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Geology and genesis of major world hardrock
uranium deposits--An overview

by

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Geology and Genesis of Major World Hardrock

Uranium Deposits--An Overview

by J. Thomas Nash

ABSTRACT

Uranium deposits in igneous and metamorphic rocks occur in many forms and geologic settings. Ages range from about 1.8 b.y. (billion years) to late Tertiary, but the most important deposits are of Proterozoic age. The largest resources are in unconformity-type veins, comprising about 21 percent of Western World Reasonably Assured Resources (WWRAR), and on the basis of the high rate of discovery over the past 10 years, these will become even more important in the future. Ultrametamorphic deposits contain about 7 percent of WWRAR, but this is chiefly in the Rössing Deposit. Classical vein-type deposits contain about 3 percent of WWRAR and are known on all continents. Igneous-related deposits in plutonic, volcanic, and magmatic-hydrothermal environments, considered very important 25 years ago, contain only a few percent of WWRAR; recent large discoveries at McDermitt and Peña Blanca, however, suggest the volcanogenic environment may prove to be a major uranium producer.

The geochemistry of uranium has not been uniform through time due to the evolution of life forms and their impact on the oxygen and carbon budget. This changing geochemistry is reflected in the character of ore deposits in time: (1) The absence of hardrock deposits older than about 1.8 b.y. must relate to the lack of oxygen in the early atmosphere, and, directly or indirectly, to the lack of oxidizing meteoric or hydrothermal fluids to transport uranium. (2) Following oxygenation of the atmosphere at about 2.2 b.y., uranium could be transported as uranyl complexes and tended to be enriched by reduction in marginal marine sediments. These sediments generally were metamorphosed in the Proterozoic, and vein-type, unconformity-type, and ultrametamorphic-type ore deposits formed in the metasediments, partly by metamorphic processes. (3) Phanerozoic hardrock uranium deposits are typically vein-type and igneous-type and are not related to regional metamorphism, but in most cases the uranium probably was derived from Proterozoic sediments. Probably more than 90 percent of the uranium in world hardrock deposits was preconcentrated in ca. 2.2- to 1.0-b.y.-old marginal-marine sediments.

INTRODUCTION

Outside the United States, important uranium discoveries in hardrock terrane have accounted for major increases in world reserves. At the present time the majority of world reserves are spread about equally between vein, quartz-pebble conglomerate, and sandstone types of deposits, but the rate of discovery of the large, high-grade, unconformity-type vein deposits will push that category into the lead very soon. However, within the United States only a few percent of the reserves and probable resources are known to be in hardrock terrane. This review of the general habitat of hardrock uranium deposits was undertaken in an effort to identify the broad geologic features that lead to formation of deposits largely unknown in the United States. Some deposits and areas described are shown on figure 1.

Organization of geologic data or classification of uranium deposits is a fundamental problem in an overview such as this. The approach used here has been organization by geology of host rocks, which really is not a classification at all because it is not systematic and does not by itself indicate relations between environments of deposit formation. Classification by process, such as proposed by McMillan (1977), has many desirable features, but at present the genesis of most hardrock deposits is so controversial that radical changes in classification occur with differing genetic opinion. The general geologic character of host rocks, however, is relatively well known and is less subjective, and thus affords a fair starting point. This approach is particularly useful for consideration of the broad geologic controls on deposits and for selection of possibly favorable terrane. It is not suited for prediction of new types of deposits; research on process-oriented, genetic classification is desirable.

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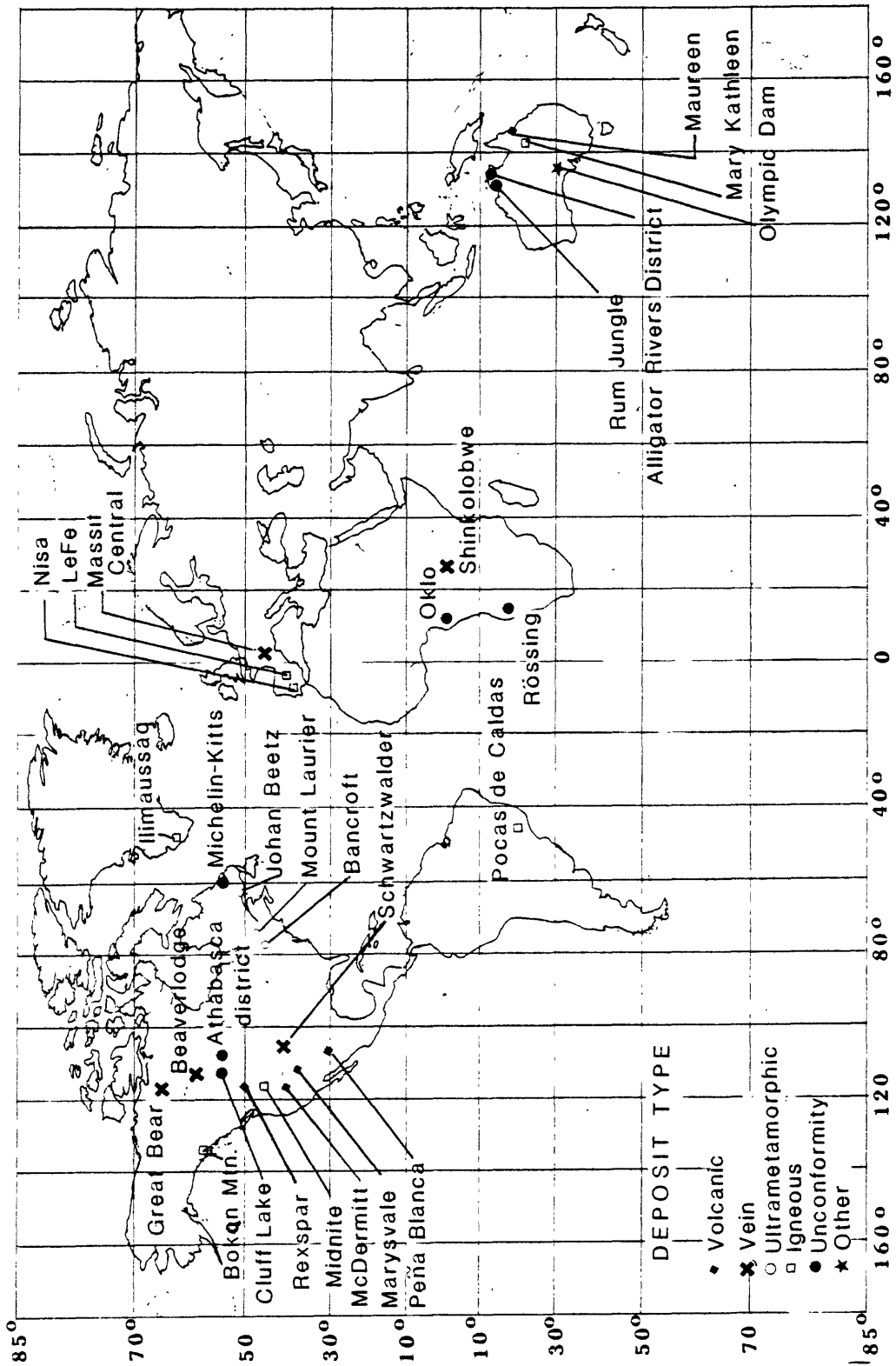


Figure 1.--Location of important uranium deposits and districts.

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ABUNDANCE AND DISTRIBUTION OF URANIUM

Great advances in chemical, isotopic, and geophysical technologies have resulted in greatly increased quantity and quality of data describing the abundance and distribution of uranium. The abundance of uranium in rocks and minerals has been reviewed in several publications (table 1; Adams and others, 1959; Rogers and Adams, 1969; and Turekian and Wedepohl, 1961. In general, uranium content increases with magmatic fractionation in the more silicic-alkalic rocks, increases in sedimentary rocks rich in organic matter or heavy minerals, and is relatively independent of metamorphic grade except in granulite facies where some uranium depletion occurs (Heier, 1973, Dostal and Capedri, 1978).

Uranium abundance is significant to such diverse studies as heat flow, petrogenesis, and plate tectonics which share a common focus on heat production. Consequently, there are abundant new data and interpretations from these fields that describe current and past uranium distribution. Physical and chemical models of the earth (e.g., Gast, 1960; MacDonald, 1963; Ringwood, 1969; Lubimova, 1969; Anderson, 1975, Wyllie, 1979) arrive at the same conclusion--that uranium concentration in the mantle must be very small, about 0.03 ppm, to explain heat flow yet prevent temperatures in excess of melting. The general equality of heat flow over continental and oceanic crust (Lee and Uyeda, 1965) requires that the suboceanic mantle be somewhat enriched in uranium because continental crust is more uraniferous than oceanic. Approximately 80 percent of uranium must be in the upper 400 km of the earth. Because the abundance of the major heat producing radioisotopes ^{238}U , ^{235}U , and ^{40}K has decreased exponentially with time, heat production in the past must have been much higher than today, causing profound implications for petrogenesis and tectonics (e.g. Sutton, 1973; Windley, 1973; Fyfe, 1976; Tarling, 1978).

Table 1.--Uranium Content of Common Rocks and Water¹

	Range (ppm)	Mean (ppm)
Meteorites	<0.001-0.02	0.01
Continental Crust		
Igneous Rocks		
Ultramafic	.001-.03	.01
Mafic, basaltic	.1-1	.75
Intermediate, andesitic	1-6	2
Granite, silicic	2-15	4
Syenite	.1-20	4
Sedimentary Rocks		
Red and green shale	1-5	3
Black shale	5-80	10
Sandstone	.5-4	1
Carbonate	.1-9	2
Evaporite	.1-.2	.1
Metamorphic Rocks ²		
Greenschist grade	.1-4	
Amphibolite grade	.1-4	
Granulite	.05-.5	
Seawater (ppb)	.3-4	2 ppb
Groundwater (ppb)	.1-40	2 ppb

¹Sources: Adams, and others, 1959; Turekian and Wedepohl, 1961; Rogers and Adams, 1969; Heier, 1973; Dostal and Capedri, 1978. See these sources for specific data.

²Uranium content is approximately that of the protolith, except for granulite grade wherein depletion by factors of 2 or more occur.

Uranium distribution in time and space.--Ore deposits of uranium show a marked association with Precambrian rocks (Bowie, 1970, 1979; Dahlkamp, 1978A; Ziegler, 1974). Rocks of late Archean-early Proterozoic age (about 2.8 to 1.8 b.y.)¹ host more than 40 percent of Western World Reasonably Assured Resources (WWRAR). About 10 percent of WWRAR are in middle to upper Proterozoic rocks, and about 50 percent are in Phanerozoic rocks adjacent to Precambrian basement according to OECD/IAEA data (table 3). The ages of the ore deposits range from Archean to Tertiary, but the uranium cycles most likely were established with the development of uranium provinces (see Klepper and Wyant, 1956; Bowie, 1979) early in earth history.

The Precambrian "association" for Phanerozoic deposits is indirect, as it involves a stage of erosion of Precambrian source rocks and sedimentation or partial melting and volcanism. For example, the Jurassic Morrison Formation, which hosts sandstone-type deposits accounting for more than 50 percent of United States reserves, was derived from a region of lower Proterozoic rocks (King, 1976) to the west and southwest (Craig and others, 1955). Similarly, Tertiary volcanic-rich sediments which host uranium deposits in south Texas appear to be derived from west Texas (Galloway, 1978) where lower Proterozoic rocks are known (King, 1976). Thus the Precambrian uranium association for these sandstone deposits appears to be either granitic clastics, or more likely, lower Proterozoic supracrustal rocks that may have been melted to provide a volcanic source of uranium.

Numerous techniques are useful in documenting uranium geochemical or metallogenic provinces: (1) bedrock chemistry (e.g. Lambert and Heier, 1968; Phair and Gottfried, 1964; Eade and Fahrig, 1971; Marjaniemi and Basler, 1972); (2) airborne gamma spectrometry (e.g. Darnley and others, 1977; Saunders, 1979); (3) analysis of uranium radon, and helium in water or sediments (e.g. Cameron and Hornbrook, 1976; Beck and others, 1977; Dyck, 1978); and (4) analysis of heat flow (e.g. Birch and others, 1968; Lachenbruch and Sass, 1971). Such studies have led to the generalization that Archean rocks contain somewhat less uranium than Proterozoic, about 1.2 ppm U compared with 2.2 ppm U (Lambert and Heier, 1968; Eade and Fahrig, 1971; Lambert and

¹1 b.y. equals 10⁹ years.

others, 1976). The nonuniform distribution of uranium and its ores in time and space appears to be related to the thermotectonic evolution of the earth.

Evolution of crust and uranium distribution.--The thermotectonic evolution of the crust and the evolution of life forms appear to have had a profound influence on uranium transport and distribution. Evolving life forms influenced the oxygen and carbon budget in the atmosphere and lithosphere, namely by creating, about 2.2 b.y. ago, an atmosphere with sufficient oxygen to oxidize uranium to the soluble hexavalent state. Later, with the rise of land plants, organic reductants became available in continental sediments. Four stages are recognized in which the distribution of uranium was irreversibly affected or the cycle of uranium was uniquely established.

Stage 1: Permibile Protocrust (ca. 4.6 to 2.8 b.y.). Following accretion of the earth from particles with average uranium content about 50 to 100 parts per billion, virtually complete melting and separation of the core occurred with attendant uranium enrichment in the upper mantle and protocrust (Birch, 1965; Murthy, 1976; Shaw, 1976) and homogenization of radioisotopes at 4.57 b.y. During the next 500-800 m.y. (million years), impacting of meteoritic material added to the protocrust (e.g. Clark and others, 1972) and possibly fragmented the protocrust and mantle (e.g. Goodwin, 1976). As heat production decreased, early protocontinents could form in the period ca. 3.8 to 3.0 b.y. (Moorbath, 1978), but the crust was so thin and ductile that no rigid plates existed, hence the term permibile (Burke and Dewey, 1973; Sutton, 1973; Tarling, 1978). The major element composition of the protocrust was more like modern oceanic crust (basaltic) than continental, judging from the abundance of mafic-basaltic volcanic rocks and greenstone belts. Older Archean rocks (especially granulites) contain less U, Th, K, and Rb than younger equivalents, which may be a primary feature or may reflect secondary depletion (e.g. Tarney, 1976; Heier, 1973). The presence of long, linear greenstone belts dated at 3.4 to 2.7 b.y. apparently indicates enough solidification of the protocrust by this time to permit volcanic arcs, similar to those of the Phanerozoic, to develop. These greenstone belts have been variously interpreted as spreading centers or as subduction zones (see White and others, 1971; Tarney and others, 1976). No uranium deposits of any type are known to have formed in this stage of earth history.

Stage 2: Stabilized Crust, Anoxic Atmosphere (ca. 2.8 to 2.2 b.y.). This stage is characterized by a thicker, more rigid crust due largely to decreased heat production (about 2 to 3 times current level). Largely as a consequence of this thermal regime two important processes began: (1) A large volume of granite was produced with increased K-U-Th contents (Engel and others, 1974; Tarling, 1978; Stuckless and Nkomo, 1978). This chemical evolution occurred when recycling (subduction?) of crust became possible due to the lower thermal gradient (see Green, 1975; Ringwood, 1975). (2) The stabilized crust supported the first intracratonic sedimentary basins (Anhaeusser, 1973; Sutton, 1979). Significantly, these basins were subsequently subjected to only little metamorphism and deformation, in contrast to older volcanic-rich belts (greenstones). The classic Witwatersrand (South Africa) and Huronian (Canada) uraniumiferous conglomerates were developed and preserved in this new environment. The recycling of uranium by a combination of sedimentary and magmatic processes that started at about 2.7 b.y. marks the beginning of uranium preconcentration that sets the stage for ore deposits. This is probably the time when uranium provinces began forming.

A third factor that was apparently crucial for creation of uranium deposits at this stage was an anoxic atmosphere which permitted mechanical transport of uraninite to placer deposits (Roscoe, 1973; Robertson and others, 1978). Holland (1962) first calculated that uraninite should not be oxidized and dissolved by ground water with PO_2 less than about 10^{-22} atm (atmosphere), and used this as a strong argument for the presence of only traces of O_2 in the atmosphere 2.2 to 2.5 b.y ago. Numerous studies (rock chemistry, carbon and oxygen isotopes, evolution of life forms, and atmospheric gases) arrive at this conclusion which I accept, despite the objections of some (e.g. Dimroth and Kimberly, 1976). (See reviews by Cloud, 1972; Schidlowski, 1976; Walker, 1977.) The geologic parallel of uranium and iron deposits of this age reflects the evolution of oxygen. Marine silica-rich banded iron formations of the Lake Superior type do not occur after oxygenation of the atmosphere (Lepp and Goldich, 1964). "All of the oxygen produced during the first few hundred million years of green-plant photosynthesis may have been used in oxidizing abundant reduced compounds, principally iron, in sea water. It is possible that oxygen began to accumulate in the atmosphere only after the oceans had been swept free of ferrous iron" (Walker, 1977, p. 263). Thus iron

formations could form in oxygenated marine environments, and uraninite-bearing placers could form on cratons because the atmosphere was not sufficiently oxygenated to cause uraninite to dissolve. Other types of uranium deposits are not known to have formed in this stage, although uraniferous conglomerates may be precursors for some.

Stage 3: Stable Sialic Crust, Oxygenated Atmosphere (ca. 2.2-0.4 b.y.). From the lower Proterozoic onward the crust behaved relatively rigidly as per plate tectonic hypotheses because it was thicker and the thermal gradient decreased to less than twice that of today. Elongate mobile belts became longer, large areas of platform quartzites and carbonates accumulated, and the first geosynclines formed along continental margins (Sutton, 1973; Windley, 1973; Tarling, 1978). Broad intracratonic basins collected chemical sediments and shallow water carbonaceous pelite-carbonate-quartzite sequences as in the Pine Creek geosyncline, Australia (Needham and others, 1980), Wollaston Group, Saskatchewan (Lewry and Sibbald, 1977), and Franceville Series, Central Africa; these sediments probably accumulated syngenetic uranium. In contrast to the preceding stage, surface waters dissolved and transported uranium as U(VI) to marginal-marine environments where algal bioherms created a reducing environment capable of precipitating uranium. During the lower to middle Proterozoic, these processes created uraniferous sediments that were protoliths to major uranium deposits. The major uranium metallogenic provinces had formed by a combination of uraniferous upper Archean granites (and possibly conglomerates) of Stage 2 plus leaching and accumulation of uranium in sedimentary basins following oxygenation of the atmosphere.

Stage 4: Development of Land Plants and Uranium Deposits in Continental Sediments (~0.4 b.y.-Present). The general tectonic and geochemical regime remained unchanged until the Devonian when land plants developed, and from them came organic and bacterial reductants in continental sediments. Uranium could now be trapped before it reached the oceans, and organic-rich sandstone-type deposits developed for the first time. Uranium also continued to be recycled by magmatic and hydrothermal processes, such as Hercynian intragranitic vein deposits in Europe linked to Precambrian supracrustal source rocks (Collomb, 1969; Ziegler, 1974).

The geochemical cycle of uranium clearly has changed with time, with important consequences for the creation of metallogenic provinces and ore deposits. The changing styles of uranium solubility and fixation, and of plate tectonics, are basic parameters in exploration concepts. Some refinements to this thinking are needed and doubtless will be forthcoming.

Distribution of Iron Formations and Uranium Deposits

Some geochemical similarities between uranium and iron suggest the utility of iron formations as a general guide to uranium-rich sediments and deposits. Two aspects of iron formations are particularly interesting with respect to uranium deposits: (1) Superior-type banded iron formation (BIF) occurs in a restricted time period, about 2.5 to 1.9 b.y. ago, generally considered to coincide with the buildup of oxygen in the oceans (see Lepp and Goldich, 1964; Goldich, 1973; Bayley and James, 1973); and (2) iron formations occur in a specific marginal-marine environment that is a good indicator of former continental margins (see Cloud, 1973; Goodwin, 1973).

It is important to distinguish, where possible, three major types of sedimentary iron formations: (1) Algoma-type, associated with volcanic rocks in eugeosynclinal settings, now metamorphosed to greenstone belts, and most prominent about 3.0 to 2.5 b.y. B.P.; (2) Superior-type, rich in chert and associated with marine shelf-facies quartzite, carbonate, and black shale, and apparently limited to about 2.5 to 1.9 b.y. ago; (3) Clinton-type hematite-siderite deposits, often with oolitic texture, formed in shallow water, and generally younger than 1 b.y. To my knowledge no uranium enrichment occurs in or along Archean Algoma-type iron formations, but younger varieties are near some uranium deposits. Some black shale horizons adjacent to Lake Superior-type BIF are uraniferous in northern Michigan. Possibly more significant are the spatial association of Superior-type iron formations and quartz-pebble conglomerate uranium deposits and the use of iron formations as regional tectonic-stratigraphic markers.

Quartz-pebble conglomerates in their best known occurrences in South Africa, Brazil, and Canada occur within the trend of Superior-type iron formations (fig. 2). In South Africa the codistribution is particularly clear. In more detail, BIF occurs in strata between the gold-uranium reefs of the Witwatersrand Supergroup (Beukes, 1973). Extensive iron formation also

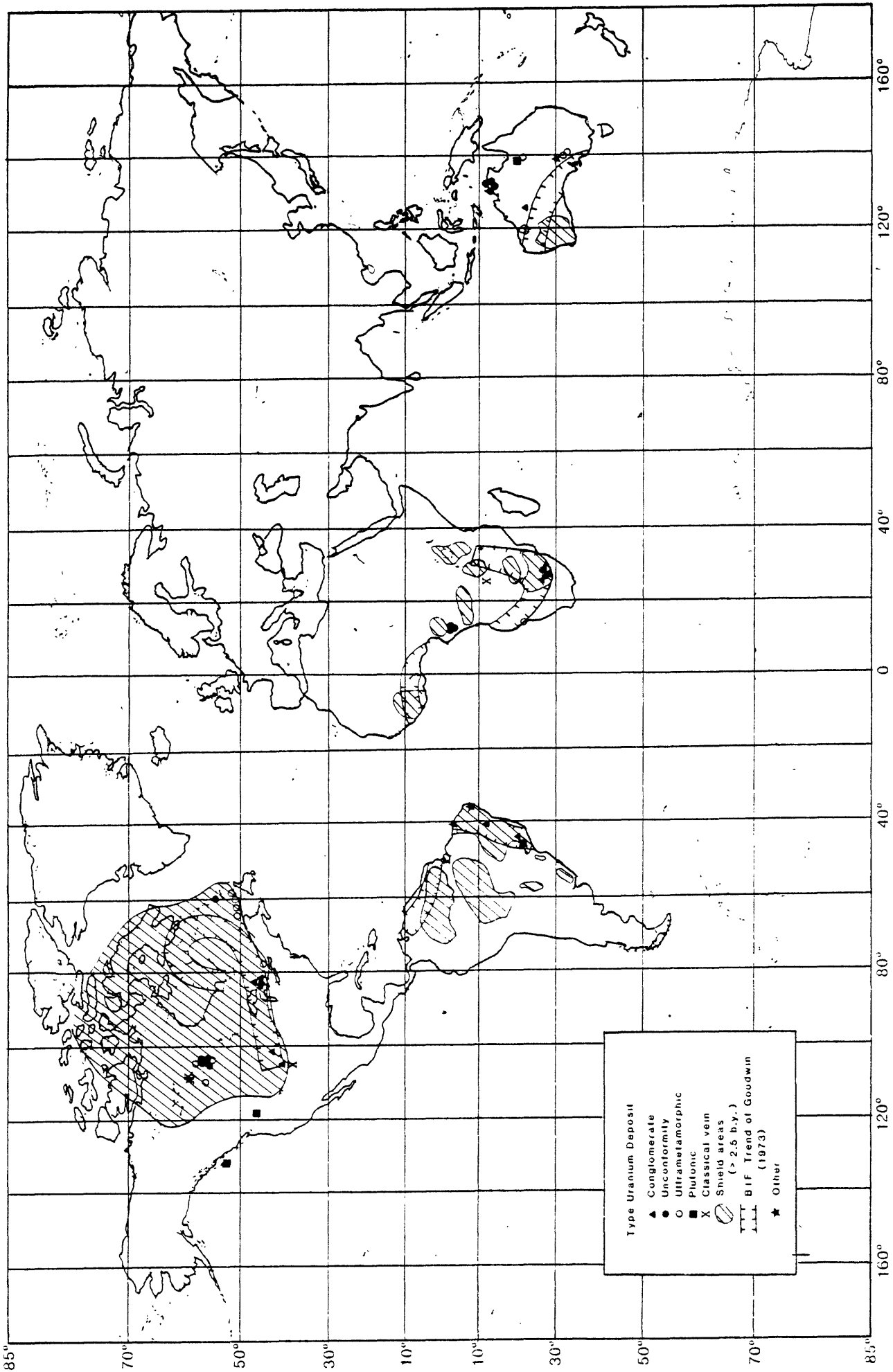


Figure 2.--Distribution of Superior-type banded iron formation and uranium deposits. Iron formation trend is from Goodwin, 1973.

occurs in the younger (2.3 to 1.9 b.y.) Kurman iron formation of the Transvaal Supergroup. In the Minas Gerais area, Brazil, uraniferous quartz-pebble conglomerate of the Moeda Formation underlies the Itabira Group famous for its oxide and carbonate-facies iron formation (itabirite) (Dorr, 1973). The Elliot Lake district, Ontario, lies in the BIF trend, but stratigraphic relations between the Huronian Supergroup conglomerates in Ontario and iron formations in Minnesota and northern Michigan are not well established; the conglomerates are probably older. In Wyoming, uraniferous quartz-pebble conglomerate prospects in the Sierra Madre and Medicine Bow Mountains occur roughly in the BIF trend; the Atlantic City BIF deposits are about 150 km north of the uraniferous belt. The significance of this codistribution, broadly speaking, is that both the uranium-rich and iron-rich sediments accumulated along continental margins in a restricted time period when oxygen was building up in the marine (iron) environment, but had not yet influenced the terrestrial atmosphere (uranium placers).

Younger lower Proterozoic sedimentary basins in Northern Territory, Saskatchewan, southwest Africa, and Colorado are suspected to have been rich in uranium, as discussed in following sections. These basins lie outside or oblique to the Superior BIF trend. However, some of these basins do contain iron-rich sediments that locally reach economic grade. In the Pine Creek geosyncline, carbonate-iron formations of Clinton or minette type occur stratigraphically above the horizons which host uranium deposits (Needham and Roarty, 1980). The ~1.0-b.y.-old Damara Supergroup in Namibia contains iron formation above the metasediments hosting the Rössing deposit. Lower Proterozoic sedimentary rocks of Colorado (Idaho Springs Formation) are locally rich in iron. These younger iron-rich rocks are not of the Superior-type; for instance, they are rich in carbonate rather than in silica, but do attest to chemical sedimentation under shallow-water marine conditions. Elsewhere in this paper, evidence is presented that this environment is also favorable for uranium enrichment in the Proterozoic in carbon-rich zones of algal activity.

UNCONFORMITY-TYPE DEPOSITS

In 1968-70, a "new" ore environment was recognized in which large, high-grade deposits occurred in metamorphosed lower Proterozoic rocks below

unconformably overlying unmetamorphosed middle Proterozoic sandstones in Saskatchewan, Canada, and Northern Territory, Australia. In Australia, it was recognized that the favorable host rocks were metasediments overlying Archean granite-gneiss complexes, as in the neighboring and previously exploited Rum Jungle district. Following two discoveries in 1968-69, Canadian explorationists came up with a series of impressive discoveries in 1975-79 which had much in common with the Northern Territory examples. The Canadian deposits, however, revealed the new fact that the deposits could occur partly or predominantly in the covering sandstone (as at Key Lake and Midwest Lake). Despite some obvious differences, many geologic features recur, suggesting common genetic processes. Most deposits are in or near graphitic-mica schist + biotite-garnet schist + dolomitic marble metamorphic sequences formed from marginal-marine sedimentary rocks. Proximity to Archean granite-gneiss complexes with reactivated migmatite fringes is common, and ore is typically in repeatedly faulted and chloritized zones. All deposits are near middle Proterozoic unconformities. Currently there is heated debate over geologic requirements and genetic significance of common features.

Saskatchewan

Geologic setting.--The Canadian shield in northern Saskatchewan consists of Archean granitoid basement, lower Proterozoic (Aphebian by Canadian nomenclature) metasedimentary rocks, and unconformably overlying unmetamorphosed middle Proterozoic Athabasca Formation (fig. 3). The lithology and structure of the area is relatively well established (Money and others, 1970; Lewry and Sibbald, 1977; Ray, 1977; Hoeve and Sibbald, 1978) despite only a few percent bedrock exposure. The lithostructural domains (fig. 3) differ in metamorphic and structural character chiefly reflecting the grade of metamorphism and deformation of Archean granitoid and lower Proterozoic supracrustal rocks. The Wollaston domain is largely amphibolite-facies lower Proterozoic supracrustals which were deposited on, then interfolded with, Archean basement to produce gneiss domes. Domains to the west, especially the Mudjatik, are largely granulite-facies migmatite produced from Archean granitoids. Metamorphic isograds dip steeply in the Wollaston domain but are flat lying to the west. A major fault zone separates the Wollaston domain from lower grade metamorphics to the east and was the site of a late Hudsonian (~1.8 b.y.) syntectonic granitic batholith. Four periods of

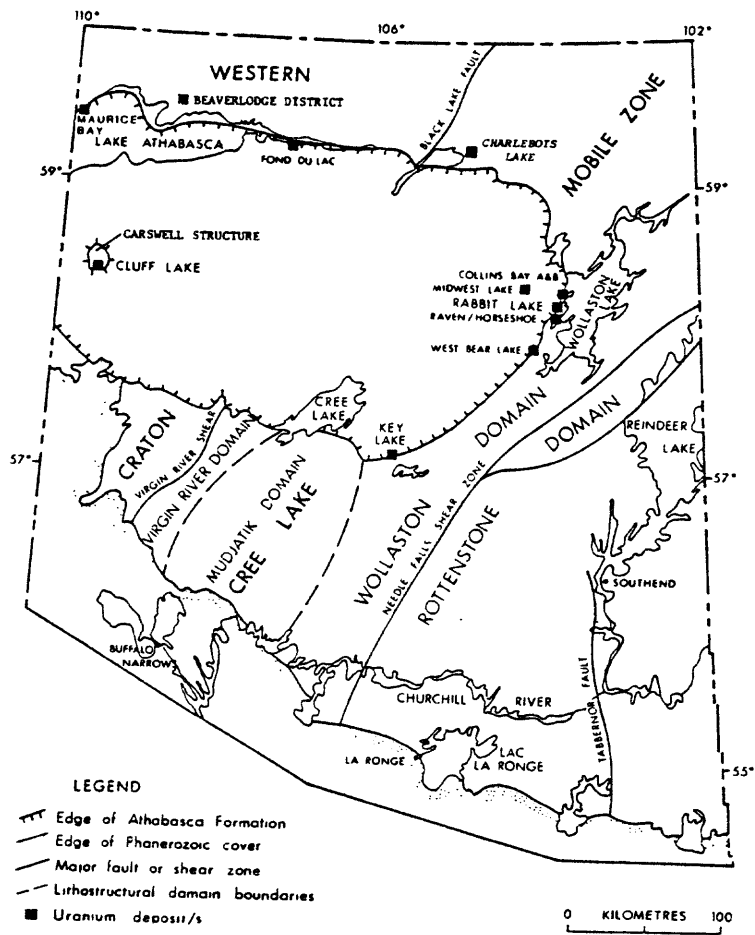


Figure 3.--Major lithostructural domains of the Canadian shield, Saskatchewan (from Hoeve and Sibbald, 1978).

deformation are noted (Lewry and Sibbald, 1977; Sibbald and others, 1977; fig. 4), including early Hudsonian rise of gneiss domes, later flattening and refolding, and two periods of faulting, some of which may have been reactivated in the middle Proterozoic.

Stratigraphy of the lower Proterozoic Wollaston Group that contains the Rabbit Lake, Key Lake, Midwest Lake, and other uranium deposits (fig. 5) includes the following units deposited unconformably on Archean granitoids (Ray, 1977; Hoeve and Sibbald, 1978): (1) metapelite with graphitic layers that are strong electromagnetic (EM) conductors; (2) calcareous meta-arkose with subordinate calc-silicate; (3) quartzite plus amphibolite with interbedded sillimanitic meta-arkose and calcareous meta-arkose. Total thickness is about 3,500 m. Shallow-water marginal-marine sedimentation is interpreted (Chandler, 1978; Hoeve and Sibbald, 1978) from the association of pelites, algal carbonates, and sodium-enriched meta-arkose and metamorphic scapolite that probably indicate former evaporite sediments. The upper part of the sequence contains more clastics and probably reflects some uplift and shallow-water marine to fluvial deposition. The regional mapping program has emphasized premetamorphic rock composition; hence few areas are mapped as migmatite, although many geologists would map much of the Wollaston domain as such (T.I.I. Sibbald, oral. commun., 1979).

Unconformably overlying the Wollaston Group is the middle Proterozoic Athabasca Formation which is predominantly unmetamorphosed fluvial quartz sandstone. Total thickness is more than 1,750 m. Sources were to the east and south and sedimentation was in a braided-stream environment (Ramaekers and Hartling, 1979). Age of the Athabasca is about 1428 ± 30 m.y. Several types and ages of hematitic alteration and bleaching have affected the Athabasca. A regolith 15 to 50 m thick, characterized by kaolinite and hematite, is developed beneath the sub-Athabasca unconformity. Chemical weathering appears to have been extensive in the area, as indicated by the deep regolith and absence of feldspathic clasts in sands and coarse basal conglomerate.

Rabbit Lake deposit.--The deposit at Rabbit Lake (fig. 3) was the first unconformity-type deposit discovered (1968), first to reach production (1975), and is the only deposit which has been mapped from mine exposures; hence geologic understanding is more advanced than for other examples (Knipping,

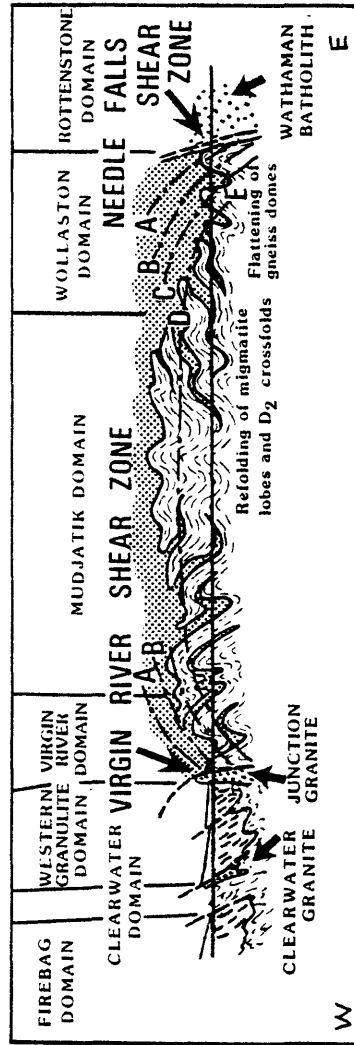


Figure 4.--Schematic cross sections across the Canadian shield, Saskatchewan, showing evolution of lithostructural domains (modified from Lewry and Sibbald, 1979). Scale of Figure 4 is approximately the same as Figure 3.

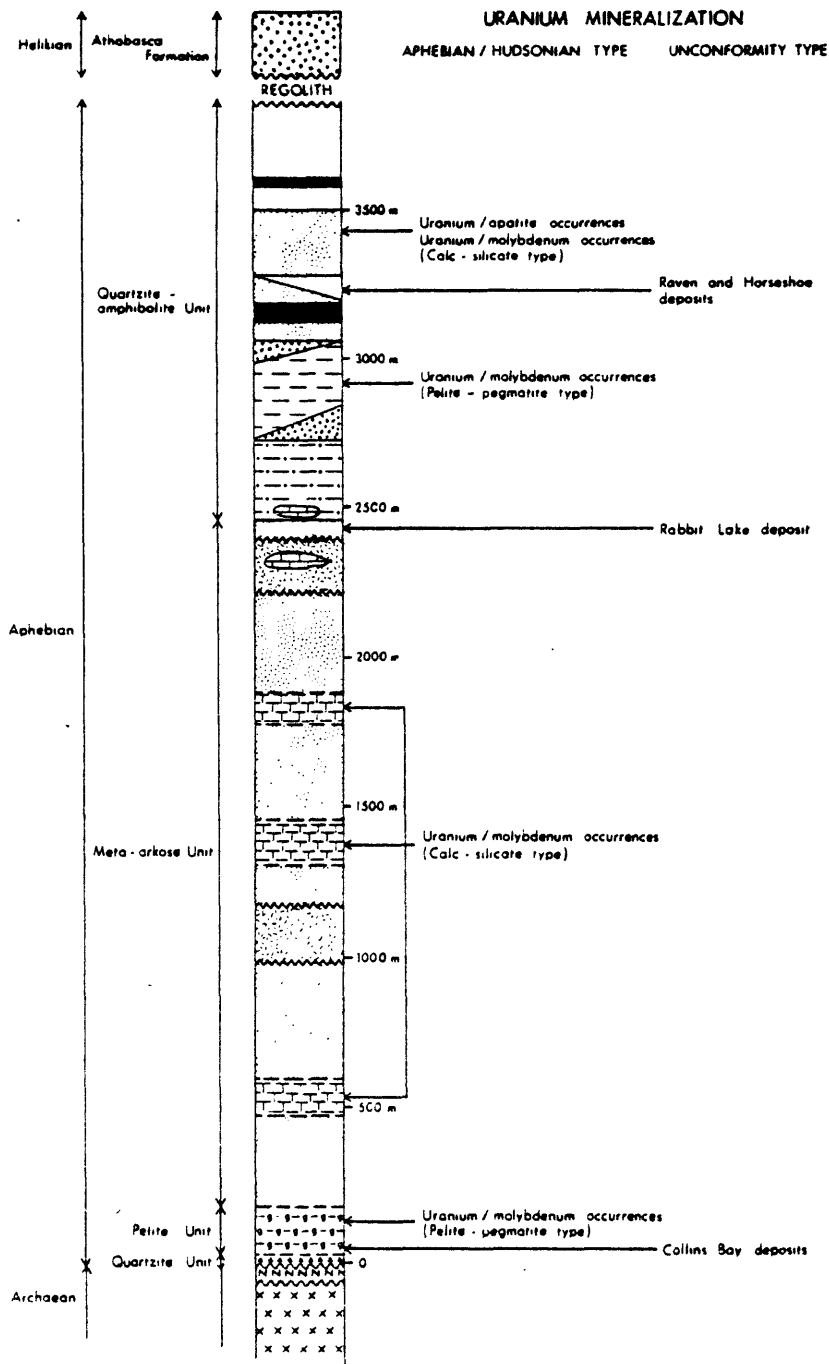


Figure 5.--Stratigraphic sequence in the Rabbit Lake area (from Hoeve and Sibbald, 1978). Stratigraphic locations of uranium deposits and occurrences are shown.

1974; Hoeve and Sibbald, 1977; Hoeve and Sibbald, 1978). The orebody is in Wollaston Group metasedimentary rocks in the upthrust block of the Rabbit Lake thrust (fig. 6). The thrust dips about 30° southeast and has at least 75 m of post-Athabasca displacement. The sub-Athabasca regolith is preserved in the downthrown block and indicates the deposit formed within about 50 m of the unconformity. Host rocks are calcareous gneisses from the middle part of the Wollaston Group (fig. 5) and are interpreted to have been calcareous arkose, impure carbonate, and dolomite (Hoeve and Sibbald, 1978). A sodium-rich (7.2 wt. % Na₂O) albite-clinopyroxene-clinoamphibole granulite termed "plagioclasite" is an important host rock. Weathering at the unconformity created a red, hematitic, kaolinitic regolith up to 50 m thick. Ore is related to several periods of movement on the Rabbit Lake fault, which displaces the Athabasca Formation. Oldest pitchblende ages are about 1,285 m.y., (Cumming and Rimsaite, 1979), clearly younger than the Athabasca.

The complex paragenesis (fig. 7) of Rabbit Lake is marked by alternating stages of hematite and pitchblende with sulfides (Hoeve and Sibbald, 1978). Alteration zones are shown on figure 6. Chloritization characterized by dark green chlorite (probably Fe-rich) after mafics precedes early pitchblende. This stage was followed by a period of magnesium and boron metasomatism (as chlorite and Mg-tourmaline, dravite), silicification, and abundant hematite. The middle stage demonstrates oscillation of oxidation potential as colorless reduced assemblages or red, hematitic assemblages precipitated alternately. Carbon formed with middle-stage pitchblende and coffinite. A late stage of sooty pitchblende and coffinite occurs along fractures with pale-green chloritic halos. Fluid inclusions in middle-stage dolomite and quartz, somewhat earlier than middle-stage pitchblende, have filling temperatures in the range 135 to 245°C and had about 30 wt percent NaCl equivalent salinity (Little, 1974; Pagel, 1977). The magnitude of pressure correction is not known.¹

¹Pressure estimate of 750 ± 150 bars (Pagel, 1977) should be considered a minimum estimate. The method of Pagel (1975)--that the temperature of solution of halite is equal to the temperature of formation, hence needs no correction for pressure because the solutions were saturated at trapping--is not in general correct. Likewise, it is not a reliable estimate of pressure. The case in which a halite daughter mineral dissolves at higher temperature than vapor phase disappearance may indicate a small pressure correction is required, but also could require a large and unknown pressure correction (Roedder and Bodnar, 1980).

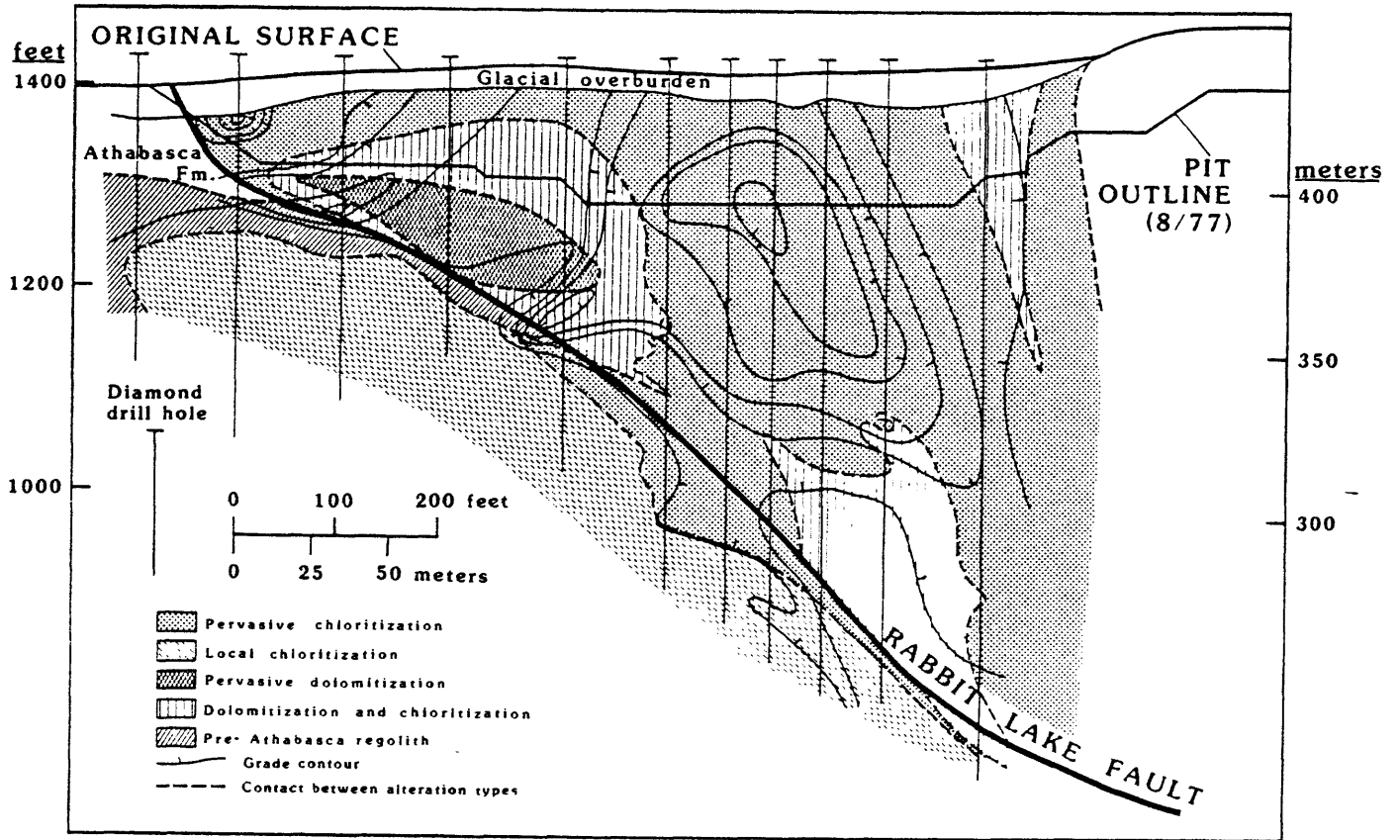


Figure 6.--Cross section of Rabbit Lake deposit showing alteration zones (modified from Hoeve and Sibbald, 1978).

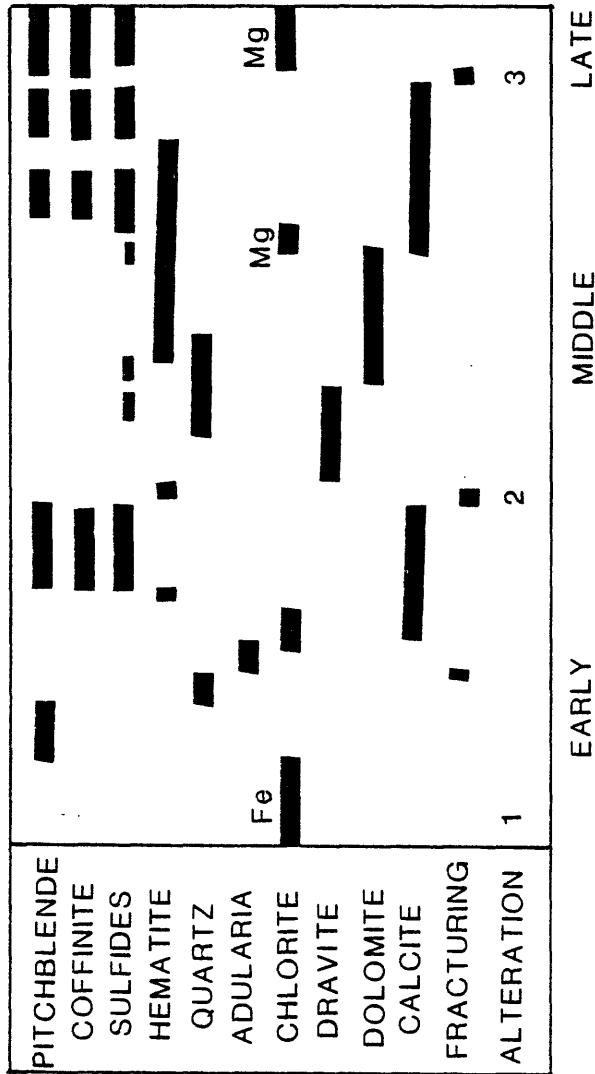


Figure 7.--Paragenesis of the Rabbit Lake deposit (modified from Hoeve and Sibbald, 1978). Alteration 1 is dark green chloritization, 2 is red alteration, 3 is pale green alteration.

Several important parameters appear to be well established for the Rabbit Lake deposit and must be incorporated in any genetic hypothesis: (1) The mineral sequence indicates oscillations in oxidation potential as recorded by alternating stages of reduced and oxidized assemblages. (2) The orebody occurs in graphite-bearing metasedimentary rocks that are bleached, and graphite is corroded or absent in the vicinity of ore. (3) Fluid-inclusion studies demonstrate that at least some stages of mineralization, including some uranium minerals, were hydrothermal at temperatures in excess of 135°C. (4) Age of ore is established as post-Athabasca Formation by structural criteria and isotopic ages (about 1075 m.y.). However, I wish to add a note of caution that older stages of mineralization may have been destroyed or obscured by overprinted alteration and veining. From these and other parameters Hoeve and Sibbald (1978) have proposed that the deposit formed at about 200°C, where oxidizing solutions moving through the Athabasca encountered methane-bearing solutions migrating up faults in the basement. Genetic hypotheses will be considered further in a later section.

Cluff Lake.--Three major deposits (with reserves >5,000 s.t. (short tons) U_3O_8 each) and many prospective deposits occur in lower Proterozoic metamorphic rocks and in Athabasca Formation within the Carswell circular structure at Cluff Lake (fig. 8; Tapaninen, 1976; Harper, 1978). The Carswell structure, 35 km in diameter, exposes Archean and/or lower Proterozoic gneisses in its central core. The structure is variously interpreted as resulting from meteorite impact or from volcanic explosion. Basement gneisses and Athabasca Formation are intruded by polymict breccias (Cluff Breccia) which contains variable amounts of lithic fragments and glassy material that yielded a K/Ar age of about 470 m.y. High-angle radial faults and flat-dipping thrust faults, both related to the Carswell structure, control much of the uranium mineralization which probably was redistributed from old mineralization during the cataclysmic event (AMOK, 1974; Harper, 1978). Mineralogy and chemistry of ores is of two types: simple and complex. The complex deposits contain abundant Au and Te (as native gold and gold tellurides), Pb-Bi-Ni-Co selenides, galena, and chalcopyrite (Tapaninen, 1976; Harper, 1978; no assays reported). The simple type contains pitchblende, coffinite, and small amounts of chalcopyrite and galena.

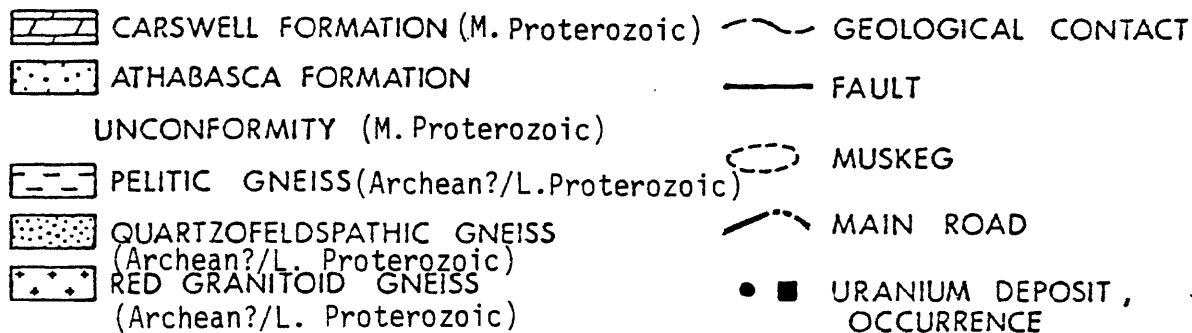
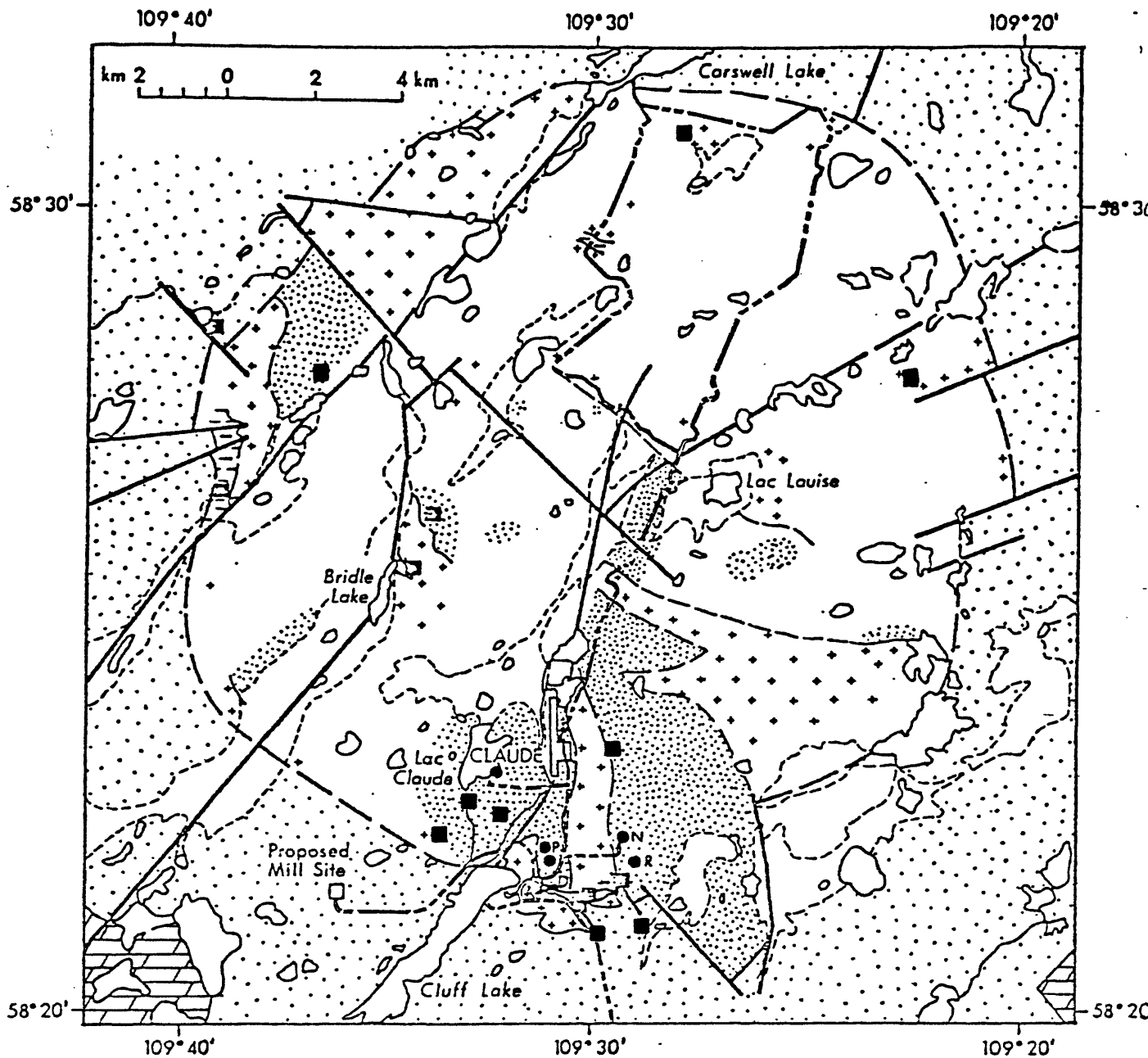


Figure 8.--Geology of the central core of the Carswell Circular structure showing location of uranium deposits and occurrences (From Harper, 1979).

The D-orebody occurs along the overturned unconformity in the Athabasca Formation and overlying quartzo-feldspathic gneiss (fig. 9). The structure is interpreted as resulting from thrusting and overturning during formation of the Carswell structure (AMOK, 1974). Much of the ore is hosted by carbonaceous pelites in the Athabasca. The D-zone has an average grade of 7 percent U_3O_8 and some sections contain up to 29 percent U_3O_8 .

The N and Claude orebodies are elongate along radial faults and much uranium is concentrated along sub-horizontal shear zones characterized by mylonite and Cluff Breccia (fig. 10). The N and Claude zones are 1200 m and 600 m long, respectively, 120 to 200 m wide, and 50 to 150 m thick. The sub-Athabasca unconformity probably was a short distance above these ore zones.

A working genetic hypothesis formulated by the Amok staff (AMOK, 1974) proposes a source for uranium in basement gneisses, mobilization into shear zones and carbonaceous pelites of the Athabasca Formation by weathering processes, and tectonic and hydrothermal remobilization, probably related to formation of the Carswell structure. Harper (1978) describes pale-green chlorite-sericite alteration, dated at 988 m.y. by K/Ar, that cuts hematitic regolith and is associated with uranium minerals. This alteration is similar to the ore-stage alteration at Rabbit Lake, according to Harper. Reductants may have been minor amounts of graphite or iron sulfides. Fluid-inclusion homogenization temperatures in the range 150° to $350^{\circ}C$ have been obtained from quartz overgrowths in the Athabasca Formation, but their age and their relation to uranium deposition are not established (Pagel, 1977; Pagel and others, 1980).

Key Lake deposits.--The U-Ni deposits at Key Lake are located on the southeastern rim of the Athabasca Basin (fig. 3) and are completely covered by Athabasca Formation or glacial deposits. Graphitic metapelites of the basal Wollaston Group host the ore and are tightly folded around remobilized Archean gneiss domes (Gatzweiler and others, 1979; Kirchner and others, 1980; Dahlkamp, 1978B; fig. 11). The graphitic beds are excellent electromagnetic (EM) conductors and provide most of the structural information for the area.

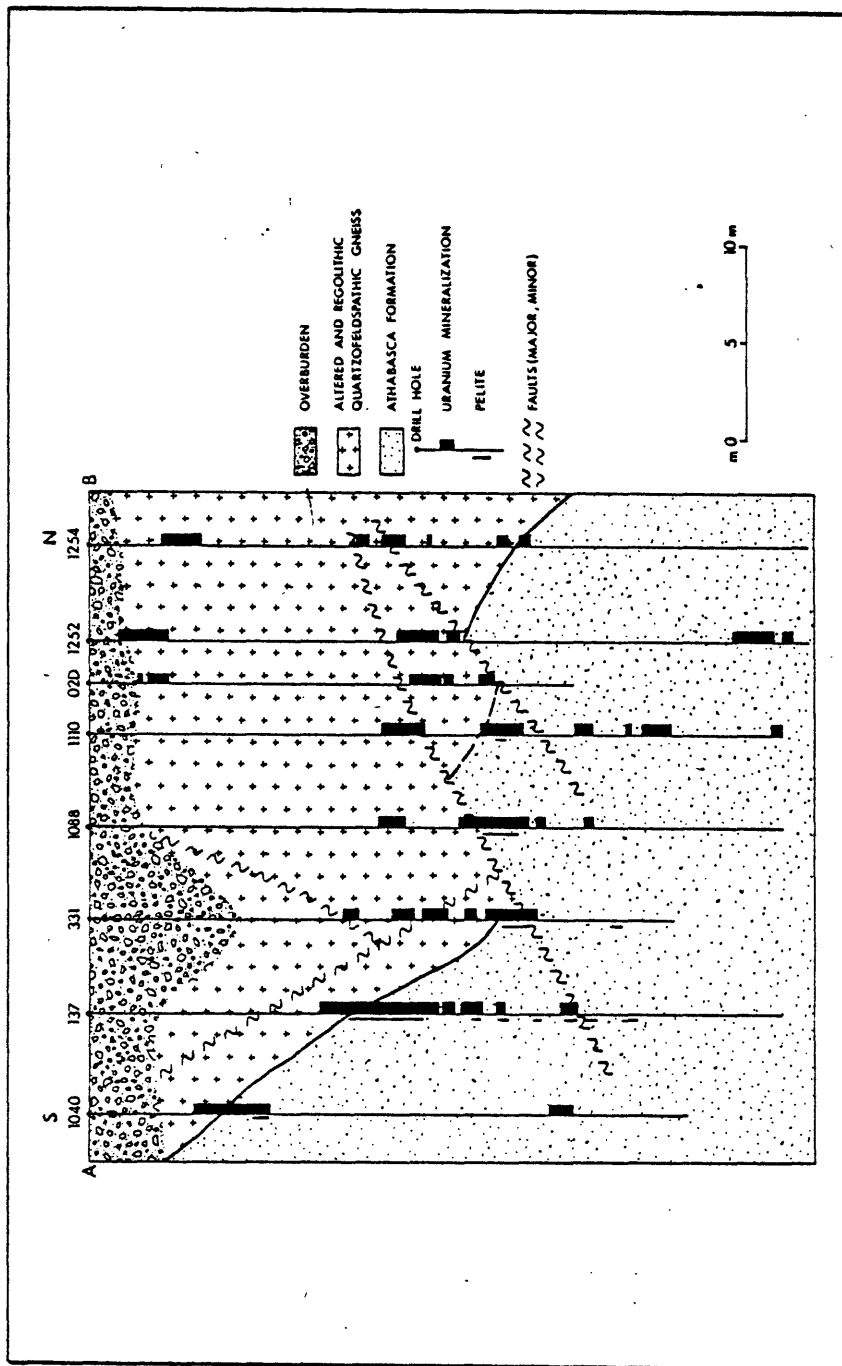


Figure 9.--Geologic cross section of the D zone orebody (from Harper, 1978).

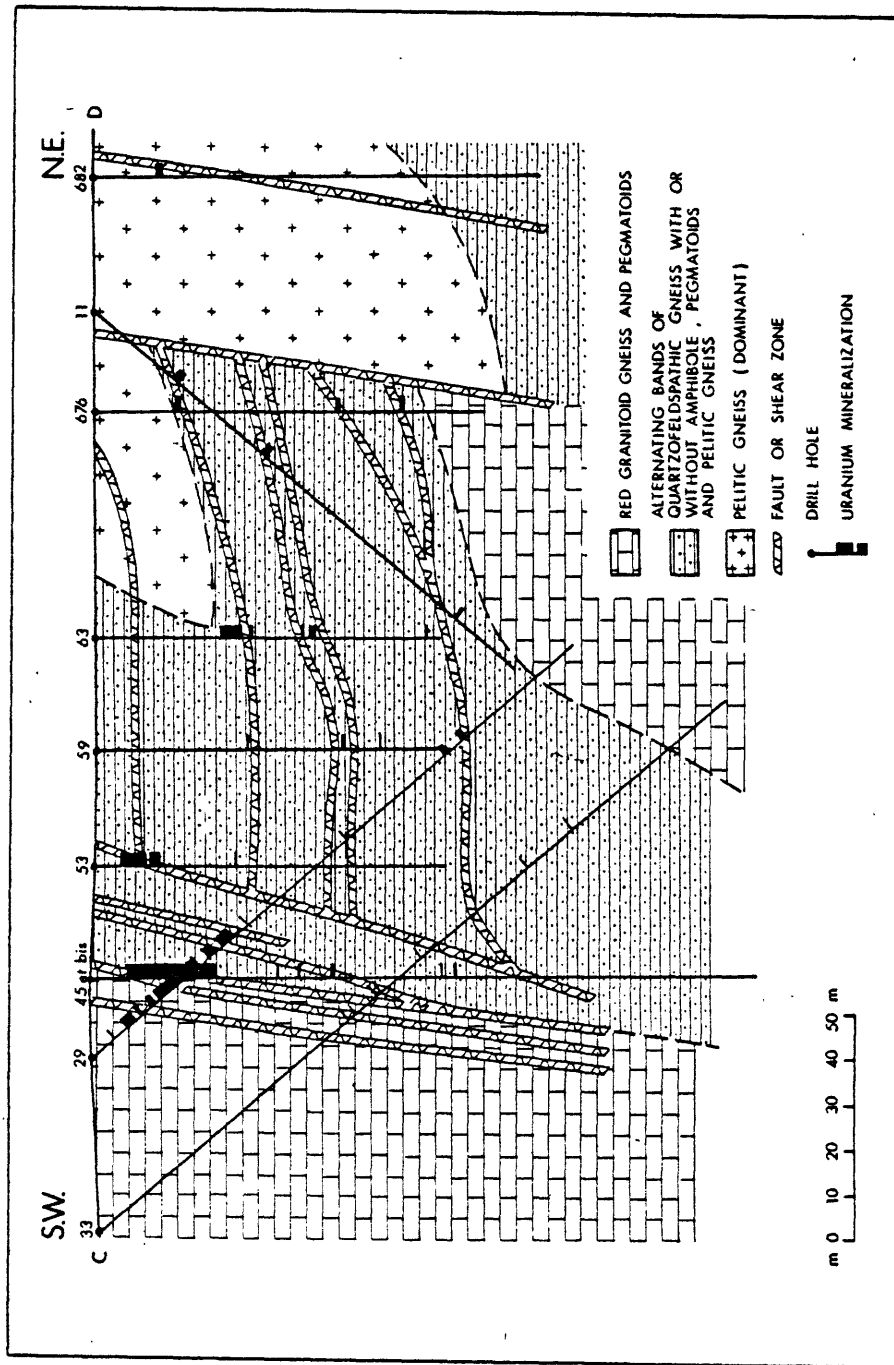


Figure 10.--Geologic cross section through the N zone orebody (from Harper, 1978).

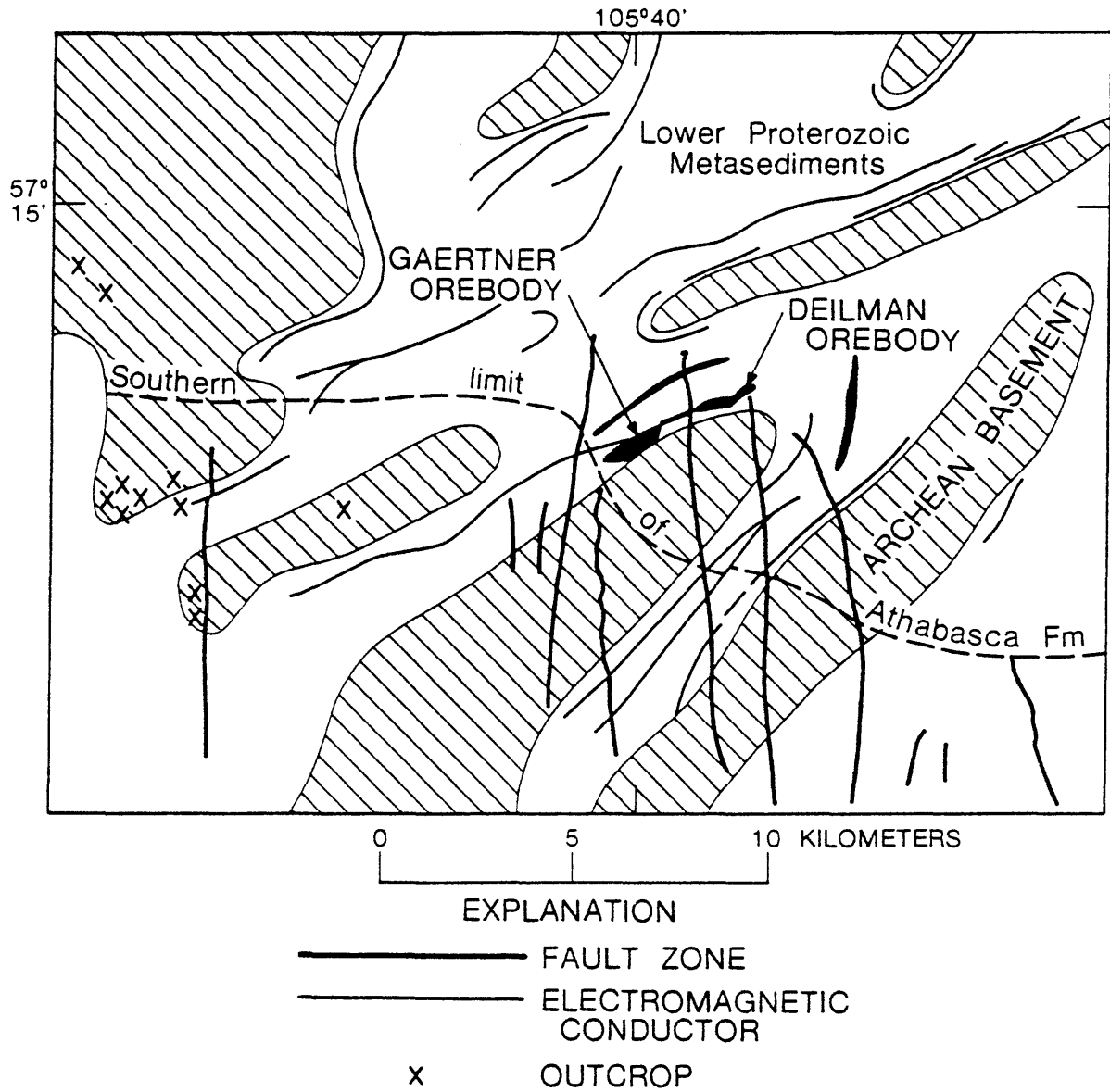


Figure 11.--Geology of basement rocks, Key Lake area (modified from Dahlkamp, 1978b).

The Gaertner and Deilman orebodies, probably continuous for nearly 5 km prior to glacial scouring, occupy a northeast-striking fault zone where it cuts the graphitic metapelite at a low angle within 400 m of a gneiss dome. The two very high-grade (>2 percent U_3O_8) deposits are 800 and 1400 m long, respectively, average about 15 m in width, and 50 m thick. Reserves are about 100,000 s.t. U_3O_8 . Most of the ore is in metamorphic rocks, but some is in sandstone. Uranium, chiefly as pitchblende, ranges up to 50 wt. % over 0.3 m. Nickel as niccolite, bravoite, gersdorffite, and other Ni-As-S phases (Watkinson and others, 1975; Dahlkamp, 1978B) is equal to uranium in total tonnage and ranges up to 45 wt. % Ni over 0.3 m. Nickel minerals are intimately intergrown with pitchblende (fig. 12) but extend beyond and below the uranium zones (Gatzweiler, and others, 1979). Mineralogical zoning is evident. Crystalline pitchblende (tetragonal U_3O_7) plus gersdorffite (Ni-As-S) grade upward into sooty pitchblende and millerite (NiS), and U_3O_7 or NiAs are not known to occur in the Athabasca Formation. Several types of alteration are reported (Dahlkamp, 1978B): (1) "kaolinite mylonite"--a kaolinized and sheared metamorphic rock of unknown former composition which is the chief host rock; (2) "chlorite mylonite"--sheared amphibolitic rock altered to Fe-rich chlorite, the second most important host rock; and (3) "sericite-chlorite-mylonite"--a sericite-chlorite-quartz rock derived from sheared biotite-feldspar-cordierite gneiss. These alterations are post-Athabasca in age (Kirchner and others, 1980). Chlorite plus sericite alteration also occurs in a zone as much as 60 m deep below the unconformity, a geometry indicating it is a weathering profile.

A polystage genetic hypothesis has been proposed (Dahlkamp, 1978; Kirchner and others, 1980): (1) syngenetic uranium precipitation at about 2200 m.y. to a grade of about 10 ppm in basal Wollaston Group pelites, (2) enrichment during diagenesis (2200-1800 m.y.); (3) hydrothermal enrichment (1800-1700 m.y.) by uranium expelled during partial melting of gneiss domes and added to adjacent metapelites; (4) retrograde metamorphism, chiefly along faults (1700-1350 m.y.); (5) supergene enrichment below the unconformity; (6) hydrothermal remobilization (1250-900 m.y.) associated with intrusion of diabase dikes and reactivation of the Key Lake fault. Fluids in the Athabasca sandstone oscillated between oxidizing and reducing and estimated P-T conditions were below 1500 bars and 300°C. Uraniferous geologists emphasize the importance of metasomatism adjacent to gneiss domes (step 3), suspect that Ni

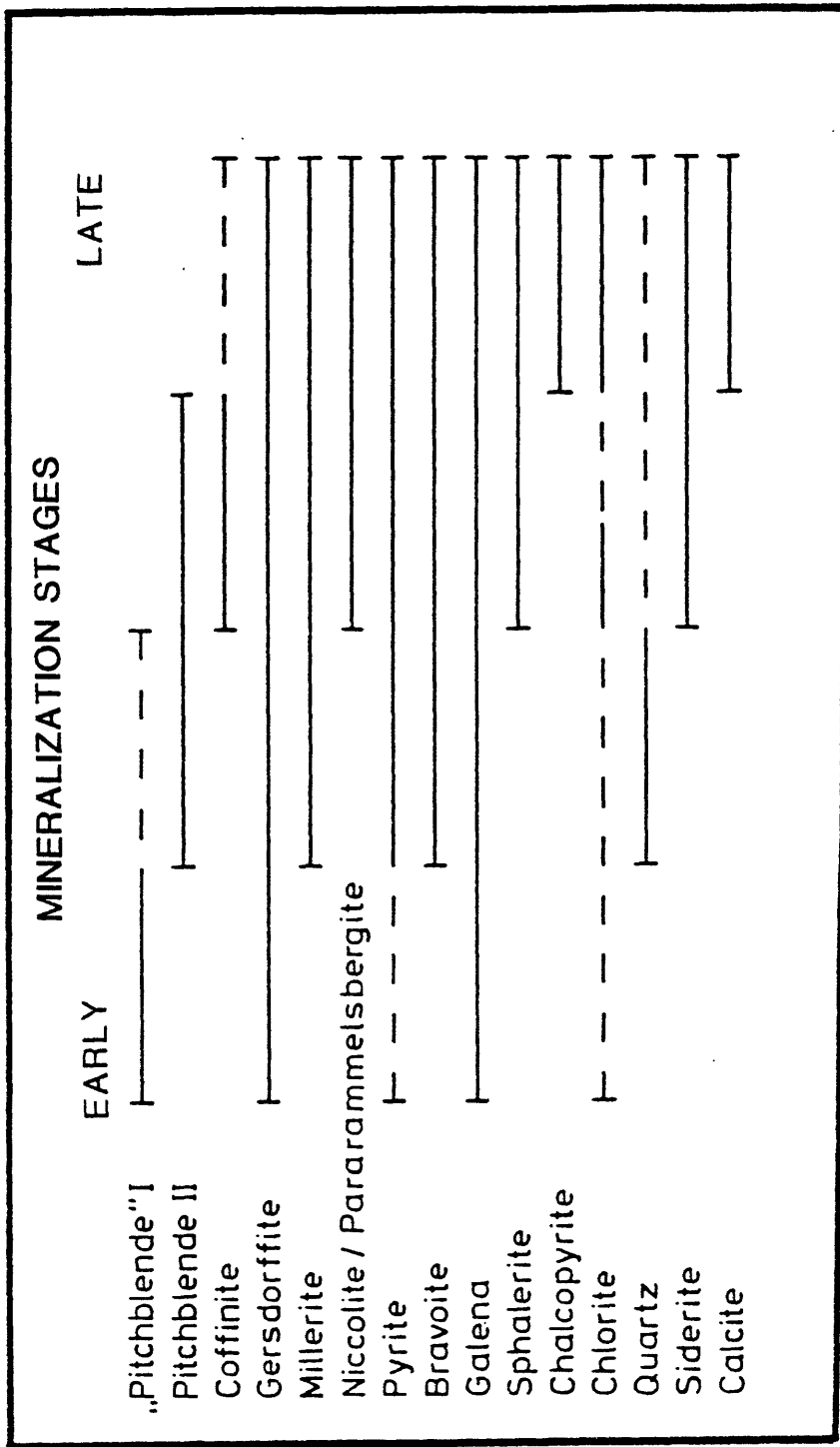


Figure 12.---Paragenesis of the Key Lake deposits (modified from Dahlkamp, 1978b).

and U came from different sources near the deposits (G. Strnad, oral commun., 1979), and feel that most of the present ore-grade mineralization probably formed post-Athabasca (step 6) (Gatzweiler and others, 1979).

Midwest Lake and other deposits in the Athabasca Formation.--Between 1976 and 1979, several unconformity-related deposits were discovered in which the chief host is Athabasca Formation and mineralization extends up to 200 m above the unconformity. Some of the recent discoveries include Collins Bay, Eagle Point, Midwest Lake, Dawn Lake (several deposits), and McClean Lake on the eastern side of the Athabasca Basin and Maurice Bay on the northwest margin of the Basin (fig. 3). These deposits are covered by Athabasca Formation and glacial deposits but produced mineralized boulders in glacial trains. Some remarkably high-grade intercepts have been announced: 24.2 percent U_3O_8 over 10 m at Midwest Lake; 5.7 percent U_3O_8 over 10 m at McClean Lake; 17 percent over 3.3 m at Dawn Lake, and greater than 20 percent at Collins Bay. The Collins Bay deposit is along a thrust fault and contains about 20,000 s.t. U_3O_8 in a zone that is about 1 km long, 90 m wide, and averages 30 m thick (B zone; Jones, 1980).

The Midwest Lake deposit (Kirwan, 1979), about 35 km west of Rabbit Lake (fig. 13), occurs along the unconformity in faulted and highly altered sandstone and graphitic metapelite (fig. 13). A 10-year program tracked the deposit from some modest, airborne radiometric anomalies, a radioactive glacial train (but the ore boulders probably came from another, unlocated deposit), anomalous lake sediments containing more than 6 ppm uranium (cf. 2 to 3 ppm normal), and a strong electromagnetic conductor several kilometers long. The EM conductor probably reflects a fault zone, alteration in the Athabasca, and graphite in basement rocks. The mineralized zone is approximately 2 km long, mostly within a 100 m width, and is covered by 150-200 m of alluvium and sandstone. Announced reserves are about 40,000 s.t. U_3O_8 at an average grade of 3.4 percent U_3O_8 , plus significant Ni and Co values (E and M. J., March, 1980). Near ore hematitic sandstone and hematitic regolith are bleached, and abundant graphite and pyrite in underlying biotite schist are destroyed. Pale-green clay matrix is developed in the ore zone.

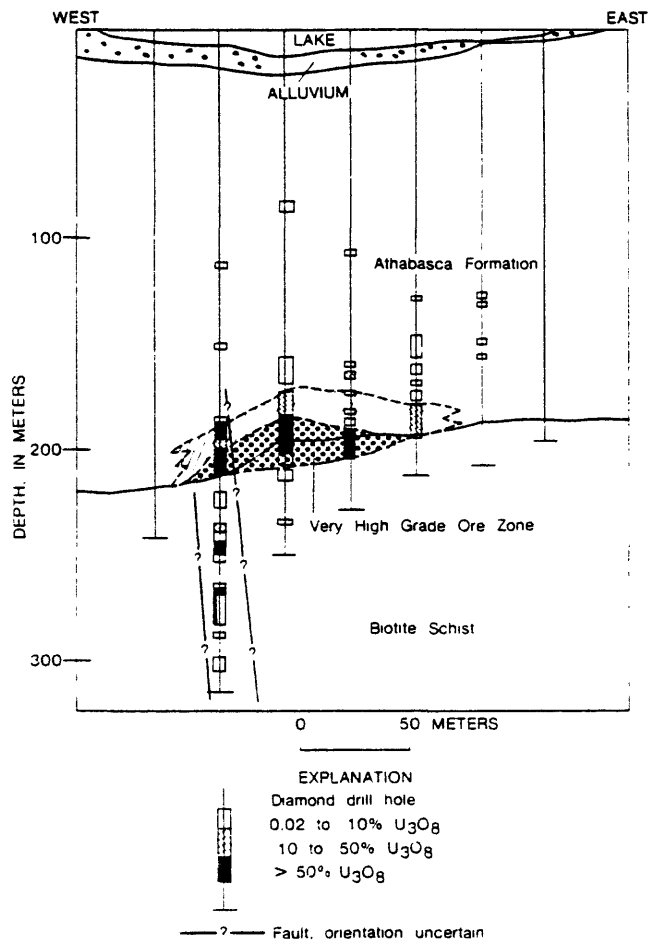


Figure 13.--Cross Section of the Midwest Lake orebody (modified from Kirwan, 1979).

Northern Territory

Geologic setting.--Regional geology of the Pine Creek geosyncline (fig. 14), very similar to that of the Canadian Shield in Saskatchewan, has been established by the Australian Bureau of Mineral Resources over the past 20 years (Walpole and others, 1968; Needham and Stuart-Smith, 1976; Needham and others, 1980; Smart and others, 1975; Page and others, 1980). Archean (2.5 b.y.) granite gneiss complexes are overlain unconformably by a thick succession of lower Proterozoic sedimentary and volcanic rocks deposited predominantly in shelf environments of an intracratonic rift valley (fig. 14). The Cahill Formation, in which the Alligator Rivers deposits are strata-bound, was deposited as Mg-rich carbonate, carbonaceous pelite, and evaporites. Regional metamorphism and deformation at about 1.8 b.y. were most intense along the South Alligator Hinge zone (fig. 14). Some basal Proterozoic sediments were partially melted with Archean granites during the regional metamorphism. Following metamorphism and folding, there was late orogenic granite plutonism (fig. 15) with probably coeval volcanism. The middle Proterozoic Kombolgie Formation, a massive fluvial sandstone that is very similar to the Athabasca Formation, was deposited unconformably on metamorphosed basement rocks sometime between 1680 and 1370 m.y.B.P.

Evidence for evaporites has been observed in and adjacent to the Alligator Rivers and Rum Jungle deposits. Recent field and petrologic studies (Crick and Muir, 1980) document pseudomorphs of magnesite and quartz after gypsum, anhydrite, and halite. Thick sequences (>200 m) of evaporite facies rocks are interpreted to have been widespread in the Pine Creek geosyncline. The implications of evaporites for uranium deposit genesis are moot at present, but it does appear significant that subtle traces of probable evaporites have been found in sequences of Proterozoic marginal-marine metasediments which host several uranium districts (Athabasca District, Bancroft District, and Shinkolobwe, and Rossing areas).

Uranium deposits are known in the Rum Jungle, South Alligator, and Alligator Rivers districts of the Pine Creek geosyncline (Dodson and others, 1974; fig. 14). The first two districts contained small but high-grade deposits in greenschist facies rocks (Fraser, 1975). Host rocks at Rum Jungle are correlative with the Cahill Formation and likewise contain ore-associated magnesite and chlorite alteration. The South Alligator deposits are in

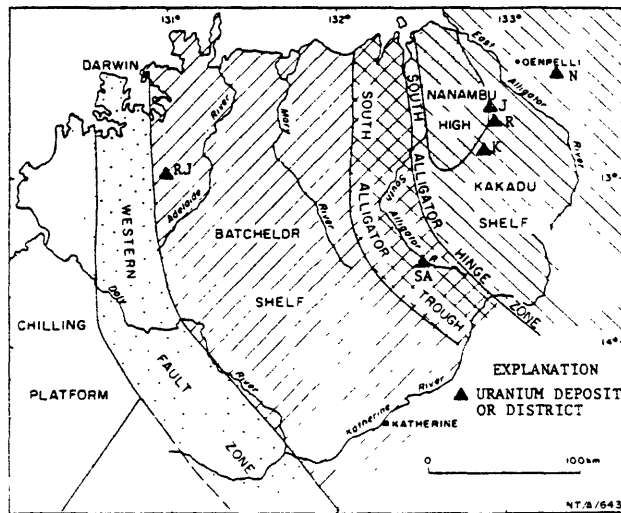


Figure 14.--Major structural elements of the Pine Creek geosyncline (modified from Stuart-Smith, et al., 1980). Uranium deposits and districts: K, Koongara; J, Jabiluka; N, Nabarlek; R, Ranger; RJ, Rum Jungle district; SA, South Alligator River district.

metasediments somewhat younger than the Cahill Formation, close to the sub-Kombolgie unconformity. The association with volcanic rocks suggests a possible genetic link (Ayres and Eadington, 1975), but this is not generally advocated for the Alligator Rivers District.

Major uranium deposits of the East Alligator River district (fig. 14) include multiple orebodies at Ranger, Jabiluka, Koongara, and Nabarlek. Announced reserves are approximately: Ranger I (No. 1 and No. 3), 110,400 s.t. U_3O_8 at 0.25 wt. % U_3O_8 ; Jabiluka I and II, 228,000 s.t. U_3O_8 at 0.39 wt. % U_3O_8 ; Nabarlek, 10,500 s.t. U_3O_8 at 2.47 wt. % U_3O_8 ; and for Koongara a very conservative 19,200 s.t. U_3O_8 (Rowntree and Mosher, 1976; Eupene, 1980).

Ranger deposits.--Three major orebodies and many prospects in the Ranger concession occur in chloritic schist and dolomitic marble, and altered equivalents, of the Lower Cahill Formation (Eupene and others, 1975; Eupene, 1980). Beneath this "mine sequence" is the footwall sequence of gneiss, amphibolite, and migmatite of the Nanambu Complex; the migmatites are believed to be developed from rocks similar to the Cahill Formation. Tourmaline-muscovite pegmatites, probably locally derived, are common in the mine sequence. A fault separates the footwall and mine sequence, the ore zones are thoroughly broken, and the Kombolgie Formation is downfaulted into one ore zone. Pitchblende ore zones are associated with carbonate rocks which are altered to magnesite, or silica-chlorite masses. Silicification is believed to have caused thinning and collapse breccias in former carbonate horizons (fig. 16). Chloritic alteration of several ages is pervasive regionally in schists and carbonates, and fills veins and breccia matrix along with pitchblende. According to Eupene (1980), the sub-Kombolgie unconformity was located a short distance above the deposits and may have caused some near-surface solution and silicification of carbonate rocks. However, uranium mineralization is also encountered at depths of about 400 m in chloritized but unsilicified carbonate rocks, which have no apparent connection to near-surface mineralization. U-Pb ages of about 1700 and 900 m.y. have been obtained from pitchblendes and galenas from Ranger (Hills and Richards, 1976); the 1700 m.y. age possibly is from pitchblende disseminated in footwall gneiss, in which case it would not be representative of ore.

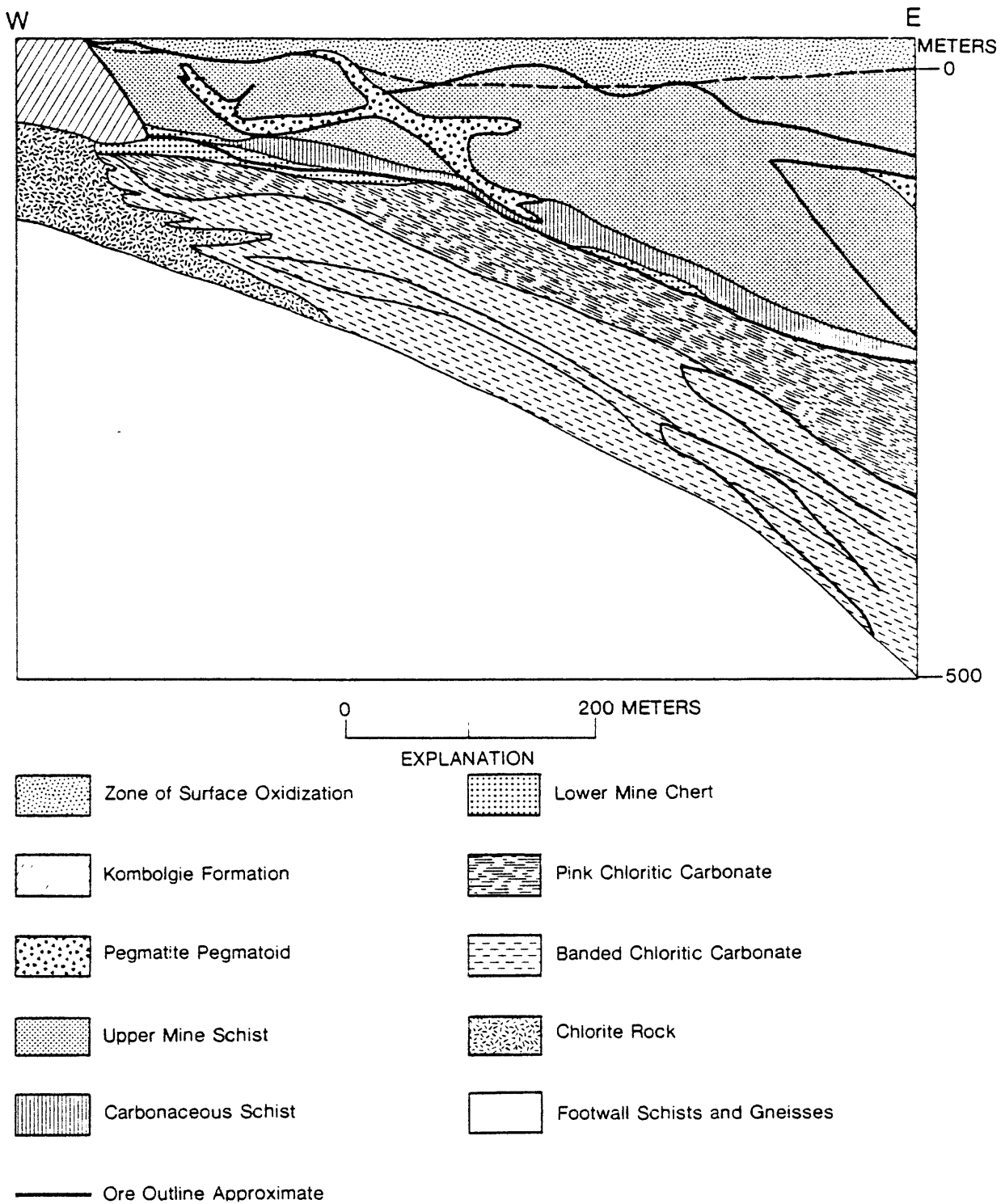


Figure 16.--Cross section of Ranger one number 3 orebody (modified from Eugene, 1980).

Ranger geologists (Ryan, 1979; Eupene, 1980) believe that the orebodies in their present form have been totally remobilized and favor an initial emplacement by hydrothermal fluids, possibly expelled during granitization of lower Proterozoic sediments accreted onto the Nanambu Complex. Graphitic schists carry only 9 to 12 percent of the ore at Ranger, Jabiluka, and Koongara, and the graphite itself is not notably uraniferous. Although there may have been some syngenetic concentration of uranium in carbonaceous shales, such rocks are considered to have contained too little uranium to generate these large deposits because mobilization for distances up to 10 km would be required to generate known tonnages (Eupene, 1980). Remobilization at about 800-900 m.y. correlates with no known geologic event, but possibly could relate to epeirogeny and development of a land surface (Eupene, 1980).

Jabiluka deposits.--Jabiluka II is the largest known uranium deposit and one of the richest metal orebodies in the world, as it contains more than 225,000 tons U_3O_8 at an average grade of 0.39 percent U_3O_8 plus about 350,000 oz of recoverable gold (Rowntree and Mosher, 1976; Hegge and Rowntree, 1978). The areal extent of the deposit is undefined on two sides. The initial discovery, Jabiluka I, is much smaller and probably will not be mined due to environmental problems. Pitchblende mineralization is in lenticular zones that favor chloritic or graphitic schists over carbonate beds (fig. 17). Two thirds of the ore is in brecciated or fractured zones as open-space fillings. Ore has been encountered over a large vertical range, from the deepest drill holes at about 700 m upward close to the sub-Kombolgie unconformity. The Kombolgie Formation, in fault contact with the Cahill, is locally chloritized but contains no ore. Ore is thicker on the upper sides of some pegmatite dikes and post-Kombolgie faults. Ore is locally out of equilibrium, indicating recent redistribution.

Geologic and isotopic dating are inconclusive. Pitchblendes and galenas have discordant U-Pb ages of about 800-900 m.y. (Hills and Richards, 1976; Gulson and Mizon, 1980). Two pitchblendes and some pyrites from Jabiluka II yield discordant ages of about 1120-1770 m.y. (Hills and Richards, 1976; Gulson and Mizon, 1979). Depending on assumptions of daughter product diffusion, 1380 m.y. may be a minimum age and 1600 m.y. a better approximation of the main mineralizing event (Gulson and Mizon, 1980). Rb-Sr dating of chlorite and sericite indicates that retrograde metamorphism occurred at about

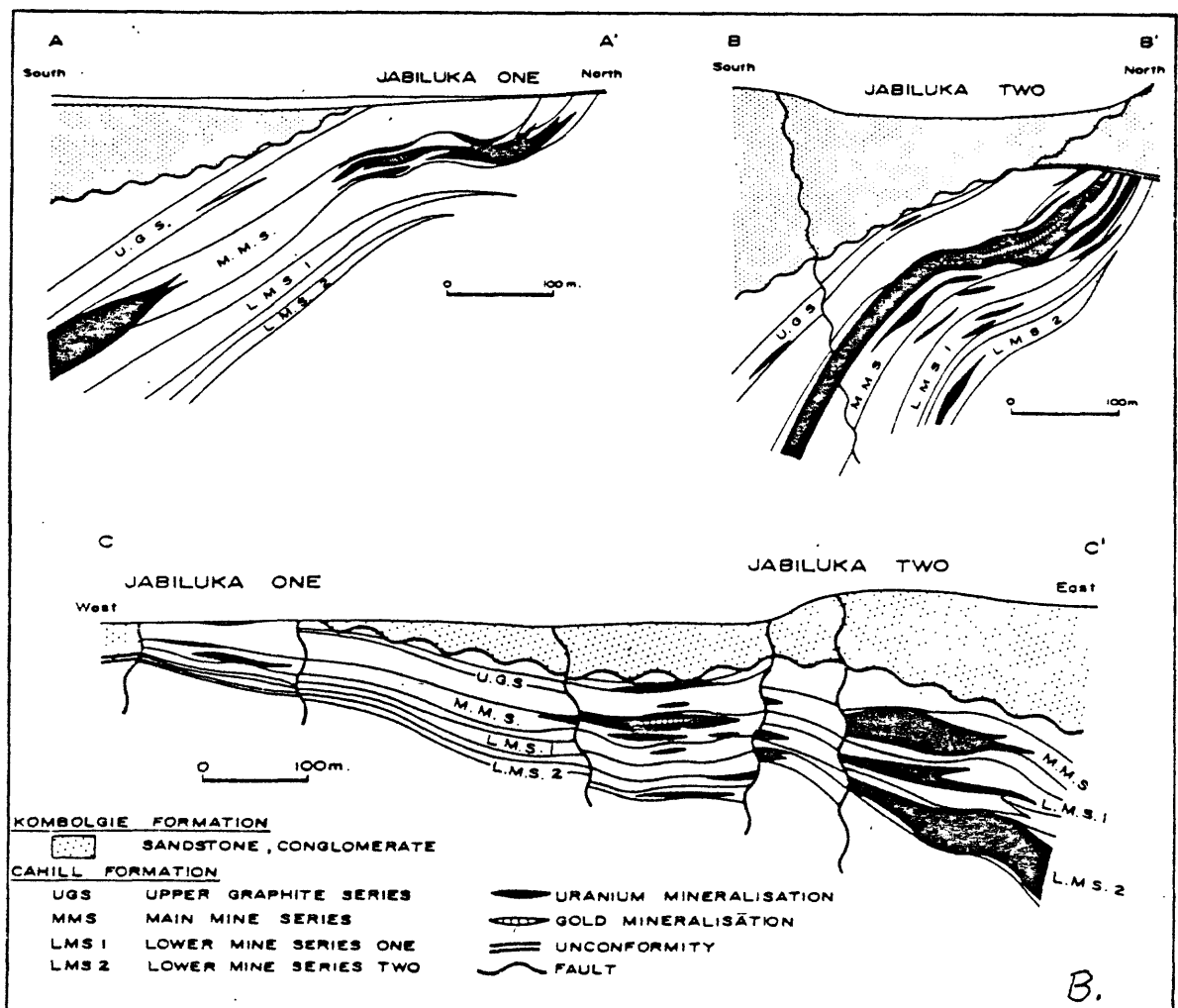
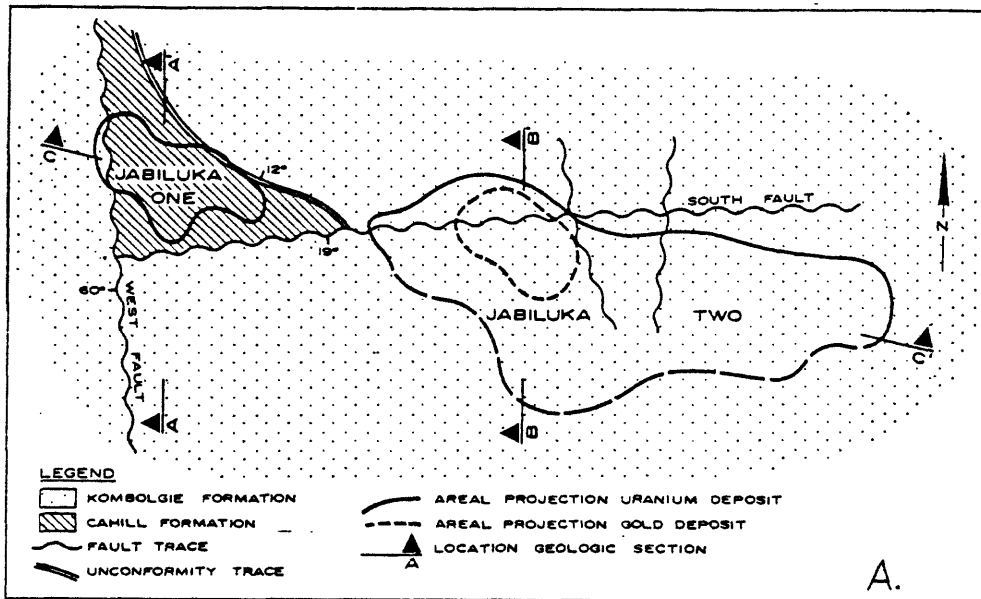
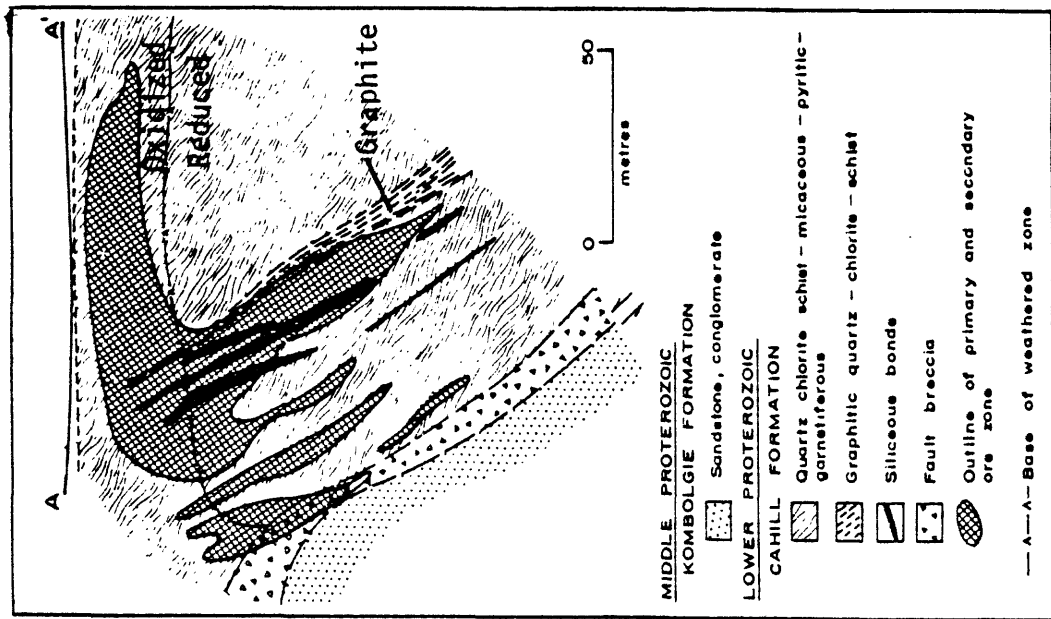


Figure 17.--Geology of the Jabiluka One and Two deposits (Hegge and Rowntree, 1978).
 A) Geologic map. B) Cross sections and longitudinal section.

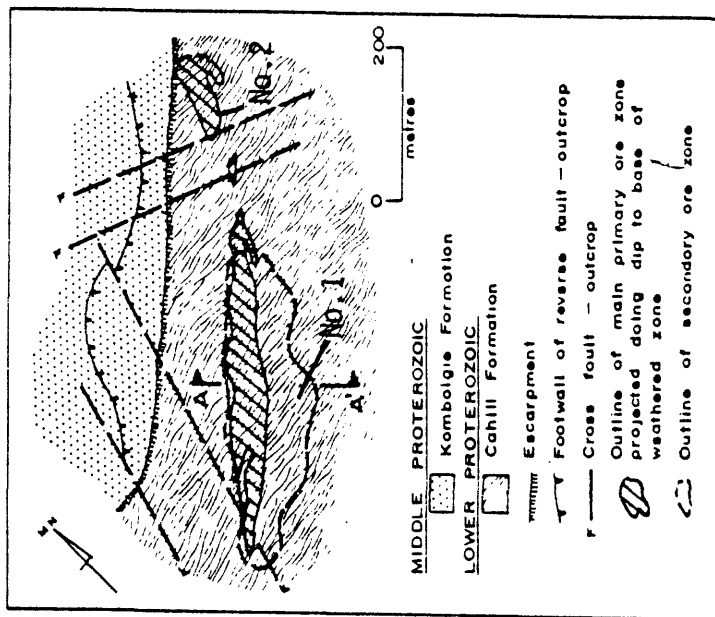
1780 to 1600 m.y. (Page and others, 1980; Riley and others, 1980). Two types of fluid inclusions rich in $\text{CaCl}_2\text{-NaCl}$ and $\text{CO}_2\text{-CH}_4$ have been observed in quartz from Jabiluka and Nabarlek; homogenization temperatures are in the range of 100° to 160°C (Ypma and Fuzikawa, 1980). The age of the quartz-pitchblende veins containing fluid inclusions is not defined, but probably is post-Kombolgie. Although geologic and isotopic age relations remain vague, the Jabiluka staff (e.g. Hegge, 1977; Hegge and Rowntree, 1978) and Binns and others, (1980) favor an initial hydrothermal stage of mineralization that was late in the metamorphic period, prior to erosion and deposition of the Kombolgie Formation. Uranium was subsequently remobilized several times.

Koongarra deposits.--The Koongarra deposits occur in quartz-chlorite schist of the Cahill Formation immediately adjacent to a graphite-schist horizon (Foy and Pederson, 1975). The main ore zone and several smaller ore shoots dip steeply, parallel to bedding. The footwall of the orebody is a steeply dipping reverse fault that downdrops Kombolgie Formation about 600 m (fig. 18). Strong structural control by the reverse fault is evident, and best ore is immediately below the graphite schist in strongly sheared rocks. Massive dolomite occurs on strike in the schist sequence and may be represented in the ore zone by banded siliceous lenses (Eupene, 1980). Pitchblende, both hard and sooty varieties, occurs in veinlets and botryoidal masses within chlorite matrix, and is disseminated along foliation. Minor amounts of pyrite, very minor chalcopyrite and galena, and subeconomic gold occur in the ore zones. The upper 25 m of the deposit is oxidized, causing a dispersion fan to the southeast (fig. 18). Several types of disequilibrium indicate movement of uranium and daughter products occurred in the last thousand to million years (Snelling and Dickson, 1979).

Nabarlek.--The Nabarlek orebody (Anthony, 1975) is a relatively small (about 10,500 s.t. U_3O_8) but very high grade (2.4 wt. % U_3O_8) deposit that was mined out and stockpiled in 1979. The orebody (fig. 19) occurred in a crush zone over a strike length of about 230 m, averaged 10 m width, dips about 45° , and was truncated at about 80 m depth by a thick dolerite sill (Anthony, 1975). Most ore was in chlorite rock (65 to 95 percent chlorite, plus sericite and hematite) that replaced chlorite schist and micaceous chlorite schist. Hematite increased in abundance in the high-grade (5 to 72 percent U_3O_8) core



B.



A.

Figure 18. --Geology of the Koongara Deposit (modified from Hegge and Rowntree, 1978).

A). Geologic map showing Koongara No. 1 and No. 2 deposits.

B). Cross section of Koongara No. 1 deposit.

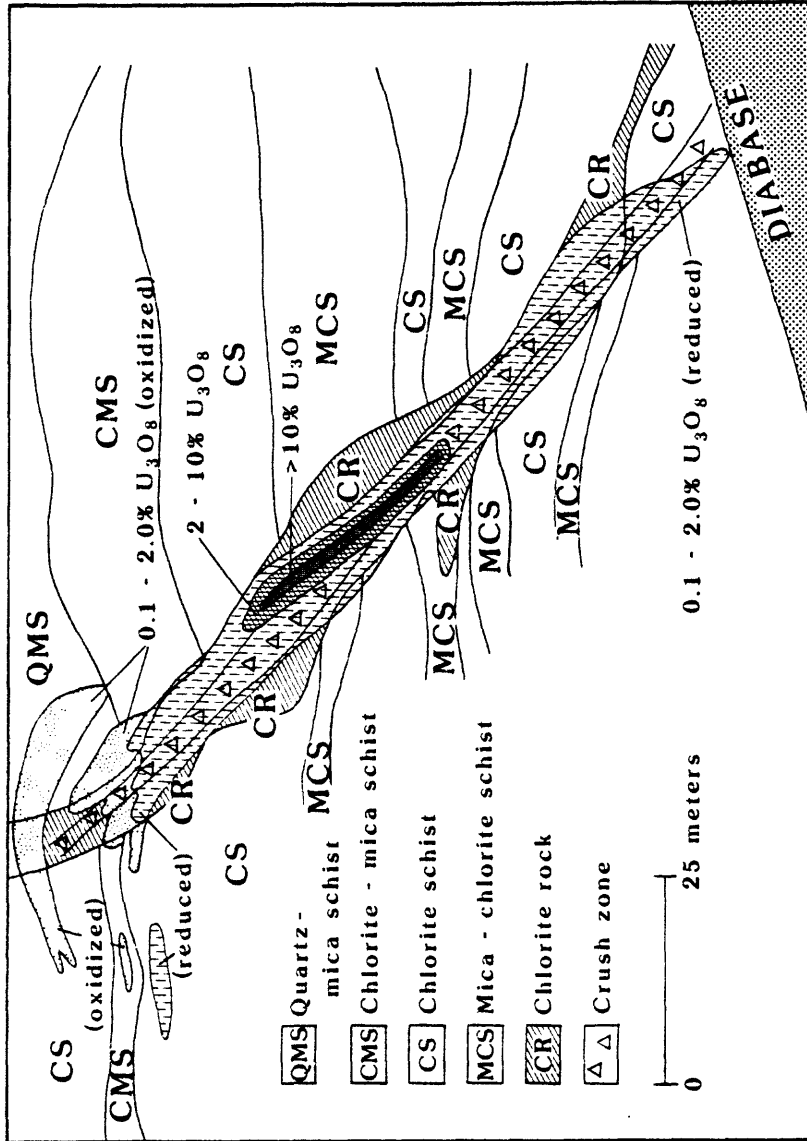


Figure 19.--Cross section of Nabarlek orebody (modified from Anthony, 1975, and Morton, 1977).

of the deposit to produce characteristic orange to red colors. Minor amounts of galena and chalcopyrite, and traces of pyrite, were disseminated through the orebody. The top of the orebody probably was approximately at the level of the sub-Kombolgie unconformity exposed a kilometer away. Uranium has not been found in schist or anatectic granite below the dolerite sill. Discordant U-Pb ages on pitchblende (Hills and Richards, 1976) were generally in the range 800-920 m.y. No carbonate rocks or graphite schists are known in lower Proterozoic rocks within 10 km of Nabarlek. This fact, the smaller size and stronger fault control, and the abundance of hematite at Nabarlek may indicate it was somewhat different from the other Alligator Rivers deposits. The Nabarlek geologist (Anthony, 1975) favors hydrothermal genesis from or adjacent to the anatectic granite below the orebody, probably with later lateral migration to avoid the intervening Oenpelli dolerite sill.

Possibly related examples

Other uranium deposits that occur in metamorphosed lower Proterozoic rocks in several areas of the world possibly add insights to the genesis of unconformity-type deposits, particularly as the examples cited below are not known to be related to a Proterozoic unconformity or covering sandstone. Oklo, Mounana, and several other important deposits in the lower Proterozoic Franceville Series of Gabon occur in weakly metamorphosed feldspathic sandstones and interbedded dolomitic and carbonaceous shales overlying Archean granite basement (Bourrel and Pfiffelmann, 1972; Chauvet, 1978; Weber and Bonhomme, 1978). The sedimentary environment may have been mixed deltaic, marine, and sebkha. High-grade ores (>0.4 percent) tend to be localized adjacent to faults and near the contact of sandstone and carbonaceous shale. Important factors seem to be: (a) sedimentation of permeable fluvial or marine beach sandstones with interbedded carbonaceous shales; (b) leaching of uranium from fertile granite basement and volcanic sediments; and (c) deposition of uranium in carbonaceous sediments with probable remobilization along faults. Ore has been dated at 2.0 b.y. Grades were rich enough to induce natural fission reactions 1.9 to 2.0 b.y. ago. These deposits seem to be a useful end-member example, uncomplicated by complex structure and high grade metamorphism, of significant uranium concentrations in organic-rich sediments in the lower Proterozoic.

The Michelin and Kitts deposits in Labrador are hosted by lower Proterozoic rhyolite and tuffaceous argillite that have been metasomatized and metamorphosed to greenschist or amphibolite grade (Gandhi, 1978). Gandhi presents strong evidence for a volcanogenic origin with subsequent metasomatic and metamorphic history that could have been analogous to processes in the Alligator Rivers district. Possibly similar Proterozoic examples include uranium- and sulfide-rich metavolcanic rocks in northern Sweden (Adamek, 1975) and New York, U.S.A. (Grauch, 1978). These examples demonstrate deposit formation from subaerial and submarine volcanics (and associated chemical sediments) by processes that do not require an unconformity or sandstone aquifer.

Genesis

Unconformity-type veins as a class probably formed in many stages, spanning more than a billion years. The genesis is probably one of the most complex of any class of metal deposit. With slightly over a decade of experience, and only one deposit exposed by mining, there clearly is a limited amount of data. Speculation on genesis seems warranted because the general geologic relations seem indicated (not proven) and these relations probably will not be revised soon. Details of geochronology, thermometry, and mineral-forming reactions probably will be refined in the next few years. Recent reviews by Dahlkamp (1978B), Hegge and Rowntree (1978), Eupene (1980), Hoeve and Sibbald (1978), Morton (1977), McMillan (1977), Kalliokoski and others, (1978), and others provide useful summaries and a range of genetic hypotheses, many portions of which I accept. My most general conclusion is that the Australian and Canadian deposits must be considered to be fundamentally the same, because their geologic habitat, probable stages of development, and final composition and geometry are similar. The deposits clearly differ in details, but this is true among sandstone-type deposits, porphyry copper-type deposits, and other deposit types.

Stage 1.--sedimentary preconcentration. The complex genesis seems to necessarily start with syngenetic or diagenetic enrichment of uranium in the sedimentary rocks within which the deposits occur or with which they are associated. Although favored by many (e.g. Dahlkamp, 1978B; Eupene, 1980;

McMillan, 1977), this enrichment cannot yet be documented,² presumably due to redistribution of uranium during metamorphism and probable recent near-surface leaching. Some general patterns that support this conclusion include:

(1) The world-wide recurrence of these deposits and numerous uranium showings of various types in lower Proterozoic platform, or marginal-marine sequences that contain carbonaceous pelites, carbonates, and commonly evaporites. Syngenetic and diagenetic uranium enrichment in such rocks clearly occurred in the slightly metamorphosed Franceville Series of similar age, Gabon. (2) The chemically diverse sediments in the sequences are appropriate sources for other anomalous elements in the deposits (e.g. As, Au, B, Cl, Hg, Mg, and Ni) as well as uranium. (3) Many authors have suggested that large deposits of other metals, such as Cu, Pb, Zn, Co, or Au, start with preconcentrations in host or nearby sediments. Although uranium-rich carbonaceous marine shales of younger age (~1,000 to 350 m.y.) are known, such as the Chattanooga Shale or Alum Shale, lower Proterozoic marginal-marine rocks may have been particularly favorable for uranium accumulation because of the presence of newly oxygenated surface and ground waters and organic activity in ocean basins.

Stage 2.--metamorphic upgrading. Metamorphism of the sedimentary rocks hosting the deposits is complex and poorly understood, but is deemed to have had a profound influence on the fate of uranium. The large deposits and numerous smaller ones are consistently in amphibolite-grade rocks near migmatized sediments and reactivated Archean granitoid cores and domes. Some smaller deposits, as in the Rum Jungle, occur in greenschist facies. It does not appear possible to specify with confidence whether uranium stayed essentially in situ within a uraniferous protolith, moved outward from the migmatite front (e.g. Ryan, 1979), or went through a magmatic stage of granites derived by partial melting of sediments (e.g. Binns and others, 1980). The stratabound nature of the ores in some districts probably reflects the location of carbonaceous beds which were the sites of preconcentration and/or metamorphic enrichment. The seemingly low uranium content of most host rocks outside of deposits may indicate that uranium was mobilized during metamorphism, possibly into the many small occurrences known within the

²The frequently cited value of 34 ppm background uranium content in the Cahill Formation is apparently not valid, as this average includes mineralized samples from ore zones (John Ferguson and R. S. Needham, discussion at Symposium on Uranium in Pine Creek Geosyncline, 1979).

districts. The form and grade of mineralization at this stage is not known, but may have consisted of disseminations and narrow stringers (as described by Binns and others, 1980) rather than large Beaverlodge-type veins because such brittle deformation would not have been likely at this stage (cf. Lewry and Sibbald, 1979). I suspect some general similarities existed with ultrametamorphic (Rössing-type) deposits at this stage--such as a confined rather than open chemical system, trapping of mineralizing solutions under anticlinal structures, and localization by graphitic beds (C-H compounds would be reactive at these temperatures). Retrograde metamorphism also occurred in the waning stages of metamorphism, and it seems to have been an important enrichment process (e.g. Binns and others, 1980; Hegge and Rowntree, 1978). It has been difficult or impossible to define the effects of retrograde metamorphism because of the overprinting of similar-appearing post-unconformity hydrothermal alteration. It is apparent, nonetheless, that ore zones were prepared by prograde and retrograde metamorphic processes, and I believe that some ore grade zones were formed prior to exposure at the unconformity.

Stage 3--supergene enrichment at the unconformity. Chemical weathering on the unconformity, especially in Saskatchewan, is indicated by regolith development and can be inferred to have mobilized uranium. High grades near the unconformity and short vertical dimensions of some orebodies, such as Key Lake, suggest supergene enrichment. However, most orebodies are not strongly zoned relative to the unconformity and much ore near the unconformity could be redistributed post-unconformity. Supergene-enriched zones would be very soluble and vulnerable to post-unconformity modification, which probably explains the difficulty of describing this stage and its contribution.

Stage 4--remobilization under sandstone cover. Most of the spectacular high-grade concentrations and the gross geometry of the orebodies were probably created after burial by considerable thickness of sandstone. Fluid-inclusion data (Pagel, 1975; Pagel, 1977; Ypma and Fuzikawa, 1980) demonstrate hydrothermal conditions near 200° C, which probably would be capable of homogenizing U-Pb isotopes to yield young ages. This event was possibly triggered by intrusion of mafic dikes in Saskatchewan (Hoeve and Sibbald, 1978) but has no known igneous counterpart in the Northern Territory,

Australia. An attractive alternative is radiogenic heat from dispersed or ore-grade concentrations of uranium in the basement (Tilsley, 1980; Fehn and others, 1978) which is postulated to have set up hydrothermal convection. Calculated flow directions are upward along structures into the overlying sandstone as at Midwest Lake. Covering sandstones have been proposed as the source of uranium (Hoeve and Sibbald, 1978) but there does not appear to be sufficient feldspathic material and heavy minerals to be a sufficient source of uranium to form deposits of this size and grade. I view the 800 to 1200 m.y. ores, especially those in overlying sandstone, as redistributed from older basement sources. An important factor in this postulated redistribution is post-sandstone faults with small displacements, probably reactivated basement faults. The covering sandstones, particularly the Athabasca, have had a complex alteration history involving repeated oxidation and reduction which probably relates to mixing of fluids, some coming from the basement. The reductant must have been mobile. Methane is a possibility (Hoeve and Sibbald, 1978), but I suspect that methane production from graphite and consequent reduction of uranium by methane would not be sufficient for kinetic reasons, although these reactions are predicted by thermodynamics. Other C-H compounds such as ethylene might be effective, however (J. S. Leventhal, oral commun., 1980). Carbonate cogenetic with pitchblende has normal carbon isotopic ratios (Binns and others, 1980; Pagel and others, 1980) rather than the large negative values predicted by isotopic fractionation between CH_4 and CO_2 (Ohmoto, 1972). An alternative mobile reductant is metastable sulfur species (Granger and Warren, 1969) that could have formed by partial oxidation of sulfides in basement rocks; there is abundant evidence for oxidation and destruction of pyrite concentrations noted within unaltered portions of host metasediments. Covering sandstones seem important as aquifers capable of introducing oxidizing waters to redistribute and upgrade the deposits.

DEPOSITS IN ULTRAMETAMORPHIC ROCKS

Introduction

Uranium deposits in or adjacent to granitoid rocks are known in many localities. Some, as in the Bancroft district, Ontario, were important producers in the 1950's. More recently the Rössing deposit, Namibia (Southwest Africa) has become famous as a very large, very low grade deposit being mass mined at the rate of about 40,000 tons per day. Genesis of these

deposits continues to be controversial, partly because a variety of processes probably operated locally. The general geologic habitat, however, seems quite clearly to be very high-grade metamorphism. I use the term ultrametamorphism as petrologists do (e.g. White and Chappell, 1977): metamorphism at temperatures and pressures high enough for partial to complete melting to occur. Silicate melts are produced and these deposits are associated with those anatectic melts. Other names have been used, such as anatectic or pegmatite, or porphyry-type deposits, but these terms apply equally well to magmatic rocks that occur far above the zone of melting. The term ultrametamorphism is used to connote the deep, very hot metamorphic environment as well as the process of partial melting. The following descriptions focus on the metamorphic rocks and probable deposition of uranium from silicate melt; it largely ignores the complications of probable simultaneous or subsequent metasomatism.

Grenville Province, Quebec and Ontario

The Grenville Province of the Canadian Shield in eastern Canada contains many uranium deposits in granitoid rocks of apparent ultrametamorphic affinity. These deposits extend over a distance of approximately 1500 km (fig. 20). From southwest to northeast the uranium localities are the famous Bancroft district, Ontario; Mont Laurier, Quebec; and Sept Isles, Johan Beetz, Romaine, and St. Augustin in eastern Quebec (Satterly, 1957; Baldwin, 1970; Kish, 1975). Recent interpretations of the geologic history of the Grenville Province (Wynne-Edwards, 1969; 1972) propose a long and complex history:

- (1) Pre-tectonic basement gneiss complex formed from volcanic rocks, greywackes, and intrusive rocks; age probably Archean, or early Proterozoic (Aphebian).
--Kenoran orogeny (2.5 b.y.)--
- (2) Pre-tectonic sedimentary rocks of the Grenville Supergroup (limestone, quartzite, arkose, pelite, volcanics); age early Proterozoic
--Hudsonian orogeny (1.7 b.y.)--
- (3) Syntectonic intrusions of anorthosite, gabbro, syenite, and quartz monzonite; age middle Proterozoic (1.4 b.y.).
- (4) Syntectonic intrusions of granite, syenite and gabbro and ultrametamorphism of the Grenville Supergroup at about 1,000-950 m.y. (Grenville orogeny).

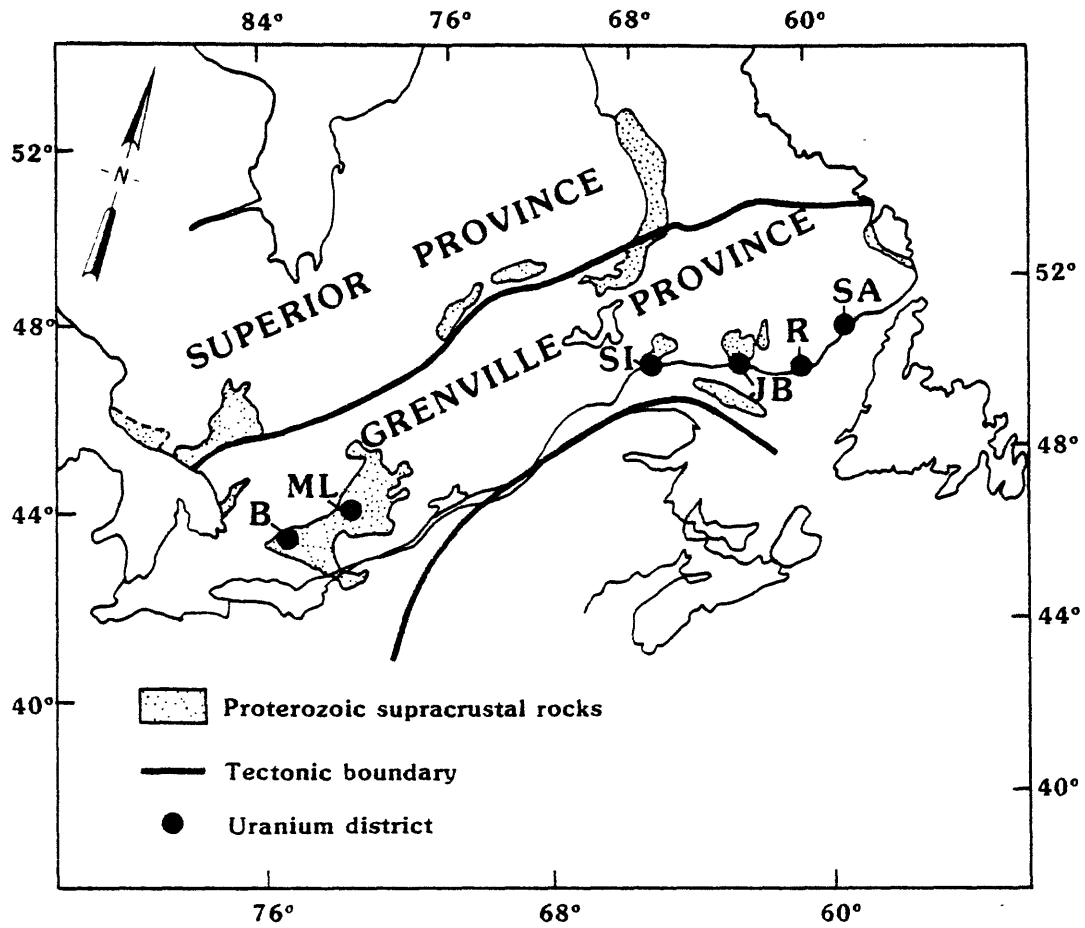


Figure 20.--Grenville Province of the Canadian Shield (modified from Wynne-Edwards 1973). Uranium districts shown: B, Bancroft; ML, Mont Laurier; SI Sept. Iles; JB, Johan Beetz; R, Romaine; SA, St. Augustine.

(5) Post-tectonic intrusion of diabase dikes.

This history is very similar to that of the Superior Province and Wollaston fold belt to the west. Uranium deposits appear to have formed from metasediments of the Grenville Supergroup during late stages of the Grenville orogeny. Uranium minerals and associated rocks and minerals yield isotopic ages of about 1000 m.y. (Robinson, 1960; Little, 1969; Fowler and Doig, 1979). The proposed sequence of sedimentation, plutonism, sedimentation, plutonism, and metamorphism, provides several times that uranium could have been recycled to ore deposition.

Bancroft district.--More than 100 occurrences of uranium in several types of deposits (table 2) occur in general association with Precambrian granitic rocks of this district (Satterly, 1957; Hewitt, 1959; Robinson, 1960; Little and others, 1972). Total production has been more than 11 million lbs U_3O_8 at an average grade of about 0.14 percent U_3O_8 . Most of this has come from the Faraday (Madawaska) and Bicroft mines in unzoned red pegmatite with production plus reserves of about 9 million and 5 million lbs U_3O_8 respectively (McMillan, 1977). The pegmatites have variable granitic to syenitic composition, medium to giant grain size, and contain peristerite, microcline, quartz, diopsidic pyroxene, amphibole, and biotite. Prominent accessory minerals are magnetite, zircon, sphene, allanite, fluorite, molybdenite, hematite, and calcite. Uranium is carried in uraninite, uranothorite, thorite, allanite, and secondary uranophane. Average uranium:thorium ratio is about 2, and the ores are rich in Ti, Zr, Mo, and S as well as Th. Anhydrite is intimately associated with pegmatitic feldspar, pyroxene, and uraninite in the Faraday Mine and is believed to be a magmatic phase (Little, 1969). Wallrocks are hematized and ferromagnesian minerals are chloritized near ore. Graphite in amounts up to 2 percent is reported by Evans (1965) for pelitic gneisses from the Bicroft mine, but no comments are made on relation to ore. Quite probably graphite is present elsewhere but has gone unreported. Uraninite yields U-Pb ages of 950 to 1090 m.y., in the same range as K/Ar and Sr/Rb dates on biotite rock samples from the post-tectonic granite pegmatites (Robinson, 1960; Little, 1969; Fowler and Doig, 1979).

Geology of the area was mapped by Hewitt (1959) but age relations have been modified by recent studies. Four granitic bodies in the area are now believed to be mantled gneiss domes following recognition of an unconformity

Table 2. Uranium deposits of the Bancroft District

[Examples indicated in parentheses, from Little and others, 1972]

-
- I. Deposits in granitic and syenitic pegmatites
 - A. Zoned pegmatites (MacDonald)
 - B. Unzoned pegmatites
 - 1. Red pegmatites (Faraday)
 - 2. White pegmatites (Zenmac)
 - II. Metasomatic deposits in limy rocks
 - A. Metasomatic deposits in marble (Canadian All Metals)
 - B. Metasomatic deposits in metamorphic pyroxenite (Bicroft, in part)
 - III. Hydrothermal deposits
 - A. Calcite-fluorite-apatite veins (Fission)
 - B. Calcite-fluorite-apatite-biotite-pyroxene veins (Cardiff)
 - C. Anhydrite-calcite-uralite veins (Faraday, in part)
 - IV. Carbonatite
 - A. Calcite-biotite-hornblende-apatite vein (Basin)
-

and recognition of migmatitic accretion of younger sediments onto the cores (Lumbers, 1975; Bright, 1976). The cores are said to be derived from "Middle Precambrian" (Archean or Apebian of Wynne-Edwards, 1972) greywacke that was metamorphosed and deformed prior to deposition of the Grenville Supergroup. The Grenville Supergroup in the area is about 5700 m of arkose, sandstone, limestone, greywacke, and tuffaceous volcanics that were metamorphosed to middle or upper amphibolite grade about 1000 m.y. ago. Grenville sediments near the granitoid cores, especially basal arkose, were migmatized and folded into the gneiss domes. This migmatite zone is proposed to be the source of the post-tectonic uraniferous pegmatite sills and dikes (Bright, 1976). Abundant tuffaceous rocks in the middle of the Grenville Supergroup are suggested as an alternate source of uranium (Bright, 1976) but these rocks apparently were not extensively migmatized. Because the uranium deposits occur in the general position of carbonate-rich beds (middle portion of the Grenville), the deposits are said to have general stratigraphic control (Bright, 1976; Gordon and Marson, 1978). The pegmatites are also mineralized where intruding rocks other than marble and strong fracture control is indicated. The pegmatites show relatively sharp contacts with enclosing rocks and angular xenoliths of mafic rocks are common. Uranium commonly is enriched along the margins of pegmatites where the ferromagnesian minerals are abundant. This compositional zoning within the pegmatites presumably reflects contamination by wallrocks. The association of uranium with iron minerals may indicate that reduction occurred to localize uranium.

Scapolite, sodalite, and anhydrite are locally abundant in pegmatites and metasomatized sediments in the Bancroft area. The causes or precursors of these minerals have not been interpreted, but they may be remobilized from evaporites in the Grenville Supergroup. Evaporites have been interpreted to exist in the Grenville Supergroup about 150 km to the southeast (Brown and Engel, 1956; Hogarth, 1979).

Mont Laurier area.--Coarse-grained granite and granite pegmatite in the Mont Laurier area, southern Quebec, contain very interesting uranium deposits but none have been mined (Kish, 1975; Allen, 1980). The area is similar in many ways to the Bancroft district 250 km to the southwest. Uranium deposits are restricted to the Grenville Supergroup, particularly the noses of major folds and at the base near basement gneiss. Uraninite and thorian uraninite are the

chief ore minerals, but where Th/U exceeds 1, uranothorite and thorite are the chief radioactive minerals (Cuney and Kish, 1978).

The oldest unit in the area is the Patibre Formation, a relatively homogenous suite of quartzo-feldspathic gneisses probably derived from greywacke. These gneisses are interpreted (Wynne-Edwards, 1969) to be Archean or early Proterozoic in age. Unconformably overlying the gneissic basement are metasediments of the Grenville Supergroup, metamorphosed to upper amphibolite grade and containing abundant migmatite. These were originally mature clastic and chemical sediments (Allen, 1980). Of special interest are graphitic metapelites (containing garnet, sillimanite, biotite, quartz, microcline, oligoclase, and graphite) and scapolite-diopside-bearing calc-silicate gneiss and marble, often rich in graphite, pyrite, and pyrrhotite. Pre-tectonic quartz monzonite and syntectonic granite pegmatite intrude older rocks. The pegmatites have 1 mm to 10 cm grain size and occur in layers from 1 cm to 20 m thick, approximately conformable to foliation in host gneisses. Concordant boundaries and lack of evidence for forceful emplacement suggest pegmatite formation was largely in situ by anatectic melting of biotite gneiss in amounts up to about 50 percent. The anatectic melt probably migrated less than 200 m (Allen, 1980). Phase relations suggest anatexis occurred at about 650°C and 5 to 6 kbar total pressure. Bulk compositions approximate that of a minimum melt in the system Q-Or-Ab-An-H₂O (Allen, 1980).

Most uranium mineralization is restricted to white pegmatites within the Grenville that contain the assemblage ilmenite-rutile-graphite. White pegmatites tend to occur in calc-silicate gneiss and marble units, whereas hematite-magnetite-bearing red pegmatites are abundant in Patibre Formation feldspathic-gneisses. The ilmenite-rutile-graphite assemblage indicates lower oxygen fugacity than for magnetite ± hematite pegmatites (Ohmoto and Kerrick, 1977) as will be discussed further. Fluid inclusions in pegmatite quartz are rich in CO₂ (Cuney and Kish, 1978).

The Mont Laurier deposits seem clearly related to in situ partial melting of "dirty" quartzo-feldspathic sandstones and arkose. Although the deposits are relatively rich in thorium, which often indicates refractory character, U and Th in this environment fractionated into the melt rather than the restite. The reasons for association with carbonate units are not clear; some

uranium could have been derived from these beds, or it may reflect the localizing effect of more reducing conditions.

Eastern Quebec.--The Grenville Province on the north shore of the Gulf of St. Lawrence contains uranium showings at Sept. Isles, Johan Beetz, Romaine, and St. Augustin (Baldwin, 1970). No mining has been done and the deposits appear to be of too low grade to exploit now. These uranium-thorium deposits are in generally similar environments, hosted by granite, pegmatite, and granite gneiss. The abundance of migmatite appears to be variable and the importance of partial melting or granitization is debated. Only the Johan Beetz area will be described as most information is available for it.

Geology of the Johan Beetz area was mapped by Cooper (1957) and the uranium deposits described by Baldwin (1970), Hauseux (1977) and Mackie (1978), from which the following description is taken. Numerous uranium occurrences have been found in the Lac Turgeon granite and an adjacent related granite. Mineralization occurs in erratic pods 0.3 to 30 m long and also as disseminations in pegmatite. Axial and nose regions of folds are preferred sites. Mineralized pods are parallel to foliation. High concentrations of uranium and thorium occur in white and gray pegmatites that contain plagioclase and biotite, but little or no mineralization occurs in muscovite-bearing white pegmatites or red pegmatites. Uranium in the Lac Turgeon granite is in uraninite, zircon, and magnetite containing probable submicroscopic uraninite (Hauseux, 1977). Uranium content of the granite is highest in coarser grained, porphyritic, plagioclase-rich zones with increased content of smokey quartz and magnetite, and red feldspar.

Descriptions of the Lac Turgeon granite differ on some important points. According to Hauseux (1977) metasedimentary "fragments" are abundant, sedimentary bedding structures are preserved, mafic bands are parallel to tectonic foliation, and contacts between the granite and metasediments are both sharp and diffuse. She favored an origin by granitization of shaley arkoses and sandstones rather than anatexis. However, Mackie (1978) pointed out that granite compositions fall in the minimum melting trough of the $Qz-Ab-An-Or-H_2O$ system and he proposed an origin by anatexis of Grenville Supergroup metasediments. Probably both observations are correct and indicate that partial melting occurred only locally, but pegmatites with intrusive

relations presumably were anatectic melts. Metasediments in the area (Cooper, 1957) include sandstone (some with ripple marks), calcareous sandstone, and probable clay- and feldspar-rich sandstone. No limestones are described. It is not clear what sedimentary rocks were the protolith for the granite and pegmatite.

Northern Saskatchewan

Charlebois Lake area.--Numerous occurrences of uranium mineralization in the "pegmatite" fraction of ultrametamorphic rocks are known in the Cree Lake Mobile Zone of northern Saskatchewan (fig. 21), the most famous being at Charlebois lake (Mawdsley, 1952; Lewry and Sibbald, 1979). In the Charlebois Lake area uraninite is disseminated in migmatite adjacent to granite bodies. The largest, highest grade deposits occur in white, fine-grained (<1 mm) leucogranite in migmatite. Rocks of this composition and texture are always in migmatite containing calcareous metasediments, leading to formation of relatively calcic plagioclase (andesine) and hornblende. Uraninite is generally associated with biotite and with molybdenum (Mawdsley, 1952). The U:Th is about 4, average grade of grab samples about 650 ppm U_3O_8 and individual samples contain as much as 1.75 wt. % equivalent U_3O_8 (Mawdsley, 1952; Lewry and Sibbald, 1979).

Other "pegmatite" occurrences in northern Saskatchewan (fig. 21) are similar to those at Charlebois and recent information (Thomas, 1979) adds new insights. In all cases uranium mineralization occurs in granite pegmatite associated with graphitic pelite and calcareous rocks, generally near the basement gneiss-supracrustal metasediment unconformity. The early hypothesis of Mawdsley (1952) that uraniferous pegmatites were derived from adjacent intrusive granites has been shown to be incorrect. The pegmatites are stratabound, both within districts and regionally, within pelitic-calcareous strata. New mapping and geochronology indicate that the granite gneiss is Archean basement, unconformably overlain by lower Proterozoic metasediments (Lewry and Sibbald, 1979). The uranium is believed to have originated in black shale and have been reworked during ultrametamorphism at about 1.7 b.y. The lithostructural situation is thus very similar to the setting of

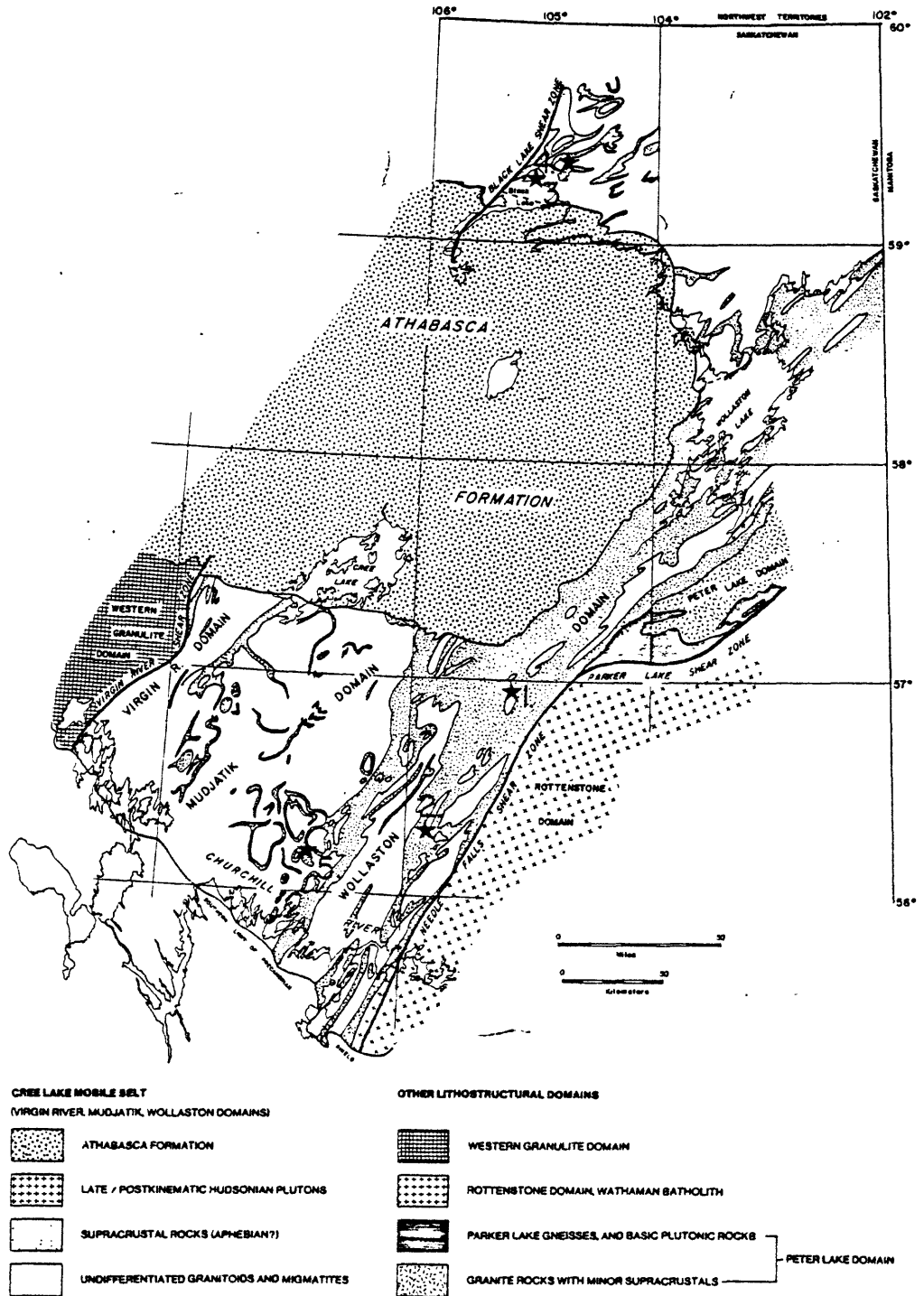


Figure 21.—Regional geology of northern Saskatchewan showing location of five ultrametamorphic deposits (from Thomas, 1979). Uranium deposits: 1) Karin Lake; 2) Pipewrench Lake; 3) Pluto Bay; 4) Charlebois Lake; 5) Cup Lake.

unconformity-type deposits in the Wollaston fold belt described earlier.

Rössing Deposit, Namibia

The Rössing deposit is the largest known ultrametamorphic deposit, containing about 300 million lbs U_3O_8 at an average grade of only 350 ppm. The general geologic setting seems well established (Nash, 1971; Jacob, 1974; Berning and others, 1976; von Backstrom and Jacob, 1979), but detailed description of the ore deposit is not available. The deposit occurs in the Damara orogen in metasediments of late Precambrian age that are highly metamorphosed and partially melted along with lower Proterozoic gneiss domes (fig. 22). Pegmatites and uraniferous Alaskitic Pegmatitic Granite (A.P.G.) are late- to post-tectonic; the A.P.G. at Rössing has been dated by Rb-Sr at 468 ± 8 m.y. (cf. 510 m.y. for the main Damara orogeny; von Backstrom and Jacob, 1979). Uranium occurs as uraninite, betafite, and hexavalent secondary minerals, chiefly in A.P.G. emplaced into calcareous metasediments (pyroxene-garnet gneiss, amphibole-biotite schist, marble) (Berning and others, 1976). Uranium is enriched in biotite selvages along A.P.G. The U:Th ratio in A.P.G. is about 20. Approximately 40 percent of the uranium is in secondary minerals, possibly representing upgrading in the unusual Namib Desert climate where nightly fog provides small amounts of moisture.

Basement in the area is augen gneiss of the 2.0 b.y. Abbabis Group. Unconformably overlying this is the Damara Supergroup, a thick (>5 km) succession of sandy, pelitic, and calcareous sediments of late Precambrian age. The basal unit (Etusis Formation) is mostly a meta-arkose, about 800 m thick. The overlying Khan Formation, about 200 m thick, is mostly calc-silicate gneiss and schist, probably derived from limy, pelitic sediments. Khan gneisses contain metamorphic anhydrite, probably from evaporite deposits (Nash, 1972). The Etusis and Khan Formations (the Nosib Group) correlate with the Lower Roan Formation of the Katanga System in the Copperbelt of Zambia (Lee and Glenister, 1976). The overlying Rössing Formation contains about 200 m of marble and calc-silicate gneiss. Fluvial and shallow-water marine sedimentation is interpreted by Berning and others, (1976). Calcareous rocks of the Khan and Rössing Formations are the chief hosts for intrusive uraniferous A.P.G. Both regionally and within the deposit, A.P.G. dikes and irregular bodies occur in anticlinal or dome structures and are "dammed up" under marble beds (von Backstrom and Jacob, 1979).

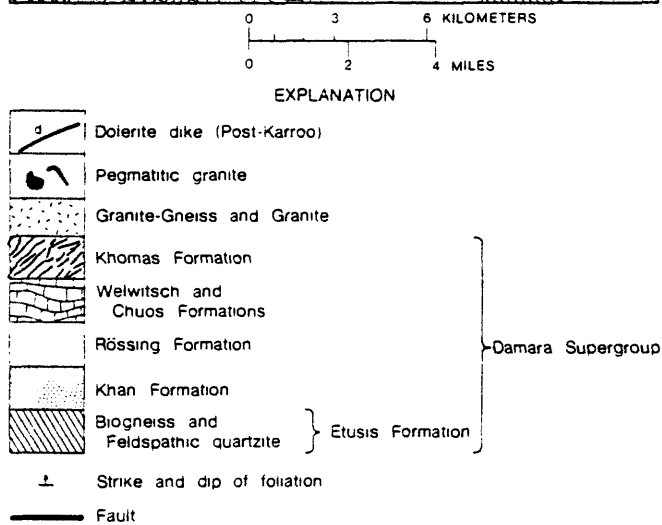
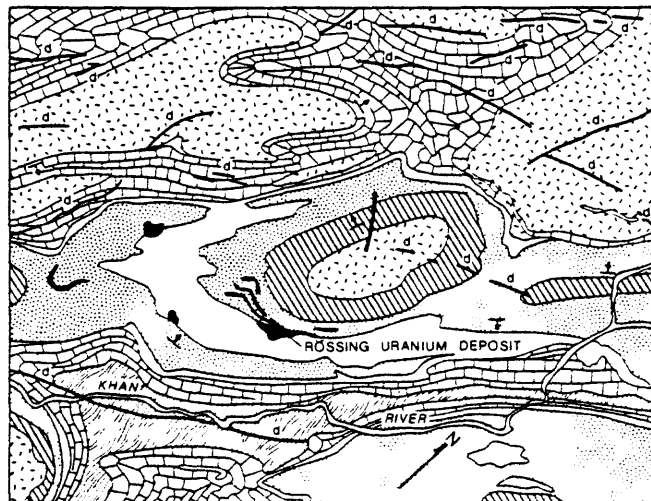


Figure 22.--Geology of the Rössing mine area (modified from Berning et. al., 1976). Note that the deposit is localized with calcareous rocks of the Khan and Rössing Formations about 3 km from the mantled gneiss dome.

Damaran regional metamorphism is interpreted to have taken place in two pulses, the latter one producing granitic melts at about 675° to 750°C and 3 to 5 kilobars. The low pressures are inferred from the presence of cordierite (Nash, 1971; Berning and others, 1976). Two sources of granitic melt rich in uranium are possible. One is basement granitic gneiss and syntectonic granite gneiss which are highly radioactive regionally (von Backstrom and Jacob, 1979). Another is arkose of the basal Etosis Formation. Berning and others, (1976) envisioned derivation of uranium from basement granite gneiss, incorporation in overlying clastics, and remobilization during anatexis. The uraniumiferous anatectic melt in the Rössing deposit rose about 750-1000 m, judging from the stratigraphy. Localization of mineralization in certain A.P.G. bodies is thought to reflect in part the uranium content of underlying rocks subjected to partial melting (Berning and others, 1976).

Uranium may have been enriched from the anatectic melt by one or more processes. One is reduction by iron in mafic xenoliths and wallrocks, resulting in the association of uraninite with hematite and with biotite (von Backstrom and Jacob, 1979). Another is reduction in Eh and increase in pH caused by assimilation of basic country rock (Berning and others, 1976). Reduction by graphite is another possibility, but graphite has been reported only by Moreau (1977). Metasomatic transfer of uranium in wallrocks is likely as into biotite selvages, but there is insufficient data to evaluate the importance of this process.

Australia

Lower Proterozoic granitoid rocks of the Willyama Complex in south Australia and New South Wales contain uranium deposits of possible ultrametamorphic origin. The Crockers Well deposit is best known (King, 1954; Whittle, 1954) but many similar deposits occur at Radium Hill (Sprigg, 1954; Parkin and Glasson, 1954), near Broken Hill (Johnson and Gow, 1975), and the deposits at Mount Painter (Youles, 1975) may be related also. A characteristic feature of these deposits is a U-Ti-Na association with uranium residing chiefly in U-Ti phases brannerite and davidite (Whittle, 1955). Average grade of these deposits is low, about 0.05 to 0.12 percent U_3O_8 (Campana and King, 1958). About 1.9 million lbs U_3O_8 was produced between 1954 and 1961 from davidite ore at Radium Hill (Blissett, 1975).

The uranium deposits are in inliers of Precambrian rocks including granites, a variety of slates, schists, gneisses, and iron formation. Metasediments in the Willyama inlier were deposited in the lower Proterozoic (>1800 m.y.). The sediments were chiefly shale, silt, sand, and impure dolomite deposited on a shallow marine shelf above Archean basement (Thompson, 1975). Metamorphism occurred at about 1700 m.y. based on Rb-Sr ages and U-Pb dates from uranium minerals. Quartzo-feldspathic gneisses were produced by anatexis, often with potassium or sodium metasomatism. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in gneisses are very high (>0.729) indicating formation from crustal rocks (Pidgeon, 1967). Biotite and muscovite mineral ages by Rb-Sr and K-Ar tend to be about 500 m.y., indicating a younger metamorphic event; this may explain a U-Th-Pb age of 580 ± 30 m.y. on absite (Th-brannerite) from the Crockers Well deposit (Campana and King, 1958).

The Crockers Well deposit (King, 1954; Campana and King, 1958) occurs in brecciated granitoid rocks (fig. 23). The ore mineral is absite associated with biotite and rutile (Whittle, 1954). The oldest rock in the deposit area is an adamellite (quartz monzonite) which was sheared and brecciated. Unstressed alaskite and albite pegmatite occur in the shear zone. Contacts of some alaskites are gradational, suggesting that metasomatism occurred. Rutile-absite mineralization is spatially associated with alaskites, and is considered to be of metasomatic origin. The metasomatism is believed to have introduced Na, U, Ti, Zr, P, and rare earth elements (King, 1954; Whittle, 1954).

Other uranium-titanium deposits at Radium Hill, Mt. Victoria, and other localities in the Willyama Complex, Olary Province (Campana and King, 1958) occur in fractured granitoid rocks. The deposits are considered to form from late-stage metasomatizing fluids released from the granitoid body in which they occur. The chronology is not well established but a recent interpretation is that the granitoids and mineralization are about 1700 m.y. old (Thompson, 1975). Because this was a period of ultrametamorphism, the uranium deposits seem to have formed in that environment but apparently not from silicate melts.

Davidite and brannerite occurrences in the Mt. Isa-Cloncurry district, Queensland (Lawrence and others, 1957; Brooks, 1975) appear to be similar to the U-Ti occurrences in the Willyama Complex. According to the brief

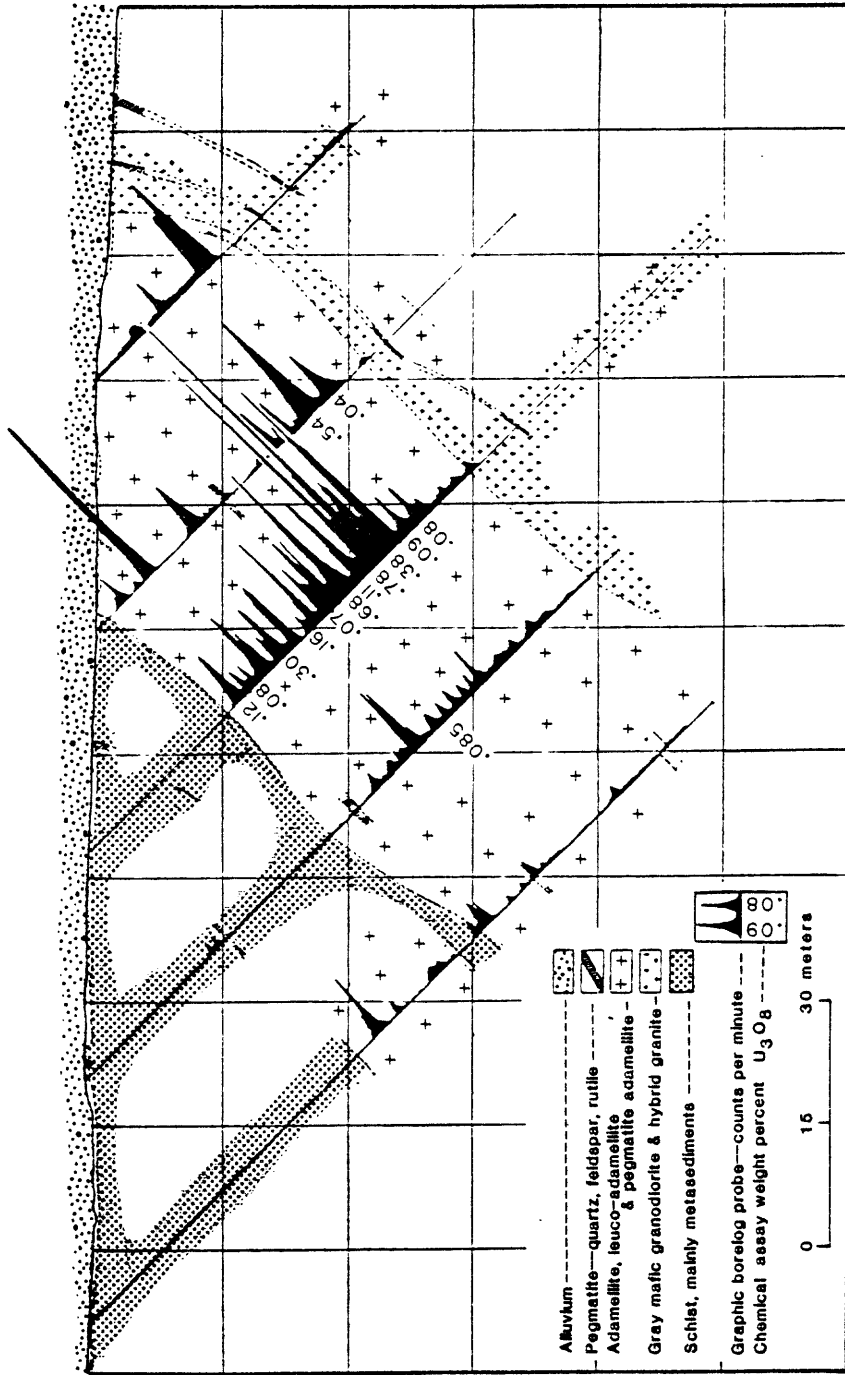


Figure 23.--Cross section of Crockers Well deposit showing distribution of radioactivity (modified from Campana and King, 1958).

descriptions I could find, these occurrences are common in the middle Proterozoic Corrella Formation. The occurrences have "pegmatitic and granitic associations" (Brooks, 1975). The Corrella Formation contains stromatolitic carbonates, siltstone and sandstone, and abundant metamorphic scapolite; a shallow-water, hypersaline, marine-shelf environment is interpreted by Plumb and Derrick (1975). A sedimentary source for uranium was proposed by Lawrence et al. (1957), partly because they recognized high-grade (granulite) metamorphism but reported no evidence for igneous activity. These occurrences as well as the nearby Mary Kathleen deposit with its unusual chemistry, described in a later section, appear instructive as examples of sedimentary preconcentration and metamorphic upgrading, probably short of partial melting.

Comments

Some general patterns are apparent in the preceding descriptions that are worth summarizing here. Although there are some exceptions, and not all observations are necessarily agreed upon, the following general patterns seem to hold for the ultrametamorphic rocks and associated uranium deposits:

- (1) They occur within about 1 km of basement granite gneiss complexes of Archean to early Proterozoic age.
- (2) They occur in supracrustal sedimentary rocks, chiefly of early Proterozoic age (except Rössing which is in upper Proterozoic rocks).
- (3) Lithologies suggest shallow-water marine shelf and fluvial sedimentation; minerals such as anhydrite and scapolite suggest probable presence of evaporites in many of the sequences.
- (4) Chemical enrichments in elements B, Cl, F, P, and S are probably explained by chemical sediments in the sedimentary sequences. Low Th contents are consistent with a sedimentary source.
- (5) Anatectic melts moved relatively short distances, essentially in situ at Mont Laurier and about 1 km at Rössing.
- (6) Some deposits, such as at Johan Beetz and Crocker's Well, may be related to metasomatic (aqueous) fluids with little or no direct precipitation from silicate melt. These deposits appear to be of smaller size and lower grade than those formed from melts.
- (7) Anatectic melts and metasomatizing fluids were confined and concentrated under anticlinal structures and strong, refractory mafic or calcic rocks.

- (8) Structural character and geochronology demonstrate that uraniferous anatectic melts were late-tectonic; two examples are about 25 and about 100 to 200 m.y. younger than the peak of orogenesis.
- (9) Graphite seems important as a probable reductant in several deposits, and possibly is present and not reported from others. Ferrous iron in biotite, amphibole, and iron oxides probably was a reductant also.

The complex subject of the origin of migmatites and anatectic melts has been reviewed elsewhere (Mehnert, 1968; Winkler, 1974; White and Chappell, 1977). Recent field and laboratory studies demonstrate that melts of granitic composition are likely to form from appropriate rocks in the crust at 650° to 700°C and several kilobars pressure. Descriptions reviewed here demonstrate that in many cases uranium is fractionated into the melt, rather than staying in the unmelted restite fraction. The distance that the melt will move is dependent on many factors such as structure, deformation, volatile content, and viscosity. The fact that these deposits occur in small bodies or stringers of anatectic melt (metatect) near the site of partial melting seems important, possibly to prevent dispersal of uranium. Geologically, it is important that the metatect does not rise far and consolidate into large plutonic bodies. One control on this is the

presence of anticlinal structures and rigid beds that confine the metatect. The presence of calcareous metasediments near uranium deposits appears important. One factor appears to be the role of reduction provided by graphite present in many of the carbonate sequences. Another factor could be the action of CO₂ and CH₄ released by the carbonates (Ohmoto and Kerrick, 1977). If large amounts of methane were produced it could reduce uranium.

A final comment concerns the amount of enrichment that can be expected in the ultrametamorphic environment. Moreau (1977) estimates an enrichment of 100-fold for Rössing, which I suspect is high. No thorough study of uranium fractionation in partial melting and subsequent deposition has been made. For partial melting involving relatively incomplete fusion (10-20 percent), as probably happened in the cited examples, the melt probably would be enriched no more than 10-fold. Enrichment of uranium during deposition from the melt also probably would be no more than 10-fold. Hence, total enrichment might be roughly 20-fold. Thus, to get ore grade concentrations, say 500 to 1000 ppm, the source rock would have to contain 10 to 50 ppm--obviously, sedimentary preconcentration helps greatly in reaching ore-grade concentrations during redistribution.

CLASSICAL VEIN DEPOSITS

This category consists of deposits with predominant structural control. Included are uranium deposits that occupy relatively simple fault and fracture zones, many of them extending to depths of about 300 to 1,500 m, in a variety of host rocks, but displaying many mineralogical and geochemical similarities. Some well known examples in metamorphic host rocks include the Fay-Ace-Verna (Eldorado) mine, Beaverlodge District, Saskatchewan; Echo Bay (Port Radium) mine, Great Bear Lake District, Northwest Territories; Schwartzwald mine, Colorado; Pribram and Freiberg districts, Eastern Europe, and Shinkolobwe mine, Zaire. Intragranitic vein deposits are best known from France, Spain, and Portugal. Two end-member compositional varieties of veins have been recognized (Everhart and Wright, 1953; Ruzicka, 1971; and others): (1) simple mineralogy and chemistry, with uranium predominantly as pitchblende; and (2) complex mineralogy and chemistry that includes Ag, Co, Ni, and other elements such as Cu, Au, Se, and As chiefly in the form of sulfides, selenides, and sulfarsenides.

Veins with Simple Mineralogy

Beaverlodge District.--Uranium was discovered in the Beaverlodge District in 1946 and production has been continuous since 1953. Production to date has been about 30,000 s.t. U_3O_8 at an average grade of 0.2 percent U_3O_8 (Beck, 1969; McMillan, 1977; Tremblay, 1978). The Fay-Ace-Verna has produced more than 15,000 s.t. U_3O_8 and is still active; the Gunnar mine produced about 8,500 s.t. U_3O_8 from 1955 to 1963. All rocks in the district are Precambrian (Tremblay, 1972; Tremblay, 1978). The Archean Tazin Group was a sequence of graywacke, sandstone, shale, and basic tuffs metamorphosed to amphibolite grade prior to deposition of the lower Proterozoic Martin Formation. Red granite and gneiss in the Tazin are considered to be of metamorphic origin (Tremblay, 1972). Most uranium deposits are in the Tazin Group. The Martin Formation is a continental red-bed sequence of arkose, conglomerate, siltstone, and some basic flows and sills. A few small deposits occur in the Martin. The middle Proterozoic Athabasca Formation occurs a few kilometers south of the district and contains some small deposits. The important vein deposits of the district are interpreted to have formed 1780 m.y. ago and underwent lead loss or redistribution at about 1110 m.y. ago and later times

(Koeppel, 1968). Pitchblende-bearing veins, breccia zones, and stock works in the district typically contain cogenetic carbonate and hematite and a few deposits, such as the Nicholson mine, contain abundant As, Se, Ni, Co, and Cu as rammelsbergite, niccolite, cobaltite, siegenite, and other complex minerals (Robinson, 1955; Beck, 1969, 1970, see ahead).

The Fay-Ace-Verna (Eldorado) mine develops adjoining orebodies in the footwall and hangingwall of the St. Louis fault (fig. 24; Little and others, 1972). The orebodies occur over a distance of more than 4,000 m horizontally, more than 1,500 m vertically, and within 100 m of the main fault. District-wide, the uranium deposits occur within about 200 m of the Tazin-Martin unconformity (Smith, 1974). Secondary enrichment occurred in the upper 100 m of the Fay mine, but in the next 1,400 m or so there is essentially no change in major mineralogy. There is, however, some vertical zonation in minor elements (Se, V, Ag, Ni, As) within the Fay mine (Tremblay, 1978).

Paragenesis of the Fay-Ace-Verna and many other deposits in the Beaverlodge district is characterized by several stages of carbonate, abundant specular hematite (in veins and wallrock alteration), and pitchblende (fig. 25). Variable amounts of coffinite and brannerite occur in the veins but their paragenetic position has not been established. Fluid-inclusion studies (Sassano and others, 1972) on stages of carbonate demonstrate a cooling trend from initial temperatures of about 440°C to final stages at about 80°C (pressure correction included). Variable liquid:vapor ratios are interpreted as indicating boiling conditions, which permits calculation that there was about 200-300 bars pressure at the top of the Fay deposit, corresponding to about 2,500 to 3,500 m hydrostatic head (750 to 1,150 m lithostatic cover). Salinities ranged from about 28 wt. % NaCl equivalent. Fluid inclusion decrepitation temperatures for samples of quartz and calcite in the range of 289° to 400°C are reported by Robinson (1955); the decrepitation method is not reliable, but the measured temperatures in this case agree well with the homogenization method.

Stable isotopic studies (Sassano and others, 1972) demonstrate a decrease in $\delta^{18}O$ with time and temperature (fig. 26), explained by progressive isotopic exchange between a metamorphic hydrothermal fluid and wallrock plus possible late stage influx of meteoric water. Carbon isotopic composition varies with hematite or sulfide association, and late-stage carbonates are

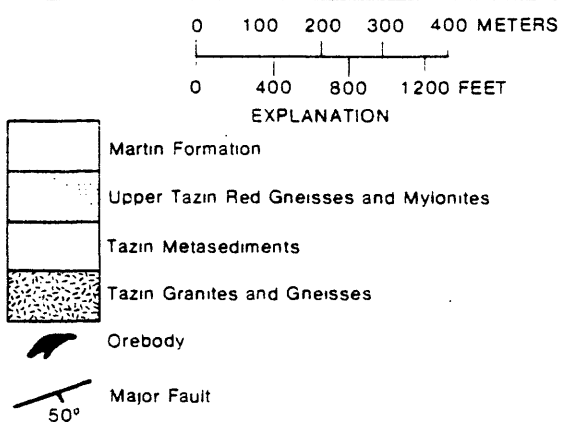
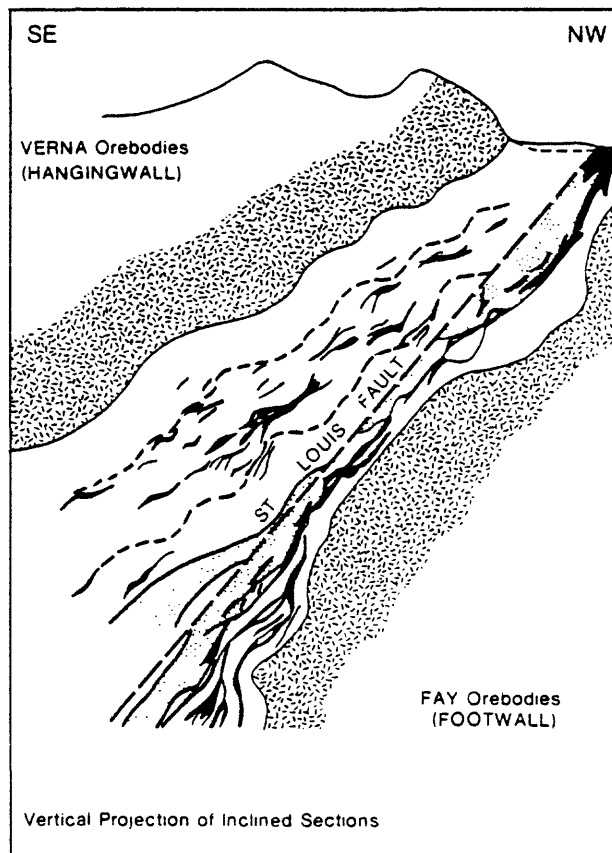


Figure 24.--Composite cross section of the Verna and Fay orebodies, Eldorado mine (modified from Little, et al., 1972). The Verna section shown is about 2.4 km northeast of the Fay section.

Approximate
Age (M.Y.) 1950

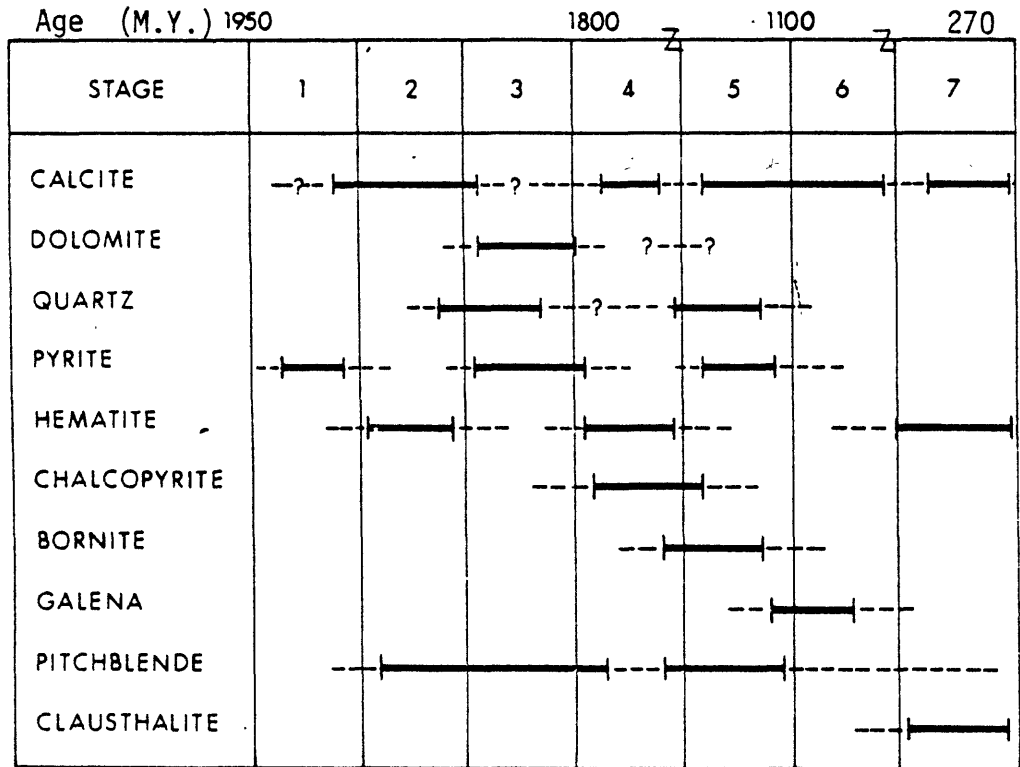


Figure 25.--Paragenesis of the major hydrothermal minerals of the Fay and Bolger mines (modified from Sassano, et. al., 1972).

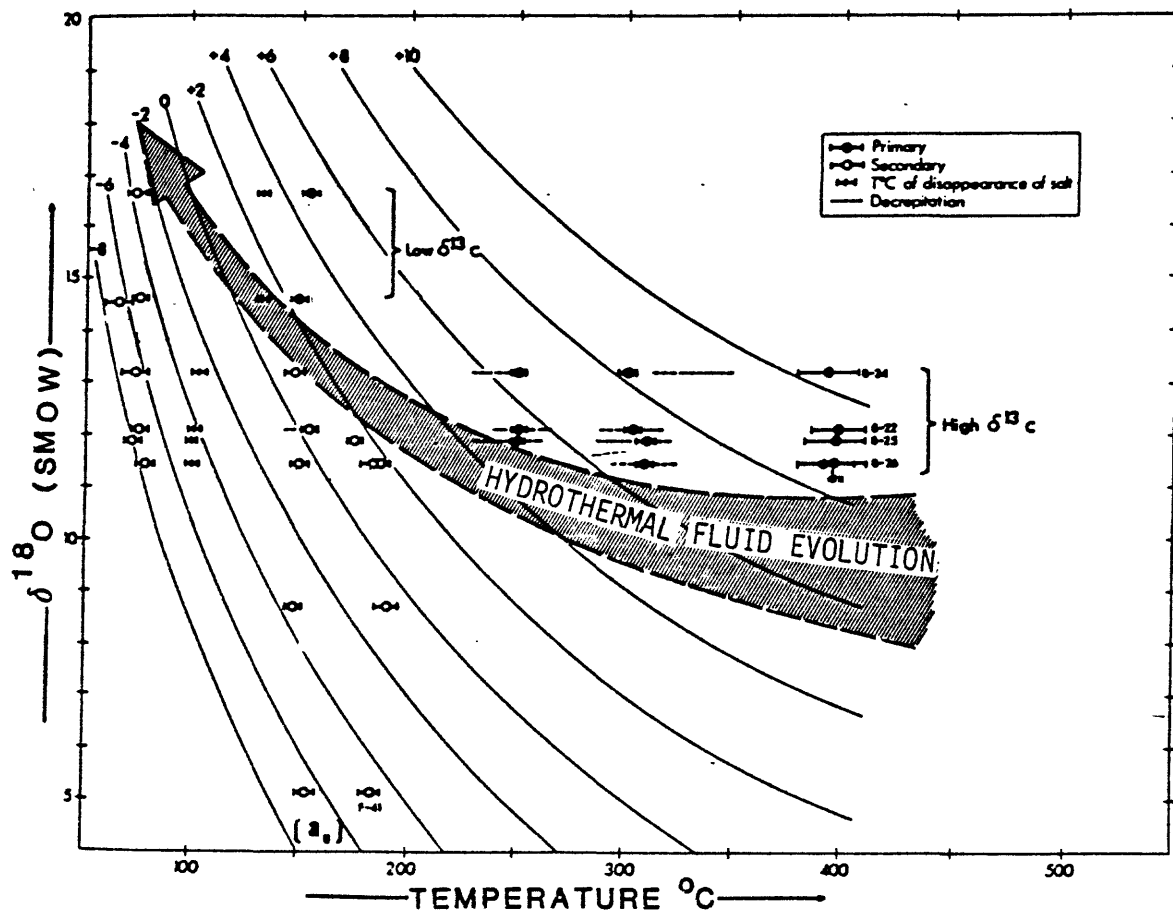
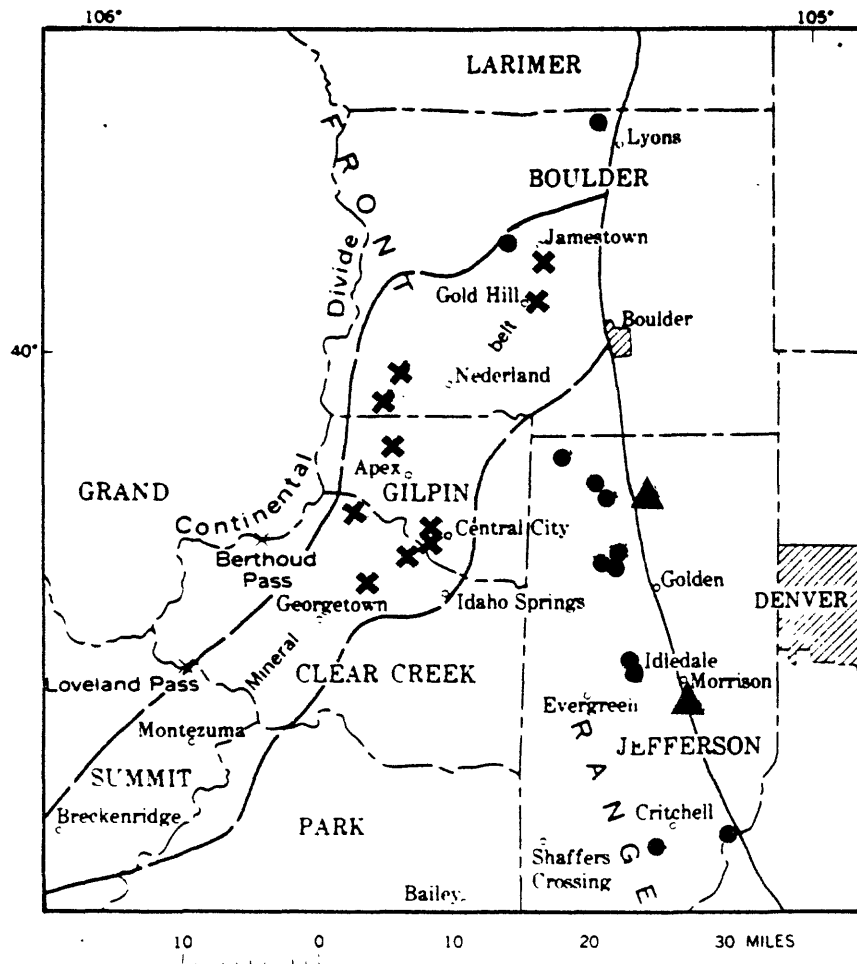


Figure 26.--Variation of temperature and $\delta^{18}\text{O}$ in hydrothermal fluids, Fay mine (after Sassano, et. al., 1972).

depleted in ^{13}C , possibly a consequence of oxidation reducing the amount of CH_4 in the hydrothermal fluid.

Although the proximity of ore zones to the Tazin/Martin unconformity suggests the possible role of supergene processes (Smith, 1974), the structural setting, stratigraphic influence, geochronology, mineralogy, and geochemistry are interpreted by many (e.g. Beck, 1969; Sassano and others, 1972; Tremblay, 1978) as indicating formation by metamorphic-hydrothermal fluids. Some consider the Beaverlodge veins to be a variety of unconformity-type deposit; similar processes may have operated, but the role of the unconformity is not evident to me and may be misleading.

Schwartzwalder deposit.—The Schwartzwalder deposit and many other smaller deposits and occurrences occur over a 90 km distance in the foothills of the Rocky Mountains, about 25 km west of Denver, Colorado (fig. 27). With production of 5,500 s.t. U_3O_8 and an equal amount of reserves (Paschis, 1979) the Schwartzwalder is the largest hardrock uranium deposit in the U.S. and the same magnitude as the Fay-Ace-Verna deposit, Saskatchewan. Host rocks are metasediments of the lower Proterozoic (~1.8-2.0 b.y.) Idaho Springs Formation, originally a sequence of shallow-water sandstone, shale, and carbonate, with some probable volcanic flows, sills, and tuffs of intermediate to mafic composition (Sheridan and others, 1967). During a 1.7 b.y. orogeny these rocks were metamorphosed to amphibolite grade and plastically deformed. Major northwest-trending breccia reef fault zones were produced in late Precambrian cataclastic deformation and reactivated in the Laramide orogeny (~50-70 m.y.) (Tweto and Sims, 1963). Structures hosting uranium deposits are subsidiary to the major structures; they may have Precambrian ancestry (DeVoto and Paschis, 1980) or may be new openings along the reactivated breccia reefs. A characteristic feature of several deposits is "flat" or "horsetail" veins which have low dip in the hangingwall about 50 to 150 m from the Illinois Vein, and steepen adjacent to the major faults (Paschis, 1979; fig. 28). Mineralized portions of faults are known to be continuous for more than 900 m vertically with no appreciable change in mineralogy or grade, but have less than 200 m strike length (DeVoto and Paschis, 1980; Wright, 1980). Mineralization continues below 900 m depth. Brittle metasediments such as garnet-biotite gneiss, quartz-biotite schist, and quartzite are favored lithologies. At a regional scale, deposits appear



- FOOTHILLS BELT URANIUM DEPOSITS
- ▲ OTHER TYPE URANIUM DEPOSITS
- × MINERAL BELT URANIUM DEPOSITS

Figure 27.--Map of the Front Range, Colorado, showing location of principal uranium deposits (modified from Sims and Sheridan, 1964). Note that the Foothills (Schwartzwalder-type) deposits occur in a belt within about 8 km of the range front and Paleozoic rocks.

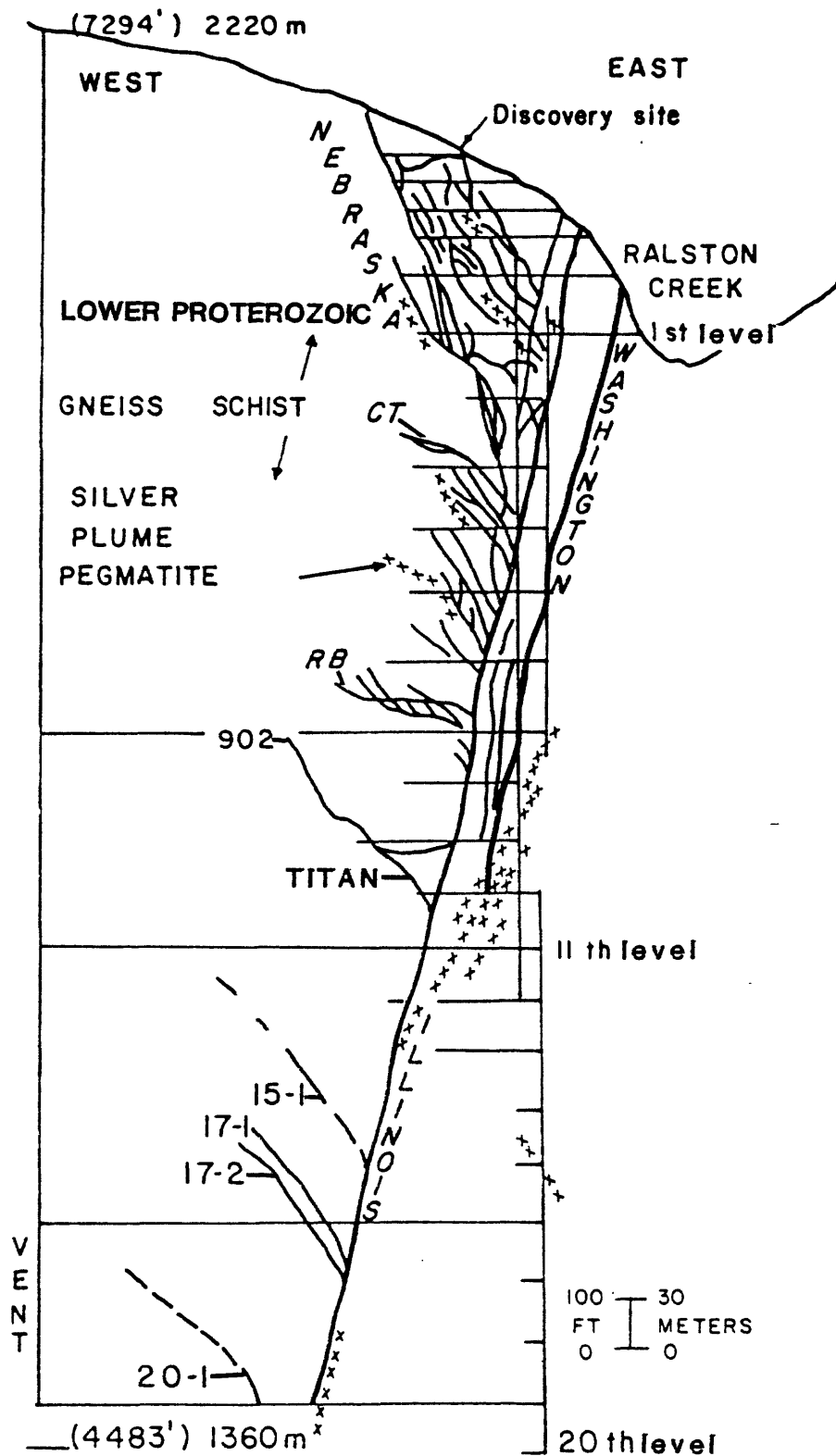


Figure 28.--Cross section of the Schwartzwalder mine showing horsetail veins in the hanging wall of the Illinois vein (modified from Paschis, 1979).

to be localized in a transitional unit less than 100 m thick made up of garnetiferous-quartz gneiss, quartz gneiss, and some other lithologies between a hornblende gneiss-calc-silicate gneiss unit (shallow water carbonate plus volcanic rocks?) and mica schist unit (marine shale?) (Sheridan and others, 1967). Another regional feature is the apparent limitation of the uranium rich veins (with minor Mo-Cu-Bi) to the foothills belt within about 8 km of the range front and Paleozoic redbeds, whereas the Laramide Mineral Belt of base and precious metal deposits with minor uranium is farther west and strikes northeast (fig. 27).

The composition and appearance of Schwartzwalder and other foothills veins resemble veins in the Beaverlodge district. Four general stages are recognized (Sheridan and others, 1967; DeVoto and Paschis, 1980; Wallace, 1979): (1) pre-ore local alteration of breccia and wallrocks to chlorite and sericite, with locally added ankerite, pyrite, and K-feldspar; (2) main-stage pitchblende and coffinite with jordisite (amorphous MoS_2), and adularia; (3) post-brecciation base-metal stage (chalcopyrite, chalcocite, ankerite; pyrite and marcasite, and (4) late-stage calcite, with minor quartz, and sulfides. Hematite is reported as either pre- or post-pitchblende. Fluid inclusions in ore-stage adularia are very small and difficult to study, but indicate temperatures in excess of about 100°C (Rich and Barabas, 1976; A. H. Barabas, oral commun., 1978). Sulfur isotopic composition of main-stage sulfides (24 samples, chiefly Schwartzwalder mine) range from +4.0 to -7.7 $\delta^{34}\text{S}$, and in late-stage colloform marcasite (7 samples) -17.7 to -38.6 $\delta^{34}\text{S}$ (Jensen and others, 1960; Heyse, 1971). The values near zero per mil have been interpreted as indicating a magmatic hydrothermal source for sulfur. However, chemical fractionation (Ohmoto, 1972) such as a pH increase (as from neutral to alkaline which is suggested by the paragenesis) would produce a fractionation of 20 to 30 $\delta^{34}\text{S}$ at 150° to 350°C , and hence a seawater sulfate source cannot be excluded. Also, lower Proterozoic seawater sulfate had an isotopic composition near zero per mil because biogenic fractionation had not yet occurred, and thus the sulfur could be remobilized from metasediments by a process that caused no fractionation.

The most likely time and setting for uranium deposition was at shallow depth (500-1500 m?) by meteoric hydrothermal fluids following Laramide uplift (Bird, 1979; Young, 1979; Wallace, 1979). Although U-Pb dates on pitchblende

from several deposits range from 52 to 73 m.y. (Sheridan and others, 1967; Heyse, 1971), structural and textural relations indicate deposition during or following movement on faults on which uplift occurred (Wallace, 1979). There is paleomagnetic evidence for rotation of sills dated at 61.9 m.y. during uplift (Hoblitt and Larson, 1975). Depending upon erosion and relief, at about 60 m.y. there probably would have been about 500 m of Precambrian rocks (to the Paleozoic unconformity) plus some additional cover by Paleozoic rocks. A hydrothermal environment is supported by the occurrence of Laramide dikes, likely heat sources, which are observed within 2 km of all deposits. These dikes and extrusive equivalents are not rich in uranium and are not to be confused with the U-rich bostonites of the Central City area 16 km to the west. The vein and alteration paragenesis indicates an alkaline environment of ore deposition, similar to carbonate-rich geothermal systems. Although fluid inclusions are not sufficiently large to permit diagnosis of boiling or loss of CO₂, these processes are likely in a shallow geothermal system. Chemical changes on effervescence or boiling are complex and do not necessarily lead to pitchblende deposition (Rich and others, 1977), but the CO₂-loss mechanism proposed for the French intragranitic vein deposits (Poty and others, 1974; Cuney, 1978; Leroy, 1978, see ahead) seems appropriate for the uranium minerals and gangue at the Schwartzwalder. The vertical continuity of these deposits is reminiscent of some epithermal base- and precious-metal deposits for which fluid-inclusion data demonstrate hydrothermal conditions near but under the boiling curve (Nash, 1973; Casadevall and Ohmoto, 1977). Reduction by ferrous minerals in wallrocks has been proposed (Adams and Stugard, 1956) but this mechanism generally is not pertinent, especially in quartzites of the Schwartzwalder mine. Oil seeps are known in Precambrian rocks in the area, and hydrocarbons could migrate upward from Cretaceous marine rocks downfaulted under Precambrian along the range-front reverse fault. Also sulfide was in the system, although in relatively minor abundance. The paragenesis and vertical continuity of these deposits are not compatible with a supergene genesis advocated by some (e.g. Rich and Barabas, 1976; Maslyn, 1978).

Intragranitic veins.--Few ore deposits in the world have been studied as intensely and continuously as the uranium veins in granite massifs in France. The history of changing genetic opinion over the past 30 years is

testimony to changing scientific fashion and methods. The earliest theory held that the deposits were hydrothermal with a direct relation to magmatic processes. In 1958, Geffroy and Sarcia cited new petrologic and geochronologic data to theorize that the veins were post-magmatic, related to zones of episyenite (desilicified, alkali-metasomatized granite), by leaching of uranium from the granites. In 1966 Moreau, Poughon, Puybaraud, and Sanselme (see also Barbier, 1974) proposed that the deposits were supergene, the result of continental weathering of "fertile" granites, citing the shallow depth of the deposits (<200 m) and correlation in space and time with the "Permian" peneplane; however, the peneplane is now considered to be Tertiary or Quaternary (Flageollet, 1977). More recently, numerous studies have elaborated on the post-magmatic changes in the granites such as the formation of episyenite and formation of accessory uraninite from uraniferous accessory minerals. Geochronologic and fluid-inclusions studies (Gangloff, 1970; Poty and others, 1974; Moreau, 1977; Cuney, 1978; Leroy, 1978) have swung the pendulum back to a hydrothermal leach mechanism similar to that proposed by Geffroy and Sarcia (1958). Four general stages seem critical to form economic deposits (Gangloff, 1970; Moreau, 1977; Cuney, 1978; Leroy, 1978):

- (1) formation of uranium-rich peraluminous granite at about 350 m.y. (Hercynian);
- (2) deuteric alteration to form muscovite and albite while leaching silica, with reconstitution of uranium into accessory uraninite at about 285 m.y.;
- (3) faulting, leaching of accessory uraninite by meteoric hydrothermal fluids, and deposition of pitchblende in low-pressure zones as CO₂ evolved (at about 275 m.y.); and
- (4) supergene remobilization and local enrichment in the Tertiary (about 30 m.y.).

The ages cited demonstrate the polystage genesis of the deposits.

Although intragranitic veins in France cannot be directly related to granite plutonism (radiometric dating indicates that ores are more than 50 m.y. younger than the enclosing granite), the deposits characteristically form in two-mica granites of distinctive form and chemistry. The granites are peraluminous, with high initial uranium content (often greater than 15 ppm), relatively low Th (Th/U <1.6), high ⁸⁷Sr/⁸⁶Sr (>0.7100), high δ ¹⁸O (>10 ‰) and high F, Li, Sn, W, Be, and Bi contents. These features can be explained by an origin through anatexis of sedimentary rocks previously enriched in these elements, and also in uranium. These are S-type granites (Chappell and White, 1974; White and Chappell, 1977; O'Neil and others, 1977). They are

syntectonic granites, generally foliated and commonly occur as sheet-like bodies in orogenic terranes (Gangloff, 1970; Le Fort, 1975; Boudette, 1977).

Granites hosting the vein deposits characteristically contain muscovite, as well as biotite, in amounts greater than about 2 percent. The muscovite is debated to be be_A^c either magmatic or post-magmatic origin. Detailed chemical, mineralogic, and geochronologic studies (e.g. Moreau and Ranchin, 1973; Cuney 1978; Leroy, 1978) suggest a secondary origin, particularly when the muscovite occurs in rocks showing evidence for removal of silica or albitization to form "mica episyenite" or "feldspar episyenite". The episyenite shows temporal and spatial relation to granitic or lamprophyric dikes that indicate a younger period of magmatism or hydrothermal activity. The altered portions of the leucogranites also show a characteristic change in accessory minerals in which secondary interstitial uraninite with low thorium content (>2 percent Th) is formed and accessory minerals such as biotite, thorite, apatite, and Fe-Ti oxides are altered (e.g. Ranchin, 1971; Renard, 1974; Le and Stussi, 1973; Cuney 1978). The major source of uranium reconstituted as uraninite is possibly biotite that has been altered to chlorite or muscovite (Jurain and Renard, 1970; Renard, 1974). During this reconstitution total uranium in the rock remains approximately constant but the uraninite-bearing granite becomes "fertile" (Moreau and others, 1966), meaning that the uranium can be leached by hydrothermal or supergene fluids. The alteration also produces a porous rock (called "sponge rock" at the Gunnar deposit, Saskatchewan) that commonly is favorable for later disseminated uranium ore as at Fanay, Margnac, and Gunnar deposits.

The ore stage is interpreted as closely following episyenitization, being part of the same thermal event, and commonly related to lamprophyre dikes. The relatively simple paragenesis typically consists of early pitchblende, followed by quartz and pyrite, in turn followed by variable amounts of hematite, ankerite, coffinite, fluorite, and minor sulfides (Cuney, 1978; Leroy, 1978). Fluid-inclusion studies indicate pitchblende was deposited at about 350°C at Margnac (fig. 29) and about 100°C at Bois Noirs from CO₂-rich fluids that effervesced in open structures. Pressure was about 100-300 bars (fig. 26). Uranium was probably transported as a uranyl carbonate complex, and possibly precipitated by a reduced sulfur species carried simultaneously in the ore fluid but which did not act until CO₂ was lost (Poty and others, 1974; Cuney, 1978; Leroy, 1978).

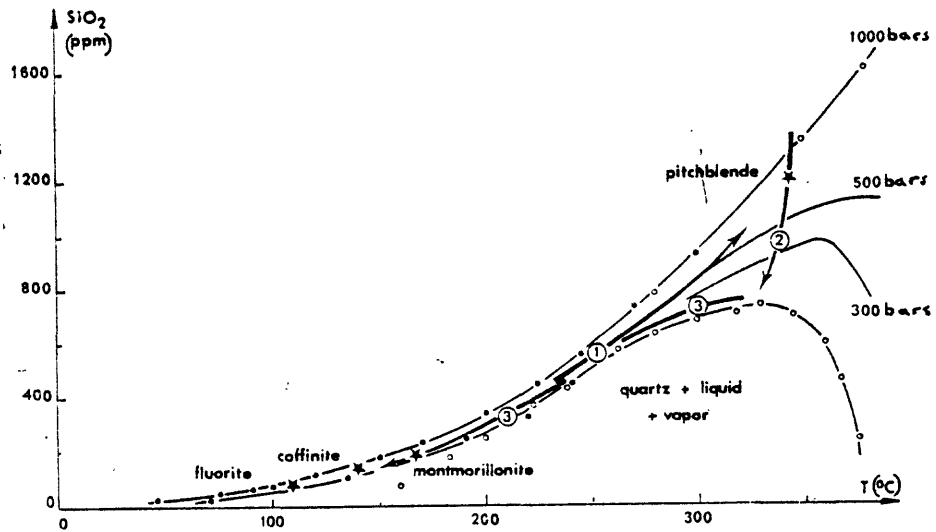
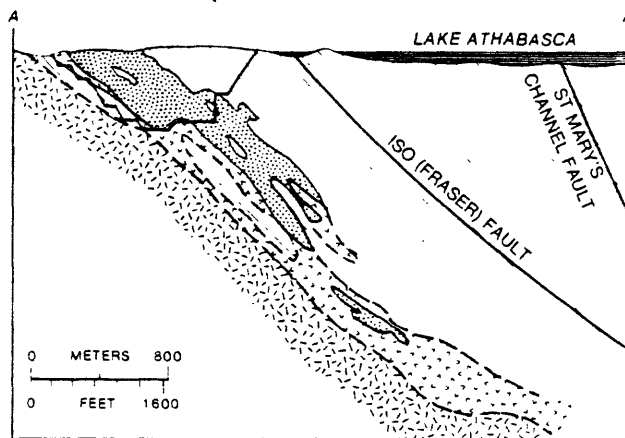
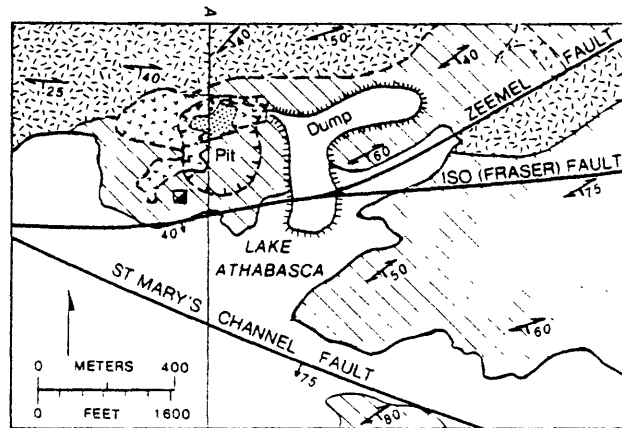


Figure 29.--Evolution of temperature and pressure during stages of mineralization at the Margnac and Fanay deposits (from Leroy, 1978). Stages: 1) mica episyenite; 2) pitchblende; 3) late marcasite, quartz, coffinite, and fluorite.

The Gunnar deposit, Beaverlodge District, Saskatchewan, appears to be a Precambrian intragranitic deposit with many similarities to the French examples. The deposit, now mined out, was in a pipe-shaped body of altered granite gneiss (fig. 30) and was worked to a depth of 425 m between 1955 and 1963 (Evoy, 1961; Lang and others, 1962; Anon., 1963). About 9,500 s.t. U_3O_8 of an average grade 0.18 percent U_3O_8 was extracted. Evoy (1961) described the petrology and structure in detail. The major uranium mineral was pitchblende, but about 10 percent of the uranium was held in uranophane, which occurred to the bottom of the deposit, more than 300 m below the water table. Uranophane appears to have been part of the hydrothermal paragenesis (Evoy, 1961). Syenitic alteration of the muscovite-bearing Gunnar Granite occurred in two stages: first, albite (An_5) replaced microcline and perthite and some quartz to produce an albite-quartz rock. Later, within the albitized zone, calcite replaced quartz to produce albite syenite (70 to 95 percent Ab_{95}). The albitization is believed to have been controlled by a fault and fracture system, and the albite syenite later was the locus of brittle fracturing that structurally controlled the stockwork ore. Pitchblende and uranophane were deposited approximately contemporaneously with carbonate, orthoclase, quartz, and kaolinite. Hematite occurred with pre-ore Mg chlorite and post-ore calcite. The unusual coexistence of K-feldspar and kaolinite (rather than sericite) possibly can be explained if silica activities were about 300 percent supersaturated with respect to quartz (Fournier, 1967). Such silica activities would presumably stabilize uranophane; this explains the unusual hydrothermal uranophane. However, the source and nature of the alkaline solutions capable of this remarkable leaching are unknown.

It is apparent that two-mica granite is only indirectly involved in the French intragranitic deposits. The active parameters heat--(dikes) and oxidizing CO_2 -rich hydrothermal fluids--presumably could operate in a similar manner on any permeable uraniferous source rock, as appears to have happened at the Schwartzwaldler mine. The chemistry of the fluids and minerals deposited will presumably vary with rock chemistry in the hydrothermal system, hence the mineralogical appearance would be quite different, particularly with respect to quartz, carbonates, and feldspars.



EXPLANATION








	Ore		Foliation, gneissosity
	Syenite		Open pit
	Gunnar Granite		Waste dump
	Paragneiss		Shaft

Figure 30.--Geologic map and cross section of the Gunnar Mine (modified from Beck, 1969). Note that ore is essentially confined to the Syenite-altered Gunnar granite.

Veins With Complex Mineralogy

Shinkolobwe.--The Shinkolobwe deposit, Zaire is a classic locality for numerous uranium and Co-Ni-S-Se minerals (Derriks and Vaes, 1956). It merits attention today for its geologic similarities with several other ore types in metasediments, including stratiform copper and unconformity-type uranium deposits. Shinkolobwe seems to be a good example of a deposit formed by redistribution of metals in marginal-marine sedimentary rocks.

Shinkolobwe is at the northwest end of the African copperbelt in dolomitic shales of the middle Proterozoic Mine Series of the Roan Group. The Roan Group produces about 20 percent of world copper, chiefly about 200 km to the southeast in Zambia. The age of the Mine Series in Zaire is bracketed between about 1300 and 950 m.y. (Cahen, 1970), and the region was complexly folded, thrust faulted, and subjected to low grade metamorphism between about 620 and 670 m.y. (Cahen, 1970). Uranium ore is post-tectonic, and dated at about 620 m.y. (Cahen, 1970). The Mine Series containing the uranium deposits is a 500 to 900 m thick section of magnesium-rich dolomites, dolomitic schist, dolomitic sandstone, and altered varieties containing magnesite and talc (fig. 31). Detailed geologic and mineralogic studies of Shinkolobwe and two smaller deposits (Swambo and Kalongwe) are reported by Derriks and Vaes (1956) and Derriks and Oosterbosch (1958). The general sequence of minerals was (1) magnesite alteration and vein-fillings; (2) pitchblende; (3) pyrite, molybdenite, and monazite plus selenium (phase unknown) with associated chloritization; (4) Co-Ni sulfides and selenides; and (5) following a period of crushing, copper minerals. Nickel, and to a lesser extent cobalt, is intimately associated with uranium. The Ni-Co ratio is zoned from 3 in uranium veins, to 0.3 in wallrocks and, away from the uranium zone, cattierite (CoS_2) contains no Ni. Derriks and Vaes (1956) emphasized the high Ni but low Cu content of the uranium zone at Shinkolobwe and the fact that Co, but not Ni, is normally abundant in the stratabound copper deposits.

Shinkolobwe and other less famous uranium deposits in the copper belt are very instructive when examined in the light of recent observations made at numerous localities around the world. (1) Although uranium is rarely mentioned in the abundant copper-deposit literature, there are more than 20 deposits in Shaba province, Zaire and an equal number occur in Zambia (Davidson, 1956; Garlick, 1961; Francois, 1974; Ngongo, 1975). These

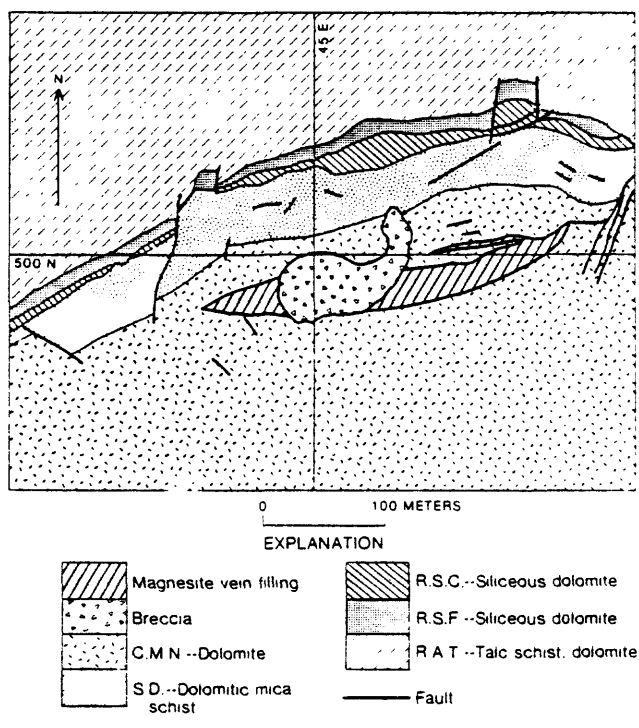


Figure 3f.--Geology of the Shinkolobwe deposit (modified from Derriks and Vaes, 1956).

occurrences and deposits are stratabound within a unit about 100 m thick in the Lower Roan Formation. The Roan Group was probably deposited in an intracratonic rift (Raybould, 1978; Bowen and Gunatilaka, 1977) that also collected stratigraphically equivalent Nosib Group sediments that host the Rossing uranium deposit and Tsumeb copper deposit in Namibia. Hence, there is evidence that large amounts of uranium accumulated in these marginal-marine sediments. (2) In the typical copperbelt deposits, considered by some to be syngenetic (e.g. Garlick, 1961), uranium occurs in a zone that was predicted by the syngenetic theory. At the Chibuluma copper deposit and at the No. 4 shaft and Kitwe barren gaps between the Mindola and Nkana deposits, uranium occurs adjacent to granite basement hills " * * * in the first sediments laid down under reducing conditions * * * ." (Garlick, 1961, p. 162; fig. 31). Garlick (1961, p. 162) offered the interpretation: "At the feather edge of the prism of stagnant water underlying the oxygenated waters, uranium oxide, molybdenum sulfide, and tungstic oxide were precipitated, generally in minor amount. This uraniferous zone is rare and narrow." The uranium content of typical copper-bearing horizons (about 50 to 100 ppm, Davidson, 1956) produces anomalous radioactivity, sufficient to justify the use of airborne scintillometer surveys as a copper exploration method (Garlick and Gane, 1961, p. 186-187). (3) The Shinkolobwe deposit is considered by copper geologists to be a remobilized, post-tectonic variety of copperbelt deposit (Mendelsohn, 1961), for which there is abundant structural and mineralogical evidence. The magnesite and Mg-silicate (talc) alteration are reminiscent of features in the Rum Jungle and Alligator Rivers Districts, Australia. Derriks and Vaes (1956) described (fig. 31) numerous breccia zones and cavities and related magnesium enrichment " * * * to the cavity that was filled by breccia." Much of the Shinkolobwe mineralization was "dammed" under the R.A.T. Nappe--a talc-chlorite altered unit emplaced by a thrust.

The Mindola uranium deposit, mined between 1945 and 1960, contains uranium as pitchblende, brannerite, and coffinite with molybdenite and vanadinite disseminated in sandstone. It occurred in a copper-barren zone (Kitwe Gap) in sediments interpreted as a sand spit adjacent to a lagoon of copper-rich sediments (Fleischer and others, 1976). Some uranium was remobilized to form coarse pitchblende, dated at 520 m.y., in cross-cutting anhydrite-dolomite-quartz veins.

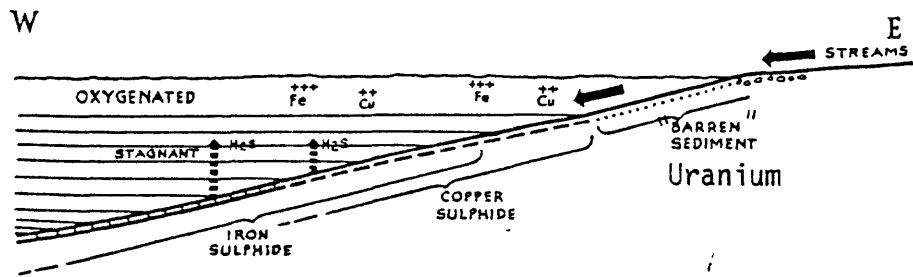
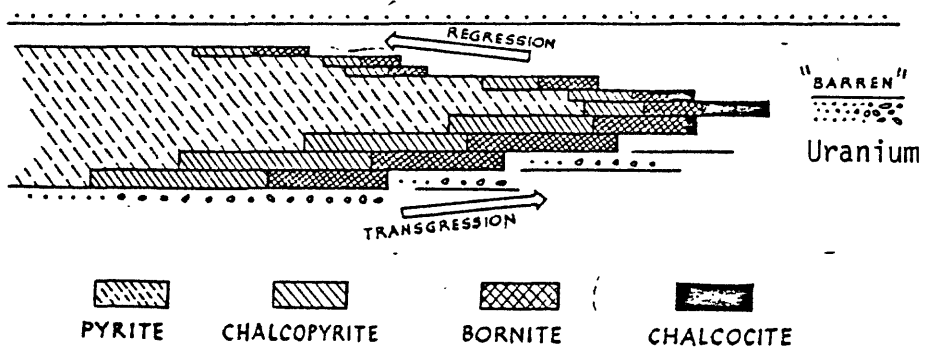
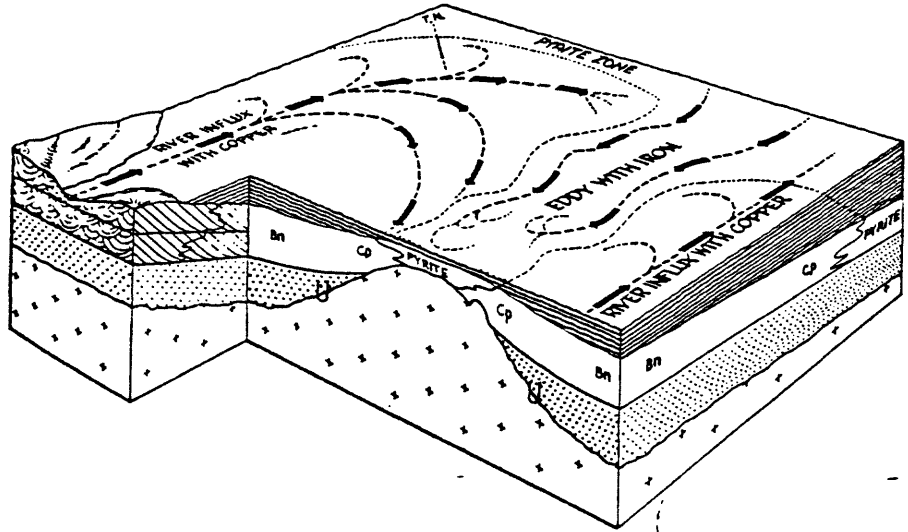


Figure 32.--Diagrams of uranium mineralization and metal zonation in the Copperbelt (modified from Garlick, 1962). A. Uranium and other metals zoned relative to a granite hill. B. Metal zonation in relation to transgression and regression of the shoreline. C. Metal zonation in relation to water geochemistry.

Recent studies of sedimentology and geochemistry of stratiform copper deposits explain some features that may relate to uranium enrichment in sediments suitable for protoliths--(1) Abundant evidence documents a near-shore marine environment with units like continental dunes and arkose adjoining supratidal dolomites, evaporites, and intertidal sandstone and bioherms (Bowen and Gunatilaka, 1977, Fleischer and others, 1976; Jung and Knitzschke, 1976; and others). In metamorphosed equivalents (as in Saskatchewan or Northern Territory), scapolite appears to be a key indicator of paleo-evaporites. (2) Intertidal stromatolytes in the Copperbelt are considered important evidence for biogenic activity and an environment favorable for accumulation of syngenetic copper (Malan, 1964). Garlick (1964) cited work by Condon and Walpole (1955) in the Rum Jungle and South Alligator River uranium districts, Northern Territory to support his interpretation that copper sulfides accumulate syngenetically in shales flanking algal bioherms. In the Proterozoic biogenic activity produced reducing environments (biogenic reduction or organic carbon) in shallow-water marine or lacustrine environments favorable for algae. (3) One possible mechanism for syngenetic metal deposition is precipitation of oxides or hydroxides, of iron, manganese, or cobalt as pH increases where streams enter an ocean; the oxides are later sulfidized (Garlick, 1961; Fleischer and others, 1976; Jung and Knitzschke, 1976). Adsorption of uranium on oxides, hydroxides, or clays should occur in this environment. This hypothesis predicts uranium enrichment on the margins of basins or adjacent to basement highs (fig. 32). (4) An alternate mechanism is deposition from epigenetic hydrothermal brines (e.g. Bartholome and others, 1973) moving up basin flanks above impermeable basement rocks. Base-metal geologists have not mentioned uranium in this model, but it probably would be derived from basement granitoids and be carried to the sulfidic environment along flowlines separate from those of copper.

Great Bear Lake district.--In the Great Bear Lake (Port Radium) District, Northwest Territories, Canada, uranium occurs with complex Ag-Cu-Ni-As-S minerals in relatively small but very interesting deposits. (Robinson and Ohmoto, 1973; Robinson and Badham, 1974, Badham, 1975). Lower Proterozoic clastic and volcanic rocks in the area have been only slightly deformed and metamorphosed. At the Echo Bay mine veins have been mined to a depth of about 400 m and have strike length of about 1.5 km. Also present in the district

are "giant quartz veins" up to 300 m wide and traceable up to 20 km along strike. Geologically the U-Ag-Cu-Ni veins, giant quartz veins, magnetite-apatite-actinolite bodies, and diabase dikes appear related and probably formed at about 1,450 m.y.

The complex mineralogy of the Great Bear District has been described and chemical evolution interpreted by Robinson and Ohmoto (1973) and Robinson and Badham (1974). Generalized stages are: (1) quartz-hematite, (2) pitchblende, (3) Co-Ni arsenides plus native silver, (4) Fe-Cu sulfides plus dolomite, (5) late native silver plus bismuth minerals. Phase relations, fluid-inclusion studies, and stable-isotopic thermometry demonstrate that temperatures fluctuated in the range about 95° to 200°C at 300 to 800 bars pressure. Stable isotopic determinations permit elegant calculations of fluid chemistry (fig. 33). Important points are: (1) progressive decrease in oxidation state, (2) decrease in total sulfur content, and (3) near constant, slightly acidic pH. Despite the abundant, precise data two divergent genetic interpretations exist: (1) sulfur was derived from seawater and metals leached from lower Proterozoic volcanic rocks (Robinson and Ohmoto, 1973; Robinson and Badham, 1974), or (2) sulfur and metals were derived from a magmatic source (Badham, 1975).

DEPOSITS ASSOCIATED WITH IGNEOUS ROCKS

It is well known that uranium tends to be enriched in silicic igneous rocks (Rogers and Adams, 1969; Rogers and others, 1978), but no economic deposits of direct magmatic origin are known in granites. Alkaline syenitic plutons do, however, contain economic or subeconomic concentrations of uranium at Ilimaussaq, Greenland, (Sørensen, 1970), Pocos de Caldas, Brazil (Andrade Ramos and Fraenkel, 1974) and Bokan Mountain, Alaska (MacKevett, 1963). Pegmatite and vein deposits also occur at the above localities. Rössing and similar deposits are considered to be ultrametamorphic rocks, as discussed earlier. Deposits of uncertain genesis also occur in contact zones of plutons, and hydrothermally altered volcanic rocks contain uranium deposits in several structural settings.

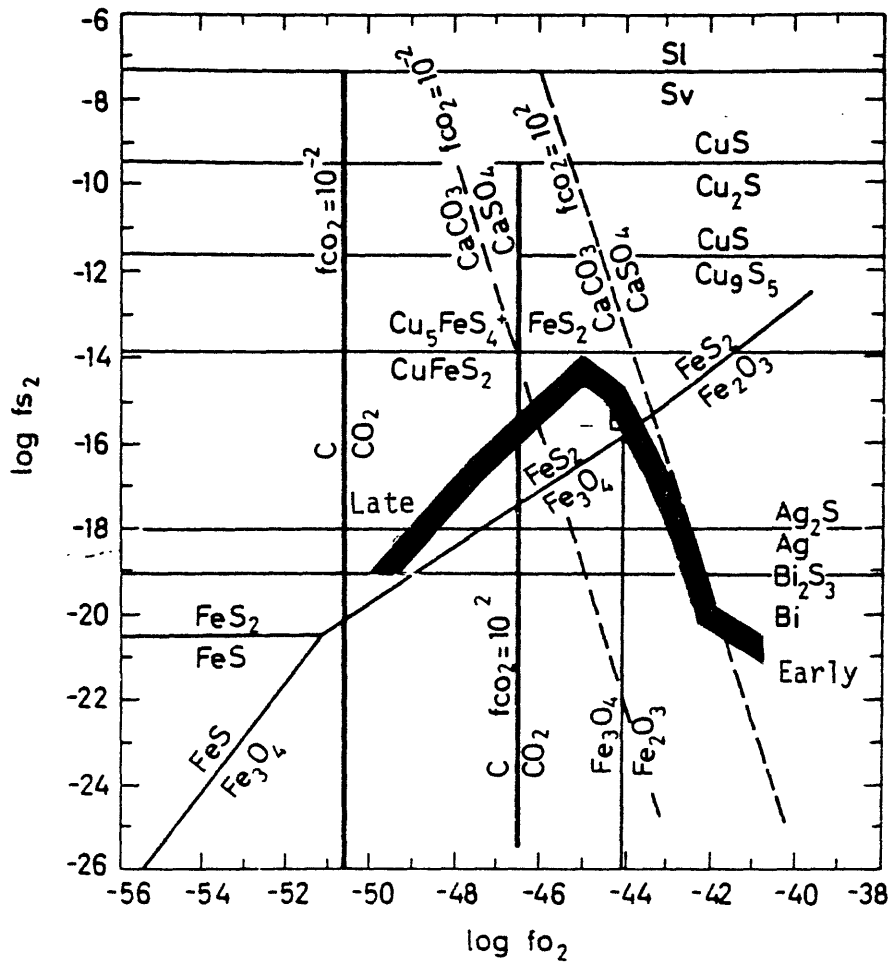


Figure 33.--Evolution of oxygen and sulfur fugacities in ore fluids, Echo Bay mine (modified from Robinson and Ohmoto, 1973). Mineral stability fields are for 150°C.

Deposits in Alkalic Rocks

Agpaitic nepheline syenites³ contain economically interesting amounts of uranium, thorium, niobium, zirconium, and rare earths in several areas of the world, most notably at Ilimaussaq; Poços de Caldas; and at Lovozero, Kola Peninsula, and Pillanesberg, South Africa. At Ilimaussaq, the rare mineral steenstrupine (a Na-Ce-Fe-Ta silicate) carries 0.2 to 0.7 wt. % U and 2.0 to 7.0 wt. % Th (Sørensen, 1962; Sørensen, 1970). Numerous other rare minerals also are present. The later stages of the ~1.2 b.y. Ilimaussaq intrusion crystallized by accreting crystals at the roof (sodalite-nepheline-syenite zone) contemporaneous with a layered cumulative below (arfvedsonite-nepheline syenite) and finally a lujavrite (aegerine-arfvedsonite-nepheline syenite) in between (Ferguson, 1964). The lujavrite usually contains about 200 to 300 ppm U and 200 to 900 ppm Th. Numerous xenoliths and dikes make U-Th values highly erratic. Local zones exceed 1000 ppm U and 5000 ppm Th, but minable zones grading more than 400 ppm are rather small and the ore is refractory (Bohse and others, 1974; Sørensen, 1970). The deposit at Ilimaussaq contains 35,000 s.t. U₃O₈ reasonably assured resources recoverable at \$50/lb. (OECD, 1978).

The pipe-like Poços de Caldas body of syenitic rocks (53-87 m.y.), about 30 km in diameter, contains the Agostinho and Cercado deposits. In these deposits the alkaline rocks are completely altered by hydrothermal and weathering processes. The ore zones at Agostinho and Cercado average 0.2 and 0.18 wt. % U₃O₈, 0.60 and 0.25 wt. % MoO₃, 0.10 and 0.03 wt. % ThO₂, and 4.2 and 0.55 wt. % ZrO₂ respectively (Andrade Ramos and Fraenkel, 1974). Lateritic weathering, as deep as 150 m, has had great geochemical influence chiefly in separating uranium from metamict zircon and creating a secondary zone zone of pitchblende below the weathered zone (Andrade Ramos and Fraenkel, 1974, Murphy and others, 1978).

The 184 m.y. Bokan Mountain alkaline granite stock in southernmost Alaska contains uranium and thorium mineralization in three modes: (1) disseminated magmatic accessory minerals in peralkaline granite; (2) disseminated U- and Th-bearing minerals in pegmatite and aplite dikes; (3) post-magmatic

³Rocks having molecular $\frac{Na_2O + K_2O}{Al_2O_3} > 1.2$

hydrothermal veins and pipe-like bodies (MacKevett, 1963; Staatz, 1978). The latter type, at the Ross-Adams mine produced about 1,000 s.t. U_3O_8 at an average grade of about 1 wt. % U_3O_8 between 1957 and 1971. A larger amount of thorium was not recovered. The veins and disseminations are rich in rare-earth elements, thorium, beryllium, niobium, and zirconium. Uranium and thorium minerals are thorian uraninite, uranothorite, thorite, and minor brannerite and coffinite (MacKevett, 1963; Staatz, 1978).

Other alkalic complexes, including carbonatites, typically show more resource potential for thorium than for uranium as uranium contents rarely exceed 75 ppm (Armbrustmacher, 1979; Olson and others, 1954). An economic exception is the Phalabora syenite and carbonatite complex, South Africa. The Phalabora copper deposit contains about 40 ppm U in the form of uranothorite which is recovered in a heavy-mineral circuit (James and Simonsen, 1978). Similar byproduct recovery of uranium may be possible from other deposits, particularly if the demand for Th, Nb, Zr, and associated elements increases.

The uranium deposits associated with alkaline rocks, with or without post-magmatic enrichment, have many features in common. Most notable are the high Th and $Th:U > 1$, and enrichment to subeconomic proportions in "incompatible" elements such as Be, Mo, Nb, Na and Zr. Definitive petrogenetic studies have not been made, and the genesis of both mineralized and non-mineralized varieties is moot (Carmichael and others, 1974; Sørensen, 1974). Derivation from the mantle is a possibility (Rogers and others, 1978), but very strong chemical fractionation, probably influenced by gravity settling of crystals, appears to be important for U, Th, and associated minor elements regardless of the mantle or deep crustal source.

Deposits in Contact Zones

Deposits located in the contact-metamorphic aureole of granite plutons are known at the Midnite mine, Washington, Mary Kathleen mine, Queensland, and many deposits in Portugal and Spain. The Midnite and Iberian deposits are best developed in carbonaceous (or graphitic) pyritic metapelites, but calc-silicate rocks also host ore at the Mary Kathleen mine and one zone at the Midnite mine. Genesis of these deposits is controversial, partly because near surface oxidation is prominent at many deposits and may have obliterated earlier stages that would bear on primary ore genesis.

The Midnite mine near Spokane, Washington, has produced about 6,000 s.t. U_3O_8 at an average grade of about 0.21 percent U_3O_8 since 1957. The oxidized and reduced uranium minerals that make up the deposits occur in medium-grade metapelite and metacarbonate of the middle Proterozoic Togo Formation immediately adjacent to a 75 m.y. porphyritic granite pluton (Barrington and Kerr, 1961, Becraft and Weis, 1963; Nash and Lehrman, 1975; Ludwig and others, 1978). The orebodies are generally tabular in form (fig. 34) and dimensions range up to 380 m long, 210 m wide, and 50 m thick. Uranium minerals occur as disseminations along foliation, replacements, and as stockwork fracture-fillings. Essentially no ore occurs in the pluton; rather, mineralization stops abruptly at the pluton margin. Pitchblende and coffinite yield Pb-U ages in the narrow range of 50 to 52 m.y.

Genesis of the deposits is still debated between possible hydrothermal and supergene mechanisms; the present ore geometry probably reflects redistribution. The adjacent granite contains anomalous concentrations of uranium (about 17 ppm U in fresh samples). Another possible source is graphitic and pyritic Togo metapelites, but anomalous uranium content has not been detected in surface samples. Pb/U geochronology indicates the deposits are about 25 m.y. younger than the granite and contemporaneous with a period of volcanism (Ludwig and others, 1978). The deposits as presently observed appear to have been formed (or redistributed) in a near surface, partially oxidizing environment that may have been mildly warmed by the volcanics. The deposition of pitchblende-coffinite-pyrite-marcasite may involve metastable sulfur species as proposed for some roll-type deposits (Granger and Warren, 1969). The petrology and chemistry of the uraniferous granite pluton and its proximity to the deposits suggests an initial magmatic-hydrothermal genesis with subsequent redistribution (Nash, 1977), although supergene emplacement from near-surface sources in the metapelite or granite in the Eocene is also a possibility.

In Spain and Portugal, contact zone deposits occur in Paleozoic carbonaceous metapelites that are locally contact metamorphosed to spotted hornfels by uraniferous Hercynian (~300 m.y.) granites (Arribas, 1970; Fernandez Polo, 1970; Matos Dias and Soares de Andrade, 1970; IAEA, 1978). Deposits at Nisa, Portugal, and Mina Fe, Spain, are similar in many aspects to those at the Midnite mine. Mina Fe is a large deposit, having drilled-out and

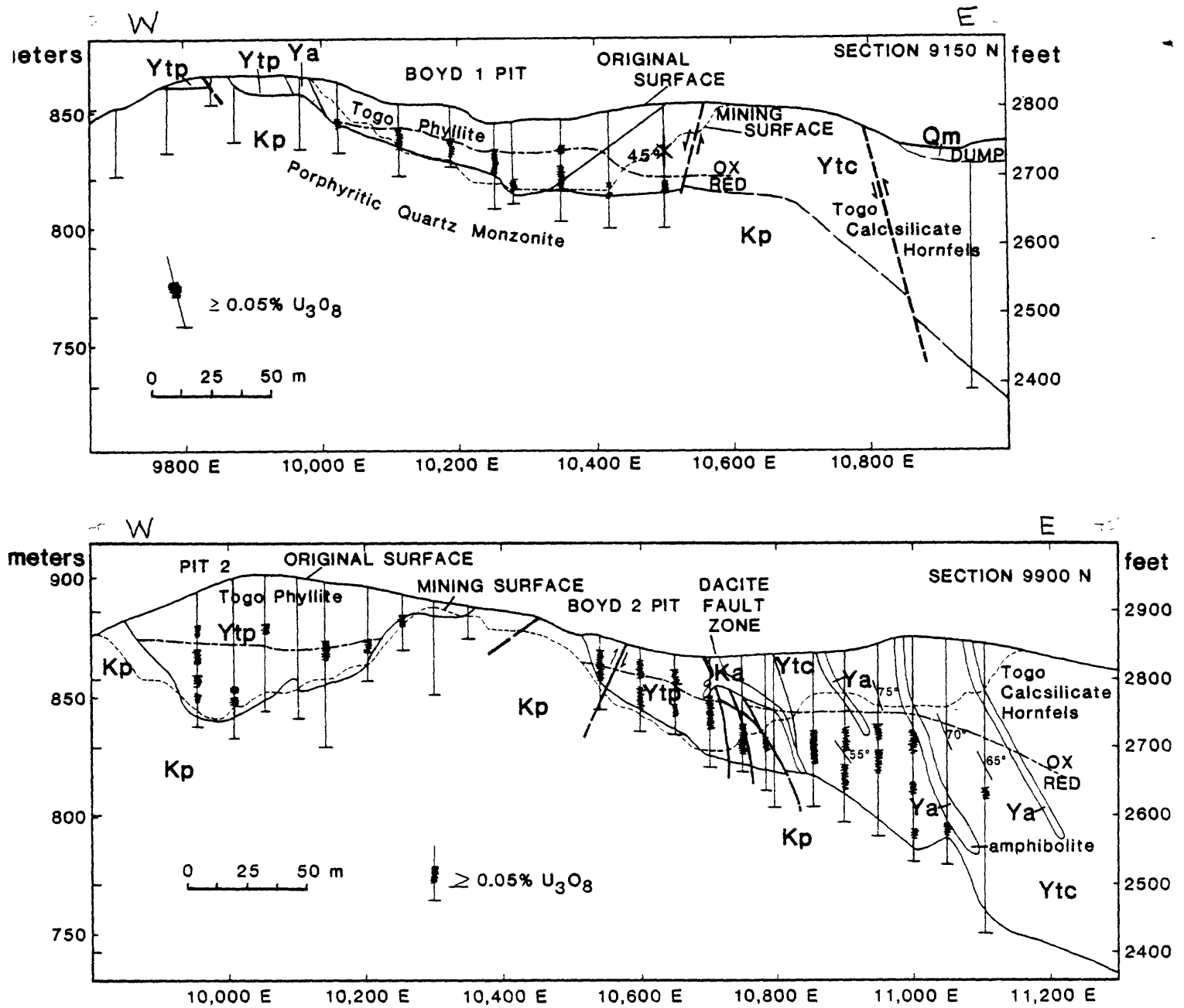


Figure 34.--Cross sections through the Midnite mine.

indicated resources of about 15,000 s.t. U_3O_8 at an average grade of about 0.05 percent (Recaredo del Potro, ENUSA, oral commun., 1980). Uranium is currently being recovered by heap leaching but a conventional mill is planned for 1982. The Nisa deposit has been mined for metallurgical bulk sampling and awaits development of a milling technique that can inexpensively overcome refractory behavior.

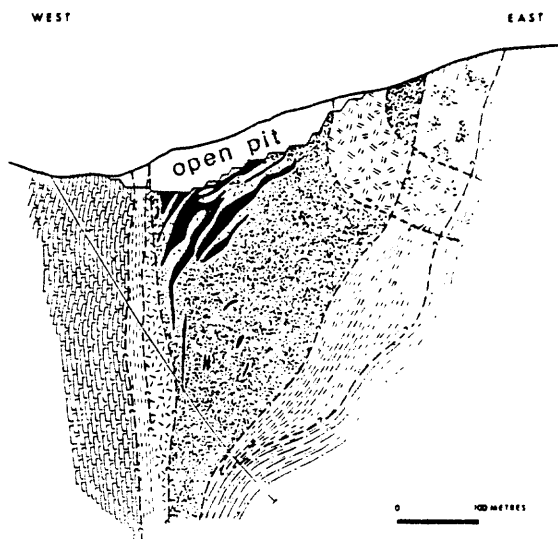
The Iberian deposits occur in highly fractured zones rather than major faults, and tend to contain predominantly hexavalent uranium minerals within about 15 m of the surface. Depth to the granite intrusives generally is not known but could be a short distance below the deposits. Alteration consists of chlorite after biotite, sericite after feldspar, and introduced chalcedonic silica and hematite, usually in the form of jasper. Reduced minerals consist of massive and spherulitic pitchblende and coffinite with pyrite and marcasite, with later chalcedony and goethite (Arribas, 1970). A supergene genesis involving leaching of uranium from granites is advocated by Matos Dias and Soares de Andrade (1970) and Fernandez Polo (1970). Arribas notes that many deposits are at the borders of plutons and that pitchblende and coffinite occur with sulfides (especially pyrite and marcasite) below the zone of oxidation. The relationship of ore zones to Mesozoic peneplains seems well established and consistent with supergene distribution or redistribution. A two-stage hypothesis has been advanced recently (Arribas and Herrero-Payo, 1979) postulating initial epithermal emplacement of uranium and supergene enrichment in Tertiary time to create economic grades. From my brief field observations in October 1980, I was impressed by the amount of iron oxides (presumably after pyrite) and deep oxidation and leaching of Mina Fe and the similar San Benito district 180 km to the south. At Mina Fe, San Benito, and Nisa I had the impression that the graphitic pyritic phyllites had widespread anomalous radioactivity that had no obvious relation to granite. The deposits seemed to be elongate or clustered along the regional strike. A sedimentary source of uranium seems possible for these deposits.

The Mary Kathleen deposit, Queensland, Australia (Matheson and Searl, 1956; Hughes and Munro, 1970; Hawkins, 1975) is the prototype contact-metasomatic deposit related to a granitic intrusion, but its genesis is far from understood. The lower Proterozoic Corella Formation, metamorphosed to granulite facies, hosts the deposit which contains (production and reserves)

about 12,000 s.t. U_3O_8 at an average grade of about 0.14 percent U_3O_8 plus about 0.02 percent ThO_2 and about 3.6 percent rare earths. Structural interpretations have changed over the years; the most recent (Hawkins, 1975) held that the Corella beds dip steeply to the west, and the ore zone terminates on a major fault (fig. 35). The radioactive Burstall Granite (Derrick, 1977) occurs 3 km east of the deposit; an older granite produced amphibolite-grade regional metamorphism. The orebody is totally within a garnet-rich "conglomerate-breccia" with average composition 40 percent garnet (Ca-Al-Fe-rich), 35 percent allanite, 10 percent apatite, 15 percent "other" including stillwellite (alanthanum borosilicate), albite, and scapolite (Whittle, 1960). Uranium resides chiefly in 0.1 to 0.01 mm diameter uraninite grains within allanite or stillwellite. Adjacent beds are pyritic quartzites, scapolite-diopside granulites, and banded amphibolite. There are zones rich in pyrrhotite and pyrite (greater than 40 percent sulfide). The source of the uranium and associated REE, Th, B, P, S, and Fe is uncertain. Most authors advocate metasomatic introduction from the eastern Burstall Granite. Hawkins (1975) suggested the possibility of remobilization from within the sedimentary pile, which is supported by the occurrence of numerous copper and uranium prospects on strike in the same unit of the Corella that hosts ore at Mary Kathleen. The unusual (unique?) chemistry of the sequence and mineralization are reminiscent of chemical sediments and volcanogenic exhalative deposits--I suggest the possibility of near isochemical metamorphism of constituents from the sedimentary sequence with relatively little redistribution.

Volcanogenic Deposits

A great variety of deposit forms and structural settings are represented by uranium deposits of probable hydrothermal origin in volcanic rocks. The discovery of apparently widespread mineralization in the McDermitt caldera complex, Nevada-Oregon (Rytuba and Glanzman, 1979), the Peña Blanca district, Chihuahua, Mexico (Rodriguez-Torres and others, 1976), and the Maureen deposit, Queensland, Australia (O'Rourke, 1975; Bain, 1977) has aroused great interest in this general environment. Although geological details differ, some common geochemical relations are evident in the evolution of the volcanic-hypabyssal complexes. Numerous structural settings are mineralized, and commonly several types occur within one district. Uranium deposits are associated with rhyolitic plugs and domes at Spor Mountain, Utah (Staatz and



LEGEND

- | | | | |
|--|---|--|--|
| | Imure scapolite marble and scapolite granite | | Orebody outcrop |
| | Scapolite alioside granite | | Cable conglomerate or breccia conglomerate |
| | Peritic quartzites with interbedded calc silicate granites | | Diorite |
| | Micaceous schist | | Algal limestone |
| | Garnetite | | Basic intrusive |
| | Felspar quartz scapolite granite with some U mineralization | | Amphibolite equivalent to diorite |

Figure 35.--Geologic map and cross sections of the Mary Kathleen deposit (modified from Hawkins, 1975),

Carr, 1964), Lakeview, Oregon (Cohenour, 1960), and at McDermitt where they occur along the ring fracture of a nonresurgent caldera (Rytuba and Glanzman, 1979). At Marysvale, Utah, the known deposits occur in faults cutting hypabyssal intrusives and outflow tuff, probably above an unexposed intrusion (Cunningham and Steven, 1978; Cunningham and others, 1980). Volcaniclastic sediments filling caldera moats (as at McDermitt), in graben (as at central Italy, Locardi, 1977), or in paleovalleys are also favored sites for uranium mineralization. A new variety of host rock is evident at the Aurora deposit, McDermitt district, where mafic flows in the caldera moat contain 8.5 s.t. at an average grade of 0.05 wt. % U_3O_8 (Roper and Wallace, 1980). Fine-grained pitchblende and coffinite are associated with abundant pyrite and leucoxene. Other deposits occur in or are associated with ignimbrites, agglomerates, ashflow tuffs, and other outflow rocks as at the Rexspar deposit, British Columbia (Preto, 1978), Peña Blanca (Goodell and others, 1978), the Maureen deposit (Bain, 1977), and U-Be tuff at Thomas Range, Utah (Lindsey, 1977;). Older, metamorphosed subaerial and subaqueous volcanogenic deposits are also recognized (e.g. Gandhi, 1978; Grauch, 1978). The volcanic rocks are nearly always silicic, but both peralkaline and peraluminous variants can be uraniferous.

These deposits tend to be rich in one or more of the elements F, Mo, Be, Li, and Hg—a classic epithermal assemblage. Lithium and mercury are possible byproducts at McDermitt (Rytuba and Glanzman, 1979); Be is economic and U subeconomic in the Thomas Range (Lindsey, 1977), and the Maureen deposit averages 13 percent CaF_2 , with zones up to 20 percent FeS_2 and 4.5 percent MoS_2 (Bain, 1977). Thorium is commonly more abundant than uranium at Rexspar (Preto, 1978) and ranges up to 150 ppm at McDermitt; rare-earth elements also are abundant at Rexspar. Alteration can be either alkaline (added K-feldspar or zeolites) or acidic (fluorite, argillization). Fluid-inclusion thermometry indicates $330^{\circ}C$ in the McDermitt domes and about $150^{\circ}C$ in the Marysvale veins. Most authors propose a magmatic source for elements such as U, F, Be, Hg, etc. and elevated temperatures. However, diagenetic or mildly hydrothermal alteration of reactive volcanic sediments probably produces solutions of similar composition. Uranium is localized by carbonaceous material at Maureen, and also at the Anderson Mine, Arizona which occurs in tuffaceous lacustrine sediments (Sherborne and others, 1979). Behavior of uranium in distal volcaniclastic rocks, as at Peña Blanca, Maureen, or

Anderson Mine, is transitional to reactions in tuffaceous sandstone environments as in Morrison or Catahoula Formations.

OLYMPIC DAM

An exciting new environment is indicated by the recent discovery of a huge Cu-U orebody at Olympic Dam (Roxby Downs), South Australia. Early estimates from 20 drill holes indicate an orebody approximately 1.5 km by 0.5 km and up to 170 km thick. This is a totally blind orebody, covered by 350 m of unmineralized rocks. Although information is very sketchy, particularly for uranium, the deposit contains thick zones of about 0.05 to 0.10 percent U_3O_8 in 1 to 2 percent Cu and an early rough estimate (World Mining, 1979) specifies about 600,000 s.t. U_3O_8 and 11,000,000 s.t. Cu. Base-metal deposits have been known for years in Lower Proterozoic (Adelaidean)-Cambrian sandstone-shale-carbonate rocks of the Stuart Shelf (Johns, 1968). A bold exploration program was initiated by Western Mining Corp. in 1974, recognizing similarities to the African Copperbelt and using a source concept that continental basaltic rocks release copper during alteration (Haynes, 1979). The first drill hole in 1975 cited on a magnetic anomaly, gravity high, and photo lineament, intersected 38 m of 1.05 percent Cu (Haynes, 1979). The mineralization occurs 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 (SADME, 1979). Uranium minerals, including pitchblende and the U-Ti oxides brannerite and davidite occur with chalcopyrite, bornite, chalcocite, digenite, and traces of carrolite (a Cu-Co-Ni Sulfide) cobaltite (CoAsS), and gold. Rare-earth elements are abundant. Gangue is hematite, barite, and fluorite (which are very abundant), plus magnetite, quartz, sericite, (SADME, 1979; Youles, 1978). The mineralogy suggests unusually high fO_2 and low fS_2 .

The uranium mineralization, even more puzzling than the copper, is probably similar to the Mt. Painter deposits 250 km to the east (Youles, 1975; Major, 1978) which occur in hematitic granite breccia interbedded with arkose, siltstone, and glacio-marine tillite. This sequence is unconformably overlain by quartz-hematite rocks, interpreted to have been a subaqueous hydrothermal precipitate. Uranium generally exceeds Cu, Co, Mo, and rare earths in the Mt. Painter deposits. Fluid inclusions indicate low salinities and temperatures

of 400°C (Youles, 1978). Submarine volcanism may be part of the setting. The thick breccia and conglomerate units, at least 800 m thick at Olympic Dam, are a key element and must reflect active faulting along platform boundaries. U-Ti oxides brannerite and davidite presumably formed by reaction with Ti liberated by sulfidation of Fe-Ti oxides in granitic debris. Uranium and copper possibly came from different sources but were concentrated together in the sulfidic environment. Finally, the Olympic Dam example seems to be a reminder that uranium deposits should be anticipated to have formed from hydrothermal fluids moving up the flanks of basins as well as from the more traditional basinward-flowing groundwater.

CONCLUDING REMARKS

Some general regional-scale patterns and associations emerge from this overview that appear valid as empirical relations even if their genetic basis is not established. It is apparent that sedimentary preconcentration in Proterozoic sedimentary rocks is an important precursor process for hardrock deposits, and that the mechanisms of solution transport and deposition in hardrock deposits are basically similar to those advocated for low-temperature sandstone-type deposits.

Western World resources occur chiefly in conglomerate-type, sandstone-type, and unconformity-type deposits (table 3). Other types are much less important, although individual deposits are known to contain as much as 50,000 to 150,000 s.t. U_3O_8 as at Yeelirrie and Rössing. If we examine world resources in terms of ore-forming processes, it is apparent that three general processes have been most important: (1) Redox processes of uranium enrichment--uranium was transported in hexavalent form and reduced at sites of deposition, for example in marine sediments of the Lower Roan Formation or hydrothermal veins at Beaverlodge. (2) Metamorphic hydrothermal transport and deposition--aqueous, metamorphic fluids transported the uranium in a metamorphic environment (prograde, retrograde, contact metasomatic) as at Jabiluka and Beaverlodge. (3) Meteoric hydrothermal transport and deposition--fluids of meteoric origin heated by thermal gradient or igneous activity were the ore fluids, as at Schwartzwalder mine and French intragranitic veins. A fourth process, igneous differentiation and related magmatic hydrothermal transport, is relatively unimportant as it seems to have produced only a few

Table 3.—Distribution of Western World reasonable assured resources by type of deposit

	WWRAR ¹ thousands s.t. U ₃ O ₈	Approximate percent	Dominant process
Conglomerate-type	450	28	Placer
Sandstone-type	540	34	Redox
Unconformity-type	368	21	Redox/ metamorphic hydrothermal
Ultrametamorphic	110	7	Anatexis
Classical veins	50	3	Metamorphic hydrothermal; supergene
Plutonic	N.L. ²	(<2)	Igneous differentiation, supergene
Volcanic	N.L.	(<2)	Meteoric hydrothermal, supergene
Calcrete	40	3	Redox
	1510		

¹Reasonably assured resources from Dahlkamp (1978A), probably at \$30/lb forward cost as in IAEA (1978).

²N.L., not listed as a separate category.

percent of world resources. Supergene processes, which are geochemically part of item 1 (redox) above, affected many hardrock deposits, but in my opinion chiefly acted to redistribute or enrich uranium previously introduced into the deposit area, and as a primary process accounts for only a few percent of uranium resources.

Transport of uranium as uranyl-carbonate complexes is suggested for several types of hardrock deposits for which fluid-inclusion and paragenetic data are available. The common association with carbonate rocks is possibly additional evidence for carbonate complexes. Fluoride complexes are likely in some fluorine-rich deposits, but in general the alteration assemblage does not seem consistent with acidic conditions required for uranyl-fluoride complex stability. Some deposits, such as at the Midnite mine, do not show evidence for wallrock oxidation by ore fluids. This raises questions regarding the possibility of transport of uranium (IV) in unoxidized solutions.

Reduction in nearly all deposits can be related to carbon, sulfide, and ferrous-iron compounds, but rarely can a unique reductant be established. Geologically, however, all three tend to occur together, and hence for practical considerations the distinction may not be crucial. In some deposits lacking obvious reductants in wallrocks, such as the quartzites of the Schwartzwalder mine, or the clean sandstone of the Athabasca Formation, an introduced reductant seems required, but the nature of that reductant is unclear. Methane is a possibility, but lab experiments to date (at about 200°C) indicate it is not kinetically active (M. B. Goldhaber, oral commun., 1980). The kinetics of reduction by hydrocarbon species need to be studied experimentally and results checked with natural situations. But in general, reduction processes in hardrock deposits appear to be basically similar to those advocated for low-temperature deposits.

Thorium is generally present in very low concentrations in important hardrock deposits. Notable exceptions are Th-rich deposits in alkalic rocks and some unusual F-rich examples such as Rexspar. The pattern of low Th content is probably explained by a combination of the low Th content in sedimentary rock precursors and the separation of U from Th by oxidation. It is possible that U and Th travel together only in reduced states in silicate melts and F-rich fluids. A puzzling matter, however, is that Th-rich, U-poor veins are characteristically oxidized, containing hematite and barite. We need to learn more about conditions of transport and fixation of thorium.

There is a tendency for anomalous to economic amounts of Cu-Co-Ni-Ag-Bi-As to occur with many uranium ore types. The reasons for this association probably involve source rock and transport-deposition conditions. Mafic rocks occur near some deposits as in the Beaverlodge and Great Bear districts, and may be a source for metals other than uranium. In the Copperbelt altered volcanic rocks are a possible source, but most observers relate metallic enrichments to syngenetic or diagenetic processes in carbonaceous-sulfidic pelites which then are a more direct source for the metals in remobilized vein-type environments. I suspect the pelitic source most commonly provides these associated elements.

There is a notable worldwide association of hardrock uranium deposits with Proterozoic marginal-marine sedimentary rocks. More specifically, the sequences tend to be of early Proterozoic age and contain very similar assemblages of metamorphosed shale, sandstone, carbonate (commonly algal and dolomitic), volcanics, evaporite, and iron formation. The tectonic setting in many of the examples was an intracratonic rift (Sawkins, 1976). Metamorphism in many areas was to amphibolite grade, but some are lower grades. The likely stratabound occurrence of uranium deposits within these metasediments is, to me, compelling evidence that uranium enrichment occurred syngenetically or diagenetically, but in none of the sequences has anomalous uranium content been demonstrated. Syngenetic or diagenetic uranium enrichment would logically occur by reduction processes due to carbon from algal bioherms or by sulfide ion produced by sulfate-reducing bacteria as in younger sediments.

Abundant or sparse evidence for evaporites has been found for the following uranium areas: Bancroft and Athabasca districts, Canada; Copperbelt and Rössing areas, Africa; Rum Jungle, Alligator Rivers, and Cloncurry (Mary Kathleen) districts, Australia; and Zechstein area, Europe. Dolomitic portions of the Franceville Series, Gabon, may reflect a sebkha environment. The sedimentary geochemistry of these areas is obscured by metamorphism but the sedimentary-geochemical environment possibly was that of modern sebkhas where supratidal dolomite and anhydrite form. Evaporation would have concentrated uranium in the brine, and the uraniferous brine could have moved into adjacent reducing beds by upward evaporative pumping or downward reflux as proposed for supratidal dolomitization.

The sebkha evaporite environment may also provide an explanation for some occurrences of abundant magnesian carbonates and silicates in uraniferous metasediments and ore deposits. Magnesite ($MgCO_3$) occurs in the Rössing area, Rum Jungle-Alligators River area, and Copperbelt, and Mg-chlorite and talc are common in these and other hardrock uranium areas. Briefly, these Mg-rich phases may require high salinity to form because it expands the stability field of magnesite (Johannes, 1970). The assemblage quartz-magnesite \pm chlorite is stable up to about $500^\circ C$ and appears to require an initial excess of $MgCO_3$ (Winkler, 1974). This may mean that for these metasediments to contain magnesite earlier magnesite must have formed during diagenesis, which has been observed in modern supratidal sediments (Alderman and von der Borsch, 1961; von der Borsch, 1976). Finally, the possibility that such supratidal diagenesis occurs from continental ground water in marginal-marine sites (von der Borsch, 1976) has intriguing speculative implications for uranium, especially considering the possible amounts of uranium in newly oxygenated ground water in the lower Proterozoic.

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