, quartz and sericite.[108]

The origin of this deposit, and a similar one at Mt. Painter 250 km to the east,[133] is not fully understood, but may be related in some way to submarine volcanism.[84] The thick breccia and conglomerate units are also a key element, probably indicating active faulting along platform boundaries. Hydrothermal solutions moving up the flanks of a shallow marine basin from a nearby intrusive source created a sulphidic environment where they encountered the granitic debris. Uranium, concentrated here with Cu, combined with Ti liberated by sulphidization of Fe–Ti oxides in the arkose to form brannerite and davidite.

The orebody is about 1.5 km by 0.5 km and up to 170 m thick. It contains thick zones of 0.05–0.10% U_3O_8 in 1–2% Cu, and early estimates[132] are that it contains about 600 000 ton U_3O_8 and 11 000 000 ton Cu. Patterson and Pitman[91] gave an estimate of 375 000 ton U_3O_8.

Peralkaline nepheline syenites

Ilímaussaq, Greenland

At Ilímaussaq at the southern tip of Greenland uranium occurs within a large peralkaline syenite intruded into lavas, intraflow sandstones and the Julianehaab granite about 1020 m.y. ago.[19] In its later stages the intrusion crystallized by accreting crystals under an impervious roof (foyaite and naujaite zone) at the same time as a layered mass (kakortokite zone) accumulated near the base of the magma chamber. Finally, a lujavrite formed in between.[43] The lujavrite commonly contains 200–300 ppm Th, but numerous xenoliths and dykes make U–Th values highly erratic. Local zones exceed 1000 ppm U and 5000 ppm Th, but minable zones in excess of 400 ppm are thin and the ore is refractory.[15] The principal ore mineral is the rare mineral steenstrupine, which contains 0.2–1.5 wt% U and 2.0–7.5 wt% Th.[119] Other radioactive minerals, such as eudialyte and monazite, are also present. It is estimated that the

Ilímaussaq deposit contains about 35 000 ton U_3O_8 reasonably assured resource at \$50/lb.[88]

Carbonatites

Araxá, Brazil

The best-known and probably most important uranium-bearing carbonatite in Brazil is Araxá, located north of Pocos de Caldas in Minas Gerais. The Araxá pipe is an intrusion of biotite–carbonatite that strongly domes the intruded Precambrian Araxá Group. Uranium and thorium are associated with pyrochlore and apatite in a highly decomposed mass of carbonatite. The roughly circular pipe is about 4.7 km in diameter and is almost completely surrounded by fenitized quartzite. The carbonatite consists largely of magnesian calcite with oxides of iron, titanium and apatite. Lesser components include pyrite, sphene, barite, ilmenite, zircon and monazite.[77] The entire carbonate mass, except for one outcrop, is covered by a weathered mantle up to 300 m thick. The mantle is composed of manganese and iron oxides, phosphate, barite, pyrochlore and monazite. Pyrochlore occurs in the residual crust and as disseminations and stockworks in fresh rock, but the richest material is in a centralized body just below the weathered mantle. This is one of the largest niobium deposits in the world (300 000 000 ton easily accessible ore). Phosphate is associated with the pyrochlore and is concentrated in the weathering mantle. Uranium is present in small amounts throughout the carbonatite. The niobium deposit contains from 0.023 to 0.05% U_3O_8, the phosphate deposit contains about 0.01% U_3O_8, REE concentrations average about 0.03% U_3O_8 and the weathering mantle averages about 0.01% U_3O_8. It is estimated that the entire deposit contains 139 700 t U_3O_8 and 1 323 000 t ThO_2.[71]

Anatectics

Rössing deposit, Namibia

The Rössing deposit is a large low-grade uranium occurrence on the southwestern flank of a large domal structure in the central part of the late Precambrian Damaran orogenic belt in Namibia (Fig. 4). Uranium minerals occur in syntectic alaskites within steeply dipping isoclinal folds of the migmatized Khan and Rössing Formations. These formations consist of highly metamorphosed and migmatized pyroxene and hornblende gneisses, amphibolites, schists and marbles. Three stages of dynamothermal metamorphism and accompanying deformation have affected the host rocks. A younger thermal event is recognized adjacent to the alaskite.[129]

Syntectic alaskites range from small secretionary lenses to large intrusive and replacement bodies. They show concordant, discordant and replacement relations with the folded metasediments. The alaskites were emplaced along shears, fractures, bedding planes and axial planes of isoclinal folds. The alaskites are mostly pegmatitic, but hypidiomorphic-granular textures are common. They consist of quartz, microcline and microcline–perthite together with accessory amounts of zircon, fluorite, molybdenite, apatite, biotite and sphene.

Uraninite, the dominant ore mineral, occurs as small euhedra poikilitically enclosed in quartz and feldspar and as finely disseminated euhedra interstitial to and along microfractures in major rock-forming minerals. Secondary uranium minerals, mostly beta-uranophane, are concentrated in the upper part of the deposit and constitute nearly 40% of the ore. They formed as replacements of uraninite or as films along microfractures as the result of upgrading in the unusual Namib Desert climate, where nightly fogs form small amounts of moisture.[14]

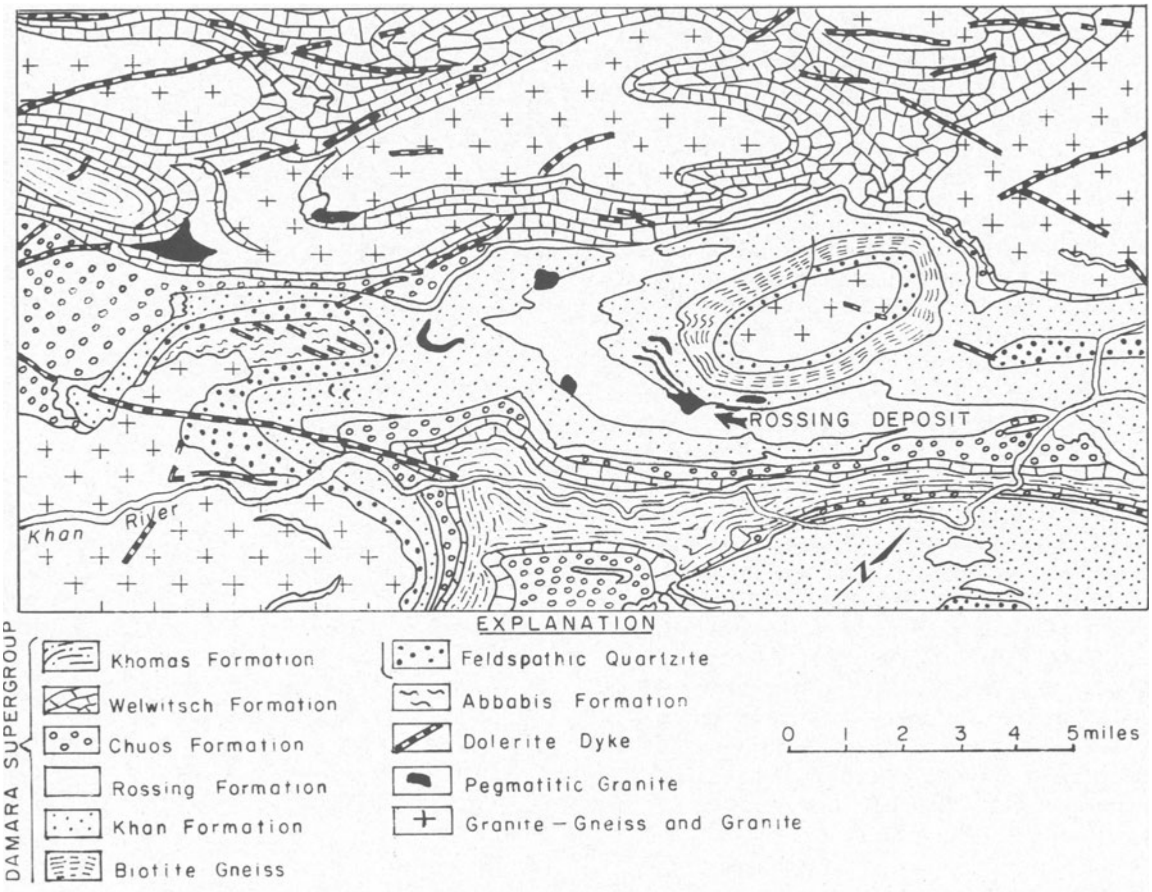

Fig. 4 Setting of Rössing uranium deposit. Modified from Smith[117]

Rössing is the largest known anatectic or ultra-metamorphic deposit, containing about 150 000 ton U_3O_8 at an average grade of 0.035% U_3O_8.

Peralkaline granites

Bokan Mountain, Alaska, U.S.A.

The Bokan Mountain uranium occurrence is associated with the late Cretaceous to early Tertiary Bokan Mountain granite pluton on Prince of Wales Island in southernmost Alaska. The granite is an epizonal, circular ring-dyke complex intruded into eugeosynclinal metasediments and a Devonian(?) plutonic sequence.[125] Its epizonal nature is shown by contact effects, roof pendants and associated hypabyssal intrusives. The lack of internal structures, discordance with structures in the metasediments and extensive alkali metasomatism suggest that it is a postorogenic intrusive.

The border zone of the 6.5-km^2 complex is a riebeckite granite pegmatite/aplite up to 13 m thick. Next inward is an aegirine granite porphyry shell about 180 m thick that grades inward into a 15-m thick transition zone in which riebeckite is the dominant ferromagnesian mineral. Ring dykes of riebeckite aplite porphyry were injected into these marginal zones. Interior portions of the complex consist of banded or massive riebeckite-bearing granites cut by aplitic plugs and ring dykes.

The uranium–thorium mineralization is localized in highly albitized shear zones as vein-like or irregular pipe-shaped bodies formed by concentrations of uranium-bearing microveinlets. The ore zones occur within or on top of syenitic masses and show intense albitization, chloritization and hematitization. MacKevett[68] and Staatz[121] also reported minor syngenetic concentrations within the magma body and in the pegmatites. They considered the veins and pipe-like bodies to be postmagmatic hydrothermal.

Uranothorite and thorian uraninite are the main ore minerals, but coffinite, brannerite and pigmentary materials are also present. Accessory minerals include calcite, fluorite, quartz, sulphides and tourmaline. U/Th ratios range from 10 to 100 in ore, but are less than 10 outside ore. The Ross-Adams mine produced about 1000 ton U_3O_8 at a grade of about 1.00% U_3O_8 between 1957 and 1971.

Granites

Midnite mine, Washington, U.S.A.

At Midnite mine, about 64 km northwest of Spokane, Washington, uranium occurs in a roof pendant of the late Precambrian Togo Formation, adjacent to a late Cretaceous quartz monzonite. The Togo consists of steeply dipping, low-grade metamorphosed black shales (metapelites) with lenses of calcareous material. It contains up to 2% iron sulphides and ubiquitous graphite. The monzonite is composed of large feldspar phenocrysts in a groundmass of quartz, potash feldspar, plagioclase and biotite. Accessory minerals are muscovite, sphene, zircon, apatite and fluorite.

The average uranium content of the intrusive is about 12 ppm. Primary uranium minerals (pitchblende and coffinite) are concentrated along small step faults and shears in the metasediments.[10] Uranium minerals occur as replacements, disseminations along foliation planes and fracture fillings. Orebodies are roughly tabular, have nearly horizontal upper surfaces and are bordered on one or more sides by unmineralized monzonite. Dimensions range up to 380 m long, 210 m wide and 50 m thick.[85] Midnite mine has produced about 6000 ton U_3O_8 at a grade of 0.21% U_3O_8 since 1957.[84]

Pegmatites

Bicroft mine, Bancroft district, Ontario, Canada

Bicroft mine near Bancroft, Ontario, is within the Cardiff plutonic complex, consisting of two gneissic granites and a gneissic syenite intruded into late Precambrian metasediments. The Bicroft pegmatites occur at the contact between the Centre Lake granite and the metasediments. The uranium-bearing pegmatites are in paragneisses and para-amphibolites adjacent to the granite. Four types of pegmatites are recognized here (pyroxene, pyroxene granite, granite and quartz-rich pegmatites), but uranium is largely restricted to the quartz-rich pegmatites.

Ore minerals are uraninite, uranothorianite, allanite, pyrochlore and betafite in a gangue of smoky quartz with accessory zircon, molybdenite, amphibole and anatase. Minor calcite and fluorite are present. Unzoned pegmatites have U_3O_8 contents of 0.024–0.117% in widths of 1–4 m.[111] Reserves for Bicroft are unknown, but for the entire Bancroft area they are 2200 ton U_3O_8 at a grade of about 0.13%.

Hydrothermal veins

Schwartzwalder mine, Colorado, U.S.A.

An example of veins with simple mineralogy is the *Schwartzwalder mine*, 25 km west of Denver, Colorado. Host rocks for this deposit are metasediments of the late Precambrian Idaho Springs Formation—a complex of sandstone, shale, carbonates and mafic intrusives.[114] Large breccia-reef fault zones formed during late Precambrian cataclastic deformation were reactivated about 50–70 m.y. ago. Structures hosting the uranium are subsidiary to the major structures (Fig. 5).

Uranium occurs in flat or horsetail veins with low dip in the hanging-wall of the major Illinois vein, but they steepen near the major faults.[90] Mineralized portions of faults are continuous for more than 900 m vertically, but strike lengths are less than 200 m.[37] Brittle metasediments are the favoured hosts.

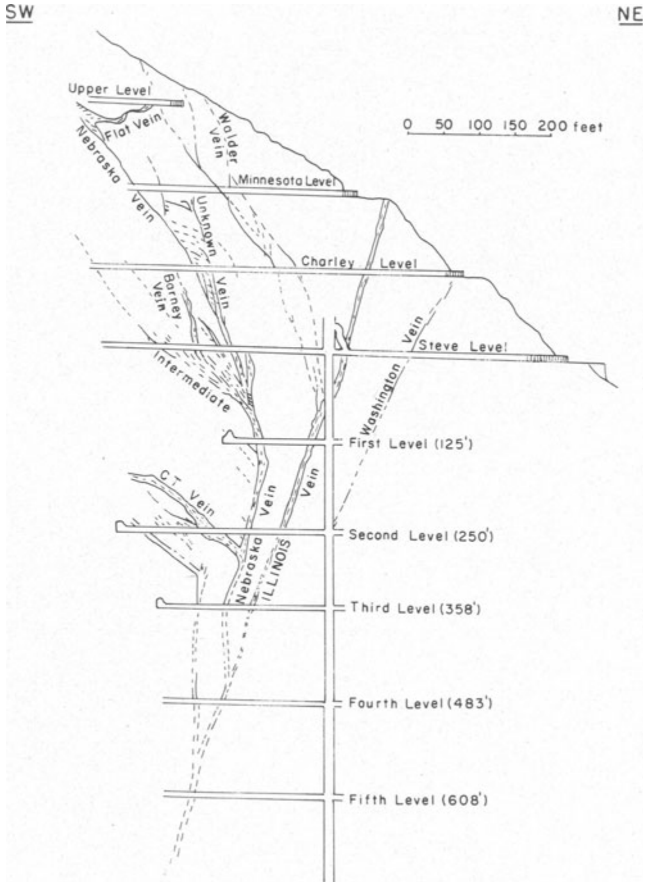

Fig. 5 Cross-section, Schwartzwalder mine. Modified from Downs and Bird[41]

Pitchblende and coffinite along with jordesite and adularia were formed during the main mineralization. A later base-metal stage added chalcopyrite, chalcocite, ankerite, pyrite and marcasite. Chloritization and sericitization are the main types of alteration. The Schwartzwalder has produced about 5500 ton U_3O_8 and has an equal amount of reserves.[90]

Shinkolobwe deposit, Zaire

An example of veins with complex mineralogy is the mined-out uranium deposit at *Shinkolobwe*, Zaire, at the northwest end of the African Copperbelt. It occurs in a faulted transported fold in metamorphosed dolomitic shales of the middle Proterozoic Mine Series of the Roan Group.[21] Uraninite and uranophane mineralization (about 620 m.y. ago) was followed by several later mineralizations in which pyrite, molybdenite, monazite, selenium, Co–Ni sulphides and selenides and copper minerals were formed. It is believed that this orebody was formed by redistribution of metals originally deposited in marine sedimentary rocks.[47] The uranium, originally weathered from granites and deposited in the marine sediments, was in low concentrations (50–100 ppm), but was remobilized during the post-tectonic metamorphism and 'dammed' under a large nappe to form the Shinkolobwe deposit.

Contact metasomatics

Mary Kathleen deposit, Queensland, Australia

The Mary Kathleen uranium deposit[35, 53] is in metamorphosed and metasomatized nearshore clastic and carbonate sediments of the lower to middle Corella Formation in northeastern Queensland, Australia. The uppermost unit of the Corella is a breccia-conglomerate formed as a cobble beach. This unit hosted most of the ore at Mary Kathleen.

The Corella metasediments occupy a broad syncline bordered on the east by the post-orogenic Mount Burstall granite. This differentiated pluton has an unusually high uranium content (1–12 ppm) and late-stage pegmatites extend westward to within 3 km of the Mary Kathleen orebody. A large north-trending eastward-dipping shear zone, extending through the metasediments toward the granite, may have served as a channelway for metasomatizing fluids from the granite.

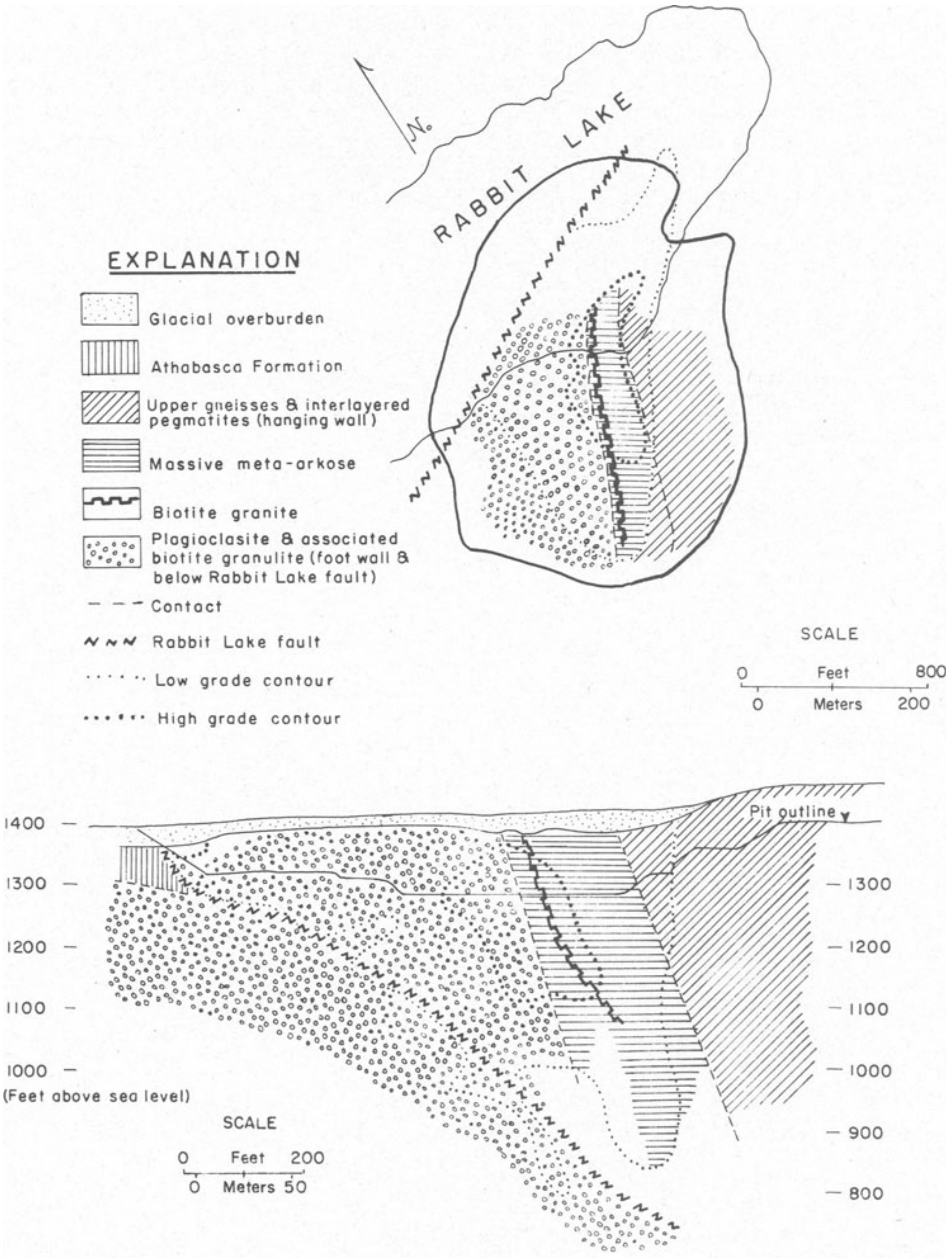

Fig. 6 Map and section, Rabbit Lake orebody, showing lithology. After Sibbald[115]

The orebody, totally within the garnet-rich breccia conglomerate near the axis of the syncline, consisted of 40% garnet, 35% allanite, 10% apatite and 15% 'other', including stillwellite, albite and scapolite.[130] Uranium occurs chiefly as uraninite within allanite and stillwellite. The adjacent beds were variously enriched in REE, Th, B, P, S and Fe. Production at Mary Kathleen was about 12 000 ton U_3O_8 at an average grade of 0.14% U_3O_8, 0.02% ThO_2 and 3.6% REE.

Vein-like types

Unconformity-related

Rabbit Lake, northern Saskatchewan, Canada The Rabbit Lake occurrence in northern Saskatchewan is an example of a monometallic unconformity-related uranium deposit.[57, 61, 65, 75, 76] It is in Aphebian metasediments of the Wollaston fold belt, along the eastern erosional edge of the unconformably overlying Helikean Athabasca Formation. The metasediments include meta-arkose, biotite paragneiss, calc-silicate rocks and marble. The Athabasca is a series of red to brown quartz sandstones and conglomerates.

The Rabbit Lake deposit, the upper surface of which is only 15 m below the plane of the unconformity, is in a steeply dipping, highly chloritized breccia zone in the metasediments (Fig. 6). Breccia fragments are cemented by dolomite, calcite and quartz. Massive and sooty pitchblende occur in veinlets and as fracture fillings and are associated with minor galena, sphalerite, pyrite, marcasite and chalcopyrite. At depth the breccia zone is terminated by a low-angle thrust that placed the Aphebian metasediments above the Athabasca sediments locally. Chloritic alteration is pervasive and zonal around the ore. Two stages of mineralization are recognized—deposition of massive pitchblende preceding chloritization and deposition of sooty pitchblende and coffinite following an intervening red alteration and leaching stage. The deposit is dated at 1100 m.y., whereas the Athabasca is dated at ≃ 1350 m.y. This deposit is reported to contain about 21 000 ton U_3O_8 at a grade of 10–15% U_3O_8.

Jabiluka II, Northern Territory, Australia The Jabiluka II uranium deposit[40, 81, 105, 116] is a polymetallic unconformity-related occurrence. This uranium–gold deposit is in the East Alligator River district, Northern Territory. It occurs in brecciated metasedimentary rocks beneath the unconformably overlying Middle Proterozoic Kombolgie Sandstone. The metasediments (Cahill Formation) consist of pyritic quartz–chlorite–graphite schist, chlorite–graphite schist and some calc-silicate rocks (Fig. 7). They have been folded into an open asymmetric syncline. Near Jabiluka II a thrust fault truncates the sub-Kombolgie unconformity and has placed the Kombolgie in fault contact with the Cahill.

Pitchblende, the principal uranium mineral, coats breccia fragments and forms veinlets up to 2 mm wide. Native gold, which assays 0.44 oz/ton, is associated with the pitchblende in part of the deposit. Associated minerals are pyrite, chalcopyrite and hematite. Ore is generally confined to extensively chloritized and brecciated zones and is most concentrated within and below graphite schists. Ore reserves at Jabiluka II are believed to be about 224 000 ton U_3O_8 at a grade of 0.45% U_3O_8.

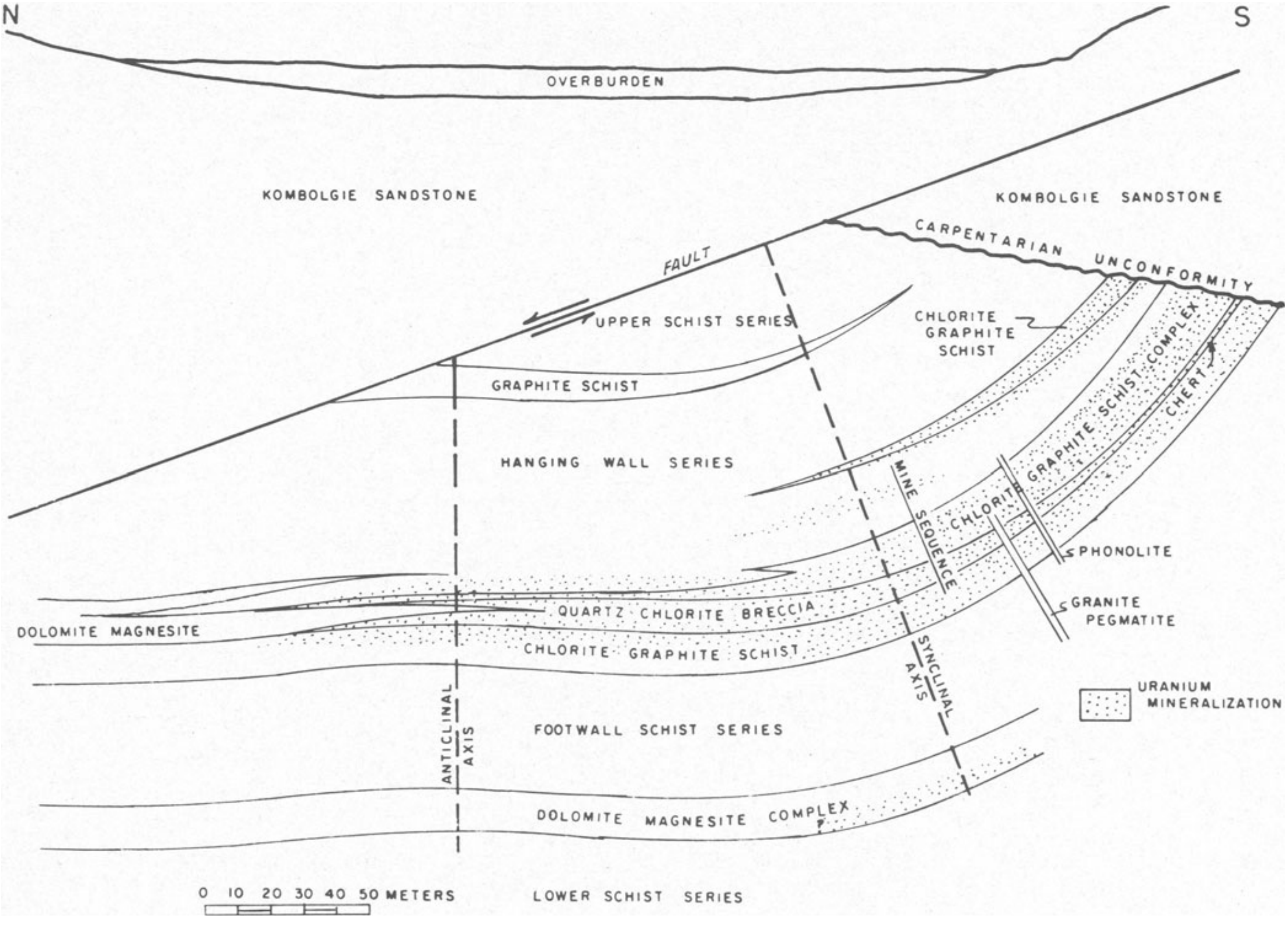

Fig. 7 Cross-section, Jabiluka II deposit. After Rowntree and Mosher[105]

Vein-like deposits in metamorphic rocks

Beaverlodge area, northern Saskatchewan, Canada

The Beaverlodge area in northern Saskatchewan is characterized by monometallic vein-like uranium deposits in metamorphic rocks.[11, 67, 110, 126] Underlying this area is metamorphosed and granitized gneiss of the Lower Huronian Tazin Group. The gneiss is unconformably overlain by continental red beds of the Middle Huronian Martin Formation.

Pitchblende and calcite occur in veins and multiple-vein systems in the Tazin, and some pitchblende occurs in the overlying Martin. Uranium-bearing veins have a strike length of more than 4500 m and they extend to a depth of more than 1645 m. The pitchblende occurs as vein fillings in shears, fractures and brecciated zones within 100 m of the St. Louis Fault. It is also disseminated in rocks adjacent to the veins. Initial pitchblende deposition (1780 m.y. ago) was followed by a thermal event that remobilized and redeposited the uranium about 1140 m.y. ago.

Echo Bay–Eldorado mine, Northwest Territories, Canada

The Echo Bay and Eldorado uranium–silver mines in northern Canada are polymetallic vein-like deposits in metamorphic rocks.[99, 100, 106] The two mines are in a vein system containing U, Ag, Ni and Cu. The veins occur in roof pendants of Aphebian sedimentary and volcanic rocks (Echo Bay Group) within a Hudsonian granitic intrusive. The margins of the pendants were thermally metamorphosed, but the centres are little metamorphosed. Mineralization occurs in green and red banded andesitic tuffs in the pendant centres. Ore occurs in three steeply dipping veins that average 0.5 m in thickness, 1500 m in length and more than 400 m in depth. Veins contain pitchblende, native silver, native bismuth with small amounts of base-metal sulphides and Co–Ni arsenides. Veins are surrounded by a halo of feldspatization, hematitization, chloritization and carbonatization.

Epigenetic types

Sandstones

Peneconcordant deposits The largest concentration of high-grade uranium in peneconcordant deposits is in the *Grants Mineral Belt* near Grants, New Mexico.[28, 52, 56, 109, 134] The uranium hosts are massive green to reddish-brown arkosic fluvial sandstones in the Westwater Canyon and Brushy Basin Members of the late Jurassic Morrison Formation (Fig 8). These sandstones have thin mudstone partings and contain much woody trash. In the Ambrosia Lake portion of the Belt the mineralized trend is as much as 2.5 km wide and more than 6 km long.

Individual peneconcordant deposits are tabular bodies generally elongate parallel to palaeo-drainage and clusters of orebodies show the same alignment. Orebodies range from 0.5 to 9 m in thickness, 20 to 240 m in width and 100 m to 2 km in length. Ore boundaries are generally sharp. Bedding planes commonly form the lower boundaries of orebodies, but the upper boundaries may be gradational. Ore tends to concentrate parallel to intraformational disconformities, along mudstone contacts and coincident with subtle low-amplitude synclinal folds. In some cases ore terminates against sharply curved surfaces (rolls).

Coffinite is the principal uranium mineral, but organo-uranium complexes and uraninite are also present. They coat sand grains black and fill interstices. In places masses of jordesite and vanadium and manganese minerals occur marginal to ore. Secondary uranium minerals are not common, but they include phosphates, silicates and hydrous oxides. Alteration consists of bleaching from red to green or grey, kaolinitization of feldspars and formation of calcite haloes. Production plus reserves in the Grants Mineral Belt total about 221 300 ton U_3O_8 at a grade of 0.15% U_3O_8.

Roll-type deposits In the *Gas Hills district of Wyoming* roll-

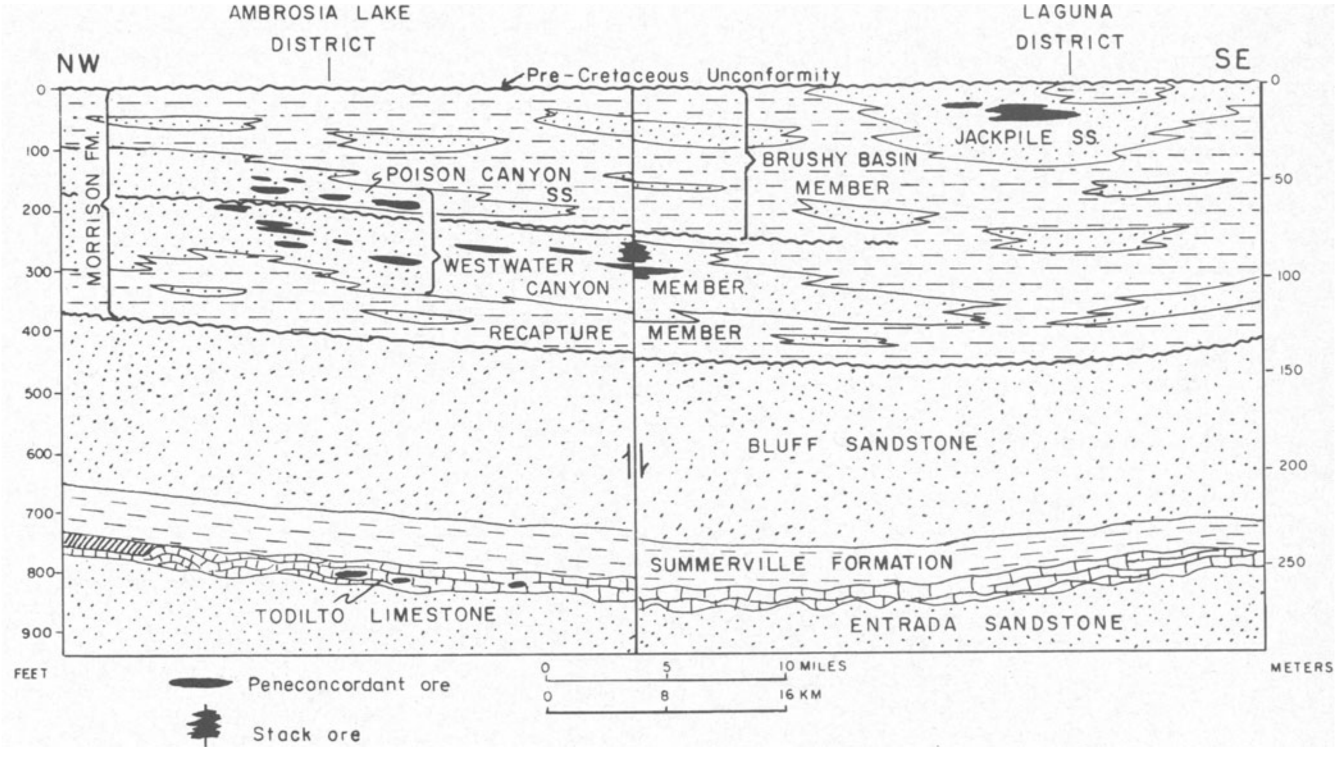

Fig. 8 Cross-section, Grants Mineral Belt. Modified from Hilpert[55]

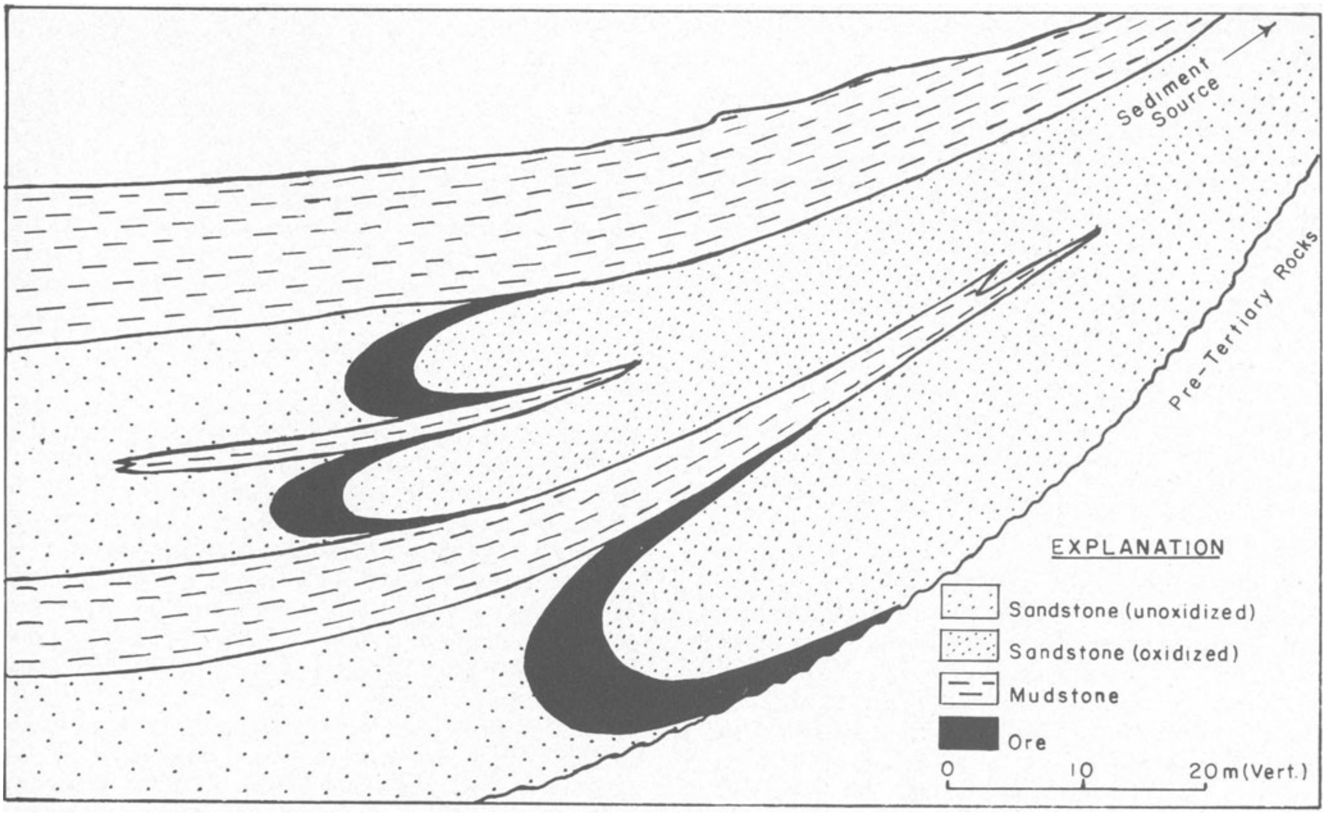

Fig. 9 Schematic diagram of roll-type uranium occurrences in Wyoming Basins

type uranium deposits occur in the upper part of the Eocene Wind River Formation.[3,4,118] The Wind River is a 90- to 245-m thick unit of cross-bedded arkosic fluvial sandstone with interbeds of mudstone, carbonaceous shale and conglomerate.

Roll-type orebodies, found below the water-table, vary from 0.3 to 8.0 m in thickness. Rolls are tongue-shaped in plan and concentric *C*-shaped in vertical section (Fig. 9). Solution fronts have been traced for several kilometres and individual orebodies extend for 1000 m or more. The thickness of the individual sandstone bed that contains the solution-front controls the ore thickness.

Ore-bearing zones have much coaly material and carbonized wood. The ore consists of uraninite and coffinite, which occur as black coatings on grains and as interstitial fillings. They are accompanied by Se, Mo and As enrichment. Oxidized zones (above the water-table) contain uranium phosphates, silicates and hydrous oxides. It is estimated that the Gas Hills district will ultimately produce about 75 000 ton U_3O_8.

Calcrete deposits

The most important uraniferous calcrete deposit is *Yeelirrie, Western Australia*.[20,23] Yeelirrie is an area of interior drainage, deep valley fills, abundant evaporite lakes and clay pans in an arid region. Valley calcretes are typically elongate masses of carbonate-cemented alluvium deposited parallel to subsurface valley drainage courses, but some form delta-like deposits that fringe salt lakes.

Uranium from weathered granites and vanadium derived from greenstones are present in the groundwater and valley-fill sediments. Uranium, vanadium and potassium concentrate downstream by evaporation and combine in the oxidizing environment to form carnotite, which fills cavities and fractures in the calcrete. Carnotite also forms in a clay–quartz unit beneath the calcrete. Resources at Yeelirrie are estimated at 47 000 ton U_3O_8 at grades of 0.05–0.10%.

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