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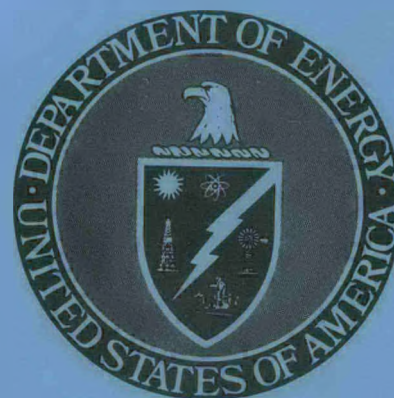
GEOLOGIC CHARACTERISTICS OF ENVIRONMENTS FAVORABLE FOR URANIUM DEPOSITS



**Field Engineering
Corporation**

Grand Junction Operations
Grand Junction, Colorado 81501

November 1978



PREPARED FOR THE U.S. DEPARTMENT OF ENERGY
GRAND JUNCTION OFFICE
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Edited by

David G. Mickle and Geoffrey W. Mathews

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INFORMATION REPORT
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PREFACE

The geologic characteristics of environments favorable for uranium deposits described in this report are intended to facilitate collection and evaluation of data for the National Uranium Resource Evaluation (NURE) program being carried out by the Grand Junction Office of the U.S. Department of Energy and its prime operating contractor, Bendix Field Engineering Corporation. The geologic characteristics and associated recognition criteria described herein are designed to assist field geologists in identifying and describing all possible geologic environments favorable for the deposition and concentration of uranium. Uniform use of a single system for recognizing and describing such environments will greatly assist the Data Integration Group of Bendix Field Engineering Corporation in assessing the uranium potential of individual environments.

The format of this report closely follows the classification given in U.S. Department of Energy Open-File Report GJBX-63(78), "A Preliminary Classification of Uranium Deposits." The only departure from the format of GJBX-63(78) is the separation of the discussion of uranium occurrences in sandstones from the other classes of uranium occurrences in sedimentary rocks. Whereas all sedimentary uranium classes are discussed in a single chapter in the volume on classification, this report discusses the sandstone class in a separate chapter.

The geologic characteristics of favorable uranium environments given in this report were derived from extensive literature surveys and from on-site studies of a few examples of most classes of uranium occurrences. Field and laboratory checking of recognition criteria is currently in progress. Until evaluative studies are completed, the recognition criteria must be considered preliminary; they may have to be modified as more information becomes available.

A thorough evaluation of these geologic characteristics and recognition criteria is essential if they are to have maximum applicability to the NURE program. We welcome all criticism, suggestions, and discussions.

URANIUM OCCURRENCES IN SEDIMENTARY ROCKS EXCLUSIVE OF SANDSTONE

by

Charles A. Jones

ABSTRACT

A classification of uranium deposits in sedimentary rocks, presented earlier (Jones, 1978), contained nine major classes. In the present report, the first eight of these classes (placers, quartz-pebble conglomerates, marine black shales, phosphorites, water, lignite and related rocks, evaporative precipitates, and limestones) are described in greater detail and summarized by a set of recognition criteria. Recognition criteria for the ninth class, sandstone deposits, are presented elsewhere (Austin and D'Andrea, this volume).

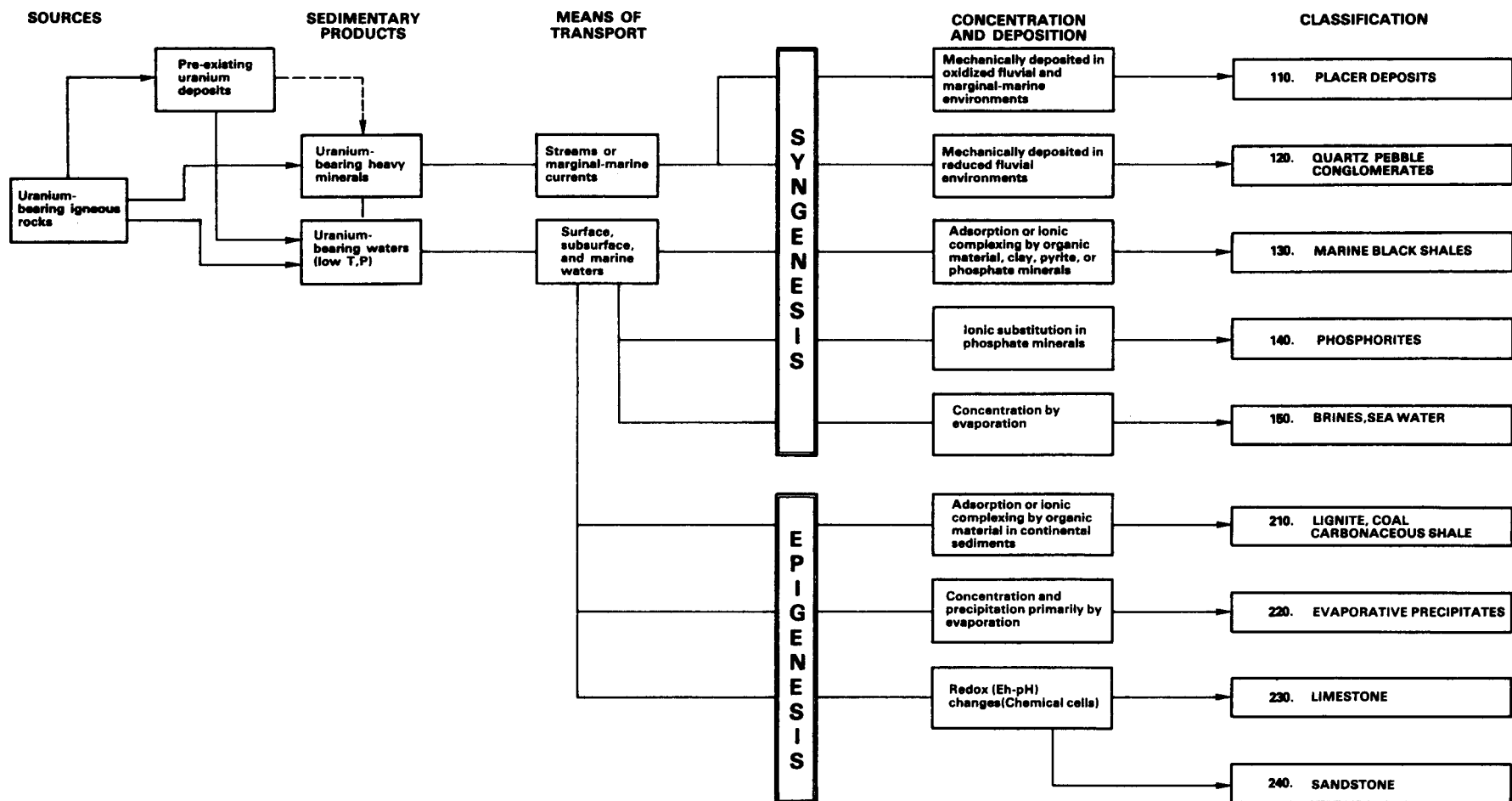
Headings for the recognition criteria include geologic setting, host-rock characteristics, uranium mineralogy, and geometry of the ore. The recognition criteria are followed by a list of selected references.

INTRODUCTION

A classification of uranium deposits in sedimentary rocks (Fig. 1) appeared in a previous report (Jones, 1978). Recognition criteria to accompany the classification and implement its use are presented here for all classes except sandstone (Class 240). Recognition criteria for sandstone-type deposits appear elsewhere (Austin and D'Andrea, this volume).

In this report, descriptions of all classes, except the sandstone class, are expanded. For each class or subclass, a specific mine, district, formation, or locality is described as an example. Wherever possible, an example is chosen for which literature and reference material are readily available. The information provided includes a general description of the deposit or locality; characteristics of the host rock; structural and tectonic setting; geochemical data; genetic interpretation(s); and size, grade, and production information. This information is then summarized in outline form as a list of recognition criteria. Specific headings for the recognition criteria include geologic setting, host-rock characteristics (age, lithology, depositional environment, and associated rock types), mineralogy of uranium and associated minerals, and geometry of the mineralized rock.

The classification and these recognition criteria are preliminary. A final report that will include more examples and further subdivision of classes into subclasses is being prepared.



Adapted from Barnes and Ruzicka (1972), and others.

Figure 1
ORIGIN OF SYNGENETIC AND EPIGENETIC URANIUM DEPOSITS IN SEDIMENTARY ROCKS

The information in this report is taken from many sources, both domestic and foreign. Units of measurement are reported here exactly as they appear in the original reference; no attempt has been made to standardize them. Thus, a mixture of English and metric units may be found within a single paragraph. Similarly, chemical analyses may be reported in terms of either uranium or U_3O_8 , and for uranium, as a percentage or in ppm. (For converting percent U_3O_8 to percent U, the following formula may be used: $\% U_3O_8 \times 0.85 = \% U$.) This lack of standardization may seem objectionable, but it will help the reader who wishes to check information given here with the original source.

Jones, C. A., 1978, A classification of uranium deposits in sedimentary rocks, in Mickle, D. G., ed., A preliminary classification of uranium deposits: U.S. Dept. of Energy Open-File Rept. GJBX-63(78), p. 1-16.

CLASSIFICATION

PLACER DEPOSITS (CLASS 110)

Placer deposits are concentrations of heavy minerals that form in high-energy fluvial and marginal-marine environments. In these environments, waves and currents selectively concentrate high-density mineral grains and winnow out the lighter grains and finer material. Minerals likely to be concentrated in a placer are dense and resistant to weathering, solution, abrasion, and impact. Few minerals with these properties contain much uranium.

In radioactive placers, most of the radioactivity will be from thorium-bearing minerals, such as monazite, zircon, thorite, and euxenite. These minerals are generally more resistant than uranium minerals to weathering and destruction during transport. A study of modern placer deposits by Davidson (1957) showed a world-wide absence of uraninite, one of the commonest and most important primary uranium minerals. Trace amounts of uranium normally will be present in a placer, but only as a minor constituent of resistant minerals such as monazite, xenotime, and thorite (Table 1). An exception is uraninite and sometimes brannerite in certain Precambrian quartz-pebble conglomerates (Class 120). Uraninite and possibly brannerite in these quartz-pebble conglomerates may be of placer origin, but apparently they were deposited under anaerobic atmospheric conditions.

Radioactive placers are composed of minerals derived from disintegration of silicic and alkalic igneous and metamorphic rocks. Such placers are located both on and peripheral to shields or regions of strongly deformed and intruded rocks. On the basis of depositional environment, two subclasses of placer deposits are recognized: fluvial (111) and beach-barrier bar (112). The placer deposits of central Idaho are examples of fluvial placers, and the concentrations of heavy minerals in certain Upper Cretaceous sandstones in the western U.S. are examples of beach placers.

Stream placers, because of their location in mountainous, high-energy environments, are ephemeral deposits and not likely to be lithified and preserved. Beach placers, on the other hand, are deposited near base level and are susceptible to burial and preservation by younger sediments. Thus, beach placers may be more likely than fluvial placers to be found in older rocks.

TABLE 1. MINERALS FROM RADIOACTIVE PLACERS AND THE
PERCENTAGE OF URANIUM AND THORIUM THEY MAY CONTAIN
(COLORADO SCHOOL OF MINES RESEARCH INST., 1976).
LISTED IN ORDER OF DECREASING URANIUM CONTENT.

Mineral	Formula	%U	%Th
Uraninite	UO_2	46.5-88.2	≤ 45.3
Thorianite	$(\text{Th}, \text{U})\text{O}_2$	≤ 44.6	43.4-87.9
Brannerite	$(\text{U}, \text{Ca}, \text{Fe}, \text{Th})(\text{Ti}, \text{Fe})_2\text{O}_6$	26.5-43.6	0.26-11.3
Betafite	$(\text{Ca}, \text{Na}, \text{U}, \text{Ce}, \text{Y})_{2-x}$ $(\text{Nb}, \text{Ta}, \text{Ti}, \text{Fe})_2\text{O}_6 (\text{O}, \text{OH})_x$	15-24.5	1-1.1
Samarskite	$(\text{Y}, \text{Fe}, \text{U})(\text{Nb}, \text{Ti}, \text{Ta})_2(\text{O}, \text{OH})_6$	8.4-16.6	≤ 3.7
Polycrase	$(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Ti}, \text{Nb}, \text{Ta})_2\text{O}_6$	5.5-12.4	≤ 4.7
Fergusonite	$(\text{Y}, \text{Er}, \text{Ce}, \text{Fe})(\text{Nb}, \text{Ta}, \text{Ti})\text{O}_4$	0.8-7.2	0.7-6.0
Euxenite	$(\text{Y}, \text{Ca}, \text{Ce}, \text{U}, \text{Th})(\text{Nb}, \text{Ta}, \text{Ti})_2\text{O}_6$	0.6-12.45	≤ 14.2
Thorite	ThSiO_4	10.1	25.2-64.1
Davidite	$(\text{Fe}, \text{R.E.}, \text{U}, \text{Ca}, \text{Zn}, \text{Zr}, \text{Th})_6$ $(\text{Ti}, \text{Fe}, \text{V}, \text{Cr})_5(\text{O}, \text{OH})_{36}$	≤ 4.4	≤ 0.12
Xenotime	YPO_4	≤ 3.6	≤ 2.2
Allanite	$(\text{Ca}, \text{Ce}, \text{Th})_2(\text{Al}, \text{Fe}, \text{Mg})_3$ $\text{Si}_3\text{O}_{12}\text{OH}$	≤ 2.95	≤ 4.35
Zircon	ZrSiO_4	≤ 2.7	≤ 13.1
Monazite	$(\text{Ce}, \text{La}, \text{Nd})\text{PO}_4$	≤ 0.1	≤ 26.4

Characteristics of fluvial and beach-barrier bar (marginal-marine) sediments and depositional environments are given in an extensive literature, some of it general and some of it pertaining to specific localities or stratigraphic units. For general references on depositional environments, see Visher (1965), Fisher and Brown (1972), Rigby and Hamblin (1972), Shelton (1973), and Reineck and Singh (1975). For geology of fluvial placers, see Lindgren (1933, p. 217-251), Bateman (1950, p. 227-244), and Jenkins (1970); for marginal-marine placers, see Murphy and Houston (1955) and Houston and Murphy (1970, 1977).

As a uranium resource, placers are low or very low grade. In addition, many of the minerals, such as monazite and zircon, that may contain small amounts of uranium are refractory and difficult to process. The low grade and refractory nature of many of the minerals lessens the attractiveness of placer deposits as a uranium resource. On the other hand, the volume of individual placers may run into the millions of cubic yards and may contain hundreds or thousands of tons of heavy-mineral concentrate. Uranium may be recoverable as a by- or co-product from such large placers if the placers also contain economic concentrations of minerals such as ilmenite, rutile, cassiterite, or gold.

FLUVIAL PLACERS (SUBCLASS 111)

The Idaho placers are located on and around the Idaho batholith in central Idaho. Radioactive minerals in the placers include monazite, euxenite, samarskite, fergusonite, thorite, xenotime, zircon, allanite, betafite, davidite, polycrase, and brannerite. All of these minerals contain uranium, but, in the strictest sense, only brannerite is a uranium mineral. In all the other minerals, uranium occurs as a substitute for another element (Table 1). Brannerite is not an abundant mineral, but is important at certain placers such as Big Meadow (Truesdell and others, 1977) and perhaps at Kelley Gulch, in the Stanley Basin, where the mineral was first described (Mackin and Schmidt, 1955). In the Red River Valley of the Elk City district, brannerite occurs in detrital grains that are intergrowths with rutile (Armstrong and Weis, 1957).

Mineralogy of the Idaho placers varies from place to place. Magnetite and ilmenite usually constitute 90 percent of the heavy-mineral concentrate. Monazite and euxenite are the commonest radioactive minerals, but in some placers where thorite is abundant euxenite may be rare or absent. The specific minerals present and the relative abundance of each are highly variable and reflect such factors as the age of the placer deposit, distance of sediment transport, and variable mineralogy of the source rocks.

The Idaho batholith is a composite mass of granitic rocks that are both metasomatic and orthomagmatic in origin. The batholith is of Late Cretaceous age and intrudes Precambrian metamorphic rocks that are, at least in part, thought to be equivalent to the Belt Supergroup. The batholith consists mainly of granite, quartz monzonite, and quartz diorite. Pegmatite and aplite dikes represent a late stage in development of the batholith. Diorite dikes and stocks and porphyry intrusions of Tertiary age are also present.

Radioactive minerals, gold, columbite, and other heavy materials in the placers originate as accessory minerals in the granitic rocks of the batholith. Mackin and Schmidt (1955) found that accessory minerals were not uniformly distributed in the granites and that the yield of heavy minerals from a particular catchment area was a function of the number and richness of local segregations of accessory minerals in the source rock. Savage (1960) suggested that these segregations began as Precambrian placer accumulations that were later assimilated and partially dispersed during metasomatic reconversion of the parent sedimentary material into granite. Whatever the origin, prospecting for these segregations is difficult because rock containing these segregations is megascopically indistinguishable from surrounding rock.

The placer deposits consist of streaks or lenses of heavy-mineral concentrations in valley-fill sediments. Some of the valley fills are as much as 100 ft deep. The principal causes for accumulation of thick valley fills on and around the Idaho batholith are: (1) block faulting during the Pleistocene, (2) late Pleistocene glacial derangement of drainage, and (3) Pleistocene basalt flows. The increase in sediment load due to periglacial conditions during the Pleistocene also contributed to valley filling (Mackin and Schmidt, 1955).

Whereas these processes tend to cause aggradation, the richest placers are not in sediments that accumulated by rapid aggradation. The richest placers are deposited by streams that are at or near grade, not those that are rapidly aggrading. Graded streams migrate back and forth, reworking and reconcentrating the heavy minerals each time. Over a period of time during which tectonic and climatic events disturb the fluvial regime, streams may move in and out of grade rapidly and repeatedly. Thus, many of the older Pleistocene channel and terrace deposits, which were deposited during periods of rapid aggradation, are leaner than deposits of modern graded streams. In some cases, sediment deposited by side streams or eroded from older, barren, bank deposits may dilute and reduce the tenor of a modern placer.

Glacial history and weathering also control the richness of a placer. Heavy-mineral yield from areas unglaciated during the Wisconsin-age glaciation is 1.5 to 3 times the yield from glaciated areas. Weathering is deeper and residual concentration of heavy minerals in soil is much greater in unglaciated areas than in glaciated areas where sediment is coarse, fresh, and unaltered.

Commonly, the richest placers are located at the head of a valley or along the sides of a valley where streams debouch from side canyons. Certain tributary streams, often relatively small ones, may drain an area underlain by source rock that is rich in accessory minerals. As these streams emerge from their side canyons, they drop part of their load and may deposit concentrations of heavy minerals together with coarse sand and gravel.

Idaho placers were originally worked for gold. Placer mining for gold dates back to the 1860s. During the 1950s and 1960s, some of the placers were worked for the rare-earth minerals columbite, euxenite, and monazite. The U.S. Atomic Energy Commission investigated at least one of the placers for uranium potential during the 1950s (Armstrong and Weis, 1957), but the U.S. Energy Research and Development Administration (1976, p. 60-65) did not list the Idaho placers as a significant resource.

Recognition Criteria for Fluvial Placers (Subclass 111)

Geologic setting:	Mountain or piedmont valleys, igneous or metamorphic source rocks of granitic composition.
Host rock	
Age:	Pleistocene-Holocene; Tertiary and older rock also possibilities.
Lithology:	Lenticular beds or stringers of heavy minerals in medium to coarse, sometimes gravelly and poorly sorted, fluvial channel deposits of moderate- to high-gradient streams.
Depositional environment:	Wide parklike valleys in youthful mountainous areas, swales and valleys in mature mountainous areas, and in piedmont valleys along the mountain front; placers localized where stream gradients flatten; stream at or near grade across depositional area; moist climate (at time of placer formation) for rapid and deep weathering of source rocks and large sediment yield is most favorable, but placers may also form in more arid climates.
Associated rocks:	Overbank deposits and terrace sands and gravels.
Mineralogy	
Uranium minerals:	Mostly heavy minerals that contain only small amounts of uranium, such as monazite, zircon, xenotime, euxinite, allanite, rare-earth oxides, and thorite; but occasionally such minerals as brannerite and thorianite.
Associated minerals:	Predictable suite of minerals derived from weathered igneous and metamorphic rocks of granitic composition, including heavy minerals such as magnetite, ilmenite, amphiboles, biotite, garnet, gold, and cassiterite.
Geometry:	Stratiform; lenticular beds or stringers that trend along the axis of the valley.

The Idaho placers have value as a uranium resource only if the uranium can be recovered as a by-product from placers mined for other minerals, such as gold, rare-earth minerals, and thorite. All of these minerals, and brannerite, have specific gravities of about 5 or greater and thus lend themselves to extraction in the same concentrate. Gravels worked for gold are likely to contain the richest concentrations of uranium-bearing heavy minerals. The concentration of heavy minerals may be 100x greater in gravel lenses than in adjacent lenses of sand.

Armstrong and Weis (1957) report analyses of samples from jig-bed concentrates collected from a dredge operation on the Red River in the Elk City district. Average uranium content in three different jig-bed concentrates was 0.11 percent (0.07-0.15 percent) uranium with 97 percent of all uranium in the +8 mesh (>2.38 mm) size fraction.

Other examples of radiometric fluvial placers include the monazite placers of North and South Carolina (Mertie, 1953; Overstreet and others, 1968; Caldwell and White, 1973); Bugaboo Creek, British Columbia (Barnes and Ruzicka, 1972); Madhya Pradesh, India (Ghosh, 1976); and the Naegi district, Japan (Murakoshi and Koseki, 1957). Mertie (1953) reported 53 analyses of monazite from the placers of North and South Carolina. Thorium averaged 5.67 percent and uranium 0.38 percent with a range of 0.18 to 0.98 percent. Source rocks for the monazite are deeply weathered quartz monzonite, granitic gneiss, and monazite-bearing schists.

BEACH PLACERS (SUBCLASS 112)

Included in this subclass are placers that form on both beaches and long-shore bars. In contrast to fluvial placers, which are usually deposited within or close to the source area, beach placers may be deposited tens or hundreds of miles from the source area. The farther the sediment is transported, the greater is the attrition and reduction in grade by solution and abrasion. Usually, only the most resistant minerals, such as monazite and zircon, survive. Radioactivity in most beach placers is mainly due to uranium and thorium in these two minerals.

A further result of transport over long distances is dilution by mixing with other sediments. Reconcentration of heavy minerals on beaches and long-shore bars only partially compensates for this process.

Both modern and ancient beach placers are known. Unlike fluvial placers, which are highly susceptible to destruction by subsequent weathering and erosion, beach placers deposited along transgressive or regressive shorelines are in much better environments for preservation. Houston and Murphy (1977) suggested that preservation is most likely in regressive sequences. Placers formed during transgression tend to be reworked as transgression progresses, whereas deposits formed during regression may be buried by lagoonal and continental sediments and thus preserved.

More than 100 fossil beach placers are known in regressive sandstones of Late Cretaceous age in the western interior of North America from Alberta and Montana southward through Wyoming, Colorado, and Utah to New Mexico and Arizona. These have been studied by Murphy and Houston (1955), Dow and Batty (1961), and Houston and Murphy (1970, 1977), and are described here as examples of beach placers.

These placers are found in several formations. They characteristically occur at the top of regressive littoral sandstones, and are overlain by a non-marine sequence of carbonaceous shale, coal, and fluvial sandstone. The massive black sandstone layers are thought to have been deposited at the top of the beach or on the back beach by storm waves (Houston and Murphy, 1977). An exception may be the placers in the Straight Cliffs Formation of the Kaiparowits Plateau, Utah. These have been described as deposits on the upper forebeach on the seaward side of barrier islands (Peterson, 1969).

The typical deposit is laminated, black-and-white sandstone averaging 15 percent heavy minerals at the base and overlain by massive, black sandstone composed of layers containing as much as 90 percent heavy minerals at the top. The black sandstone is characterized by large-scale, very low-angle, seaward-dipping cross-laminations. In some deposits the lower, black-and-white sandstone is separated from the upper, black sandstone by a zone of high-angle cross-bedding with laminae that dip both seaward and landward. The lower, black-and-white sandstone is considered a foreshore deposit; the high-angle cross-bedded middle unit is considered a foreshore-ridge deposit; and the upper, black sandstone is considered an upper-foreshore and backshore (beach and backbeach) deposit. The thick, black layers richest in heavy minerals are thought to have been deposited at the top of the beach during storms by combined gravity-shear sorting. Under gravity-shear sorting, as each lamina is deposited, small, heavy grains sink to the bottom and larger, light grains rise to the top of the lamina. Subsequent waves entrain the light grains and repeat the process. The light grains, which are kept continually in motion, are effectively sorted out, while the heavy grains remain (Houston and Murphy, 1977).

Many of the beach placers are elongate and can be taken as shoreline indicators. Orientation of the beach placers agrees favorably with shorelines determined from paleontologic and regional paleogeographic studies (Houston and Murphy, 1970). Where cross sections through the deposits have been observed, individual black-sand layers are wedge-shaped, with the thick end toward the west, or landward, and the thin end feathering seaward. Modern black-sand deposits in Australia have a similar orientation. Thus, geometry and orientation are not only an indication of the origin of these deposits, but may also be useful in estimating the size and trend of poorly exposed beach-placer deposits.

Provenance studies indicate two major types of source rocks: volcanic and sedimentary. Beach placers derived mainly from volcanic source rocks are identified by oxyhornblende, intergrown iron-titanium-oxide (opaque) minerals, and euhedral zircon. Placers derived largely from sedimentary sources are characterized by ilmenite, rounded zircon, and rounded monazite. Volcanic source areas are more important in Alberta, Montana, and northern and eastern Wyoming; sedimentary source areas are typical in southwestern Wyoming, Colorado, Utah, New Mexico, and Arizona. In general, beach placers derived from sedimentary sources contain the most uranium, because of their greater zircon and monazite content.

Black-sandstone deposits are most abundant in Montana and northern Wyoming. In these areas two major periods of black-sand deposition took place, one at about 80 to 82 m.y. and the other at 71 to 72 m.y. These episodes are thought to coincide with igneous activity or with deformation associated with the emplacement of the Idaho and Boulder batholiths (Houston and Murphy, 1977).

Sand in these fossil beach placers is very fine grained. Samples with a predominance of light minerals have modal diameters of 0.15 to 0.21 mm. Samples that consist predominantly of heavy minerals have modal diameters of about 0.10 mm. These fine grain sizes are indicative of low-energy conditions along the beach. The beaches probably were broad and relatively flat (Houston and Murphy, 1977).

Characteristically, the black sands in these deposits are hard and well cemented. They are resistant to erosion and are frequently found as cap rock on buttes. Where they occur as cap rocks, overburden is thin or absent, and they can be easily strip mined. However, because of their hardness, they cannot be processed as easily as unconsolidated fluvial and beach-placer sands; this may have an adverse effect on their development.

These deposits vary greatly in size. One of the largest, the Dugout Creek deposit of Wyoming, is 2.7 mi by 1,500 ft. Thickness of this deposit is as much as 25 ft; the average thickness is 11 ft. Other known deposits are smaller (Houston and Murphy, 1970, Table 1).

Typically, the grade of these deposits increases upward, from about 5 to 15 percent heavy minerals to greater than 50 percent at the top. Some deposits contain as much as 90 percent heavy minerals at the top. The upward increase in grade has been attributed to seaward migration of rich backbeach deposits over lower-grade forebeach deposits during regression (Houston and Murphy, 1970).

Analysis of 570 samples taken throughout the Rocky Mountain region shows that opaque minerals constitute about 26 percent; zircon, 2.0 percent; and monazite, 0.2 percent (Houston and Murphy, 1970, p. 245). For a 20-million-ton deposit of black sandstone with 2 percent uranium-bearing zircon containing 2.5 percent uranium, total uranium yield, assuming complete recovery, would be 10,000 tons of uranium or 11,790 tons U_3O_8 .

In summary, whereas total volume of heavy minerals in these beach placers is large, and problems of access and mining are minimal, these deposits are not economic because of induration and low concentrations of uranium. Conceivably, if the deposits were mined for titanium and rare earths, the uranium could be recovered as a by-product.

Other examples of beach and near-shore placers are described from the mouth of the Nile, Egypt (Higazy and Naguib, 1958) and Apalachicola River, Florida (Tanner and others, 1961); Folkstone, Georgia, and Trail Ridge and Jacksonville, Florida (Southern Interstate Nuclear Board, 1969, p. 166-171); and both the eastern and western coasts of India (Wadia, 1956; Mahadeyan and others, 1958).

Recognition Criteria for Beach Placers (Subclass 112)

Geologic setting:	Shorelines of epicontinental seas; igneous or metamorphic source rocks of granitic composition; richer placers may be linked to uplift, deformation, or volcanism in the source area.
Host rock	
Age:	Not age restricted.
Lithology:	Clean, well-sorted lenses of black-sand concentrations; commonly interbedded or associated with light-colored, well-sorted, quartzose beach or barrier-bar sands; beach sands characterized by thin, even laminations with both seaward- and landward-dipping cross-beds.
Depositional environment:	Beaches, or in some cases offshore bars; modern placers on both high- and low-energy coasts; burial and preservation of fossil placers most likely along low-energy shorelines during regressive (?) phases.
Associated rocks:	Marine-shelf muds; marginal-marine sands; and lagoonal, deltaic, and continental sediments.
Mineralogy	
Uranium minerals:	Ordinarily none; uranium present in small amounts in other minerals such as monazite and zircon.
Associated minerals:	Quartz and other resistant minerals; the exact suite depends upon source rocks and relative maturity of coastline.
Geometry:	Stratiform; elongate parallel to shoreline; in cross section, lenticular to wedge-shaped (blunt end, landward).

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QUARTZ-PEBBLE CONGLOMERATES (CLASS 120)

The following characteristics distinguish quartz-pebble conglomerates from conglomeratic placers (Class 110) or conglomeratic-sandstone deposits (Class 240): quartz-pebble conglomerates are restricted to the lower Proterozoic, they are highly pyritiferous, and they contain primary uranium minerals that are possibly detrital. On the basis of these three characteristics, quartz-pebble conglomerates are considered a separate class of deposit. It is not clear from the term "quartz-pebble conglomerate" that these deposits are different from other conglomeratic deposits, but, because the term is commonly used, it is also used here.

Quartz-pebble conglomerates are apparently restricted to the early Proterozoic (early Precambrian X). The two classic localities are Witwatersrand, South Africa (Liebenberg, 1958; Whiteside, 1970; Minter, 1976), and Blind River-Elliott Lake district, Ontario, described below. Similar deposits are known in Brazil (White, 1955, 1964; Bateman, 1958; Gross, 1968), Australia (Robertson, 1974), and elsewhere in Canada (Robertson, 1974). Recently, in the U.S., exploration has focused on apparently similar conglomerates in the Black Hills, South Dakota (Hills, 1977), and Medicine Bow and Sierra Madra Mountains, Wyoming (Miller and others, 1977; Houston and others, 1977; Graff and others, 1977). All of these conglomerates have been dated at 2,200 to 2,700 m.y., and all unconformably overlie an Archean basement of granite and metamorphic rocks.

Uranium minerals, chiefly uraninite, together with pyrite, gold, and other heavy minerals, occur in the chloritic or sericitic matrix of oligomictic conglomerates. The clasts in oligomictic conglomerates are composed almost entirely of quartz, chert, or quartzite. Polymictic conglomerates, which occur in the same stratigraphic sequences, are comparatively barren of uranium.

The origin of quartz-pebble conglomerates is controversial. It is generally agreed that the ore-bearing rocks were deposited in fluvial, and, in some cases, lacustrine, and marginal-marine or deltaic environments. Whether the uranium itself is syngenetic (placer), hydrothermal, or redistributed is an unresolved problem. Most literature, including recent papers by Minter (1976) and Robertson (1976), support a detrital or placer origin for the uranium. If the uranium is detrital, these Precambrian deposits are unique among placers, in that the uranium is contained in uraninite, brannerite (Blind River), and the hydrocarbon thucholite. Uraninite, brannerite, and thucholite are rarely present in upper Proterozoic and Phanerozoic placers because they are unstable during weathering and transport in an oxidizing environment. Survival of these easily weathered minerals and thucholite in a placer deposit is presumed due to an anaerobic atmosphere during the early Proterozoic.

Precambrian quartz-pebble conglomerates are low-grade uranium resources. At Witwatersrand, where uranium is a by-product of gold mining, grade may run as low as 0.01 percent U_3O_8 ; however, individual deposits may range in size from 5,000 to as much as 150,000 tons U_3O_8 . At Blind River, deposits are rich enough for uraninite and brannerite to be the chief economic minerals. The Blind River-Elliott Lake deposits are discussed here as an example of uraniferous quartz-pebble conglomerate.

Blind River-Elliot Lake Deposits

The Blind River-Elliot Lake district is in Ontario, north of Lake Huron. The ore is in lowermost Proterozoic fluvial conglomerates at the base of the Huronian Supergroup.

The Huronian Supergroup consists of a thick series of quartzite, conglomerate, argillite, arkose, and siltstone. Deposition of the supergroup was cyclic, each cycle beginning with conglomerate or conglomeratic sediment at the base. The lowermost formation in the supergroup, the Matinenda Formation, contains the initial Huronian conglomerates. These are the ore-bearing quartz-pebble conglomerates.

The Matinenda Formation (Lower Mississagi of some authors) is composed at the base of greenish arkose and conglomerate. These are overlain by gray quartzite, which is overlain by argillite of the McKim Formation. The Matinenda and McKim Formations constitute an overall fining-upward, transgressive sequence that onlaps progressively toward the northwest. Colors throughout are greenish and gray, indicative of the reduced state of iron in the rocks.

Thickness of the Matinenda ranges from less than 1 ft in the north of the district to 700 ft in the south. Locally, thickness varies due to topographic irregularities of the Archean basement. Ore-bearing conglomerates are usually low or basal in this formation, but may be found as high as 150 ft above the base.

The conglomerates are lenticular and range from a few inches to 3 ft in thickness. Trough cross-bedding is typical. The conglomerate was laid down in braided-stream channels, with lateral migration coalescing the channel deposits into thin sheets (Robertson, 1976). Cross-bedding and pebble orientation indicate a source to the northwest, but locally currents were strongly influenced by basement topography. Ore-bearing conglomerates are located mainly in valleys on the basement surface underlain by greenstone, but at least one deposit is on the flank of a granite paleohigh.

Massive tholeiitic basalts that appear to be subaerial flows are present locally within the Matinenda Formation. Known uranium orebodies are marginal to the volcanic rocks; thus, the flows may have controlled the courses of streams that deposited the uraniferous conglomerates.

Typical uraniferous oligomictic conglomerates of the Matinenda Formation consist of well-rounded, well-sorted quartz pebbles in a matrix of quartz, feldspar, sericite, and pyrite (Robertson, 1976). Average pyrite content is 15 percent. The ore minerals, brannerite, uraninite, and monazite, are also in the matrix. Thucholite is present both in the ore and as a postore secondary material in fractures. Gummite (soddyite and uranophane) is rare, except at the Spanish American Mine. Uranothorite and coffinite have also been identified.

Pyrite is present in the matrix, in grains that are rounded or subhedral. In some cases, pyrite is massive. Evidence of replacement or fracture-filling by pyrite is rare. Origin of this pyrite is uncertain. It has been suggested that the pyrite is either detrital or is formed by sulfidization of detrital magnetite.

A wide variety of minerals, especially heavy minerals, have been described from the ore-bearing conglomerates. Despite this variety, the quantity of heavy minerals is too small, some have claimed, for a placer derived from granitic source rocks (Davidson, 1957).

Brannerite is the most abundant ore mineral at some mines, uraninite at others. Brannerite typically is found as ovoid, reddish-brown to black grains. It is present as a two-phase composite of uranium-rutile or uranium-anatase with bladed rutile surrounding a uranium-and-rare-earth-oxide core (Robertson, 1976). Rounding, which may be due to fluvial transport, could be an indication that the brannerite is detrital. Rice (reported by Derry, 1960), believed the original detrital brannerite had been progressively altered and degraded to rutile and anatase, with concomitant loss of uranium. In a more recent paper, Ferris and Ruud (1971) suggested that brannerite was a low-temperature, diagenetic mineral. They believed that uranium, possibly from detrital uraninite or leached from surrounding sediment, replaced iron in decomposing ilmenite. They further suggested that iron, freed from ilmenite, detrital magnetite, or other ferromagnesian mineral, may have combined with volcanic sulfur to form the pyrite present in the matrix.

Uraninite generally occurs as black, subhedral to rounded grains, approximately 1 mm in diameter. Rounding may indicate a detrital origin of the uraninite. Derry (1960) stated that the ThO_2 content of the uraninite (5 to 6 percent) is more typical of pegmatitic uraninite than hydrothermal types, and this perhaps also supports a detrital origin. However, Patchett (reported by Robertson, 1976) suggested uraninite may have formed as a result of leaching of brannerite by hydrothermal solutions. Other arguments against a detrital origin for both brannerite and uraninite are given by Davidson (1957).

Origin of the Blind River uranium minerals is uncertain and controversial, as the foregoing remarks indicate. The almost exclusive restriction of uranium to the coarse, oligomictic conglomerates at both Blind River and the Rand district has led many mining geologists to favor the detrital (placer) theory of origin. The chief argument against a detrital origin for either uraninite or brannerite is that these minerals are rare and do not persist in modern, highly oxidizing fluvial and marginal-marine environments. Thus, it is argued, the early Proterozoic atmosphere must have been anaerobic and reducing. For further discussion of this matter, see Pettijohn (1975, p. 596-597) and Roscoe (1973).

Whatever the origin of uranium in these conglomerates, exploration and development have proceeded profitably at both Blind River and Witwatersrand by regarding the deposits as detrital. This is so because the ore is restricted to the conglomerates. If the ore is actually hydrothermal, lithology is nevertheless a control: hydrothermal or even supergene solutions would doubtless favor passage through the relatively permeable conglomerates in preference to the less-transmissive, finer-grained quartzite and argillite that bound the conglomerates. In either case, the exploration target is a stratiform ore-body confined to oligomictic quartz-pebble conglomerates. For an extended discussion of the origin of quartz-pebble conglomerate ores, see papers by Davidson (1957, 1964), Derry (1960), Robertson (1976), and Robertson and Steenland (1960), and other papers cited in this section.

The conglomerate-bearing Matinenda Formation unconformably overlies an Archean basement of granites, greenstone, and minor mafic intrusives. Age of the Archean rocks is >2500 m.y. (Robertson, 1976). Aerial gamma-spectrometer surveys have shown that much of the Archean granitic terrane north and northwest of Blind River-Elliott Lake contains anomalous uranium. Especially anomalous are areas underlain by massive, red quartz monzonite. If the uranium ores in the conglomerate are detrital, these red granites north and northwest of Blind River are the probable source.

The Archean rocks were subjected to a prolonged period of weathering and erosion sometime after 2500 m.y. ago. Valleys were formed in easily eroded greenstone belts, and a deeply weathered regolith developed over the granite. Where the regolith is preserved beneath Huronian sediments and can be studied, the following are noted: plagioclase is altered to sericite; ferromagnesian minerals are absent; and iron, especially ferric iron, has been lost. Only quartz and microcline are present to preserve a relic granite texture. At places, the regolith grades upwards into a pre-Huronian, sorted, sericitic arkose that may be bedded and cross-bedded.

Loss of iron, especially ferric iron, suggests that Fe^{3+} was reduced in an oxygen-deficient environment to Fe^{2+} and leached from the weathered zone. The presence of ferrous iron and tetravalent uranium in both the regolith and Huronian sediments also indicates anaerobic conditions. If atmospheric oxygen were available during the Archean and early Huronian, ferric iron would have been the stable form, and uranium would have been oxidized to the hexavalent form and removed by leaching.

Radioactive minerals are not limited to the Matinenda Formation at the base of the Huronian, but are present in subeconomic quantities in conglomeratic and arkosic facies at intervals throughout the supergroup. In the lower Huronian, radioactivity is due to uranium associated with pyrite; in the upper Huronian, radioactivity is due to thorium associated with ferric-oxide minerals. Because of the low Th/U ratios in the Matinenda conglomerates, Davidson (1957, p. 670) argued "that the bankets are not sedimentary assemblages." The change from tetravalent uranium minerals and pyrite in the lower Huronian to thorium and ferric-oxide minerals in the upper part apparently reflects an increase in atmospheric oxygen during the Huronian. Climate may also have played a role. Coarse deposits, interpreted by some as glacial, are characteristic of the lower and middle Huronian, whereas the upper Huronian was apparently deposited in a drier, warmer climate. Red beds also occur for the first time in the Precambrian sequence, in the Gowganda Formation, near the top of the Huronian Supergroup.

Closely following the end of Huronian deposition, the area was subjected to a long history of folding, intrusion, and metamorphism. The Matinenda is involved in a syncline to the north and anticline to the south (Robertson, 1976, Fig. 2b). Matrix chlorite indicates low-grade metamorphism in the greenschist facies. Neither deformation nor metamorphism is believed to have affected uranium mineralization to any extent with the possible exception of a certain amount of redistribution and/or diagenetic recrystallization.

The Blind River-Elliot Lake deposits are in three different channel systems or zones (Derry, 1960, Fig. 1). Ore zones strike northwest and are laterally extensive compared to their thickness. The largest is 9700 m wide. Thickness of ore zones ranges from 0.6 m to 36 m. In several of the mines, two or more ore-bearing conglomerate zones are found in vertical sequence, separated by several meters of barren arkose or quartzite. Grade of ore is generally higher where thickness of the conglomerate and degree of pebble packing (least matrix) are greatest (Derry, 1960).

Between 1955 and 1973, the Blind River-Elliot Lake area produced 1.5 billion dollars worth of uranium from ore grading 2 lb per ton (0.1 percent U_3O_8). Reserves, as of 1973, were estimated at 350,000 tons of U_3O_8 at a cutoff grade of 0.05 percent. Unproven resources may double the estimated reserves (Robertson, 1976). By-products from the uranium operation have been minor amounts of thorium and yttrium. Unlike Witwatersrand, gold is present only in trace amounts in the Blind River ores.

Recognition Criteria for Quartz-Pebble Conglomerates (Class 120)

Geologic setting:	On or peripheral to Archean shields; source rocks of granitic composition.
Host rock	
Age:	Lower Proterozoic; 2.2 to 2.7 b.y. appears to be most favorable, but may be too restrictive.
Lithology:	Oligomictic, pyritic quartz-pebble conglomerate composed of well-rounded quartz, chert, or quartzite pebbles in a matrix of quartz, feldspar, pyrite, and heavy-mineral grains, and sericite or chlorite; metamorphosed into greenschist facies; typically trough cross-bedded.
Depositional environment:	Chiefly braided-stream; lacustrine and marginal-marine environments may also be represented; anaerobic atmosphere.
Associated rocks:	Quartzite, arkose, siltstone, argillite, and polymictic conglomerates; lithologic sequence may be cyclic.
Mineralogy	
Uranium minerals:	Uraninite and/or brannerite; at some places, uranothorite, coffinite, gummite, and thucholite.
Associated minerals:	Pyrite, gold, and wide variety of detrital minerals; chlorite or sericite in matrix.
Geometry:	Stratiform; thin and lenticular beds, often coalesced into thin sheets.

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MARINE BLACK SHALES (CLASS 130)

Black shales are common in the stratigraphic record, and most contain more uranium than the average sedimentary rock. However, few black shales contain more than 0.005 percent U, and this is a convenient lower cutoff for classifying a shale as uraniferous. All of the known large and rich uraniferous black shales are of Paleozoic age. Their distribution is worldwide. They are referred to in the various literature by names such as carbonaceous shale, graphitic shale, bituminous shale, phosphatic shale, or alum shale.

Uraniferous black shales are marine. They are thin, widespread stratigraphic units that appear to have accumulated very slowly on or adjacent to tectonically stable continental platforms. Some of the richest and thickest deposits seem to have been deposited near the platform margin and are genetically related to phosphorite deposits (Class 140). Preorogenic stability also seems to be a requirement.

These shales are found in stratigraphic sequences that commonly include siltstone, limestone, and other shales. Interbedded phosphorite, chert, or bentonite may also be present. Some black shales are part of cyclic deposits with sandstone and limestone; other black shales are siliceous and may be lateral equivalents of siliceous volcanic rocks.

Most uraniferous black shale is evenly laminated, but dense, breaking with a conchoidal fracture when fresh. These shales are characterized by dark color, high organic-matter content, presence of pyrite or marcasite, and the absence or sparsity of calcium and magnesium carbonates. Pyrite occurs as lenses, nodules, or finely disseminated particles. Carbonates may be present as separate and discrete, thin beds, but the uraniferous black shales themselves are distinctly noncalcareous. Most uraniferous black shales also contain small quantities of other metals, such as titanium, copper, chromium, molybdenum, manganese, vanadium, phosphorous, and rare earths. These elements and uranium tend to be evenly disseminated throughout the shale. In some black shales phosphate minerals may be present as nodules, concretions, or disseminations in phosphate-rich layers. Phosphate nodules are usually richer in uranium than the surrounding shale, but there are exceptions.

Black shales contain large percentages of organic matter. Most of the organic matter is sapropelic and derived from marine algae. Many of these shales, such as the Chattanooga and the Swedish alum shales, contain enough bituminous organic matter to be a source of shale oil.

Uranium content in black shales generally increases with increasing amounts of organic matter. For example, the Chattanooga shale contains an average of about 20 percent organic matter and 0.006 percent uranium, whereas, selected samples of coalified wood and spores from the Chattanooga contain as much as 0.7 percent uranium (Mutschler and others, 1976; Klepper and Wyant, 1957). Parts of the Swedish alum shales contain about 30 percent organic matter and about 0.02 percent uranium. Nodules of kolm in the alum shales that contain 79 percent organic matter contain as much as 0.4 percent uranium (Klepper and Wyant, 1957).

Uranium content in black shale typically ranges from 0.005 percent to as much as 0.02 percent. Certain organic-rich beds may contain as much as 0.X percent uranium. Different beds or units usually contain different amounts of uranium, but the grade of a particular bed is commonly uniform and predictable over a large area. There is some indication that uranium content is higher in beds that are finely laminated or in those that are the finest grained. Beds or members that conceivably could be mined are typically several feet thick and may cover thousands of square miles.

No uranium minerals, as such, have been identified from unweathered black shales. Secondary uranium minerals are occasionally reported from weathered outcrops, but they are exceptional. Uranium in black shales is believed to have accumulated syngenetically. At the time of deposition, bottom conditions must have been anaerobic and strongly reducing. Uranium may have been extracted from sea water by organic matter, or by phosphate minerals, pyrite, or colloidal clay. In some cases, marine waters may have been enriched in soluble uranium by local volcanism or intense weathering of granite terrain in a nearby continental source area.

At places where the distribution of uranium within a shale bed or series of beds is spotty and irregular, epigenetic enrichment or redistribution of uranium by connate or supergene waters may have occurred. This would be an unusual case. Uranium concentration usually is remarkably uniform in black shales.

Marine black shales are low-grade resources. Because they are commonly widespread, it is easy to be impressed with the millions of tons of uranium they contain. Obtaining the uranium would, in many cases, require strip mining over hundreds of square miles. If uranium could be extracted by an in situ process, perhaps in conjunction with a shale-oil project, these black shale deposits may become very important.

At the present time, the two largest and best-known uraniferous black shales in the free world are the alum shale of Sweden (Svenke, 1955; Swanson, 1960, 1961; Anderson, 1975; Carlsson, 1977) and the Chattanooga Shale and its stratigraphic equivalents in the U.S.

Chattanooga Shale

The Chattanooga Shale is a widespread marine black shale of Devonian age. It is present in Tennessee, Georgia, Alabama, Kentucky, Mississippi, Kansas, Arkansas, Oklahoma, Illinois, and Missouri (Conant and Swanson, 1961). Most of the appraisal of the Chattanooga as a uranium resource has been carried out in and around the central-Tennessee outcrop area (Conant and Swanson, 1961; Mutschler and others, 1976). This area extends beyond central Tennessee to adjoining parts of south-central Kentucky, northern Alabama, and northwestern Georgia. Within this area of about 35,000 sq mi, the Chattanooga Shale is a persistent unit that averages 30 ft in thickness.

The Chattanooga is part of a late Devonian to early Mississippian sequence of marine black shales deposited across the central and east-central U.S. and northward into Canada. The Chattanooga appears to have been deposited at the southern end of a shallow sea bordered on the southeast, south, and west by a stable, nearly peneplained lowland underlain mostly by carbonates (Conant and Swanson, 1961, Fig. 12). Sediment supply from this area was probably small in volume and very fine grained. To the east and northeast, black shales inter-tongue with continental clastics derived from an orogenic source area that lay farther to the northeast. To the north, in Pennsylvania and the Virginias, the basin subsided more rapidly, and black shales thicken to as much as 10,000 ft.

In Tennessee, the Chattanooga consists of three members, the Gassaway Member at the top, the Dowelltown Member in the middle or at the bottom, and a thin Hardin Sandstone Member at the base in some localities. The Gassaway Member has been the chief target of investigation, because it has long been known that the Gassaway is about twice as uraniferous as the Dowelltown. Mean uranium content for the Gassaway Member is 57 ppm, whereas for the underlying Dowelltown it is 23 ppm (Mutschler and others, 1976). The Gassaway Member averages approximately 15 ft in thickness, with a range from 6 ft or less to as much as 38 ft.

Unweathered shale of the Gassaway Member is grayish-black and massive. It breaks with a conchoidal fracture. Weathered shale is medium- to dark-gray and finely fissile. Paper-thin siltstone partings and films or lenses of pyrite and marcasite are present throughout. On outcrop the pyrite breaks down, and at some places yellow and white secondary "bloom" minerals are present.

The Gassaway is divided in the middle by a 2- to 3-ft unit of interbedded black shale and gray, silty claystone. This shale-and-silty-claystone unit is both lighter-colored and less-uraniferous than the black shale above or below it. As a rule, for the Chattanooga and other black shales, the lighter-colored, less organic, and coarser-grained strata contain the least uranium.

In northern Tennessee and south-central Kentucky, the uppermost beds of the Gassaway contain phosphatic nodules. These nodules become more abundant in the sandy, basal portion of the overlying Maury Formation. Shale containing phosphate nodules generally has a lower uranium content than the bulk of the member that contains no nodules. If the shale were mined, phosphate from the Maury and uppermost Gassaway would be a possible by-product.

Carbonized plant debris in the Chattanooga Shale is abundant. It consists mainly of macerated and unidentifiable fragments that make up about 20 percent of the black shale by weight. It fills all the interstices and coats the minute mineral grains, and probably serves as a binding agent (Conant and Swanson, 1961). Fossil remains of land plants that presumably drifted into the Chattanooga sea and of planktonic marine algae have been identified. The organic material is coalified to vitrain and, in one very thin seam, ranks as bituminous coal. Oil yield by pyrolytic destruction of organic material in the Gassaway Member is in the neighborhood of 8 gal per ton. This compares rather unfavorably with yields of 15 to as much as 65 gal per ton from oil shale of the Green River Formation. For a given horizon in the Gassaway, uranium generally increases with oil yield, but this depends in part on the nature of the organic material.

Organic material in black shales is of two types: sapropelic and humic. Sapropelic matter is derived mainly from algae; humic matter mainly from woody (land) plants. Sapropelic organic matter yields 4 to 5 times as much oil as humic, but humic matter usually contains far more uranium than sapropelic. The implication is that uranium content of a black shale may be high if a significant part of the organic matter is humic.

Paleogeographically, the Chattanooga Sea was hemmed on three sides by land and enclosed large island areas (Conant and Swanson, 1961, Figs. 12 and 13). In such a setting, and given the humid climates of the middle Paleozoic, the contribution of a considerable amount of humic material from land seems assured. In a more open-sea situation, humic matter would probably be far less abundant or might be restricted to near-shore areas where it might be masked or diluted by a high rate of mud accumulation. Much of the organic matter in marine black shales is sapropelic, but if the amount of humic matter is significant, the amount of uranium in the shale may be above average.

Uranium in the Chattanooga was probably deposited syngenetically with the clay, silt, and the organic material that constitutes the shale. No uranium minerals are known from unweathered shale; the uranium is more or less evenly distributed throughout the shale, probably adsorbed from sea water on plant debris and clay particles (Swanson, 1960).

Conant and Swanson (1952) argued that the mud of the Chattanooga accumulated very slowly in shallow marine waters, mostly less than 100 ft deep. Their estimate of the accumulation rate was 1 ft in 150,000 years. Bottom sediments were unoxxygenated and rich in plant debris and sulfur acids. The slow rate of mud accumulation allowed sufficient time for organic material to adsorb comparatively large quantities of uranium from sea water.

If the foregoing interpretations are correct, then the slower the rate of mud accumulation, the greater the amount of uranium in the mud; the greater the ratio of organic matter to mineral matter (silt and clay), the greater the uranium in the shale. Shales, other than the Chattanooga, that share these characteristics of slow accumulation in normal marine waters and high organic-matter content should be favorable.

In general, the most uraniferous parts of the Chattanooga or any of its members are the most massive, least silty, least calcareous, darkest (richest in organic content), and most pyritic.

For the Gassaway Member in central Tennessee and adjoining areas, mean uranium content is 57 ppm, with a standard deviation of 9 ppm (Mutschler and others, 1976). For a given horizon, uranium exhibits fairly uniform lateral distribution for horizontal distances of several miles. Vertically, the upper part of the Gassaway Member is slightly more uraniferous than either the lower part or the gray siltstone in the middle (Conant and Swanson, 1952; Swanson, 1960, Fig. 3). Over a 12-county area in central Tennessee, the Gassaway Member is estimated to contain 4.2 to 5.1 million short tons of uranium in 76 to 91 billion short tons of shale rock. Based on projected demand in the U.S. for the period 1975 to 2000, the Gassaway could supply 75 percent of the cumulative demand for that period (Mutschler and others, 1976, p. 23).

Recent work by Provo (1977) on the Ohio Shale, a Chattanooga Shale correlative, showed that uranium decreases from Tennessee northwestward into eastern Kentucky. This fact was established earlier by Conant and Swanson (1961). Provo pointed out that, although the Ohio Shale is of lower grade, it is a much larger potential resource because it has much greater volume due to northward thickening. Whereas the Gassaway Member runs about 60 ppm uranium and averages 15 ft in thickness, for a possible yield of 4 to 5 million short tons, the entire Ohio Shale in eastern Kentucky runs about 30 ppm over a thickness of as much as 600 ft, for a possible yield of 6×10^{12} short tons. Provo found that uranium content of the Ohio Shale varies little from one member to another, as long as units of similar lithology were compared. In contrast, the Gassaway Member of the Chattanooga Shale was perhaps twice as rich in uranium as the underlying members. Apparently the northern equivalents of the Chattanooga are both of lower grade and more uniform in uranium content than the Chattanooga Shale in Tennessee.

Technical problems and economic factors loom especially large for low-grade resources such as the Chattanooga Shale and its equivalents. For a discussion of problems related to underground mining, strip mining, and solution mining of the black shales; processing of shale; and reclamation of disturbed ground, see Mutschler and others (1976).

Recognition Criteria for Marine Black Shale (Class 130)

Geologic setting: Shallow, partially enclosed epicontinental sea; adjoining land areas tectonically stable for a long period of geologic time; no large influx of sediment.

Host rock

Age: Not age restricted, but usually found in lower- to middle-Paleozoic-age rocks.

Lithology: Black, organic, massive, very fine-grained, pyritic shale; evenly laminated but dense and non-fissile when fresh; non-calcareous; may contain thin beds or partings of siltstone and beds that are phosphatic or that contain phosphatic nodules; may contain recognizable, often coalified, plant fossils.

Depositional environment: Shallow sea; brackish to nearly normal marine salinity; anaerobic, strongly reducing environment; low sediment supply and very slow rate of accumulation.

Associated rocks: Siltstone, sandstone, phosphate-rich shales, other shales.

Mineralogy

Uranium minerals: None, except for occasional secondary minerals; uranium adsorbed on organic material and possibly on pyrite, clay, and in marine phosphate minerals; uranium disseminated evenly throughout a given stratum.

Other minerals: Pyrite, phosphate minerals; bituminous hydrocarbons.

Geometry: Stratiform.

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PHOSPHORITES (CLASS 140)

Phosphorites are sedimentary rocks composed principally of phosphatic minerals. Some would restrict the term to include only marine rocks that contain more than 20 percent P_2O_5 (Stowasser, 1975). The latter definition is perhaps the most useful.

Like marine black shales (Class 130), phosphorites that are significantly uraniferous are of marine origin and constitute extensive but low-grade deposits of uranium. Grade typically runs from 0.005 to 0.03 percent uranium, and tends to increase with increasing P_2O_5 content. Most high-grade phosphate deposits (>30 percent P_2O_5) contain more than 0.01 percent uranium (McKelvey, 1955). (These figures apply to the phosphate particles only, not to the whole rock.)

Uraniferous phosphorites are distinctly noncalcareous. Uranium content drops significantly if the CO_2 content of the rock exceeds 2 percent (McKelvey and Nelson, 1950), even if the rock is highly phosphatic. The ability of carbonate ion to complex the uranyl ion and hold it in solution probably accounts for the relative lack of uranium in calcareous sediments (Bachelet and others, reported in Altschuler and others, 1958, p. 83).

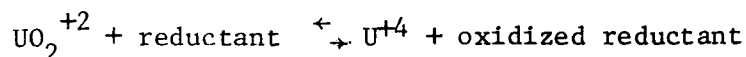
The thickest and richest phosphorites, and the most uraniferous, are those deposited on the outer parts of continental shelves where upwelling of deep marine waters has taken place. Deep marine waters are saturated with respect to phosphate and therefore constitute a likely source for phosphate. These phosphorites are commonly found in thick, miogeosynclinal sequences in which they are typically associated with black shales, chert, carbonaceous mudstone, and only minor amounts of limestone (McKelvey and others, 1953). The Phosphoria Formation of Idaho, Wyoming, Montana, and Utah is an example.

Platform phosphorites are generally nodular rather than bedded. Most platform phosphorite is associated with sandstone, limestone, and glauconite, and is not appreciably uraniferous. An exception is the Bone Valley Formation of central Florida (Subclass 142) which has been reworked and enriched by re-exposure to sea water during a subsequent transgression. Although enrichment is an epigenetic process, these deposits are classified here, somewhat arbitrarily, as syngenetic, because the initial uranium in the apatite is syngenetic.

Marine phosphorites consist chiefly of microcrystalline apatite (carbonate-fluorapatite) in the form of laminae, pellets, oolites, nodules, and skeletal or shell debris. The general formula of carbonate-fluorapatite is $Ca_{10}(PO_4, CO_3)_6(F, OH)_{2-3}$. Uranium may be present in carbonate-fluorapatite as a substitute for calcium. The ionic radii of tetravalent uranium (0.97 Å) and divalent calcium (0.99 Å) are so similar that substitution of uranium for calcium is possible (Altschuler and others, 1958). The difference in charge between these two cations is balanced by substitution of different anions, chiefly CO_3^{2-} , F^- , and OH^- . Uranium in the U^{+6} state is present in many samples of marine apatite, but is due chiefly to oxidation during subaerial weathering (Altschuler and others, 1958, p. 72).

Analyses by Dietz, Emery, and Shepard (1942) showed that apatite nodules of recent origin dredged from the sea floor off southern California contained as much as 0.004 to 0.012 percent uranium. It seems reasonable, therefore, that marine phosphorites derive much, if not all, of their uranium from sea water at the time of their formation.

Most uranium in sea water is present as hexavalent uranium in uranyl ion, UO_2^{+2} . Some tetravalent uranium is produced according to the reaction:



If apatite is precipitating, it will adsorb the reduced uranium and prevent the above reaction from reaching equilibrium. This will promote additional reduction of uranium and ensure a continual supply of U^{+4} (Altschuler and others, 1958). Uptake of uranium by apatite does not require that apatite be precipitating simultaneously with adsorption. It can also occur by ion exchange with previously deposited apatite. Thus, previously precipitated apatite, at or near the sediment-water interface, may continue to adsorb uranium for some time. Slow rates of sediment accumulation obviously work in favor of this process.

Uranium-bearing phosphorites are considered to be syngenetic. Whether more uranium is incorporated during precipitation or shortly after precipitation is unknown. As long as uranium is adsorbed during or soon after precipitation, and at the sediment-water interface while the newly deposited phosphorite is still soft sediment, uranium in the phosphorite is considered syngenetic, or essentially so. There is some evidence that marine apatite may form diagenetically by replacement of carbonate (Emigh, 1967). Should this be proven, uranium-bearing phosphorites would have to be reclassified as epigenetic.

Like uranium in marine black shales (Class 130), uranium in phosphorites is usually disseminated rather uniformly throughout a given bed or horizon. Discrete uranium minerals are rarely present. Secondary uranium minerals, such as tyuyamunite in the Phosphoria Formation, autunite in the Bone Valley Formation, and torbernite in the Moroccan deposits, have been reported, but these are so sparse that they are neither of economic interest nor particularly important as prospecting guides.

There are four types of sedimentary phosphate deposits in addition to marine phosphorites. These are residual phosphorites, phosphatized rock, river-pebble deposits, and guano. Residual deposits are concentrations of phosphorite derived from the weathering of marine phosphatic limestone. Phosphatized rock is formed by solution of phosphate from overlying rock and deposition by replacement or filling of interstices in underlying rocks. River-pebble deposits consist of fluvial concentrations of phosphate nodules derived from older phosphatic rocks, usually marine phosphorites. Guano deposits are composed of animal (chiefly bird and bat) excrement. Guano deposits are typically small and contain practically no uranium. All of these deposits are low in uranium and of little interest, with the exception of marine phosphorites and with the possible exception of river-pebble deposits, whose uranium content depends upon the uranium content of the parent material. In general, only phosphate deposits that formed in the sea or that were exposed to sea water at some time are appreciably uraniferous.

URANIFEROUS PHOSPHORITES OF THE PHOSPHORIA TYPE (SUBCLASS 141)

Phosphate deposits within the Permian Phosphoria Formation are found over a large area in Montana, Idaho, Wyoming, Utah, and Nevada. The richest phosphate deposits are in southeast Idaho, near Montpelier, and in adjoining parts of Montana, Wyoming, and Utah.

The Phosphoria Formation consists of two transgressive-regressive marine cycles. Each cycle consists of a lower carbonaceous phosphatic shale member overlain by a chert or carbonate member. The lower phosphorite-chert couplet (Meade Peak Phosphatic Shale Member and the Rex Chert Member) is thickest in southeast Idaho, where it ranges up to 1300 ft in thickness. The upper couplet (Retort Phosphatic Shale Member and Tosi Chert Member) is thickest in northwestern Wyoming and southwestern Montana, where it may be as much as 300 ft thick. Most of the phosphorite mining and uranium exploration has been in the thick lower phosphatic-shale member. Eastward into Wyoming, the phosphatic shale and chert members intertongue or intergrade with lateral (shoreward) facies of carbonates, sandstones, redbeds, and evaporites (McKelvey and Carswell, 1955; McKelvey and others, 1956).

Phosphorite and mudstone are the lithologic end members of the phosphatic shales. The phosphorite consists of carbonate-fluorapatite, $\text{Ca}_{10}(\text{PO}_4, \text{CO}_3)_6\text{F}_{2-3}$ (Altschuler and others, 1958) or francolite $\text{Ca}_5(\text{PO}_4, \text{CO}_3)_3(\text{F}, \text{OH})$ (Emigh, 1958, 1967). In most of the phosphatic beds, and especially in the most phosphatic beds, phosphate is present as submicrocrystalline carbonate-fluorapatite aggregated into fine-grained, structureless pellets. Varying amounts of detrital minerals, carbonate, and carbonaceous matter also generally are present. In addition to pellets, phosphate grains may be oolitic or pisolitic, or they may consist of fish scales, phosphatic brachiopod shells, or phosphatic casts of small gastropods. Uranium generally is greater in pelletal phosphorite than in phosphorite composed of fossil material.

Nearly all phosphorites and phosphatic beds contain uranium, but the content varies from 0.001 to as much as 0.65 percent. The uranium is acid soluble and for the most part tetravalent. It is dispersed and appears to substitute isomorphously for calcium in carbonate-fluorapatite (Altschuler and others, 1958). With the exception of tyuyamunite found along joint surfaces at places in the Crawford Mountains, Utah, no discrete uranium minerals are known. Phosphatic rocks near the surface in the Crawford Mountains are extremely weathered. Tyuyamunite probably is the result of limited amounts of uranium being leached from the weathered phosphorites.

When fresh and unweathered, phosphorite beds are hard and dark brown or black. The interbedded mudstones are pyritic. Weathered phosphorites are friable and brown to light colored. Topographically, weathered phosphorites may form valleys between more-resistant units. Weathering results in relative phosphate enrichment by removing carbonates, carbonaceous matter, and minor metals including some depletion of uranium.

The phosphatic shale members are most phosphatic either at both the top and bottom or only at the bottom of the member. In southeast Idaho, the entire Meade Peak Phosphatic Shale Member averages 11 to 12 percent P_2O_5 , but beds 5 to 10 ft thick near the base and at the top of the member run 25 to 33 percent P_2O_5 . Uranium content, from bed to bed, generally increases with increasing P_2O_5 content. The correlation between uranium and P_2O_5 is strongest for beds and samples that contain the largest amounts of uranium; but for beds containing comparatively small amounts of uranium, the correlation may actually be negative (McKelvey and Carswell, 1955). Variations in uranium content relative to P_2O_5 may be due either to temporal or areal variations in uranium content of sea water at the time of deposition or to variations in the sedimentation rate. When sedimentation is slow, each crystal of apatite is in contact with sea water for a longer time and may adsorb more uranium.

Uranium content also varies regionally with total phosphate content of the formation. Both uranium and phosphate generally increase westward from Wyoming into southeastern Idaho. However, the increase in uranium is not due solely to the regional westerly increase in phosphate, because even for beds that remain essentially constant in phosphate, uranium may still show a westerly increase.

The reasons for variation in uranium content from one phosphorite bed to another, or within the same bed over a large area, are apparently complex and not well understood. However, uranium generally increases with P_2O_5 for the richer beds, and uranium content of individual beds is relatively constant over large areas. McKelvey and Carswell (1955) determined that phosphate beds of minable thickness (>3 ft) that contain more than 31 percent P_2O_5 generally contain 0.01 to 0.02 percent uranium.

McKelvey and Carswell (1955) interpreted the Phosphoria phosphorites as the offshore or distal facies of a shelf-to-shore facies sequence. In this and an earlier paper (McKelvey and Nelson, 1950), McKelvey and coworkers concluded that the uranium was syngenetic with the phosphorite. As evidence of syngeneses they cite uraniferous phosphorite beds persistent over thousands of square miles with little change in either lithology or uranium content. McKelvey and Nelson (1950) suggested that the mineralization process was chemical adsorption of tetravalent uranium at sites normally occupied by calcium on the surface of precipitating apatite crystals. (The chemistry of uranium in phosphorites may be more complex than some of the early literature indicates. See Sheldon, 1959.) Citing Dietz and others (1942), who found that sea water at depths of a few hundred meters is saturated with calcium phosphate, McKelvey and Nelson considered the edge or outer part of the continental shelf to be the most favorable place for phosphorites to form. Along the edge of the shelf, cold, phosphate-rich waters could ascend and flood the outer part of the shelf, while land-derived detritus that could mask or dilute phosphorite accumulations would be at a minimum due to the distance from the coast. This concept of phosphorite deposition on the outer part of the shelf was used by Sheldon (1964) to explore successfully for phosphorites in southern Turkey.

A characteristic suite of sediment types seems to accompany the phosphorites (Sheldon, 1964). These sediment types include black shale, chert, and carbonate. With the exception of black shales, these sediment types are characterized by a paucity of fine-grained detritus. This is consistent with a depositional site some distance from shore and where upwelling of deep, cold marine waters would occur. Both Emigh (1967) and Sheldon (1964) considered deposition to have been in fairly shallow water, where the bottom was periodically touched by wave energy to winnow out the fine fraction. Distance from shore and a shallow, shelving bottom (McKelvey and Carswell, 1955) both may apply. Phosphorite and chert indicate an abundant supply of phosphorous and silica. As cold waters ascend and spread over the shelf they may be expected to warm, lose CO_2 , and increase slightly in alkalinity to a pH of about 7.5 or more (Sheldon, 1957, 1964). Such alkaline conditions would allow apatite to precipitate, and the same upwelling would fertilize shelf waters with nutrients that would allow silica-, phosphate-, and carbonate-secreting organisms to flourish. Thus, cherts, carbonates, and shelly phosphatic beds within the same facies sequence as the phosphorites are accounted for.

A different view on the origin of phosphorites was given by Emigh (1958, 1967) and Degens (1965). They suggested that carbonate fluorapatite forms by early metasomatic replacement of CO_3^{-2} by PO_4^{-3} in previously deposited carbonates. The origin of phosphorites then becomes one of early diagenesis (epigenesis) rather than direct precipitation (syngensis). The origin of uranium in the phosphorites was not discussed by Emigh or Degens, but presumably would also be early diagenetic. Phosphoria-type phosphorites are classified here as syngenetic. If the phosphorites are diagenetic, this phase of diagenesis is apparently very early.

A feature of the more uraniferous phosphorites that seems to be characteristic is a very slow rate of sediment (phosphorite) accumulation. The Phosphoria Formation, where it is highly phosphatic, is about 200 to 500 ft thick, yet it spans a major part of the Permian from Leonardian to Guadalupian (Sheldon, 1964).

Some of the shale beds associated with the phosphorites are black and superficially resemble certain uraniferous black shales, such as the Chattanooga. Most of these black shales are not appreciably uraniferous. However, two zones of black shale, each a few feet thick and containing up to 0.012 percent uranium, have been discovered in western Wyoming (Sheldon, 1957). These beds lie just below a widespread phosphatic zone near the top of the Meade Peak Phosphatic Shale Member, although the beds themselves are virtually nonphosphatic. These black shales are interpreted as a deeper-water facies than the phosphorites and they grade eastward into phosphorites. Origin of uranium in these nonphosphatic beds is presumably as described for marine black shales (see Class 130). This genetic association of black shale and phosphorite should be kept in mind during evaluation and assessment of rocks of either lithology.

Recognition Criteria for Uraniferous Phosphorites of the Phosphoria Type
(Subclass 141)

Geologic setting: Outer part of continental shelf in areas of upwelling cold water and limited supply of silt and clay.

Host rock

Age: Not age restricted.

Lithology: Hard, dark-brown to black beds of cryptocrystalline carbonate-fluorapatite, commonly in the form of small pellets, but also as oolites, pisolites, or phosphatic fossil material; light-colored and friable when weathered.

Depositional environment: Outer continental shelf away from coarse clastics and shallow-water, near-shore carbonates; in water shallow enough to permit fine-grained detritus to be winnowed out; very slow sedimentation rate.

Associated rocks: Chert, black shales, mudstone, and possibly some carbonate rocks (fine-grained detrital and chemical miogeosynclinal assemblage); toward paleoshoreline these facies and phosphorites intertongue or intergrade with sandstone, limestone, redbeds, or evaporites.

Mineralogy

Uranium minerals: Carbonate-fluorapatite, a uranium-bearing mineral.

Associated minerals: Pyrite in adjacent mudstone and shale; clay, quartz, and other fine-grained detrital minerals.

Geometry: Stratiform.

URANIUM-BEARING PHOSPHORITES OF THE LAND-PEBBLE TYPE (SUBCLASS 142)

The phosphate deposits in the land-pebble district of west-central Florida constitute one of the world's most important sources of phosphate. These deposits differ from those of the Phosphoria Formation in that they are associated with a sequence of carbonates and transgressive sandstone. Black shale and chert are absent. Deposits of the land-pebble district occur within a 1,000-sq-mi area east of Tampa Bay and south of Lakeland, Florida. The chief phosphate-producing unit is the Bone Valley Formation, but the underlying Hawthorne Formation is also somewhat phosphatic.

The Hawthorne Formation (Miocene) ranges from 0 to several hundred feet in thickness. It consists mainly of limestone, quartz sand, smectite, and scattered grains or nodules of apatite. Where it is exposed in open-pit mines, the top of the Hawthorne is a buff to yellow, sandy and clayey, slightly phosphatic dolomite. In one test well, dolomite changes abruptly to sandy, slightly phosphatic limestone 80 ft from the top of the formation.

The Hawthorne Formation, locally called bedrock, is uneconomic for phosphate. It averages less than 5 percent P_2O_5 and contains about 0.001 percent U_3O_8 (Table 2). When apatite grains are considered by themselves, they also are low in both phosphate and uranium. The richest grains and nodules may run 32 percent P_2O_5 and 0.01 percent U_3O_8 , but the average is about 20 percent P_2O_5 and less than 0.005 percent U_3O_8 (Cathcart, 1955).

At the very top of the Hawthorne Formation is a thin and discontinuous residual clay. The clay is sandy and it contains a phosphatic residuum of primary apatite grains and nodules and secondarily phosphatized limestone pebbles. Locally this clay unit is referred to as "bedclay". It grades downward into hard dolomite and was probably derived from the dolomite by carbonate leaching during a period of late-Miocene or early-Pliocene weathering. At places this clay contains sufficient phosphate to be mined together with the overlying beds of the Bone Valley Formation. The bedclay ranges from 7 to 20 percent P_2O_5 and 0.002 to 0.015 percent U_3O_8 . Most of the uranium in the bedclay is concentrated in residual apatite grains (Cathcart, 1955).

The Bone Valley Formation (Pliocene) unconformably overlies the Hawthorne, and can be divided into a lower unit and a thinner, upper unit. The lower unit is as much as 50 ft thick, but averages about 20 ft. It consists of a phosphatic, pebbly and clayey sand that is characterized by crude graded bedding (Altschuler and others, 1958, Fig. 7). The pebbles and phosphatic fraction of the sand are composed of apatite. The remainder is quartz sand and smectite. Individual beds may consist of either a graded (fining-upwards) conglomerate of apatite nodules or a sand composed of apatite and quartz. The lower part of the Bone Valley Formation, referred to locally as "matrix," plus the economic part of the underlying bedclay, constitute the phosphate ore that is mined in the land-pebble district. Land pebble is the local term for the apatite nodules.

TABLE 2. PHOSPHATE AND URANIUM ANALYSES, LAND-PEBBLE DISTRICT, FLORIDA.
DATA FROM CATHCART (1955) AND ALTSCHULER AND OTHERS (1955).

		Average for formation, percent		Apatite nodules only, percent	
		P ₂ O ₅	U ₃ O ₈	P ₂ O ₅	U ₃ O ₈
Pleistocene terrace sands		0.5	0.001		
Aluminum phosphate (leached) zone	overall	8-10	0.012		
	base				as much as 0.X
Bone Valley Formation	upper		0.002 to 0.003		
	lower	10-20	0.008	pebble: 29-34 apatite sand: 32-37	0.008 to 0.050 0.004 to 0.030
Hawthorne Formation	residual clay	7-20, avg. 8	0.002 to 0.015, avg. 0.005		
	dolomitic part	<5	0.001	<20, but as much as 32	<0.005, but as much as 0.10

Average matrix contains slightly less than 20 percent P_2O_5 and 0.008 percent U_3O_8 . At the mill, the matrix is sorted into three size products: pebble, slime and flotation feed. Pebble (+14 mesh, or 1.4 mm) runs 29 to 34 percent P_2O_5 and 0.008 to 0.50 percent U_3O_8 . Slime (-150 mesh, or 0.1 mm) averages 15 percent P_2O_5 and 0.005 percent U_3O_8 . Flotation feed is the intermediate-size product, and consists of quartz and apatite sand. Apatite-sand concentrate from the flotation feed runs 32 to 37 percent P_2O_5 and 0.004 to 0.03 percent U_3O_8 .

The coarser phosphate nodules, the "pebble" fraction, run higher in uranium and lower in phosphate than the finer-concentrate fraction (apatite sand). Uranium content of the pebble fraction averages 0.01 to 0.02 percent U_3O_8 , and the P_2O_5 content averages about 31 percent, whereas, in the finer-grained concentrate, the apatite particles commonly run 0.005 to 0.15 percent U_3O_8 and 34 percent P_2O_5 . However, within a given size fraction, uranium tends to increase with P_2O_5 content of the apatite. The coarser pebbles may be enriched in uranium relative to the smaller material because they were less susceptible to burial and therefore were exposed to sea water for a longer time.

The upper part of the Bone Valley Formation is about 8 to 10 ft thick and consists of massively bedded sand and clay. It contains only traces of clastic phosphate as apatite grains or nodules near the base. Uranium runs only 0.002 to 0.003 percent U_3O_8 . Contact between upper and lower units of the Bone Valley is gradational over a few inches to a foot or more.

Overburden in the land-pebble district consists of three units, or zones. These are the relatively nonphosphatic upper part of the Bone Valley Formation, a leached zone in the upper and sometimes also the lower parts of the Bone Valley, and the overlying barren Pleistocene terrace sands. The leached zone is a potential source of uranium in addition to the lower part of the Bone Valley.

The leached or aluminum-phosphate zone varies from a few inches up to 25 ft in thickness, and averages about 4 ft. It has formed by acidic waters percolating downward through the unit (lateritic weathering). The leached zone is not a stratigraphic unit. It is irregular in section and may affect either the upper unit or both units of the Bone Valley Formation. Depth and extent of the leached unit conforms to the topography, being thickest and most intensely developed along the courses of the Peace and Alafia Rivers and their larger tributaries. Conformance of the leached zone to the topography is indicative of its origin by weathering and supergene processes.

The leached zone is characterized by aluminum-phosphate rather than calcium-phosphate minerals, and by a basal horizon of uranium enrichment.

Within the leached zone, apatite $[Ca_{10}(PO_4CO_3)_6F_{2-3}]$ and montmorillonite have been leached and replaced. Smectite is replaced by kaolinite, and apatite by the aluminum-phosphate minerals crandallite $[CaAl_3(PO_4)_2(OH)_5 \cdot H_2O]$, millisite $[(Na,K)CaAl_6(PO_4)_4(OH)_9 \cdot 3H_2O]$, and wavellite $[Al_3(PO_4)_2(OH)_3 \cdot 5H_2O]$. Where the replacement of leached apatite is incomplete, the leached zone is highly porous due to unfilled voids.

In typical sections of the leached zone, apatite (carbonate-fluorapatite) is still present at the base and only incipiently leached and altered (Altschuler and others, 1958, Fig. 11). In the middle of the zone, crandallite and millisite are found, and at the top, where alteration is most thorough, wavellite. During leaching and alteration of clays and phosphate minerals, uranium is released and transported downward by descending acid ground waters. At or near the base of the leached zone, the acidic solution is neutralized by calcium phosphate (Altschuler and others, 1958) and the uranium adsorbed by the porous, partly leached apatite. Uranium in the leached zone is always associated with calcium phosphates in preference to aluminum phosphate. Thus uranium lies concentrated at the base of the leached zone where apatite is still present, and to a lesser extent in the middle or just above the base where crandallite (calcium aluminum phosphate) is present.

Average uranium content throughout the leached or aluminum-phosphate zone is 0.012 percent U_3O_8 , a two-fold increase over unaltered rock of the lower unit in the Bone Valley Formation. Individual specimens from the basal part of the leached zone may contain as much as 0.X percent U_3O_8 (Altschuler and others, 1955).

Three origins have been suggested for uranium in the land-pebble phosphates: ground water (epigenesis), precipitation from sea water (syngeneses), and secondary enrichment from sea water (syngeneses-epigenesis) (Altschuler and others, 1958). With the exception of uranium at the base of the leached zone, these deposits are classified here and elsewhere as syngenetic (Cathcart, 1955). Uranium at the base of the leached zone is the result of supergene-epigenetic processes, and is a special case. Ground water is ruled out for the Bone Valley Formation, because mineralization by uranium-bearing ground water would have affected sand-size apatite grains as well as the coarser nodules. However, sand-size apatite in both the Hawthorne and Bone Valley Formations contains less uranium than the coarser nodules.

During the Miocene, when the Hawthorne Formation was being deposited on a relatively shallow bank, uranium was probably adsorbed from sea water by primary apatite precipitating on the bottom. Many of the sand-size and finer apatite particles in the bedclay and overlying Bone Valley Formation are probably primary uranium-bearing apatite, reworked, at least in part, from the underlying Hawthorne Formation.

The coarser-grained phosphatic materials consist of aggregate or complex nodules and phosphatized limestone. It is probable that much of this material was also derived from the Hawthorne Formation and was reworked, perhaps repeatedly, during the Pliocene Bone Valley transgression. Some of the phosphatized limestone contains Hawthorne-age fossils and apatite pseudomorphs after calcite as evidence of reworking and secondary phosphatization.

The Hawthorne-derived apatite appears to have adsorbed additional uranium from sea water during the Bone Valley transgression. Apatite in the lower Bone Valley is typically richer in both uranium and phosphate than apatite material in the Hawthorne. Thus is the case made for secondary (epigenetic) enrichment

of the reworked apatite. It has been suggested that the coarser nodules (pebble) in the Bone Valley contain more uranium than the sand-size apatite concentrate because the nodules were exposed to sea water longer by virtue of their size and slower burial (Cathcart, 1956).

In addition to the land-pebble district in west-central Florida, there is also the north Florida phosphate (or pebble) district and the Ocala hard-rock phosphate district (Southern Interstate Nuclear Board, 1969, Fig. 12). All of these Florida phosphate deposits are uraniferous to some degree, as aerial radiometric surveys have shown (Cathcart, 1954; Moxham, 1954).

A report by the Southern Interstate Nuclear Board (1969) states that Florida pebble deposits may contain some 600,000 tons of U_3O_8 , the recovery of which may be feasible as a by-product of commercial phosphate production. The report does not state specifically whether this 600,000-ton figure includes all Florida pebble deposits or just those in the Bone Valley Formation. Deposits to the north, in North Carolina, South Carolina, and Georgia, may contain 750,000 tons of U_3O_8 .

Commercial recovery of by-product uranium from wet-process phosphoric acid for phosphate-fertilizer production is being developed. About 90 percent of the uranium in phosphate ore is leached during digestion of the ore rock by sulfuric acid. Uranium is recoverable from the resulting phosphoric acid by solvent extraction, yielding a product of 97-percent- U_3O_8 purity. Modular, onsite units for uranium recovery, and a 1,000-ton-per-year central processing plant have been constructed (Stowasser, 1975). It is not clear whether the leached (aluminum phosphate) zone will be utilized for uranium extraction or whether it will continue to be stripped and discarded. If the aluminum-phosphate zone, particularly the basal part, were mined, it would significantly increase the potential of the district as a producer of by-product uranium.

Recognition Criteria for Uraniferous Phosphorites of the Land-Pebble Type
(Subclass 142)

Geologic setting: Platform or bank along near-shore margin of narrow (?)
Continental shelf.

Host rock

Age: Not age restricted.

Lithology: Pebbly and clayey phosphatic sandstone; pebbly phases
consist of phosphatic nodules in sand and clay matrix;
sandy phases consist of both quartz and apatite
grains.

Depositional
environment: Shallow marine.

Associated rocks: Carbonates and marine sandstone.

Mineralogy

Uranium minerals: Carbonate-fluorapatite, a uranium-bearing mineral.

Associated
minerals: Clay, quartz, and other detrital minerals; Al and
Ca-Al phosphate minerals in weathered zones.

Geometry: Stratiform.

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WATER (CLASS 150)

Surface water, ground water, hot springs, oil-field brines, sea water, and mine and mill waters are all included in this class. None of these are "deposits" in the usual sense. They are not concentrations of crystalline minerals in rock. Nevertheless, some of them do constitute a possible source of uranium, and one of them, mill waters, is being utilized.

All natural waters contain uranium. Typical values for fresh surface and ground waters are in the range of 0.05 to 10 ppb uranium (Rogers and Adams, 1970, Table 92-1-2). These values are so low that, given present-day technologies and economic conditions, fresh water is not a practical source of uranium.

Although fresh water contains only very small amounts of uranium, water samples from mining districts may run several hundred to several thousand parts per million. Such values are very high for fresh water, and are encouraging when encountered in a geochemical sampling program.

The two waters most likely to yield uranium economically are sea water and mine and mill waters. Sea water contains about 3 ppb uranium and is present in enormous volume. Leach solutions at copper mills may run about 10 ppm uranium. Both sea water and mill waters have been studied as a source of uranium. Pilot plants for the extraction of uranium from sea water are being considered by at least one country, and uranium is already being recovered from leach solutions at at least one copper mill in the U.S.

Mine and Mill Waters

Certain mine and mill waters are potential sources of uranium. Water in uranium mines may run 5 to 15 ppm U_3O_8 (Woodmansee, 1975, Table 6). Selected analyses that exceed 5 ppm U_3O_8 are given in Table 3. Whether mine waters could be used as a source of uranium would depend upon these waters maintaining both a high uranium concentration and a substantial and reliably constant rate of flow. It may only be in exceptional situations that both of these conditions obtain.

Uranium in leach solutions at copper operations may run 1 to 5 ppm U_3O_8 (Woodmansee, 1975, Table 6). A study by the U.S. Bureau of Mines at 14 copper operations in the western U.S. indicated that an annual production of 1000 tons of U_3O_8 at competitive prices would be possible from these operations (Bieniewski and others, 1971). Although recovery of uranium from mine and mill waters is not yet widely practiced, Westinghouse (Wyoming Mineral Corp.) is currently extracting uranium from leach solutions at Kennecott's Bingham Canyon copper mine, Utah.

TABLE 3. SELECTED ANALYSES OF MINE WATERS THAT CONTAIN MORE
THAN 5 PPM U_3O_8 (FROM McCARN AND FREEMAN, 1976).

MINE	LOCATION	U_3O_8 ppm	REMARKS
Schwartzwalder	Jefferson County, CO	12	Vein deposits in Precambrian rock
Hargerty Prospect	Saguache County, CO	28-168	
Pitch Mine	Saguache County, CO	93.0	Fault-controlled veins in Paleozoic limestone
Deremo Mine	San Miguel County, CO	6.6	
Wencor Paydirt Pit	Fremont County, WY	8.0	Open pit: Battle Spring Formation (Eocene), Crooks Gap area
Sunset Pit	Fremont County, WY	24	Open pit, Wind River Formation, Gas Hills area
Vecca Pit	Fremont County, WY	5.5	Open pit, Wind River Formation, Gas Hills area

Sea Water

Uranium concentration in sea water is relatively constant, in the range of 1 to 4 ppb (Rogers and Adams, 1970, Table 92-1-1). An often-quoted average value is 3 ppb. As far as total uranium is concerned, sea water is potentially one of the largest resources, containing an estimated 5 billion tons of uranium (Woodmansee, 1975).

Considerable research has been done on the extraction of uranium from sea water. Principal investigating countries have been Japan, England, U.S.A., and Germany. Japan has progressed beyond initial studies and is planning a pilot plant to be operational by 1983. A 1000-tonne/yr recovery plant is tentatively planned for 1990 (NuclearFuel, 1977)

Problems with the extraction of uranium from sea water are great. The dominant problem is to ensure large and constant volumes of new sea water and to prevent processed sea water from being recycled through the plant. To obtain 1000 tonne/yr of uranium, 1 trillion tonnes of sea water will have to be processed. Cost estimates for the Japanese project vary from \$70 to \$300 per lb.

Several plans for extraction of uranium from sea water have been investigated. These include combined desalination-uranium extraction plants, pumped-water plants, and tidal-powered plants. Uranium production from the largest desalination plant now under consideration is estimated to be only about 1 tonne/yr. For either a pumped-water or tidal-power system, the enclosure of large areas of sea water along a coastline seems to be necessary. Some estimates are that for a 10,000 tonne/yr system, an enclosed tidal lagoon of 300 to 400 sq mi would be required. Enclosure on such a large scale may be environmentally objectionable. For further discussion of these matters, see Llewelyn (1975).

Although extraction of uranium from sea water may be possible, it will probably remain impractical for most countries for some time to come. However, if world demand requires exploitation of increasingly low-grade resources on land, or if export of uranium on the world market becomes politically complicated, uranium in the sea may take on new importance.

Closely related to sea water in open oceans as a source of uranium are anomalous waters in inland seas. Barnes and Ruzicka (1972) mention the Aral Sea as containing significant amounts of uranium, but they do not say how much. The Caspian Sea, which has a similar geologic history, contains 3 to 10 ppb uranium (Rogers and Adams, 1970, Table 92-1-1). Both the Caspian and Aral Seas are vestigial seas of once-larger bodies of sea water that were connected to the oceans in the early Tertiary.

The Black Sea might also be included here. It is a restricted sea, rather than an inland sea. The Black Sea is still connected to the open ocean via the Mediterranean and the very narrow Bosphorus, but its surface waters are less saline than normal sea water, due to restricted circulation through the Bosphorus and the comparatively large influx of fresh water. Water in the

Black Sea contains about 2 ppb uranium, about the same as normal sea water. The Black Sea might contain more uranium than it does, but recent study has shown that planktonic coccoliths biogenically remove uranium from the water. When the coccoliths die, they sink to the bottom and the uranium becomes incorporated in organic-rich mud (Mining Congress Journal, 1978). Thus, the value of a restricted sea, like the Black Sea, may be as a sink for uranium in the bottom sediments, if the necessary life forms are present, rather than the water itself as a source.

Saline and Playa Lakes

Saline and playa lakes obtain their high concentration of dissolved salts by evaporation. Characteristically, these lakes are found in hot, dry climates. Saline lakes are intriguing possible sources for uranium, because surface and ground waters, commonly containing several parts per billion uranium, deliver their dissolved loads to these lakes over long periods of geologic time. However, some of the better-known examples, such as the Great Salt Lake, do not contain exceptional concentrations of uranium. By one analysis, the Great Salt Lake contains only about 5 ppb uranium (Stewart and Bently, 1954).

Walker Lake, Nevada, is much higher in uranium. It contains about 130 ppb uranium (Lawrence Livermore Laboratory, 1976). Total uranium in Walker Lake may be about 600 ton (Mining Engineering, 1976). However, recovery of any but an initial small amount of uranium from a source such as Walker Lake would probably be very impractical because of the limited supply of uranium-bearing water in the lake and the diminishing concentrations of uranium that would ensure during extraction.

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LIGNITE, COAL, AND NONMARINE CARBONACEOUS SHALE DEPOSITS (CLASS 210)

Lignite, coals, and carbonaceous shale are among the least uraniferous sedimentary rocks, but locally they may contain enough uranium to constitute a deposit. Included in this class of host rocks are carbonaceous shales, peat, lignites, and all ranks of coal. The term "carbonaceous" is used for rocks containing organically derived carbon either in the elemental form or in chemical combinations with hydrogen and other elements normally present in living organisms (Vine, 1962). The bulk of the carbonaceous material in rocks of this class is derived from land plants.

Individual beds of uranium-bearing lignite, coal, and nonmarine carbonaceous shale are typically thin and laterally discontinuous. In the case of lignite, thicknesses commonly range from inches to a few feet. The thicker beds are commonly mineralized only at the top, with grade decreasing downward toward the base (Denson and Gill, 1955, Fig. 141C). Some lignites, especially the thinner ones, may be mineralized throughout. In many cases mineralization is spotty or irregular, and only parts of a given bed may be mineralized.

In addition to uranium, mineralized beds often contain anomalous quantities of other metals, such as As, Be, Co, Cu, Ge, La, Mo, Ni, P, Pb, Se, Sn, Ti, V, Y, Zr, and rare-earth elements. None of these elements are necessarily indicative of either the presence of uranium or the amount of uranium that may be present; however, at a given deposit, many of these elements may be correlated strongly with uranium and probably share the same supergene origin.

Identifiable uranium minerals in deposits of this class are either absent or secondary in origin. Most of the uranium seems to be held in organic ionic compounds similar to humic acids (uranyl humates). Secondary minerals, such as meta-autunite and metatyuyamunite, are occasionally present in some of the higher-grade deposits.

Most uraniferous, nonmarine carbonaceous rocks were deposited on low-lying coastal floodplains or in continental basins. These rocks are frequently interbedded with or overlain by acidic tuffs or tuffaceous sedimentary rocks. Some lie within basins bordered by rocks known or likely to contain uranium, such as granite, uraniferous sandstone, and (or) mineralized rocks in metal-mining areas.

Age of continental carbonaceous rocks ranges from Silurian to Quaternary and is coincident with the age of vascular land plants. Most of the larger and richer uranium-bearing deposits, at least in the U.S., are in rocks of Tertiary age.

In general, rocks of this class, even the very fine-grained carbonaceous shales, will not be easily mistaken for marine carbonaceous rocks (black shales of Class 130). Where coaly material is concentrated in discrete seams or stringers, there should be no confusion, because coal and lignite do not normally form in marine environments. Some coals and lignites may have been deposited in brackish-water environments, such as bogs, swamps, and lagoons,

along coastlines. Intertonguing relationships of these deposits with normal marine sediments may obscure the origin of the carbonaceous beds. Nevertheless, the carbonaceous beds should probably be assigned to this class if they are coaly or highly lignitic.

Nonmarine carbonaceous shales, although commonly dark colored, are not usually black or as dark as marine shales. Furthermore, they are most likely to be siltstone or mudstone rather than a true shale. Plant debris in these so-called "carb shales" is typically scattered throughout the rock, or it may be concentrated along bedding planes. Plant debris, even if metamorphosed to coaly flecks in the rock, is often identifiable as fossil wood. In the case of marine carbonaceous shales, the organic material usually occurs as microscopic particles or as coatings on silt and clay. A further difference is that organic material in marine rocks tends to be predominantly algal (sapropelic), rather than woody or herbaceous (humic) (Vine, 1962).

Other differences between marine and nonmarine uranium-bearing carbonaceous rocks are these: Uranium in the marine rocks is generally syngenetic and coextensive with a particular bed or group of beds. In the nonmarine rocks, uranium is usually epigenetic and locally distributed within a bed or group of beds. Nonmarine carbonaceous rocks are generally much less laterally extensive than marine carbonaceous rocks (Klenner and Wyant, 1957).

Among the rocks of this class, carbonaceous shale, high-ash lignites, and subbituminous coals seem to contain the largest amounts of uranium (McKelvey, 1955). Individual deposits of uraniferous lignite and coal in the U.S. commonly range from 0.005 to 0.01 percent uranium, but certain deposits may run as high as 0.X percent uranium. Deposits range in size from less than a square mile to about 100 square miles and contain from less than 100 to over 10,000 tons of uranium. Although many deposits are low-grade, relatively small, and localized, ore grade can be materially upgraded by burning or retorting combustible carbonaceous rocks. Most or all of the uranium remains in the ash (Klepper and Wyant, 1957).

Uranium in lignite, coal, and carbonaceous shale has been attributed to several origins: precipitation from uraniferous groundwater (epigenetic, post-coalification), concentration either by growing plants or decaying plant material (syngenetic, precoalification), or precipitation from hydrothermal solutions. A hydrothermal origin has been proposed for uranium at the Leyden mine, Jefferson County, Colorado (Gude and McKeown, 1953). At the Leyden mine, uranium is in a coal bed cut by a shear zone, and is probably best considered a vein-type deposit (Class 730). In other deposits, uranium may have been derived by leaching of acidic or alkalic intrusive rocks, veins, or uraniferous marine sedimentary rocks. In the case of Upper Cretaceous and Tertiary lignite in the western U.S., uranium seems to have been leached from overlying tuffs and tuffaceous sandstone and transported by groundwater to underlying lignites. Uraniferous lignite in the southern Williston Basin is an example.

Uraniferous Lignite in the Williston Basin

The Williston Basin is a broad area of some 225,000 sq mi in western North Dakota, northwestern South Dakota, eastern Montana, and adjacent parts of Canada. It is unusual among interior basins of North America because of its very large size, long-continued subsidence, and its relatively complete stratigraphic section. Strata representing all geologic periods of the Phanerozoic are present. The total section is nearly 17,000 ft thick. Since Precambrian time, the Williston Basin has been a large downfolded structure on the broad platform between the continental interior on the east and the geosyncline to the west. Prior to the early Late Cretaceous, sedimentation was dominantly marine; since the Late Cretaceous, sedimentation has been continental, with the single exception of the Paleocene Cannonball Sea deposits. Today, the basin is covered largely by a few feet to as much as 2,700 ft of Upper Cretaceous and Tertiary continental sediments that dip gently toward the center of the basin (Hansen, 1972; Keefer, 1974).

During the Paleocene and Eocene, the western interior basins were sites of extensive coal and lignite accumulation. The Fort Union Formation (Paleocene) and Wasatch Formation (Eocene) are the chief coal-bearing units. Only the Fort Union is present in the Williston Basin, and the coaly material it contains is lignite. Lignite is so extensive in the Williston Basin that it constitutes the largest reserve of lignite in the U.S., most of it in western North Dakota and eastern Montana (Averitt, 1975).

The sequence of continental sediments in the Williston Basin begins with the Hell Creek Formation. The Hell Creek Formation (Late Cretaceous) consists of dark-gray, bentonitic claystone; silty shale; and gray-brown, lenticular sandstone. The lenticular sandstone is considered fluvial, or possibly a brackish-water deposit. Local occurrences of carnotite and becquerelite are present in Hell Creek sandstone and carbonaceous shale in the Long Pine Hills of eastern Montana. (See Denson and Gill, 1965, Fig. 1 and Pl. 1 for localities.) At places, the Hell Creek contains thin lenses of lignite in the upper part of the formation, but lignite in the Hell Creek is not commercial. In the East Short Pine Hills, South Dakota, one relatively high-grade uranium deposit of lignite is known (Denson and Gill, 1965, p. 7). The Hell Creek Formation conformably overlies the Fox Hills Sandstone, the uppermost marine unit of Late Cretaceous age. The contact with the Fox Hills is gradational. The upper contact of the Hell Creek Formation with the overlying Fort Union is also conformable, and is placed at the base of the first persistent lignite bed.

The Fort Union Formation (Paleocene) is composed of four members, the Ludlow, Cannonball, Tongue River, and Sentinel Butte. The Ludlow Member consists of gray to yellowish-tan sandstone, gray shale, and thick, lenticular beds of lignite. At Slim Buttes and Cave Hills, South Dakota, and at Long Pine and Ekalaka Hills, Montana, the lignite is appreciably uraniferous. Locally, at Slim Buttes, the lignite contains as much as 0.X percent uranium, and the interbedded sandstone contains uranophane.

The Cannonball Member enters from the east and intertongues with the Ludlow Member. It pinches out toward the west and does not extend into Montana. The Cannonball consists of marine sandstone and shale. It is noted and named for the large calcareous concretions it contains. It is not known to contain anomalous uranium.

The upper part of the Fort Union is made up of the Tongue River and Sentinel Butte Members. The Tongue River consists of massive, gray to tan sandstone, siltstone, and shale. It contains lenticular beds of fluvial quartz sandstone and thick, persistent beds of lignite. At Medicine Pole Hills, North Dakota, and at Cave Hills and Lodgepole Butte, South Dakota, the Tongue River lignites are uranium bearing. The Sentinel Butte Member is composed of dark-gray, bentonitic claystone and shale and brown to buff sandstone. The Sentinel Butte also contains lignite, and many of the lignite beds are radioactive. Relatively high-grade uranium deposits in lignite and carbonaceous clay are reported in the Sentinel Butte along the Little Missouri River escarpment in North Dakota.

The Paleocene Fort Union Formation is truncated by a pre-Oligocene erosional surface. Over large areas of the Williston Basin, the upper members of the Fort Union have been removed by erosion. The period of erosion that followed deposition of the Fort Union marked a change from low-lying-floodplain and coal-swamp depositional environments to uplifted floodplains traversed by higher-gradient streams. The middle- and upper-Tertiary formations that overlie the Fort Union lack the highly carbonaceous and lignitic sediments of the Paleocene and are instead highly tuffaceous. This tuffaceous material is considered by many to be the source for uranium in the underlying lignite.

The post-Paleocene rocks consist of the White River Group and the Arikaree Formation. The White River Group consists of two formations, the Chadron (lower Oligocene) and Brule (middle and upper Oligocene). The Chadron Formation is composed of dark-gray bentonite and light-gray, tuffaceous claystone, siltstone, and sandstone. At places, thin interbeds of lenticular freshwater limestone are present. The coarser-grained sandstones often form well-defined channel deposits within the finer-grained sediments. Some of the sandstone is arkosic and gravelly, especially at the base. At many places, the basal gravelly or conglomeratic zone at the contact with the underlying Fort Union is a golden-yellow color due to oxidation by groundwater.

The Brule is composed of buff to pinkish-tan, massive, tuffaceous siltstone; nodular claystone; and channel sandstone. Stratigraphic studies for economic purposes often make no attempt to differentiate the Chadron from the Brule; rather, they are mapped together as White River Group.

The Arikaree Formation (Miocene) unconformably overlies the White River Group. Where the White River Group has been removed by erosion, the Arikaree rests directly on the Fort Union. Like the White River Group, the Arikaree is tuffaceous. It is composed of greenish-white to light-gray, massive, tuffaceous sandstone and siltstone, with subordinate amounts of dolomite or dolomitic limestone, shale, and conglomerate. The Arikaree contains large amounts of disseminated ash. Some ash is present in thin beds that are relatively pure, but of local extent. Rocks of the Arikaree Formation are porous and permeable, and

groundwater circulates freely. As a result, some of the ash has been devitrified, resulting in deposition of silica as nodules, laminae, and concretions. Local occurrences of carnotite are reported in dolomite from West Short Pine Hills, South Dakota (Denson and Gill, 1965).

In summary, the Tertiary stratigraphic sequence in the southern Williston Basin consists of a lower set of strata that contains lignite and an upper set that is highly tuffaceous. In the area of the common corner of North Dakota, South Dakota, and Montana, the lignite has been extensively studied for its uranium content (Denson and Gill, 1965). Some beds of lignite contain an average of 0.18 percent uranium. The lignites at Slim Buttes, South Dakota, serve as an example of these deposits.

Slim Buttes is located in Harding County in northwest South Dakota. The buttes are typical of a series of mesa-like topographic features that extend across the southern part of the Williston Basin from northwest South Dakota (Slim Buttes, Cave Hills, and Short Pine Hills) into southeast Montana (Long Pine and Ekalaka Hills) and northward into western North Dakota (Chalky Butte, Little Badlands, and Killdeer Mountains). Each of these mesa-like features is an erosional remnant capped by tuffaceous rocks of the White River Group and (or) the Arikaree Formation. Below these tuffaceous caprocks lies the lignite-bearing Fort Union Formation.

At Slim Buttes, only the Ludlow Member of the Fort Union is present. It dips gently toward the northeast, and consists of yellowish-brown, poorly indurated, fine-grained sandstone and siltstone; gray clay shale; and lignite. Directly below the pre-Oligocene erosion surface and the overlying tuffaceous rocks, the Ludlow is varicolored. Rocks in this altered zone are various shades of yellow, orange, and pink that contrast sharply with both underlying and overlying rocks. Thickness of the altered zone ranges from a few feet to about 50 ft. The most highly altered rocks are adjacent to topographic highs on the pre-Oligocene erosion surface. Relief along this surface is judged to be about 100 ft at Slim Buttes. Varicolored beds grade downward into rocks of normal yellowish-brown color, and this suggests that the alteration is due to extensive weathering.

Rocks of the Ludlow Member are poorly exposed at most places, due to vegetation, talus, and landslide debris from the overlying White River Group and Arikaree Formation. Because of poor exposure, lignite beds are traceable only for short distances along the face of Slim Buttes; but core-hole data in the Mendenhall area, near the center of Slim Buttes, indicates that lignites are the most persistent beds in the Ludlow (Gill and others, 1959). However, correlation of specific lignite beds between widely spaced exposures or drill holes is difficult, because the lignite beds vary in thickness and may diverge or join within short distances.

Lignite beds range from soft and earthy to hard, dense, and woody. They are classed as banded coals, having an alternation of fine-textured (attrital) coal layers and woody layers that contain large fragments of trunks and roots. At some places, fine-textured (attrital) layers contain more uranium than woody layers, but texture and composition of lignite seems to be less important than stratigraphic position and permeability of superjacent beds.

Lignites containing 0.005 to 0.02 percent uranium, with concentrations in the ash of 0.05 to 0.1 percent uranium, are numerous and extensive in the Slim Buttes area. High-grade deposits in lignite and carbonaceous shale were identified at nine localities by Denson and Gill (1965). Eight of the nine occur in the southern part of the buttes, and most of these are along the axis of a shallow syncline. At six of the nine localities, the White River Group is absent, and the highly permeable Arikaree rests directly on the truncated edges of the Ludlow. The radioactive beds vary considerably in thickness and uranium content. Among those in the southern part of the buttes, thickness ranges from 0.3 to 2 ft, and uranium varies from 0.05 to 0.33 percent.

The deposits bear no apparent relationship to the age of the member or to the relative age of the strata within a member. Rather, mineralization favors those lignite beds either stratigraphically or topographically nearest the unconformity at the base of the tuffaceous Oligocene and Miocene rocks (Denson and Gill, 1955, Fig. 141). Exceptions can be explained by the presence of impermeable siltstone or shale above unmineralized lignite high in the section, and by permeable sandstone associated with mineralized lignites lower in the section (Denson and others, 1959, Fig. 8; Denson and Gill, 1965, Fig. 17). In general, uranium content is usually higher where a lignite is overlain by sandstone than where the same bed is overlain by less-permeable strata such as siltstone or shale. The less-permeable strata isolate the underlying lignite from descending mineralized groundwater.

At other localities in the Williston Basin, lignite beds that overlie permeable sandstones may be mineralized along the base of the bed. The principle is the same. Lignites proximal or adjacent to permeable sandstones are the most likely to be mineralized.

Another factor influencing uranium mineralization at Slim Buttes is the matter of which of the younger tuffaceous units directly overlies the Fort Union. The underlying lignites are often found to contain more uranium where the Arikaree rests directly on Fort Union than where the Chadron overlies the Fort Union. Thick, impervious bentonites in the Chadron apparently act as barriers to descending mineralized groundwaters.

At most localities across the Williston Basin, uranium is apparently disseminated in carbonaceous material. Distinct uranium minerals are rare or absent. At a few places, secondary uranium arsenates, phosphates, and vanadates are present along joints and bedding planes in the carbonaceous rocks, especially those containing higher-grade uranium deposits (Denson and others, 1959; Denson and Gill, 1965). At Slim Buttes, carnotite is present in a silicified sandstone in the Chadron Formation (Gill and Moore, 1955), and uranophane is reported from a sandstone in the Ludlow member.

A column sample of unweathered lignite from the southern end of Slim Buttes was analyzed by Schopf and Gray (Denson and Gill, 1965, p. 43). The sample averaged 0.04 percent uranium and contained visible pyrite and analcime. According to Schopf and Gray, pyrite formed during early diagenesis, whereas analcime was formed later by groundwater transferring sodium, aluminum, and silica into the coal from the overlying tuffaceous sediments. Thus, analcime is an indicator of the extent of groundwater circulation. Analcime is most abundant in lignites overlain by porous sandstone of the Arikaree Formation.

Analysis of 69 samples of lignite and carbonaceous shale ash from the Ludlow Member at Slim Buttes shows that the elements Be, Co, Cr, Ge, La, Mo, Ni, Pb, Sc, Se, V, Y, Yb, and Zr all correlate positively with uranium (Denson and Gill, 1965, p. 53-54, Pl. 18). None of these elements are necessarily pathfinder elements that indicate anomalous concentrations of uranium but their presence and covariance with uranium are consistent with and support the hypothesis that mineralization is or was a supergene process. The overlying tuffaceous formations are the probable source of most of these elements, including uranium (Denson and Gill, 1965).

Volcanic materials in the White River Group and the Arikaree Formation show appreciable radioactivity and at some localities are associated with secondary uranium minerals. Rocks of the White River Group and the Arikaree Formation contain an average of 0.0015 percent uranium, about 12 times that of the average sedimentary rock (Denson and Gill, 1955). Analyses of groundwater from White River and Arikaree strata indicate that uranium and other metallic elements are being leached today from these volcanic materials. In support of this, Gill and Moore (1955) have shown that spring water issuing from the tuffaceous units at Slim Buttes contains 10 to 30 times more uranium (41 ppb) than water from the Fort Union and Hell Creek Formations (4 ppb). (See also Denson and Gill, 1965, p. 56-60).

A correlation observed by Scott and Barber (1958) is that uranium tends to be more concentrated in groundwater that contains large amounts of bicarbonate ion (HCO_3^-). Analyses of two samples of spring water issuing from the base of the tuffaceous units in the Slim Buttes area ran 367 and 544 ppm bicarbonate. Uranium in these samples was 0.03 and 0.04 ppm (Denson and others, 1959). It is possible that these highly alkaline waters with high bicarbonate content were, and perhaps still are, the mineralizing solutions.

For more information on trace-element chemistry of uraniferous coal and lignite, see Drever and others (1977), Pipiringos (1966), and Denson and Gill (1965).

The direct correlation of uranium with ash content has often been noted. In the southern part of the Williston Basin, higher-grade uranium deposits occur in carbonaceous beds that contain about 35 to 40 percent ash. At Slim Buttes, where the beds generally contain less than 35 percent ash, the most uraniferous beds contain an average of over 30 percent ash, whereas the weakly mineralized beds contain an average of less than 20 percent ash (Denson and Gill, 1965, Pl. 18c). The weakly mineralized, low-ash beds at Slim Buttes seem to be relatively dense and impervious to mineralizing groundwaters. A certain amount of ash apparently is needed to "open up" the rock and give it required permeability.

Thickness of a lignite also seems to be important. In the southern Williston Basin, it is generally true that beds 2 ft or less in thickness contain the most uranium and are most favorable. Lignite beds much in excess of 2 ft generally have lower ash contents and are more impervious.

At other localities in the Williston Basin, uranium content has been observed to drop off again where ash content exceeds 40 percent. The explanation in this case may be that carbon and carbon compounds decrease as ash content goes up, thus providing fewer sites for the adsorption of uranium.

Several hypotheses have been advanced to account for uranium in the Williston Basin lignites. These hypotheses are discussed by Denson (1959), Denson and others (1959), and Denson and Gill (1965). It seems probable from the foregoing discussion that uranium mineralization is supergene (epigenetic). It is believed that uranium was originally held by volcanic ash in the overlying Oligocene and Miocene formations, and that the uranium was leached by groundwater during weathering and devitrification of the ash. Groundwater, percolating downward, carried the uranium to the underlying lignites. Organic material in the lignite captured the soluble uranium, either by ion exchange or by the formation of uranium-organic compounds (Breger and Deul, quoted in Denson and others, 1959).

There has been no uranium production from lignite at Slim Buttes. However, commercial recovery of uranium from lignite was attempted at four localities in North and South Dakota during 1963-1965. Three tons of impure lignite yielded about 1 ton of ash. The ash was shipped to several mills for recovery of uranium. Over the three-year period 1961-63, about 150,000 tons of uraniumiferous lignite containing U_3O_8 valued at \$9 million was mined and processed. The general area contains additional strippable lignite with a potential mined value of about \$30 million (Averitt, 1975; Mitchell, 1965).

Recognition Criteria for Uraniferous Lignite (Class 210)

Geologic setting:	Low-lying, poorly drained areas on coastal plain or within continental basins; granitic, silicic-volcanic, or other uraniferous source rock nearby; structural features, such as faults, joints, shallow synclinal troughs, and unconformities, may be important locally as a control on movement of mineralizing groundwater.
Host rock	
Age:	Coincident with abundant land plants, thus Devonian, possibly Silurian, or younger; Late Cretaceous- and Cenozoic-age rocks perhaps optimal; older Mesozoic and Upper Paleozoic rocks likely to contain less favorable coals of higher rank.
Lithology:	Thin, discontinuous beds of lignite and carbonaceous shale; both lithologies pyritic: uraniferous lignite in seams a few inches to a few feet thick; drab to dark-colored carbonaceous shale with carbonaceous material scattered or concentrated along bedding planes in siltstone or silty shales.
Depositional environment:	Paludal environment on coastal floodplain or within continental basin; high water tables and abundant vegetation; most favorable sites may be near centers or marginal to areas of silicic volcanism.
Associated rocks:	Tuffs or tuffaceous rocks; fine-grained floodplain, lacustrine, and paludal or lagoonal siltstone and silty shale; fluvial sandstone; in coastal environments, may intertongue with marine rocks.
Mineralogy	
Uranium minerals:	Usually none; uranium adsorbed by uranyl humates(?); secondary uranium minerals occasionally noted at richer deposits.
Associated minerals:	Pyrite, diagenetic zeolites (analcime).
Geometry:	Stratiform, but usually patchy and irregular; commonly, only the top of the seam is mineralized.

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EVAPORATIVE PRECIPITATES (CLASS 220)

Uranium occurrences and deposits belonging to this class are assigned on the basis of both process of mineralization and host rock. If mineralization results directly from evaporation of saturated waters, or if evaporative concentration is a relatively important contributing mechanism, the deposit may belong to this class, depending upon the host rock. Parent fluids for evaporative precipitates include marine-lagoonal waters, river and lake waters, and groundwaters.

Host rocks or sediments for this class include evaporites (marine-lagoonal, sabkha, lacustrine, and playa) and unconsolidated sediments such as alluvium, colluvium, deeply weathered bedrock, and soil. Inclusion of evaporites with soil-like materials in the same class is not meant to imply genetic similarities among them, but only that these hosts, in spite of their diversity, may serve as depositional sites for uranium minerals deposited by evaporation or by complex processes that involve evaporative concentration. In keeping with the overall scheme of the classification, if evaporite-type uranium mineralization is found in, say, carbonaceous rocks, sandstones, or carbonate rocks, they should be classified under the class that bears the name of the rock type. All others should be classed here. For example, under Class 230, mention is made of deposits in limestone caves. Those deposits may have formed, at least in part, by evaporation or by an evaporation-associated process. Some of these deposits are actually in silts and muds within the caves, but, at least in a broad sense, the minerals occur within the limestone, and thus, they are classified with limestones.

In deposits and occurrences of this class, uranium is in the oxidized, hexavalent state, as colorful "secondary" uranium minerals. These include carnotite and tyuyamunite (vanadates), minerals of the autunite group (phosphates), uranophane (a silicate), and sometimes more-complex minerals such as schroëckingerite (a fluo-carbonate-sulfate).

Examples of this class are carnotite-bearing calcretes of Western Australia and Namibia (South-West Africa) and schroëckingerite in Wyoming. Some of the calcretes are economic. The Wyoming schroëckingerite is subeconomic. In addition to these, uranium concentrations in sabkha and playa sediments are a possibility, although these environments are largely unexplored.

One of the most important deposits of this class is the uraniferous calcrete deposit at Yeelirrie, Western Australia (Lanford, 1974; Carlisle and others, 1978). Yeelirrie is in an area of internal drainage, deep valley fills, abundant salt lakes, and well-developed claypans. Annual rainfall is less than 10 in., and evaporation rate is 14 to 20 times the annual rainfall. Yeelirrie-type or valley calcretes are typically elongate deposits parallel to valley drainage courses. Other calcretes are in delta-like deposits that fringe salt lakes. Calcretes form where near-surface carbonate groundwaters evaporate and lose CO₂ to the atmosphere. Uranium and potassium from weathered granites and vanadium from nearby greenstones are present, together with carbonate, in the groundwater. Where the groundwater rises near surface, evaporation concentrates the ions in solution and CO₂ escapes into the atmosphere. Loss of CO₂ raises the pH so that carbonate can precipitate, followed by precipitation of carnotite.

Carnotite is present in the calcrete as disseminations, cavity fillings, and as veinlets filling fractures. It is also present in the clay-quartz unit that underlies the calcrete. The richness of the Yeelirrie deposit is due to subsurface ponding and upwelling of groundwater caused by a bedrock-controlled constriction at the lower end of the ore body and a flattened gradient upstream from this orebody. Resources at Yeelirrie are estimated to be 94 million lb U_3O_8 .

The largest known occurrence of schroeckingerite in the world is located in the Lost Creek area of the Red Desert, Wyoming (Sheridan and others, 1961). The schroeckingerite occurs as a caliche-type deposit in continental Tertiary formations and in the overlying, unconsolidated Quaternary deposits. These rocks and sediments are structurally involved in a northwest-trending syncline cut by northwest- and northeast-trending sets of faults. The occurrences transgress lithologic boundaries and appear to be related to the water table. Most of the schroeckingerite is at a depth of 2 to 8 ft.

The schroeckingerite apparently forms by a caliche-like process. Groundwater in the vicinity of the deposits runs as high as 46 ppm uranium. This water rises in the capillary fringe above the water table, and schroeckingerite is precipitated either by evaporation or by evaporation accompanied by other, unknown mechanisms. Source of the uranium is believed to be concealed deposits of relatively high-grade primary uranium minerals located at depth or at some distance from the schroeckingerite along faults.

The mapped occurrences of schroeckingerite are in an elongate area of about 1.4 sq mi. Analyses of samples ranged from 0.001 to 0.063 percent uranium. Most samples contained less than 0.050 percent. These deposits are considered a low-grade resource.

Sabkhas and playas generally are not considered highly favorable environments for uranium deposits. They are mentioned here because it seems likely that sooner or later significant occurrences will be found in one or both of these environments. It might be argued that metals in sabkhas and playa deposits are syngenetic, because metals and evaporative sediments both precipitate from the same parent fluid, sea water for sabkhas and fresh water for playas. However, if the sabkha or playa deposit is highly metalliferous, the enrichment is probably a diagenetic process similar to that suggested by Renfro (1974) for copper shales. According to Renfro's hypothesis, evaporative pumping draws subsurface marine and fresh water up through the sabkha sediments. Over a long period of time, the low concentrations of metals in marine and fresh water may significantly increase the metal content in the sabkha evaporite deposits. Evaporative pumping must also play a significant role in a highly metalliferous playa deposit. It can be anticipated that, if economically significant concentrations of uranium are present in sabkha or playa sediments, uranium-rich source rocks will be nearby, or the uranium may have been mobilized from over a large area and concentrated along redox boundaries or by other mechanisms, such as those postulated for Yeelirrie.

Yeelirrie-Type Deposits

The carnotite-bearing calcretes of Australia, of which the deposits at Yeelirrie are the best known and most important, are located in Western Australia (Carlisle and others, 1978, Fig. 4.1; Langford, 1974, Fig. 2). Similar deposits are present at Langer Henrich and elsewhere in South-West Africa (Namibia). Australian calcretes are described here.

It is difficult to give a succinct definition of calcrete. Most geologists, on first impression, would probably regard the Australian calcretes as some form of caliche deposit. The terminology for caliche, calcrete, and similar carbonate deposits is confusing and often conflicting. This problem is reviewed by Reeves (1976).

Caliche, broadly considered, is the accumulation of carbonate, commonly in sheet-like layers, at or near the surface of soils in semiarid to subhumid climates. The carbonate is usually calcareous. These surface and very near surface deposits may form in several ways, but in each case evaporation of carbonate-bearing waters is the dominant process. The two most often cited mechanisms for caliche formation are (1) evaporation of carbonate-bearing groundwater in the capillary fringe just above the water table, and (2) downward transport by vadose water of carbonate from A and B soil horizons to the lower B or C horizon. Other mechanisms are described by Goudie (1973) and Reeves (1976).

With the possible exception of caliches related in origin to lakes and streams (Goudie, 1973), the various processes by which caliches form can be considered pedogenic, that is, as part of the soil-forming process. This interpretation implies an essentially in situ process in which carbonate is redistributed vertically through the soil and concentrated in sheet-like horizons that tend to be laterally extensive within a soil profile.

Calcretes, such as those of Western Australia, South-West Africa, and perhaps elsewhere, are considered by some to be a variety of caliche. However, uranium and ground-water geologists of Western Australia maintain that the calcretes of the Yeelirrie type are distinctly nonpedogenic, although these calcretes may have certain chemical and morphological features in common with pedogenic caliches.

The calcretes of Western Australia, of which Yeelirrie is an example, are secondary deposits that result from the wholesale introduction of carbonate by groundwaters moving laterally through alluvium, soil, and deeply weathered bedrock to the site of precipitation. Transportation is a matter of lateral movement rather than vertical redistribution. Caliches draw their authigenic carbonate from soil, dust, loess, ash, organic debris, or air, whereas, the carnotite-bearing calcretes draw their carbonate, potassium, uranium, and vanadium from a large catchment area of deeply weathered rock. The carbonate precipitate and calcrete forms where slowly advancing groundwaters converge and rise near the surface along the axial portions of broad alluviated valleys (valley calcretes). Precipitation is a result of evaporation of groundwater and loss of dissolved CO_2 . Evaporation and loss of CO_2 are also instrumental in the deposition of uranium as carnotite, as explained below.

Geometry of valley calcrete is much different from that of pedogenic caliche. Valley calcretes occupy only the axial portions of broad, mature paleovalleys and present-day valleys, or deltaic areas where these drainages enter salt lakes. In contrast to the laterally extensive, sheet-like deposits of most caliches, the geometry of valley calcrete is such that, in plan, the length to width ratio is very high. This elongate, axial geometry and the dominance of groundwater transport of carbonate, as opposed to in situ pedogenesis, serve to distinguish calcretes from typical caliches.

Calcretes and caliches do have several attributes in common. Their composition and textures are similar, sometimes indistinguishable, and they both form in the oxidized zone of weathering, most commonly in arid and semiarid climates. However, valley calcretes are not necessarily associated with a soil profile, although the upper surface may develop a profile and thus resemble a soil caliche. For elaboration of the calcrete-versus-caliche problem, see the paper by Carlisle and others (1978). This paper is also the source of most of the information in the discussion that follows. Other sources are Dall'aglio and others (1974), Langford (1974), and Mann (1974, 1976).

The area that contains the uraniferous calcretes is in the central part of Western Australia, in an area of closed drainage and saline lakes. With few exceptions, the calcretes of economic interest are located west of the great sandy deserts, south of the Tropic of Capricorn, north of the "Mengies Line," and inland, east of the "Mackering Line" (Butt and others, 1977, Fig. 1). Hereinafter, this area will be referred to as the "area of interest," with the understanding that calcretes do occur elsewhere, as, west of the Mackering Line and to the east, toward the sandy deserts in the interior of the continent.

Within the area of interest, soils are neutral to acid, groundwaters are fresh to moderately saline and neutral to alkaline, and vegetation consists of shrublands with eucalyptus trees common only along the intermittent streams. South of the Mengies Line, soils become alkaline, ground water is saline and acidic, and vegetation is more abundant in shrublands and open forests. The climate is also milder south of the Mengies Line. Rainfall is higher, evaporation rates lower, and annual temperatures somewhat lower. Calcrete does not form south of the Mengies Line; caliche does (Carlisle and others, 1978, Table 4.3).

The Mackering Line runs north, then northeast through the western part of the calcrete region. West of the Mackering Line, rejuvenated streams flow to the sea, dissecting and eroding the calcretes, which remain only as remnants on terraces above present river levels. East of the line, drainage is internal, and calcretes are intact, and some may still be forming. Chains of salt lakes are present along intermittent drainages, and these appear to represent remnants of ancient river systems that radiate from the broad continental divide, which passes to the west of Yeelirrie and Wiluna (Butt and others, 1977, Fig. 1).

Climate, topography, geologic history, and composition and configuration of bedrock are all factors or controls in the formation of Australian calcretes and associated carnotite.

The present climate in the area of interest is semiarid, with hot summers and mild winters. Rainfall is irregular, occurring almost entirely in the Australian late summer and fall. The climatic summary is as follows: annual mean rainfall, 170-250 mm; annual mean temperature, greater than 19° C; annual evaporation rate (potential), 3300-4200 mm (Carlisle and others, 1978, Table 4.3). It should be noted that the evaporation rate is greater than 10 times the precipitation. Apart from brief periods of surface runoff that follow occasional heavy storms, drainage is normally entirely subsurface. Yeelirrie is at the approximate center of the area to which these climatic data apply.

The Yeelirrie drainage basin is relatively large, with an area of about 3000 km². The basin heads at the Major Continental Divide, 60 km upstream from the orebody, and ends in a salt-pan lake 75 km downstream from the orebody. Interfluvial divides are broad and consist of the Old Plateau surface, underlain by deeply weathered granite. The lateritic profile on the granite consists of an upper, resistant ferricrete duricrust, 1 to 3 m thick; a transitional zone, up to 10 m thick; and a pervasively kaolinized "pallid" zone that grades downward into weathered bedrock. A discontinuous escarpment, called a "break-away", separates the Old Plateau from the New Plateau. The New Plateau slopes away from the breakaways, first as a pediment, on both the pallid zone of the Old Plateau laterite and on weathered granite, and finally as a broad, extremely flat basin filled by alluvium, soils, calcrete, and salt-pan evaporites.

The longitudinal gradient of the valley changes smoothly from 0.45 percent near the headwater to about 0.075 percent near the Yeelirrie Homestead, about 15 km downstream from the orebody. However, at the lower end of the orebody, the valley narrows from about 45 km to only 18 km, and here, in the vicinity of the orebody, the gradient flattens to 0.02 percent. This narrowing is due to outcrops and near-outcrops of granite that restrict the width of the valley either by virtue of their relative resistance or because of a larger-than-usual supply of alluvium from breakaways and pediments on both sides of the channel just below the orebody. This restriction of the valley and the flattening of the gradient immediately upstream are thought to have slowed the flow of groundwater and to have been instrumental in forming the orebody as explained below.

Neither the long-valley nor cross-valley profiles show any evidence of rejuvenation. This attests to tectonic stability and also to a certain amount of climatic stability over the region during the last 25,000 years, the period during which the calcretes are presumed to have formed. The only exception is at Lake Miranda, the salt pan at the lower end of the Yeelirrie drainage, where deflation and possibly differential compaction have lowered base level as much as 2 m, resulting in local dissection of deltaic calcrete.

Of the 3000 km² in the Yeelirrie drainage basin, about 25 percent is scant to extensive outcrop consisting of about equal parts laterite and less-weathered granite rocks. Greenstone and associated rocks are exposed exclusively on the western margin of the basin and constitute only about 5 percent of exposed bedrock. Thickness of sediments above bedrock toward the middle of the valley is said to be seldom more than 30 m and commonly less in the vicinity of the orebody (Western Mining Corporation, 1955).

Calcrete begins to appear at the surface along the axis of the Yeelirrie Valley 30 km downstream from the headwater divide, about midway between the divide and the orebody. Calcrete continues from the orebody nearly without interruption for 115 km to saline Lake Miranda. Strongest development of the calcrete is about 15 km upstream from the orebody, where two tributaries, each with calcrete, enter the main channel. From that point down to the orebody, calcrete is about 5 km wide and varies in thickness from about 4 to 7 m.

Bedrock in the area of interest is Archean granite and greenstone of the northern Yilgarn Block, in the central part of the Precambrian Western Shield of Australia (Trendall, 1975). About 50 percent of the Yilgarn Block is composed of granitic rocks. These rocks range in composition from quartz monzonite to syenite, and include migmatites, belts of gneissic rock, large areas of post-orogenic quartz monzonite, and pegmatite and quartz-pyrite veins. Age of these rocks is 2.6 to 2.7 b.y. Uranium contents of 2 to 25 ppm have been reported in similar rocks from the northern part of the Yilgarn Block.

North-northwest-trending belts of metamorphic rocks are infolded with the granitic rocks. These belts consist of a geosynclinal series of greenstone, felsic volcanics, amphibolites, gabbros, and metasedimentary rocks that include banded iron formation and quartzite. Metamorphic grade is greenschist to low-pressure amphibolite facies.

The Archean rocks of the Yilgarn Block are mineralized. Gold has been produced at numerous places, and deposits of vanadium are known at two places in the greenstone belts. Mafic rocks in the greenstone belts are the likely source of vanadium in the carnotite and also a source of calcium and magnesium for the calcrete carbonates. The granitic rocks are considered the source for potassium and uranium in the carnotite.

The Yilgarn Block has been stable and emergent throughout the Phanerozoic. The present-day internal drainage and associated chains of salt lakes appear to be disconnected remnants of a drainage system established in the Mesozoic. A peneplained surface, the "Old Plateau," was established under a humid climate during the Cretaceous. Deep weathering under warm, humid climate produced a deep laterite as much as 40 m thick on the peneplained surface during the Oligocene and Miocene. Rejuvenation during the late Miocene or Pliocene resulted in erosion of the laterite, locally exposing bedrock and creating a new, lower erosion surface, the "New Plateau" (Western Mining Corporation, 1975, Fig. 5). This cycle of erosion ended with the onset of periods of increasing aridity that apparently began in the Pliocene. As a result of aridity, meager runoff was insufficient to transport sedimentary debris. Valleys became choked with sediment, and salt lakes formed along the courses of the fragmentized drainage systems. The "New Plateau" is in part a depositional surface (alluviated plains along the central portions of valleys) and in part an erosional surface (pedimented Archean basement rocks on the flanks). It is along the drainage lines and lake margins of the alluviated valleys that the uraniferous calcretes have formed.

In alluviated valleys of low relief, groundwater flows toward the center or axis of the valley and may approach the surface without actually emerging as a seep or flowing stream. In some cases the capillary fringe above the

water table is shallow enough for carbonate-bearing groundwater to move upward during periods of strong evaporation to a level where both water vapor and CO₂ are lost to the atmosphere. Evaporation and loss of CO₂ both cause carbonate to precipitate. Deposition will occur mainly where topography, bedrock morphology, permeability barriers, and salinity-density differences cause groundwater to slow and rise toward the surface. This model fits the calcretes of Western Australia rather well.

A generalized stratigraphic column for the Yeelirrie orebody consists of a clay-quartz unit (20 to 25 m) overlying bedrock, calcrete (3 to 7 m), and overburden (1 to 2 m) (Western Mining Corporation, 1975, Figs. 6-8, Table 1, and p. 5-9). Commonly, but not always, the contacts between units are gradational.

The clay-quartz is the original valley-fill material. It is a mixture of red-brown clay and detrital quartz grains. Detrital quartz may be segregated into occasional grit bands, and some of these grit bands are arkosic. Carbonate is absent. The clay-quartz extends down to bedrock. At the top of the clay-quartz is a transition zone with some carbonate present as veinlets. This transition zone may be cavernous and silicified and may locally contain abundant celestite.

For the purposes of logging, the Western Mining Corporation defined calcrete as those carbonate-rich rocks with less than 10 percent relict inclusions of clay-quartz and loam. At the bottom, a 1- to 2-m layer may contain more than 10 percent clay-quartz relics, but is still considered part of the calcrete, because it is so high in carbonate content.

Every stage in the elimination of these inclusions can be seen from bleaching, incipient carbonation round the edges and transgressive carbonate veinlets, to a stage where their former presence is indicated merely by slightly darker ghosts, giving the calcrete a mottled appearance. (Eric Cameron, quoted in Carlisle, 1978).

The character of the calcrete is highly variable. One of the more common varieties is white, hard, porcelaneous, nodular, and cavernous. Where this variety crops out, it forms pronounced mounds. Other calcretes are soft and friable, powdery or earthy. There is a complete range of intermediate types between the porcelaneous and earthy varieties.

The overburden is divided into two units. The upper, surficial layer is composed of brown loam, sand, or clay that locally may be impregnated with a siliceous hardpan. Below the upper loam and overlying the calcrete is a second unit, a carbonated loam that consists of gravelly, nodular concretionary carbonate, with more planar-structured carbonated loam or hardpan just above the calcrete.

Excluding the transitional zones, the three units, clay-quartz, calcrete, and overburden, can be mineralogically described as follows (Western Mining Corporation, 1975; Carlisle and others, 1978, p. 69-71). The clay-quartz consists of 45 percent kaolin, 33 percent quartz, and 7 percent illite, smectite, and feldspar. The grit and arkosic bands are more quartzose and feldspathic, respectively.

Quartz and kaolin are virtually eliminated from the calcrete. They are replaced by carbonate and smectite. The earthy varieties of calcrete contain more smectite than the porcelaneous clacrete. Average carbonate content is about 70 percent in the porcelaneous varieties, and somewhat less in the earthy varieties. Most of the carbonate is dolomite. In the transition downward into the clay-quartz, calcite appears and dolomite decreases. At the top of the calcrete, in the earthy calcrete, calcite reappears, and is present upward into the overburden.

Composition of the overburden varies with the nature of the superficial material. Smectite and quartz are dominant, but other clays, detrital feldspar, calcite, gypsum, and siliceous hardpan are also present in varying amounts.

Carnotite is the only uranium mineral reported from calcretes of Western Australia. Thorium is absent. Carnotite is present throughout the section, from the carbonated loam of the overburden down through the calcrete into the clay-quartz. The brown carbonated clay-quartz probably contains the bulk of the mineralization. Earthy calcrete may also be very well mineralized. Although carnotite is present throughout the profile, most is in the carbonated units.

The carnotite occurs as a thin film on the walls of cracks and voids in porcelaneous calcrete and is dispersed through the earthy calcrete. It is also present as coatings on fractures and fault planes. Only minor amounts of clay and silica deposited in the voids of porcelaneous calcrete are later than the carnotite. The carnotite is clearly epigenetic, although some may be nearly contemporaneous with formation of the calcrete.

Much of the carnotite has a greenish to olive-green tint. Another common trait is the presence of a thin film of microcrystalline quartz. In the rich porcelaneous-calcrete ore, carnotite occurs as small crystals (<0.1 mm) on the walls of dehydration and solution cracks with microcrystalline quartz forming a thin crust over the carnotite crystals. This quartz crust clearly protects the carnotite from dissolution and probably inhibits the loss of radon gas.

Three types of nonpedogenic calcrete are recognized in the area of interest. Each contains significant carnotite. Valley calcretes occupy the axial portions of the broad, flat alluviated valleys of the New Plateau. Surface water rarely flows in these valleys. Runoff from the flanks of the catchment basin usually infiltrates before reaching the valley floor and flows below the surface until it reaches the axis of the valley and the calcrete aquifer. Gradients along axial drainages are very low, about 0.5 percent near headwaters to as little as 0.02 percent at Yeelirrie. The thickest and widest valley calcretes occur where bedrock or some other feature causes a decrease in slope and where the water table approaches the surface.

The other two types of calcrete are deltaic calcrete and groundwater lacustrine calcrete. The deltaic calcretes occur where paleodrainages and valley calcretes enter salt lakes. Groundwater lacustrine calcretes are found around the shorelines of many salt lakes in the valley calcrete area. Only the valley calcretes are considered in this discussion.

The Yeelirrie occurrence is the largest and richest calcrete uranium deposit known. The Yeelirrie deposit was discovered by anomalies detected during an aerial radiometric survey. Subsequent drilling and two open-cut exploratory trenches allowed Western Mining Corporation to announce (1972 and later reports) ore reserves of 46,000 tonnes of U_3O_8 at an average grade of 0.15 percent, of which 24,000 tonnes are 0.36 percent or above. These figures apply to an orebody approximately 6000 m long, 5000 m wide, and 8 m thick.

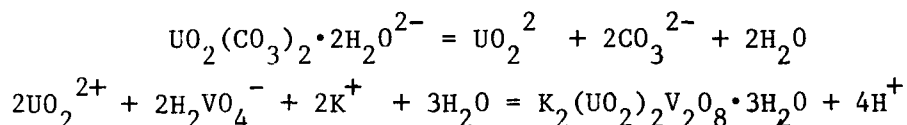
Origin of the valley calcretes of Western Australia is debated. The most likely hypotheses all take into account the climate. The present period of aridity began about 25,000 years b.p. The valley calcretes are judged to be no older than this, and some deltaic and lacustrine calcrete is apparently forming today (Carlisle and others, 1978).

The principal impact of the dry climate on calcrete and carnotite genesis is through soil moisture, both vadose and phreatic. The area of carnotite-bearing calcretes coincides with soil-moisture regime designated Aw (Carlisle and others, 1978). This area is one of low, episodic, seasonal rainfall; moderate to high temperature; and very high potential evaporation that greatly exceeds precipitation for every month of the year. Hypotheses of genesis that have received the most serious consideration all incorporate aridity and high evaporation rates as direct or indirect mechanisms in the formation of calcrete and carnotite.

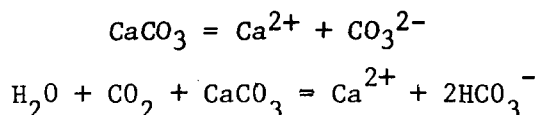
It is clear that both calcrete and associated carnotite are secondary (epigenetic), groundwater-derived deposits. Bases for this statement include the observations that calcrete both cements and replaces the initial alluvial (clay-quartz) sediments; carnotite occurs as disseminations and as coatings on grains and in open spaces in the calcrete; carnotite is grossly concentrated in subhorizontal layers close to the ground surface or near present or former water tables; and finally, anomalous amounts of uranium and vanadium present in groundwater down-drainage from known deposits suggest that reworking and reconcentration have been important in the past and are taking place today.

The problem is to account for (1) the precipitation of hexavalent uranium from carbonate-bearing groundwater solutions (because carbonate solutions are effective solvents for uranium) and (2) the precipitation of uranium as the potassium-uranium vanadate, carnotite, instead of the calcium uranium vanadate, tyuyamunite. The problem of genesis is discussed by Dall'aglio and others (1974), Langford (1974), Mann (1974, 1976), and Carlisle and others (1978). Carlisle and others (1978, p. 107-127) summarize this literature, together with their own observations and conclusions. Only the genetic mechanisms that they consider important for the valley calcretes are presented here.

The partial pressure of carbon dioxide, PCO_2 , is critical in precipitation of uranium as carnotite from groundwater solutions. In oxidizing, alkaline groundwaters, uranium travels as uranyl di- and tricarbonat complex ions. In a simple solution containing only these ions plus potassium and hexavalent vanadium, loss of CO_2 , either to soil above the water table or to the atmosphere, causes the uranyl-carbonate ions to dissociate and permits carnotite to precipitate (Carlisle and others, 1978, p. 117). Using uranyl dicarbonate as an example, the reactions are:



Loss of CO_2 drives both reactions to the right and decreases the solubility of carnotite. However, with carbonate in the system, as at Yeelirrie and the Western Australia calcretes, some amount of CO_3^{2-} , HCO_3^- , or H_2CO_3 is always present and ready to form uranyl-carbonate complex ions. If CO_2 is removed, pH will increase, and CaCO_3 will become less soluble and may precipitate as calcrete, removing Ca^{2+} , CO_3^{2-} , and HCO_3^- from solution:



Depending on the increase in pH due to CO_2 loss, carnotite may become more or less soluble. A pH of 8 is about maximum for stability of carnotite in a simple K-U-V-O₂-H₂O-CO₂ system (Langmuir, 1978, p. 19-23, Figs. 18-20a.).

The actual situation in a calcrete environment, however, is not simple. The simplifications assumed for models and in experimental work discussed below and in papers previously cited, in general, do not allow for the effects of impurities; surface reactions with clays, iron oxides, or fine-grained carbonate; the effects of grain size, colloids, or organic activity; polymorphism observed in CaCO_3 ; or other factors, such as reaction rates and nonequilibrium reactions. Furthermore, uranyl complexes with anions such as OH^- , SO_4^{2-} , PO_4^{3-} , F^- , and Cl^- have not been investigated in the context of the calcretes. Nevertheless, most of the discussion of genesis is in terms of carbonate and carnotite equilibria, with the understanding, usually tacit but sometimes expressed, that the assumptions may be oversimplifications.

As mentioned before, loss of CO_2 increases pH and, in groundwater containing uranium, vanadium, and potassium, may induce precipitation of uranium as carnotite. The loss of CO_2 is probably facilitated at places such as Yeelirrie, where groundwater is forced near the surface by the constriction of the valley at the lower end of the orebody. This process, however, requires a buffer, because carnotite redissolves above a pH of 8 (Langmuir, 1978, Fig. 19, 20a). No buffer has been identified, so the mechanism of CO_2 loss by itself is too simple.

Once P_{CO_2} has fallen to a value in equilibrium with the atmosphere, further evaporation will increase the salinity of the groundwater, and this will in turn further reduce the solubility of CO_2 . Calcite will continue to precipitate by evaporative concentration, and activity of CO_3^{2-} ion may fall. This may lead to precipitation of carnotite at or before complete desiccation. And, indeed, dissolved K, U, and V increase "irregularly and disproportionately down the valley portions of [Yeelirrie and one other drainage] by about an order of magnitude due to evaporation" (Carlisle and others, 1978, p. 121). Concentration of K, V, and decarbonated uranyl ion occasionally may have reached high enough values to cause precipitation of carnotite.

Carlisle makes clear, however, that carnotite in calcrete is not part of a lacustrine evaporite series in which successive layers of chemical precipitates are deposited as salinities are increased. Mineralogy, textures, morphology, and distribution of uraniferous valley calcretes argue against a lacustrine evaporite model. Furthermore, carnotite is not most abundant in the salt lakes, where salinities are the greatest. Carnotite mineralization at the margin of salt lakes is in carbonate mounds, typically updrainage or elevated above the hyper-saline waters. However, minor amounts of gypsum in mineralized valley calcretes indicate that evaporative concentration in the soil-moisture zone, particularly in areas of retarded groundwater flow or upwelling groundwater, is capable of producing highly saline waters. High potassium concentrations in these waters could induce precipitation of carnotite upon mixing with incoming uraniferous waters. Whether or not evaporative concentration is the mechanism of importance, it plays an important role, because it builds up the concentrations of necessary ions, all except carbonate species which, at least in theory, remain controlled by P_{CO_2} .

Another possible mechanism is the "common-ion" precipitation of carnotite with calcite or dolomite. This could occur where Ca^{2+} and Mg^{2+} are in solution, without access to CO_2 , together with K^+ , V^{5+} , and uranyl-carbonate complex ions. Precipitation of calcite or dolomite from this solution will decrease concentration of CO_3^{2-} ion and promote dissociation of the uranyl-carbonate complex ions, which in turn will lead to the precipitation of carnotite. This common-ion effect might be expected wherever carbonate-rich waters mix with saline waters enriched in $CaSO_4$ or an anion, such as Cl^- . In such event, carnotite and carbonate should be contemporaneous and strongly associated, the carnotite being finely disseminated throughout the carbonate. Contemporaneity seems to be the case in young mounds observed in some of the newer deltas, and the disseminated texture is observed in thin sections of these young deposits.

In the valley calcretes, highly evaporated waters can develop, locally approaching the ionic concentrations of the salt lakes. Strongly carbonated, uraniferous groundwaters mixing with these concentrated solutions may possibly precipitate calcite by the common-ion effect and carnotite by CO_3^{2-} depletion. Dissolution and reprecipitation of carnotite by changes in groundwater chemistry would account for secondary concentrations along fractures and open spaces in the older calcretes.

A fourth mechanism is precipitation of carnotite through oxidation. The concentrations of vanadium and uranyl ion that can be carried in aqueous solution together with potassium are significantly increased if vanadium is in the tetravalent state, as $VO(OH)^+$ or $HV_2O_5^-$, rather than in the pentavalent state, as $H_2VO_4^-$, which is required for precipitation of carnotite (Mann, 1974). It can be postulated that slightly reducing waters carrying uranyl and tetravalent vanadium ions would become oxidizing when forced near the surface, as at Yeelirrie. The resulting oxidation of V^{4+} to V^{5+} would reduce the solubility of carnotite and possibly permit precipitation. Eh-pH probes of some drill holes have shown that the redox boundary for V^{4+} and V^{5+} occurs today at only a few meters' depth. An attractive feature of this model is that it allows mobilization of vanadium from bedrock or from adsorptive sites on laterite and clay under present-day climatic conditions.

The fifth and last mechanism discussed here concerns the adsorption and nucleation on clay and other minerals. Some of the richest carnotite mineralization is in the "earthy" calcrete in the upper parts of the calcrete, and in clay-quartz below the calcrete where carnotite is associated with carbonated clay. The earthy calcrete may contain as much as 50 percent smectite, and the mineralized zones in the clay-quartz may contain up to 45 percent kaolinite and minor other clays. Clays and other finely divided minerals, possibly including carbonate, because of their large surface areas and surface free energies, enable nucleation to take place with smaller free energies of activation than are required for nucleation of a solute in saturated solution. Although the mechanisms and quantitative relationships are poorly known, the capacity of clays, organic matter, and other finely divided mineral material to adsorb metal ions and to catalyze precipitation may be significant in the uraniferous calcretes of Western Australia.

In conclusion, it should be restated that genesis of carnotite in Yeelirrie-type valley calcretes is uncertain. The foregoing remarks briefly describe several of the more probable mechanisms. In reality, several of the mechanisms may act in concert. For expanded discussion of this problem, see Carlisle and others (1978).

Recognition Criteria for Uraniferous Calcrete (Class 220)

Geologic setting:	On or adjacent to areas of granitic rocks and greenstone which have been exposed to weathering and leaching; moderate to low topographic relief and tectonic stability; large drainage basins; carbonate-bearing groundwater with anomalous uranium and vanadium; calcrete formation along drainage.
Host rock	
Age:	Late Pleistocene to Holocene; older deposits likely to be destroyed by leaching.
Lithology:	Porcelaneous to earthy calcrete (dolomite and smectite) that replaces alluvial clay (kaolinite) and detrital quartz.
Depositional environment:	Axial portions of valleys; warm, dry climate; low annual rainfall that is sporadic and seasonal; very high evaporation rates throughout the year; runoff mostly subsurface.
Associated sediments:	Alluvium.
Mineralogy	
Uranium minerals:	Carnotite.
Associated minerals:	Calcium carbonate and dolomite; detrital quartz, feldspar, and clay.
Geometry:	Elongate, high length-to-width ratio; lenticular in cross section.

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URANIUM OCCURRENCES IN LIMESTONE (CLASS 230)

Carbonate rocks are those that consist of 50 percent or more carbonate minerals. The commonest carbonate rocks are marine limestone and dolomite. Other carbonate rocks include lacustrine limestone, marl, travertine, tufa, and an assortment of impure carbonate rocks that may contain up to 50 percent sand, silt, saline evaporite minerals, and organic matter as impurities. Uranium-bearing rocks assigned to this class should meet the 50-percent-carbonate-mineral criterion.

Limestone, dolomite, and other sedimentary carbonate rocks generally are among the least-uraniferous rocks of the earth's crust. Commonly cited values for uranium range from parts per billion up to about 4 ppm (Bell, 1963). Most of these values are for relatively pure marine limestones in which only syngenetic uranium is present. For limestone or other carbonate rock to contain more than a few parts per million uranium, one of two conditions must be met: either the carbonate rock must be impure, or the uranium must be epigenetic.

It is well known that hexavalent uranium is highly soluble in the presence of substantial concentrations of carbonate or bicarbonate ions. This also appears to be true for tetravalent uranium (Bell, 1963, p. A2; McClaine and others, 1956, p. 30). Thus, in oxidizing environments in which carbonate sediments are commonly deposited, carbonate and bicarbonate-ion concentrations will be high and will hold uranium in solution and prevent it from precipitating with the carbonate sediments. Even if the carbonate rock was deposited in a reducing environment and contains H_2S or sulfurous organic substances, the presence of high concentrations of carbonate ion will work to keep uranium in solution (Garrels and Christ, 1965, p. 253-255). These observations explain the very low concentrations of syngenetic uranium in relatively pure carbonate rocks. Most, if not all, syngenetic uranium will be associated with noncarbonate impurities.

Among the impurities capable of holding small amounts of uranium are certain detrital heavy-mineral resistates, marine apatite, fluorite, and some kinds of organic matter (Bell, 1963). Very small percentages of heavy minerals may be present in carbonate rocks that contain a large detrital-sand component. However, the small amount of these minerals, usually a fraction of a percent of the whole rock, and the small percentage of uranium they contain (Table 1, p. 4) greatly restrict the likelihood that a carbonate rock containing expected percentages of these minerals could be of economic interest.

Sedimentary or marine apatite is present in some marine carbonate rocks. In fact, a completely gradational series exists between a pure carbonate end-member and a pure phosphate end-member. Some but not all marine apatite contains a certain amount of uranium (0.00X to 0.0X percent) as a substitute for calcium in the apatite lattice. This substitution can occur at the time apatite is initially precipitated (syngensis) or later, during diagenesis. Much of the uranium in marine apatite is considered to be syngenetic. Carbonate rock that contains uraniferous marine apatite as an impurity may contain as much as several parts per million uranium, which is usually presumed to be syngenetic (Bell, 1963). However syngenetic uranium has been shown to be significant only in some highly phosphatic rocks (Altschuler and others, 1958).

Limestone and dolomite that contain only small amounts of phosphatic impurities will not be favorable host rocks. Carbonate rocks that contain significant amounts of uraniferous apatite should be classed under marine phosphorites (Class 140).

Fluorite, especially the purple variety, often contains or is accompanied by uranium. Fluorite is uncommon in carbonate rocks, except in those that have been metamorphosed or altered by hydrothermal or other mineralizing solutions. Where the rock has been altered and fluorite and uranium introduced, the mineralization is of course epigenetic. An example is the Todilto Limestone discussed below. However, Bell (1963, p. A3) noted that some limestones, such as the Salem Limestone in Missouri, do contain fluorite and bear no evidence of metamorphism, alteration, or epigenesis. If fluorite in certain carbonate rocks is indeed syngenetic, whatever uranium the fluorite by itself may contain will certainly be insignificant.

The presence of organic matter may be another matter. Some forms of organic matter can adsorb uranium, and some organic acids can form uranium salts. Conceivably, organic matter could react with uranium-bearing solutions to deposit uranium. Alternatively, bacteria living on the organic matter might generate enough H_2S to lower the pH into the stability range of uraninite. Economic deposits in limestone formed in either of these two ways are presently unrecognized as such or unknown. This may be because carbonate rocks with a sufficiently high organic-matter content are not common, or because carbonate ions work against precipitation or adsorption even in many highly reducing environments.

Conclusions drawn from the foregoing discussion are these: syngenetic uranium is an insignificant constituent of nearly pure carbonate rocks, but may be present in quantities of as much as a few parts per million if certain impurities with which uranium may be associated are present. The only favorable carbonate rocks seem to be those capable of serving as hosts for epigenetic uranium.

Bell (1963) divided epigenetic uranium deposits in carbonate rocks into four types: (1) hydrothermal veins, (2) efflorescent deposits, (3) deposits in karst terrains, and (4) peneconcordant deposits. For the purposes of this classification, a vein-type deposit in a carbonate rock would be classed under vein-type deposits in sedimentary rocks (Class 730; Mathews, this volume). Included here as epigenetic deposits in limestone are peneconcordant deposits, efflorescent deposits, and deposits in karstic limestones.

Peneconcordant deposits are tabular, lenticular, or irregularly shaped masses that are in general concordant with the gross sedimentary structures of the host rock. Locally these mineralized areas are discordant and cut across sedimentary structures. This local discordance is one of the chief indications that mineralization is epigenetic rather than syngenetic (Finch, 1959).

The Todilto Limestone is the best-known and largest example of a peneconcordant-type deposit in a carbonate rock. However, as will be apparent from the discussion below, many of the characteristics of the Todilto and its uranium mineralization seem to be peculiar and exceptional, and may not be at all typical of other peneconcordant orebodies that may be discovered in limestone.

The Todilto is a varved, thinly laminated, and chemically precipitated limestone with silty interbeds and lenses. Primary mineralization consists of uraninite in the crests of small anticlines and domes. The limestone is commonly brown and fetid, but the rock surrounding the ore is strongly bleached and recrystallized, with little or no trace of a reducing agent (Gablemen, 1970). At places, especially in the shallower zones, uraninite is partially oxidized, and secondary uranium minerals fill joint stockworks sometimes at a considerable distance from primary uraninite.

Efflorescent deposits are powdery encrustations produced on rock surfaces by evaporation of mineralized water. Efflorescent epigenetic uranium minerals, such as tyuyamunite, carnotite, and uranophane are found in cavities, on fractures, and on exposed surfaces of many kinds of rocks, including carbonate rocks. In carbonate rocks, these secondary uranium minerals may occur along bedding planes and joints and within small cavities and vugs little widened or enlarged by solution, as in the Miller Hill area, Carbon County, Wyoming (Vine and Prichard, 1959). They may also occur in large caverns, in cave breccias, and in bedded cave-fill deposits of clay and silt in limestone units that have undergone extensive karstification. Deposits in the Madison Limestone in the Pryor-Big Horn Mountains, Montana and Wyoming, are examples (McEldowney and others, 1977).

Todilto Limestone, Grants District, New Mexico

The original discovery of uranium in the Grants district was in the Todilto Limestone. Subsequent discoveries a few miles to the north in the Morrison Formation have dwarfed the importance of the Todilto; nevertheless, the Todilto is the most important discovery of uranium in limestone in the U.S. and one of the few commercial discoveries in the world (McLaughlin, 1963).

The Grants district is located in McKinley and Valencia Counties in west-central New Mexico (Gabelman, 1956, p. 390). Structurally, the district is situated at the southern end of the San Juan Basin and on the northeast flank of the Zuni Uplift.

The Todilto Limestone is one of a series of formations that dip to the north and northeast away from the Zuni Uplift. On their updip edges, these formations form a series of cuesta ridges and racetrack valleys that rim the Zuni uplift. Two of these cuesta ridges have been prominent in uranium exploration in the Grants district (New Mexico Bureau of Mines and Mineral Resources, 1963, Frontispiece). The lower cuesta is formed by the Entrada Sandstone and capped by the Todilto Limestone. The dip slope of this cuesta is called the Todilto or limestone bench. The upper cuesta consists of the

uppermost-Jurassic Bluff Sandstone and Morrison Formation and is capped by sandstone of the Cretaceous Dakota Formation. Some of the sandstones in the Morrison are highly uraniferous (Class 240) and account for most of the ore produced in the district.

At the type locality, Todilto Park in northwestern McKinley County, the Todilto consists of 16 ft of mudstone overlain by 4 ft of limestone and another 5 ft of mudstone. To the southeast, in the Grants district, the Todilto is predominantly limestone and has a maximum thickness of 25 to 30 ft. Farther east, along the eastern part of the San Juan Basin, the limestone facies is much thinner, and the upper part of the formation is a thick, massive, but areally restricted gypsum facies as much as 111 ft thick. The presence or absence of this gypsum facies may be an influence on mineralization. In the Laguna district, on the southeast side of the San Juan Basin, known uranium deposits in the Todilto occur in islandlike areas in which gypsum is absent between the limestone facies of the Todilto and the overlying Summerville siltstone (Gabelman, 1970).

At the Grants district, the Todilto is a very finely laminated to massive, dark-brownish-gray, dense limestone which is relatively pure CaCO_3 . The less silty and unmineralized phases consist of about 96 percent CaCO_3 , 1 percent MgCO_3 , and <0.01 percent P_2O_5 (Bell, 1963). Very thin siltstone interbeds and partings are present in the middle and lower parts, and thin seams of gypsum may be present toward the top.

The limestone facies commonly smells of H_2S and is supposedly petroliferous. Black carbonaceous matter appears to be abundant in some beds and along some bedding planes, but analyses have indicated an organic-carbon content of only 0.2 to 1.0 percent (Hilpert, 1963). Bell (1963) reported that attempts to extract organic matter from Todilto Limestone were unsuccessful, and that the limestone is not and possibly never was petroliferous. Bell believed the non-descript organic matter may represent plankton. Anderson and Kirkland (1960) demonstrated that the paper-thin laminae of the Todilto were varves (non-glacial), and that the organic varve layer was sapropel derived from phytoplankton.

In the Grants district the Todilto can be divided into a platy lower zone, a crinkly middle zone, and at places a massive upper zone (McLaughlin, 1963). The platy lower zone is usually 10 to 15 ft thick and is a dense, fine-grained limestone, with generally regular bedding that ranges from thinly laminated up to beds 6 in. thick. Thin siltstone and sandstone partings are common, and gypsiferous beds are present locally.

The crinkly middle zone is 3 to 6 ft thick. Bedding ranges from very thinly laminated up to a few inches thick, and is marked by conspicuous crenulations up to several inches across. Larger folds with wavelengths and amplitudes up to several feet are also present but widely spaced. These folds and the smaller crenulations are decollement structures in that beds above and below are undeformed. The deformation seems to be plastic, penecontemporaneous deformation within soft sediment, probably due to the tendency for calcareous mud to creep down the depositional slope, with slippage along clay-varve laminations or shale partings (Rapaport and others, 1952). (Another possibility

is that thin anhydrite layers may have hydrated to gypsum. This would have produced swelling, which in turn may have caused the crinkly deformation [Bell, 1963]. Subsequent leaching of gypsum would give the rock increased secondary porosity for admission of mineralizing solutions).

The massive upper zone, where present, is generally less than 5 ft thick. It is a medium-bedded to massive limestone. At many places it is recrystallized to a coarse or giant grain size, and at most localities it is highly discontinuous and irregular in thickness.

Contacts between these three zones are irregular and frequently obscure. At places, bedding in the crinkly zone is obscured by recrystallization, causing it to be indistinguishable from the massive upper zone. The contacts often must be selected arbitrarily on the basis of gross lithology. At the Flat Top mine, discussed below, the crinkly layer is indistinct; only the platy lower zone and the massive upper zone are recognizable. Both are mineralized.

Contact of the Todilto with the underlying eolian Entrada Sandstone is conformable and transitional. The normally orange-brown sandstone of the Entrada is either white or varicolored (light-gray to lavender) in a leached zone 10 to 30 ft below the contact with the Todilto. This leached zone cuts across bedding and is apparently secondary.

The contact of the Todilto with mudstones of the overlying Summerville Formation is highly irregular and variable in character. At places the contact appears to be erosional (McLaughlin, 1963); elsewhere, it appears to intertongue or possibly to be gradational with limestone lenses occurring as much as 30 ft above the lowest mudstones (Gableman, 1970). The gradational contact apparently reflects a gradual change from limestone to siltstone deposition. Yet, at other places, limestone inclusions in the Summerville seem to be due to low-angle faulting along the contact that has broken and dragged portions of the upper Todilto into the overlying Summerville. Each of these interpretations may be correct for one locality or another. The contact relationships are complex and apparently variable.

Origin of the Todilto is debated. The Todilto was deposited in a basin about 300 mi from east to west and about 250 mi from north to south. Depositional conditions within this basin have been considered to be restricted marine in a partially closed basin, lacustrine in a totally enclosed saline lake, or a combination of the two.

Harshbarger and others (1957) depict the Todilto basin as a gulf or bay connected on the northwest with the Summerville sea in Utah via a narrow strait in extreme northeastern Arizona. They favored a marine source for the Todilto on the basis of stratigraphic position, the large quantity of gypsum in the upper Todilto in the eastern part of the basin, and fossil fish from five localities that were stated to have "marine affinities."

Anderson and Kirkland (1960) re-examined the problem and concluded that the basin was either an enclosed saline lake, or, if open to the sea, a mixed paralic basin, perhaps more than half of the salines being derived from the drainage area. Their evidence included the overall absence of marine fossils in the Todilto, the presence of freshwater ostracods, the likelihood that the problematic fish with "marine affinities" are actually freshwater fish that entered the basin during flood or drought, and the calculations that freshwater streams in the Todilto basin could have contributed enough calcium, sulfate, and carbonate to account for the limestone and gypsum facies that constitute the Todilto.

Uranium in the Todilto occurs in three types of deposit (Gableman, 1970). Unoxidized (primary) deposits consist of the pitchblende variety of uraninite, which occurs in local masses or disseminations as a replacement of limestone. These deposits occur at depth, beneath the zone of supergene oxidation, or in shallower areas where they seem to be protected from oxidation by overlying impermeable limestone. Unprotected deposits of primary pitchblende in the oxidized zone are more or less converted to secondary minerals such as tyuyamunite, metatyuyamunite, and uranophane. Vagrant secondary deposits are those that never contained primary pitchblende; rather, they consist of uranium that has migrated a considerable distance from primary deposits and in many cases cannot be related to a particular primary deposit. The pitchblende and oxidized pitchblende deposits are found in the crests of anticlinal folds, whereas the vagrant secondary deposits occupy joint stockworks, usually in structural sumps.

The Todilto in the Grants district is deformed by a series of northeast-trending folds. Average wavelength of these first-order folds is about three miles. Virtually all the Todilto ore deposits are within the syncline portions of these first-order folds. Crests of adjoining large-scale anticlines are barren of significant deposits. Second- and lesser-order folds are also present. Whereas most of the Todilto ore is within first-order synclines, it is at the same time found along the crests of intermediate- and smaller-order anticlines situated within the broader synclines.

Numerous faults have been mapped in the Grants district, but apparently none are mineralized except for secondary uranium minerals that are supergene.

Deposits at the Flat Top mine in the Poison Canyon area of the Grants district serve as an example of uranium mineralization in the Todilto. The Flat Top mine was mapped by Gabelman (1970), who considered the deposit a prototype replacement orebody of about 50,000 tons in the top of a shallow, elongate dome. The Poison Canyon area occupies one of the broad, shallow, first-order synclines on the northeast flank of the Zuni Uplift. A map by McLaughlin (1963, Fig. 1) shows 52 orebodies within the Poison Canyon syncline (secs. 23-26, T. 13 N., R. 10 W. and secs. 29-31, T. 13 N., R. 9 W.), while adjoining large-scale anticlines are relatively unmineralized.

Uranium deposits in the Todilto Limestone in the Poison Canyon area tend to be in long, pod-shaped bodies that follow the axes of smaller anticlinal folds within the Poison Canyon syncline. Axes of many of these smaller anticlines have the same general north or northeast trend as the Poison Canyon syncline, but some trend to the east. The Flat Top deposit, now mined out, was exceptionally large and was more an elongate lens than a long pod (Gableman, 1977, Fig. 15B).

The Flat Top orebody was a virtually unoxidized primary replacement of limestone by pitchblende that occurred above the water table at a depth of about 100 ft. The ore was an elongate lens generally coincident with the crest of the Flat Top dome. On the crest of this dome, the entire thickness of the formation was mineralized. On the flanks, the base of the ore rose off the lowest part of the Todilto, and gradually pinched out against the overlying Summerville siltstone. The ore-waste boundary was generally sharp, without a halo or zone of decreasing grade. In detail, the Flat Top orebody was composed of six smaller pods and irregular lenses, forming a reticulate pattern coincident with the axes of third- and fourth-order anticlines (Gableman, 1970, Pl. VIII).

All the small orebodies and the large composite deposit were enclosed by a wide alteration envelope in which limestone had been bleached, organic carbon removed, and bedding and jointing progressively destroyed by recrystallization in outward-decreasing intensity. Siltstone interbeds had been altered to illite, smectite, and smectite-chlorite.

Bleaching and recrystallization are generally coextensive, but at places unbleached limestone may be moderately to strongly recrystallized. Both bleaching and recrystallization are strongest along anticlinal crests. Strongly bleached limestone is very white and nearly pure calcite. Organic matter has apparently been removed by acid leaching and oxidation. Along anticlinal crests the platy lower unit is markedly thinned, and the upper unit markedly thickened. Some of the thinning in the lower zone may be stratigraphic, but most is apparently structural and due to pressure solution during folding, precipitation occurring along the crests of the anticlines. Perry (1963) suggested that the recrystallized masses along anticlinal axes were algal reefs, but this suggestion has not been accepted by all workers (Gabelman, 1970, p. 4).

Dominant primary uranium mineralization in the Flat Top orebody is pitchblende; coffinite is minor. Accessory primary minerals include fluorite, manganese oxide, hematite, pyrite, barite, and black vanadium oxides, probably montroseite and haggite. Fluorite is present as colorless and deep-purple grains up to 1/2 mm in diameter. The fluorite replaces pressure-recrystallized limestone, usually near uraninite, but also up to several feet away. Fluorite precedes uranium mineralization in the paragenetic sequence (Gabelman, 1970).

All six ore lenses that constituted the Flat Top orebody consisted of uraninite or coffinite concentrated into small spots or lenses, each no more than a few inches long (Gabelman, 1970). Each spot or lense replaced limestone along bedding planes or along early, short, tight, healed fractures at high

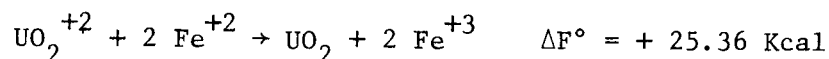
angles to the bedding. (Bell [1963, p. A14-15] described mineralization elsewhere in the Todilto as following silty layers, rather than replacing limestone.) Late, wide tension fractures are filled with coarse calcite and commonly with vagrant secondary uranium minerals, but little primary uranium. Each small spot or lense is usually enclosed by concentric envelopes, manganese oxide on the inside and hematite on the outside. The recrystallized limestone in the vicinity of ore is also chloritized and dolomitized, although the introduction of iron and magnesium is interpreted by Gabelman (1970) to be pre-ore.

Original source of the uranium and method(s) of solution transport remain in question (Lavery and others, 1963). Igneous-hydrothermal, volcanic-ash, granitic, and syngenetic sources have all been proposed. Evidence for either a hydrothermal source or source-bed leaching from ash, granite, or another source is conflicting. Perhaps uranium originated in the Morrison Formation by volcanism and related hydrothermal activity and was reworked by groundwater moving along faults and joints into the underlying Todilto. Stratigraphic separation between the two formations is about 500 ft. It is also conceivable that mineralization in both Morrison and Todilto was simultaneous.

Controls of mineralization within the Todilto are both physical and chemical (Gabelman, 1970). Physical controls of mineralization are those that influence permeability. Throughout the Grants district, whether in the Morrison Formation or Todilto Limestone, ore is limited to semipermeable beds (Lavery and others, 1963). The limitation of ore to semipermeable beds suggests that a good host rock should be permeable enough to permit large quantities of uranium-bearing solutions to pass through, but of low enough transmissivity to prevent either a thorough leaching of precipitants prior to ore deposition or leaching of the ore after deposition. Lavery and coworkers consider the Todilto to be a semipermeable rock in this sense. Because of both pressure recrystallization and tensional fracturing along anticlinal axes, these axial areas were seen by Gabelman (1970, p. 25) as selective permeability tunnels through the limestone which localized all the important orebodies within the crest of anticlinal folds.

Organic carbon is often invoked as the chemical control on deposition of epigenetic uranium. Although very small amounts of organic matter are present in the Todilto, organic matter may not have been the principal precipitating agent, because it is not present in the recrystallized parts of the Todilto that contain the ore. The hematite-pitchblende and manganese oxide-pitchblende associations suggest that these oxides may have participated in the formation of pitchblende.

One of the most common megascopic occurrences of hematite in the Flat Top mine is a hematite-enriched zone enclosing pitchblende. One possibility is that uranyl ions passing through the rock in solution oxidized ferrous iron in pyrite, clay, chlorite, or some other mineral. The oxidized iron may then have migrated outward to form hematite while the reduced uranium was deposited in the center as pitchblende. This reaction is discussed by Woody and George (1958) and Gabelman (1970) and can be expressed as:



Alternatively, ferrous iron may have traveled in the ore fluid but may not have taken part in reduction of uranium until a favorable preliminary reaction took place. Manganese, vanadium, and carbonate complex ions would have been available for this preliminary reaction (Gabelman, 1970).

Other possibilities include the reduction of uranium by hydrogen ion and the transport of uranium to the depositional site as a stable uranous-carbonate complex.

In the first case, hydrogen is known to reduce uranium in the presence of a suitable catalyst (Bunji and others, 1964). A starting catalyst for the Todilto ore has not been identified, but the limited carbonaceous matter is a possibility.

In the second case, a uranous-carbonate complex $[U(CO_3)_5]^{-6}$ is known to be stable in solutions containing excess HCO_3^- or $CO_3^{=}$, both compatible with a limestone environment (McClaine and others, 1956). The complex ion is dissociated and uranium precipitated by addition of OH^- or H^+ . Thus, uranium may have been transported in the reduced form to the site of deposition and precipitated by the destruction of the uranous-carbonate complex (Gabelman, 1970, p. 26-27).

Initial discoveries of ore in the Todilto ran 0.3 to 0.5 percent U_3O_8 and were small, producing only about 10 tons of U_3O_8 each. Subsequent discoveries revealed larger orebodies. The typical size of these larger orebodies was about 200 to 300 ft in length by 50 ft in width. Most of these larger orebodies ran about 0.3 percent U_3O_8 and contained less than 20 thousand tons of ore. The Flat Top orebody, as mapped by Gabelman (1970, Pl. VIII), was exceptionally large. It was approximately 400 ft long and 250 ft wide, with ore-grade rock as thick as 9 ft. Total production at the Flat Top through 1969 was 46,256 tons of ore that averaged 0.22 percent U_3O_8 and 0.11 percent V_2O_5 .

Recognition Criteria for Deposits of the Todilto Type (Class 230)

Note: The Todilto Limestone and its uranium mineralization are exceptional in many ways. It is expected that other uranium-bearing limestones may have characteristics that are different from those of the Todilto.

Geologic setting:	Limestone deposited in saline lake or mixed, marine bay-lacustrine basin; limestone in sequence of homoclinally dipping sedimentary rocks on edge of basin bordering uplift; sandstones within sedimentary sequence also uraniferous; permeability of limestone increased along fold axes by fracturing and recrystallization.
Host rock	
Age:	Not age restricted.
Lithology:	Fine-grained, dense, light-gray to dark-brownish-gray, varved limestone with subordinate interbedded siltstone; organic varve layer is sapropelic, derived from freshwater or marine phytoplankton; middle of unit extensively deformed by penecontemporaneous deformation; extensively bleached and intensively recrystallized and mineralized along crests of second- and smaller-order anticlines.
Depositional environment:	Marine embayment with restricted connection to open sea, or saline lake, or mixed marine bay-lacustrine; seasonally controlled sedimentation (varved) with alternating layers of organic detritus and chemically precipitated(?) limestone; fossils and biogenic structures extremely rare and probably indicate fresh or brackish water.
Associated rocks:	Continental sandstone (eolian and fluvial), siltstone, mudstone; lacustrine or marine-bay siltstone; gypsum.
Mineralogy	
Uranium minerals:	Chiefly uraninite, minor coffinite; secondary uranium minerals: tyuyamunite, metatyuyamunite, uranophane.
Associated minerals:	In paragenetic sequence (Gabelman, 1970): chlorite, dolomite, hematite, manganese oxide, pyrite, fluorite, barite, vanadium oxides (montroseite, haggite).
Geometry:	Generally stratiform; long pods or lenses along crests of anticlines.

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SANDSTONE-TYPE URANIUM DEPOSITS

by

S. Ralph Austin and R. F. D'Andrea, Jr.

ABSTRACT

Three overall factors are necessary for formation of uranium deposits in sandstone: a source of uranium, host rocks capable of transmitting uranium-bearing solutions, and a precipitant.

Possible sources of uranium in sandstone-type deposits include groundwaters emanating from granitic highlands, arkosic sediments, tuffaceous material within or overlying the host rocks, connate fluids, and overlying black shales. The first three sources are considered the most likely.

Host rocks are generally immature sandstones deposited in alluvial-fan, intermontane-basin or marginal-marine environments, but uranium deposits do occur in well-winnowed barrier-bar or eolian sands. Host rocks for uranium deposits generally show coefficients of permeability on the order of 1-100 gal/day/ft².

Precipitants are normally agents capable of reducing uranium from the uranyl to the uranous state. The association of uranium with organic matter is unequivocal; H₂S, a powerful reductant, may have been present at the time of formation of some deposits but may go unnoticed today. Vanadium can serve to preserve the tabular characteristics of some deposits in the near-surface environment, but is considered an unlikely primary precipitant for uranium.

Uranium deposits in sandstone are divided into two overall types: peneconcordant deposits, which occur in locally reducing environments in otherwise oxidized sandstones; and roll-type deposits, which occur at the margin of an area where an oxidized groundwater has permeated an otherwise reduced sandstone. Uranium deposits are further broken down into four subclasses:

Subclass 241: Roll-type deposits that occur in intermontane basins and (or) close to the source of the host sediments (example: Gas Hills, Wyoming).

Subclass 242: Roll-type deposits that occur in coastal-plain environments and (or) at some distance from the source of the host sediments (example: South Texas).

Subclass 243: Peneconcordant deposits that occur in discrete channels scoured into underlying strata (example: Monument Valley-White Canyon Districts, Utah-Arizona).

Subclass 244: Peneconcordant deposits that do not occur in discrete scours or channels (example: Uravan Mineral Belt, Colorado-Utah).

INTRODUCTION

Uranium deposits in sandstone account for most of the production and reserves in the U.S. Productive sandstones are fluvial or marginal marine, rarely eolian. The ages of sandstone host rocks range from Paleozoic to Tertiary. However, most sizeable deposits in the U.S. are in the Chinle Formation, of Triassic age; the Morrison Formation, of Jurassic age; or various Tertiary formations which range in age from Paleocene to Miocene.

Three factors are necessary for formation of a uranium orebody in sandstone:

1. A source of uranium,
2. host rocks capable of transmitting uranium-bearing solutions, and
3. a precipitant(s).

SOURCE OF URANIUM

Factor 1, the source, is usually not apparent. Five possible sources are: (1) hydrothermal (telethermal) solutions, (2) connate fluids, (3) tuffs in host rocks or overlying strata, (4) granitic rocks, including arkosic or feldspathic host rocks, and (5) overlying "black shales" (Shawe, 1976).

Theories of hydrothermal uranium sources, which were once strongly advocated (for example, Kerr, 1957), have almost entirely lost favor. Grutt (1972) attributes this to the discovery of large deposits in Wyoming far from centers of appropriately timed igneous activity.

Connate fluids have been suggested as possible sources for uranium and other metals in sedimentary rocks (Noble, 1963; Shawe, 1976).

Tuffaceous rocks are ubiquitous; they occur frequently, often unrecognized, in nearly any geologic sequence one might select (Ross, 1925). Although tuffaceous beds commonly occur either within or above uranium host rocks (advocates of the tuff-leach theory commonly ignore tuffs occurring in underlying rocks), they also bear similar relationships to barren sandstones. Furthermore, tuff-derived clays have the capacity of adsorbing more uranium than is likely to have been present in the unaltered tuff, so that uranium may not actually be released by argillic alteration of tuffs. However, tuffs devitrified without, or prior to, argillization may release a significant amount of uranium.

Hypotheses involving granitic sources for uranium in arkosic or feldspathic sandstones offer the opportunity for two periods of leaching of uranium from the same material. During weathering and erosion, labile uranium is released into the sediments and percolating waters as the sandstone body is formed (Hurley, 1950). In addition, most sandstones undergo diagenetic alteration of minerals that survive weathering; some of these minerals may contain uranium. This is especially true if erosion and deposition are so rapid that detritus is only briefly exposed to the weathering cycle and if chemical weathering is minimal.

Austin (1963, 1970) has documented postdepositional dissolution of unstable high-temperature feldspars (which may be present as either a tuffaceous or detrital component of the host rock), magnetite, ilmenite, and amphiboles which have survived weathering. These minerals probably represented a significant portion of the host rocks before diagenesis, and, although the fraction of uranium in the minerals may be minuscule, the total amount of uranium released during destruction of the minerals may be important. Table 1 shows the average uranium content and its range in selected common minerals of igneous rocks.

Dissolution of refractory heavy minerals (such as allanite, monazite, zircon, and various multiple-oxide minerals) during diagenesis and mineralization is less well documented. Such minerals commonly contain high percentages of uranium (Larsen and Gottfried, 1961) and usually survive the weathering cycle. If the minerals contain sufficient uranium (or thorium) to be metamict, their solubilities are likely to be somewhat higher than predicted thermodynamically. Thus, these minerals may yield some uranium during alteration of the host sandstone.

Davis (1969) found that rocks altered by uranium-bearing solutions contain more uranium than "unaltered" rocks presumably unaffected by such solutions. Conversely, Renfro (1969) and R. A. Laverty (written communication) found that "altered" ground contains less uranium than "unaltered." These investigations provide contradictory evidence regarding altered zones of host rocks as the source of uranium in the deposits. As discussed above, several common minerals which ordinarily contain small amounts of uranium are partially or completely destroyed during diagenesis and (or) mineralization. Since these processes are more intense in altered than in unaltered zones, any uranium released during alteration should be available for transport down-dip and incorporation into an orebody.

Shawe (1976) advocates "black shales" as a source of uranium in underlying mineralized sandstone. However, the Cretaceous Mancos Shale, chosen as an example, is not highly rich in organic matter and therefore is not a "uraniferous black shale" in the sense of Jones (this volume).

Shawe suggested that connate waters squeezed from the shale during compaction may have produced the bleached zones in underlying sandstones. However, the partition factor for uranium between water and suitable adsorbing organic material (Szalay, 1965), and the strong probability that uranium was reduced before the shale was compacted, might make transport of uranium into the underlying sandstone by this process difficult.

Boberg and Runnels (1971) showed that the uranium content of the South Platte River increases downstream as the contribution of surface waters draining the Pierre Shale (Mancos equivalent) and younger rocks containing coal beds increases. This is in agreement with the work of R. C. Malan (oral communication) which showed that the uranium content of the Arkansas River similarly increased downstream as the contribution of waters draining the Pierre Shale increases. In fact, after crossing the Pierre Shale, the South Platte and Arkansas Rivers are among the most uraniferous stream waters in the world. This is good evidence that such shales probably retain most of their uranium until oxidative weathering releases it. Surface waters draining such shale

TABLE 1. URANIUM CONTENT OF COMMON MINERALS OF IGNEOUS ROCKS

Mineral	Average U Content, ppm (After Larson and Gottfried, 1961)	Range in U Content, ppm (After Rogers and Adams, 1974)
Quartz	1.7	0.1- 10
Feldspar	2.7	0.1- 10
Biotite	9.1	1.0- 60
Hornblende	7.9	0.2- 60
Pyroxene	3.6	0.1- 50
Apatite	65.0 ¹	10.0-100

¹Data from Hurley and Fairbairn (1957).

areas before infiltrating host sandstones are a much more likely source of uranium than are overlying "black" shales. An overlying "black" shale may be an important source of uranium if fractures leading to the underlying sandstone remain open and if the shale adjacent to them is oxidized. In fact, the "black-er" the shale, the more likely uranium is to remain in the reduced state within the shales, and the less likely the shale is to be an important source for uranium in underlying sandstone.

It appears that, where lignite overlies a permeable sandstone, the superjacent lignite is the more likely to be mineralized; the same relationship should be true for black shales and sandstones, since the more readily mineralized lignites are impure varieties and are somewhat gradational into carbonaceous shales (Denson and Gill, 1965; Jones, this volume). H. B. Wood (written communication) reports that where lignite overlies a permeable sandstone, the lignite and only a very thin layer of adjacent sandstone contain significant uranium.

Dall'Aglia (1971) stated that uranium in natural waters may reach anomalous values even in streams draining rocks with normal uranium content. Kashirtseeva (1964) suggested decrease in concentration of uranium to 1 ppb in ground waters in the formation of a uranium deposit. This apparent contradiction is due both to the enormously greater solubility of uranium in the hexavalent than in the tetravalent state and to the ability of certain forms of organic matter to adsorb uranium and other metals. Szalay (1964) cited enrichment factors for uranium in organic matter of 10,000:1 over the amount in associated ground waters.

Regardless of hypotheses concerning the source of uranium forming deposits in sandstone, the favorability of a given area must not be discounted because of the absence of an obvious source of uranium.

HOST ROCKS

Fluvial sandstones containing sizeable uranium deposits are commonly first-cycle sediments and are either feldspathic or arkosic; some mineable deposits occur in quartzose and cherty sandstone and in pebble conglomerates which contain more clasts of older sedimentary rock than granitic debris. Many host sandstones are tuffaceous. Feldspar itself may not be necessary for the formation of uranium deposits, but feldspathic or arkosic detritus is an indicator of the environments of rapid erosion and sedimentation usually associated with uranium deposits.

Host rocks range from boulder conglomerates to siltstones. Medium- to coarse-grained sandstones are, perhaps, the most common hosts (Grutt, 1972). They are rarely evenly bedded; bedding tends to be lenticular, as is typical of fluvial deposits. Some deposits occur in distinct channels. Eolian host rocks commonly contain small lacustrine lenses; the bedding of marginal-marine deposits tends to be lenticular. Mudstones may be locally associated with coarser sediments. Turner-Peterson and Peterson (1978) have documented the association of organic-rich mudstones with uranium-bearing sandstones in several areas of the U.S. and ascribe reduction of uranium to humic acids derived from the mudstones.

Favorable host sandstones commonly occur near the margins of sedimentary basins where rapid deposition of detritus from rapidly or moderately rapidly rising highlands has occurred. However, the distance from the basin margin appears to be important only insofar as it affects the type of sedimentation. Under proper conditions, favorable host rocks may persist for many miles into the basin. Marginal-marine sediments may occur many miles from the sediment source, but still far from the center of the basin. The deeper parts of the basin are relatively unfavorable sites because of the relative fineness and impermeability of the sediments, the probable stagnation of possible ore-forming fluids, and the likelihood that solutions that do reach the basin center will be too reducing to contain appreciable uranium. The apparent favorability of basin margins may also be due to the fact that many are recent or present positive areas and have good exposures of the host sedimentary rocks.

Massive, uniform sandstone bodies are not likely to contain significant uranium deposits. Even the thicker, more-uniform sandstone lenses in some producing districts are less likely to be mineralized than their thinner, less-uniform counterparts. However, the size and degree of uniformity of favorable sandstone lenses may vary from district to district. The optimum thickness and uniformity of a favorable lens tends to be greater in districts in which individual deposits are relatively large.

One criterion for assessing favorability of an area for sandstone-type uranium deposits is recognition of zones of permeability, or "plumbing."

As pointed out by Ore (1963, 1964), every fluvial tract contains a zone of greatest through-going permeability; it generally corresponds to the mean position of the stream channel during deposition. This may appear in the sediment as a distinct channel within the same or an underlying formation; it always exists, regardless of whether a visibly distinguishable channel is present. Lack of through-going permeability is a principal factor in the lack of mineralization in many barren channels in or near orebodies.

Similar zones of through-going permeability occur in marginal-marine and eolian sandstones, although they are formed by different processes and therefore have different geometries. These permeable zones similarly control fluid flow and, therefore, localization of mineralization. Open fractures or faults may be of secondary importance in localizing the deposition of uranium in sandstones. Permeability information may be quite useful in frontier exploration and is readily available for many areas in USGS Water Supply Papers.

Coefficients of sandstone permeability encountered in the literature may range from .01-5000 gal/day/ft², while the range for uranium host rocks is more restricted. Table 2 shows permeability data for actual uranium deposits in several host formations.

TABLE 2. PERMEABILITIES OF URANIUM HOST ROCKS

Formation	Coefficient of Permeability (gal/day/ft ²)	Source
Wasatch Fm., Powder River Basin, Wyo.	3-72 (avg≈30)	1
Salt Wash Member, Morrison Fm., Colo.-Utah	1.6-12	2
Oakville SS, S. Tex.	~100	1
Catahoula Fm., S. Tex.	35	1
Jackson Group, S. Tex.	22	1

¹Source of data proprietary.

²Jobin, 1962.

Another criterion is the distinction between "used" and "unused plumbing," that is, between permeable zones through which mineralizing solutions carrying significant amounts of uranium and (or) other metals have passed, and those showing no evidence of this process. These are commonly designated as "altered" and (along with zones not penetrated because of lesser permeability) "unaltered" ground, respectively.

The most obvious indications of the probable passage of at least small amounts of uranium-bearing solutions are anomalous uranium content and (or) radioactivity. However, such anomalies may indicate only isolated uranium occurrences.

Unoxidized uranium deposits can be thought of as sulfide deposits slightly contaminated with uranium. Since the sulfides oxidize in the weathering environment, the outcrops of host sandstone within uranium areas may be stained by limonite and (or) hematite. According to Grutt (1972), this local feature, which has been noted in all areas, results from the oxidation of pyrite contained in the host sandstone. However, true gossans are present only in rare instances. Sandstones colored by "limonite," and especially hematite, are common in both favorable and unfavorable areas. These colors vary with mineralogy (mixtures

of goethite, lepidocrocite, or hematite, in various proportions), degree of crystallinity, particle size, concentration, distribution, degree of hydration, and admixtures of clay and manganese minerals. All of these and other parameters affect the color of the rock.

Fundamentally, the problem is distinction of iron oxides originally deposited with the sediment; those formed by direct oxidation of magnetite, ilmenite, and other ferrous-oxide minerals; and those formed by oxidation of ferrous-sulfide minerals in a uranium deposit. However, not all sulfide concentrations in sandstones contain uranium. Barren sulfide concentrations and their oxidation products may or may not indicate favorability for uranium.

Color differences may permit distinction of "altered zones" which immediately suggest favorability (Shawe, 1976). More commonly, differences in color are subtle and may not be recognizable to one unfamiliar with a given area. Colors indicating "altered ground" vary from area to area and range from yellowish to slightly greenish grays, through browns and reds, to pinkish or purplish-pink tones.

PRECIPITANTS

Due to the lower solubility of uranium in the reduced than in the oxidized state, the most common precipitant for sizeable uranium orebodies in sandstone is a reductant. Many substances have been invoked as uranium reductants. These include: coaly or lignitic vegetal remains; unidentified, structureless organic matter; petroleum; "dead oil"; natural gas; hydrogen sulfide; hydrogen; and pyrite or other sulfide minerals. Local concentrations of vanadium are also of extreme importance in preserving uranium (and associated radioactivity) at the surface during oxidation, since carnotite, tyuyamunite, and other uranyl vanadates are the least soluble of the oxidized uranium minerals. Vanadium probably does not play a major role in localization of uranium in unoxidized uranium deposits, but secondary uranyl vanadates may be the best surface indicators of favorability for unoxidized deposits in the subsurface.

Lignitic or subbituminous coaly materials are strong adsorbers of uranium. Adsorption is finite and reversible (Szalay, 1964). Uraniferous coaly material in sandstones commonly contains uraninite and (or) coffinite. Coaly material may adsorb uranium until concentration and other conditions allow desorption due to crystallization of one of these minerals. The cycle could be repeated, or it may be continuous once adsorbed concentrations are high enough and crystallization has begun.

Most structureless organic material containing uranium has been identified as humic rather than sapropelic (Breger and Deul, 1955; Haji-Vassiliou and Kerr, 1973). Hausen (1959) disputed this for some uraniferous substances with physical properties resembling asphalt.

Structureless organic material (associated with molybdenum minerals) and vegetal remains (molds of aquatic plants in lacustrine lenses) have been observed even in eolian deposits.

Because of the nearly universal presence of sulfides in sandstone-type deposits and the known effectiveness of H_2S in reducing uranium (Jensen, 1958), H_2S is a probable precipitant for most sandstone-type uranium deposits. Hydrogen sulfide is a powerful reductant and is present in some deposits; it may have been present in all deposits. Jensen (1958) credited R. M. Garrels with suggesting a reaction by which hydrogen, an even more effective reductant, is produced by the action of H_2S on iron oxides. The role of sulfide minerals, especially relatively stable species such as pyrite, in reducing uranium is questionable; it may be more likely that the same reductant which reduces uranium is instrumental in forming sulfides.

Jensen (1957, 1958) attributed production of H_2S and the subsequent precipitation of uranium to sulfur-reducing bacteria, chiefly Desulfovibrio desulfuricans. Later, Granger and Warren (1969), relying in part on the work of Updegraff (1969) and Cheney and Trammell (1973), advocated a disproportionation reaction involving intermediate-valence sulfur compounds for the production of H_2S . Updegraff, who relied on the work of Drouot (1967), found few bacteria of any kind and no sulfur-reducing species in a number of samples from various uranium deposits. As pointed out by Schmitt-Collerus (personal communication, 1970), the kinetic energy of disproportionation of intermediate-valence sulfur compounds is low, and the reaction is likely to be correspondingly slow, whereas the kinetic energy of bacterial reduction is high, resulting in rapid production of H_2S (Al-Sawaf, 1977).

Although petroliferous organic materials rarely contain significant amounts of uranium (Haji-Vassiliou and Kerr, 1973), sulfur-reducing bacteria thrive at an oil-water interface (Mekhityeva, 1967). The H_2S produced in this environment is capable of reducing hexavalent uranium.

Therefore, the presence of petroliferous materials in or near a uranium deposit suggests a possible source for a precipitant. Al-Sawaf (1977) documented the ability of sulfur-reducing bacteria to use natural hydrocarbon gases as food. Thus, the absence of visible organic material in a sandstone does not imply the absence of a precipitant for uranium nor lack of favorability.

SUBCLASSIFICATION OF URANIUM DEPOSITS IN SANDSTONE

Uranium deposits in sandstone exhibit similarities and differences in various parameters. Various classifications have been proposed based on selected parameters (Bailey and Childers, 1977; Dahlkamp, 1978) or on theoretical considerations (Barnes and Ruzicka, 1972; Ruzicka, 1975; Cornelius, 1976). Differences in almost any parameter selected tend to be gradational among various deposits, and acceptance of theoretical classifications depends on acceptance of the theoretical basis. Any classification scheme, therefore, is rather arbitrary. Even various parts of the same deposits may differ in important parameters, as in the northern and southern ends of Southwestern Lisbon Valley, Utah, for example.

The subdivision used here is simple but arbitrary. All deposits in sandstone are here subclassified as either peneconcordant or roll-type. Parts of most deposits of either type may show some features considered characteristic of the other.

BASIS FOR SUB-CLASSIFICATION

Two important (although somewhat abstract) criteria are used to distinguish roll-type and peneconcordant deposits:

1. In roll-type deposits, the ore trends (roll-front or redox interface) are extremely sinuous, but can be considered approximately normal to depositional trends of the host sandstone (crudely strike oriented). In peneconcordant deposits, the ore trends are essentially parallel to the depositional trends of the host rock.

2. In roll-type deposits, "alteration" refers to oxidation of iron- and titanium-bearing minerals, while in the peneconcordant deposits, "alteration" refers to a halo around the ore in which iron is reduced from Fe^{3+} to Fe^{2+} . ("Primary" alteration, associated with the ore-forming process, should not be confused with alteration of pyrite to limonite caused by weathering.)

Presumably the differences in characteristics between roll-type and peneconcordant deposits result from important differences in the processes by which the ores were formed (Fischer, 1970). The peneconcordant deposits seem to have formed as "one-shot affairs" (Garrels, 1957) in locally reduced areas ("pods" or "patches") in otherwise oxidized sandstones. The roll-type deposits seem to have formed at the down-dip limit of pervasive oxidation of an originally reduced sandstone. Furthermore, roll-type deposits seem to be dynamic and ephemeral, forming from oxidation and recycling of pre-existing vanadium-deficient ($\text{V} < \text{U}$) ores. "Stack" ore, as at Ambrosia Lake, seems to be similarly derived from redistribution of preexisting ore with $\text{V} < \text{U}$, although in this district the redistribution was along faults.

As discussed earlier in this section, sandstone-type uranium deposits in various districts may show characteristics which are completely gradational from one end-member of this classification to the other. The vanadium content of the original, reduced ore may be a key factor in the preservation of wholly tabular characteristics of certain deposits. Figure 1 shows the V/U ratios of several districts for which adequate vanadium data are available (vanadium assays on at least 75 percent of the total ore production). The individual districts within the Uravan Mineral Belt have V/U ratios of 3:1 to 7:1, and can be considered to have little, if any, redistributed uranium (although the mineralogies of the oxidized and reduced ores are decidedly different, the morphology and tenor of the oxidized and reduced portions of the orebodies are essentially similar, and the surface ores are generally in approximate radiometric equilibrium). Carnotite and tyuyamunite have V/U ratios of approximately 1:1, and both vanadium-rich and vanadium-deficient ores will tend to approach this ratio, although from opposite directions. In the vanadium-rich deposits, vanadium will fix virtually all available uranium as uranyl vanadates, while in

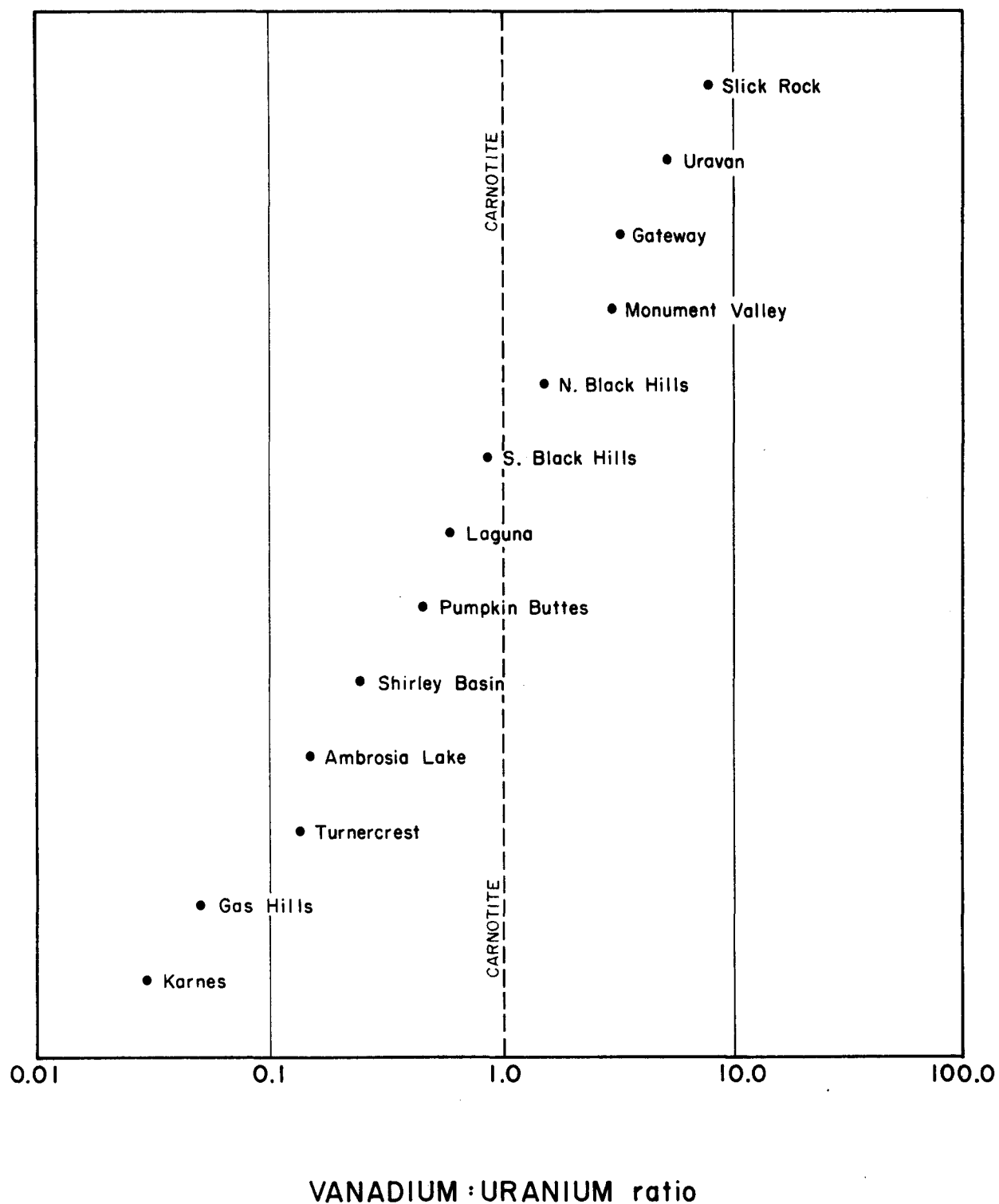


Figure 1. Vanadium-to-uranium ratio of selected uranium deposits. (Source of data: unpublished U.S. AEC ore-buying records, U.S. Dept. of Energy, Grand Junction, Colorado.)

vanadium-deficient ores, uranium will fix what little vanadium is available, and secondary minerals will be dominantly phosphates (for example, autunite) or silicates (for example, uranophane), with only minor amounts of the uranyl vanadates. Oxidized vanadium-deficient mineralization generally shows a daughter-product-excess type of radiometric disequilibrium ($eU > cU$); reduced ores down-dip will tend to be daughter-product-deficient ($eU < cU$). As seen in Figure 1, V/U ratios in the oxidized roll-type deposits of the Pumpkin Buttes and Black Hills areas are near 1:1, while districts with sizeable reduced deposits (e.g., Gas Hills, South Texas) all show V/U ratios much less than 1:1. An interesting intermediate is Ambrosia Lake, in which the original ore is of the peneconcordant type, but with a V/U ratio less than 1. Here, as mentioned earlier, there are significant quantities of redistributed ("stack") ore. The vanadium-to-uranium ratio and mineralogy of oxidized uranium occurrences, therefore, may be used to predict the occurrence of other deposits down-dip from the outcrop.

ROLL-TYPE DEPOSITS

The term roll, as applied to uranium ore, originated in the Uravan Mineral Belt as a miners' term for features in which the ore "rolled" up or down from the stratigraphic horizon being followed in mining. The resulting interface between ore and barren ground, often quite sharp, is curvilinear in vertical transverse section.

Features similar in shape were also termed rolls in the Wyoming ores and were found to have geological and geochemical implications not immediately evident in the Uravan deposits. There is no agreement regarding the relationship between the Wyoming and Uravan rolls, although Adler (1974) makes a distinction based on the genetic implications of the rolls in the two areas. Fischer (1970) has written an excellent paper noting the similarities and differences between the Wyoming and Uravan deposits. In our paper, usage is consistent with Adler's (1974) distinction: the Uravan "rolls" are considered to be a subsidiary feature of the orebodies, while the Wyoming and Texas ores are termed "roll-type" because the shapes of the orebodies imply genesis in a dynamic ground-water system.

Typical roll-type deposits consist of a zone of "altered" sediment, generally tongue-shaped and extremely irregular in detailed plan, bordered on the top and bottom by "unaltered" (actually less-altered) sediments. The term "altered" is unfortunate in this usage, since the entire sandstone host rock is commonly altered to some degree, such as bleaching of feldspars. The "altered" zone is commonly more intensely altered. The term "barren interior" has been proposed (King and Austin, 1966). However, in deference to common usage, the term "altered" is used here. A sharp, visible boundary, the solution front (sometimes termed the interface), borders the altered zone and separates it from the ore.

The roll-type orebody is commonly crescent-shaped in vertical transverse section and often lobate in plan; it is sharply separated from the altered sediment on the concave side by the solution front. The contact between the roll-type orebody and unaltered ground is commonly gradational and is strictly an economic cutoff. The solution front everywhere separates the altered and unaltered zones, but ore does not occur along its entire length.

Modifications of the ideal crescent shape of the roll are common and may produce S-shapes, compound crescents, and other irregular forms in the solution front. The horns of the crescent are commonly elongated and are generally confined by less-permeable strata above and below. They generally conform to the bedding. These features are termed, respectively, the upper and lower limbs of the roll. Subsidiary rolls may occur along the upper and (or) lower limbs. These are attributed to uneven advancement of the solution front, thought to move from the concave toward the convex side. The advancement of the solution front may also leave behind relict orebodies within the altered zone where conditions for their preservation are favorable.

The configuration of the solution front and the deposition of ore beyond it are controlled by permeability and the amount of precipitant present. The effects of these two parameters on the configuration of the solution front are shown diagrammatically in Figure 2 sketched from an exposure in the Lucky Mc mine, Gas Hills, Wyoming.

For the purpose of resource-assessment calculations, roll-type deposits are further subdivided into subclass 241, typified by the Wyoming roll-type deposits, and subclass 242, illustrated by Texas roll-type deposits.

Adler (1974) distinguishes between the Wyoming and Texas types on the basis of the geochemical environment of formation and source of reductants. Much of the evidence regarding the source of reductants in uranium deposits is based on interpretations of sulfur-isotope data (for example, Jensen, 1958; Warren, 1972). Shettel (1978) has reinterpreted existing sulfur-isotope data and has been able to simulate the sulfur-isotope distribution for the Gas Hills, Wyoming, using a double Rayleigh fractionation model, which requires neither sulfur-reducing bacteria nor disproportionation between unstable sulfur species. Neither the bacterial nor disproportionation theories adequately explain the lack of sulfur mass balance (sulfur precipitated $\ll$ sulfur dissolved) in the roll-type deposits. In light of the uncertainty regarding the source of reductants in the roll-type deposits, we feel a distinction of this type is purely artificial. Our distinction between the two subclasses is made largely on the basis of depositional environments of the host rock. The Wyoming deposits occur in fluvial stream-channel or braided-stream and alluvial-fan sediments deposited close to the source in rapidly filling intermontane basins, while the Texas deposits occur in marginal-marine, fluvial and barrier-bar sediments deposited some distance from the source in a coastal-plain environment. The individual Texas deposits are normally smaller than the Wyoming deposits, probably because the strike-oriented growth faulting of the coastal-plain sediments disrupts the permeability of the host rocks and decreases length of the down-dip path of solution flow.

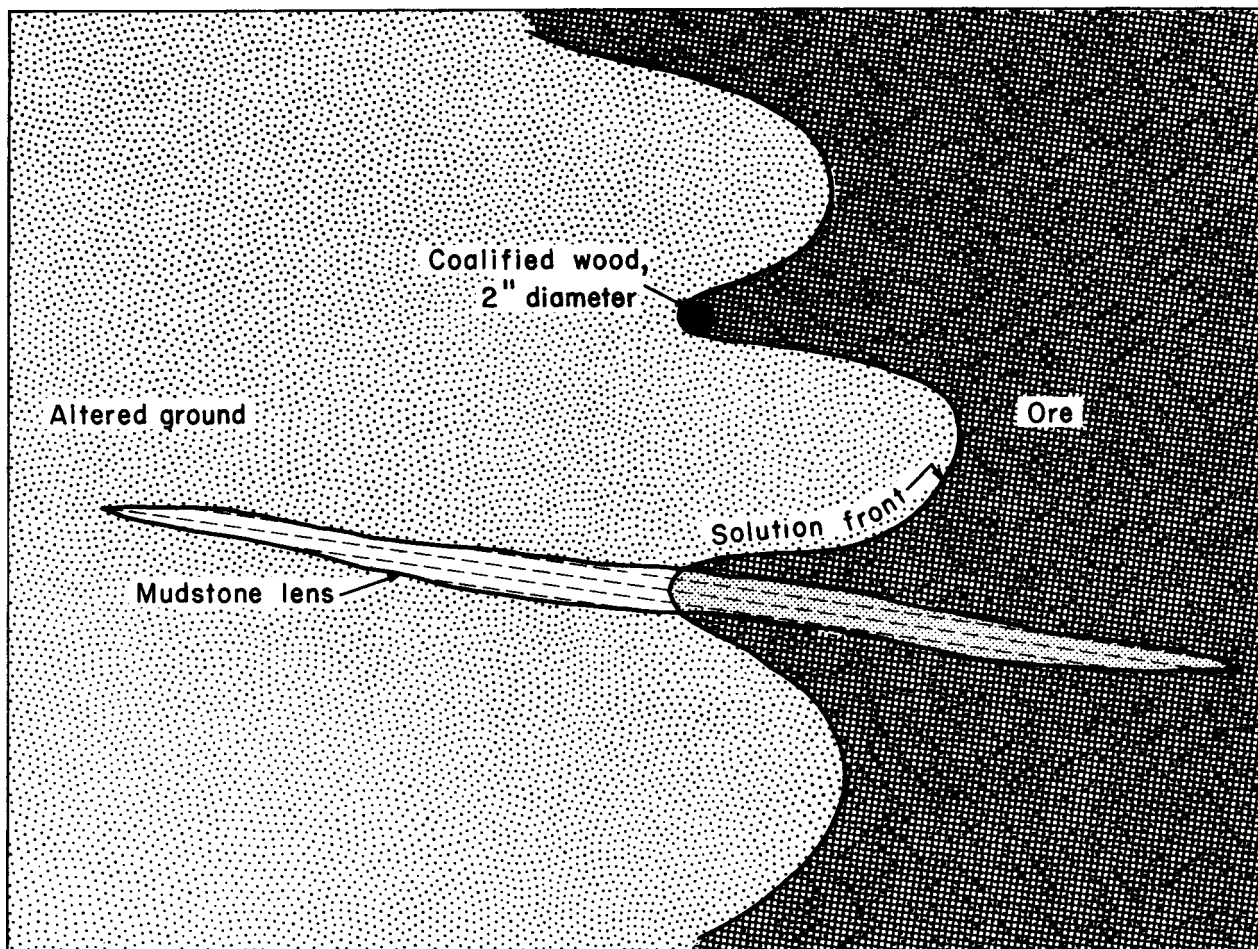


Figure 2. Rough sketch showing effects of precipitant (coalified wood) and reduction in permeability (mudstone lens) on vertical configuration of solution front.

Roll-Type Deposits of the Gas Hills, Wyoming (Example of Subclass 241)

Introduction. Uranium was discovered in the Gas Hills by Neil E. McNeice in 1953 (Anderson, 1969). The occurrence was in phosphatic concretions with autunite on their surfaces. The Gas Hills deposits were thought to be small, shallow, and largely oxidized. Only deeper drilling discovered the large, high-grade deposits.

Host Rocks. Uranium in the Gas Hills area of Wyoming occurs in the upper arkosic facies of the Wind River Formation (Eocene). Host rocks range from siltstone, through arkosic and feldspathic sandstone, to boulder conglomerate in which boulders 1 ft or more in diameter have been mineralized. The host rocks are various shades of gray, except where oxidation of sulfide minerals has produced yellowish to reddish-brown iron oxides. Even originally pink feldspars and granite boulders have been bleached to gray or nearly white, although the interiors of some quartzite cobbles (diameter 4 in.) show their original pink or red color. The upper Wind River Formation was derived from the pink granite of the Granite Mountains to the south. Maximum thickness of the upper arkosic facies of the Wind River is about 800 ft (Anderson, 1969).

The underlying lower Wind River Formation contains reddish to orange strata and had been termed ferruginous by Zeller and others (1955). The overlying White River and Wagon Bed Formations are dominantly tuffaceous and light-colored, commonly some shade of gray.

The host rocks originally dipped northward, but now dip toward the southwest because of the collapse of the Sweetwater Arch to the south. This reversal of dip is not typical of other Wyoming roll-type deposits.

Sources of Uranium. There are at least three possible sources of the uranium in the Gas Hills. As mentioned earlier, the sediments in the upper arkosic facies of the Wind River Formation were apparently derived from the nearby Granite Mountains, which stood considerably higher in Eocene time than at present. Stuckless and Nkomo (1978) report that, based on isotopic and Th/U ratios, the Granite Mountains lost a considerable portion of their uranium approximately 40 m.y. ago. Uranium might have entered the favorable host rocks as uraniferous groundwater emanating from the Granite Mountains or it might have originated by dissolution of the sediments themselves during alteration. In addition, tuffaceous material in the overlying White River and Wagon Bed Formations might have supplied uranium to percolating groundwaters.

Zeller and others (1955) reported channels filled with permeable sediments in the overlying White River Formation. There, channels cut entirely through the otherwise impermeable White River Formation to the upper Wind River Formation and are aligned with the three zones of mineralization. Thus, "plumbing" in overlying or underlying strata that connects with ore-bearing beds must not be overlooked. It is possible, however, that the principal drainage from the Granite Mountains occupied approximately the same position during most of Eocene time, and that these channels are merely stacked above the most-permeable zones in the underlying upper Wind River Formation.

Structure. The lower Wind River Formation was deposited unconformably on the pre-Tertiary rocks that form the Dutton Basin (Gas Hills) anticline and is overlain conformably by the upper Wind River Formation and later Eocene rocks. Mesozoic rocks crop out on the crest of the anticline just north of the uranium district. The Dutton Basin and Rattlesnake anticlines may have played an important role in localizing stream flow during Eocene time, resulting in the observed stacking of the channel sands in the district.

Alteration. Limonitic areas at and near the surface may indicate underlying oxidized and leached ore zones, but not all limonitic zones are demonstrably associated with ore. The surface, oxidized, altered ground is very difficult, if not impossible, to distinguish from unaltered ground.

In the subsurface, unaltered ground is light-gray and has a "fresh" appearance. Because of its gradational contact with unaltered ground, ore ranges in color from only slightly darker gray to dark-brown or nearly black. Altered ground is lighter in color than unaltered and has a bleached, "dead," or lusterless appearance, largely due to partial kaolinization of feldspars. Some feldspars are partly dissolved, and quartz is etched.

Conglomerate in altered ground and ore contains large granite clasts having a highly altered, bleached, "rotten" (probably kaolinized) rind about 1/8 to 1/4 in. thick that is easily separable from the inner, less-altered portion. Such pebbles and cobbles might be recognized on the surface and may indicate the former presence of a solution front.

Geochemistry and Mineralogy. Selenium is concentrated in and near the roll front, especially in altered ground. Molybdenum is similarly concentrated in the transition zone between ore and unaltered ground and extends some distance into both zones, often along the lower limb. These concentrations may be observed on pit walls. Selenium produces a pink (sometimes orange, due to impurities) bloom of native selenium. Blue coloration indicates molybdenum (ilsemanite). Neither of these elements is likely to be recognizable in surface exposures without chemical analyses, except for the possible presence of selenium-indicator plants (Astragalus, or locoweed).

The light color of altered ground is due to partial solution of mafic minerals, although this is difficult to demonstrate quantitatively (E. A. Noble, oral communication). Noble recognized three different types of pyrite in unaltered ground, ore, and altered ground, respectively. These are described by King and Austin (1966). Photomicrographs of the three types are in U.S. AEC Workshop Paper 7A (King and Austin, 1965, unpublished), available for inspection at BFEC Technical Library, Grand Junction, Colorado.

Diagenetic pyrite in unaltered ground is commonly euhedral to subhedral, sometimes twinned, and variable in habit; it is clean, bright, and larger than in either the ore or altered ground. Ore-zone pyrite occurs in aggregates of minute crystals commonly showing triangular, probably octahedral, faces. It is partially coated with black material (organic material, amorphous iron sulfides, and [or] uraninite). The X-ray pattern of one sample shows lines of both pyrite and a sulfur-deficient species, perhaps troilite or hydrotroilite.

Berner (1970) has shown FeS to be an intermediate product during production of FeS₂ by bacterial reduction of sulfate. Pyrite in altered ground is in discrete, untarnished, euhedral crystals and is most commonly cubic in habit. Some bright, untarnished marcasite has also been observed in the altered zone. Corresponding differences in habit have been observed among the pyrites of these respective zones in other Wyoming roll-type deposits (Crooks Gap and Shirley Basin).

Differences in habit of pyrites are not likely to be observed at or near the surface, because of oxidation. Dominance (not merely presence) of one of these pyrite types is a reliable indication of the zone penetrated by drilling.

Reductants. The upper Wind River Formation contains coalified logs and other vegetal remains, which are commonly enriched in uranium compared to the surrounding sandstone in ore zones. This type of material may also serve as the locus of remnant ore in altered ground. Amorphous organic material is also present in the ore; its amount commonly increases with grade.

Petroleum, some of it semisolid, occurs in the Lucky Mc Project 6 pit near the north end of the district. The petroleum is later than the ore, as it is associated with faults that displace the ore. An oil well within a few hundred feet of a wall of this pit has produced from a horizon only a few hundred feet below the bottom of the pit. A drill core from near the southern end of the district contains blebs of liquid petroleum. These occurrences, and unconfirmed reports of natural gas from some of the pits, suggest that rocks underlying much of the area contain at least small quantities of petroleum and (or) natural gas.

Although the petroleum may not be uraniferous, both liquid and gaseous hydrocarbons may have served as food for sulfur-reducing bacteria, which would have provided H₂S in sufficient quantity to reduce the uranium.

Geometry and Size of Deposits. Uranium occurs in an area about 5 mi wide and 20 mi long. It occurs in three roughly north-trending belts known as the East, Center, and West Gas Hills. The solution front can be traced for miles along each of these belts and may be mineralized to ore grade continuously for thousands of feet along the front. In other areas, the same solution front is barren. The thickness of an ore body is limited by the thickness of the permeable sandstone unit, which is bounded by less-permeable strata. Large rolls may contain ore-grade material for more than 100 ft normal to the trend of the belt, excluding any "lime" ore that may be present above and (or) below the altered zone.

The West and Center Gas Hills are parts of the same solution front. Armstrong (1970) also considered the East Gas Hills as a part of the same sinuous front. Part of the ore in the East Gas Hills (that in the finer sandstones and siltstones) resembles trend (peneconcordant) rather than roll-type orebodies. Anderson (1969) considered that such ore is younger than the associated roll-type ore, because of its radiometric disequilibrium ($cU > eU$).

Marks (1978) considered that ore was controlled in part by a lessened gradient of the groundwater surface. Some ore is controlled, or at least preserved, by perched water tables.

Production in the Gas Hills to date has been over 19.6×10^6 tons of ore, averaging 0.20 percent U_3O_8 . Total production for the district will probably exceed 100×10^6 lb U_3O_8 .

Roll-Type Deposits of South Texas (Example of Subclass 242)

Introduction. Roll-type deposits of South Texas occur in very gently dipping sandstones of fluvial-channel and strand-plain and barrier-bar systems. They appear to be associated with grabens or half-grabens. Volcanic ash, the probable source of uranium, and hydrogen sulfide, the reductant, are plentiful. Molybdenum and selenium are the most-reliable elements, other than uranium, that can be used to indicate uranium concentration. Although both oxidized and reduced deposits are present, the bulk of the reserves are contained in the reduced deposits; the oxidized deposits will receive only brief discussion in this section. (For a far more complete description of some typical oxidized deposits, the reader is referred to Bunker and MacKallor, 1973, and Dickinson and Sullivan, 1976.)

The initial discovery of radiometric anomalies in South Texas was made near Tordilla Hill in western Karnes County in 1954, during an airborne scintillometer survey for petroleum (Eargle, 1970). Shortly thereafter, an amateur rockhound discovered the first mineable uranium ore. Subsequently, the area was very heavily prospected, and most of the surface uranium shows and (or) radiometric anomalies were found. The initial discoveries were mostly uranyl (oxidized) ores of the autunite type. It was not until later in the history of the area that reduced ores were found down-dip from the surface mineralization.

Host Rocks. Host units for uranium deposits in South Texas are the Deweesville Sandstone Member of the Whitsett Formation (Jackson Group, late Eocene), the Frio Clay (Oligocene?), the Catahoula Tuff and Oakville Sandstone (Miocene), and the Goliad Sand (Pliocene) (Eargle and others, 1975). Arendt (1977) and T. R. Butts (personal communication) noted geochemical evidence of existing or still-forming areas of uranium concentration in the Lissie Formation of Pleistocene age. Host rocks commonly dip 1° or less.

The uranium deposits of Karnes County occur in the Jackson Group, of late Eocene age. Virtually all economic deposits in the Jackson Group occur in strike-trending strand-plain and barrier-bar systems (Fisher and others, 1970). An organic-rich lagoonal system and a dip-oriented fluvial-delta system containing permeable channel sands occur landward of this trend. Fisher and others (1970) stated that sedimentary environments favorable for formation of uranium deposits are those in which strand-plain and barrier-bar sands are interbedded with lagoonal and paludal muds. These authors further noted that fluvial channel sands in the Jackson Group are virtually devoid of mineralization. Presumably, the fluvial channel sands are too permeable to allow

deposition of uranium. This relationship, however, is difficult to understand, considering the propensity of uranium deposits to form in fluvial sandstones elsewhere in the U.S. and in other South Texas rocks of ages other than upper Eocene.

Most uranium deposits of the Duval area occur marginal to fluvial channel sandstones of the Catahoula Formation. (The major exception is the Pliocene Goliad Sand above the caprock of the Palangana salt dome.) Galloway (1977) has described two distinct fluvial systems in the Catahoula: the Gueydan system, deposited in the Rio Grande embayment, and the Chita-Corrigan system, deposited in the Houston embayment. The Gueydan system comprises high-bedload channel-fill and crevasse-splay facies, surrounded by coastal-lake and flood-plain tuffaceous siltstones, mudstones, and claystones. The Chita-Corrigan system is dominantly mixed-load channel-fill and crevasse-splay facies, surrounded by interchannel lake and floodplain deposits. Although the Chita-Corrigan system contains favorable depositional environments and has considerable uranium potential, most of the known uranium shows are in the Gueydan system. One possible explanation for the paucity of uranium in the Chita-Corrigan system is that the climate was too humid during Chita-Corrigan deposition, and uranium was leached from the volcanic component of the sedimentary rocks during deposition (Galloway, 1977). The Gueydan, westernmost of the two systems, was also probably closer to the source of the volcanics.

In the Live Oak area, a dip-oriented channel facies of the Miocene Oakville Sandstone is mineralized where it intertongues with channel-margin clays and overbank facies (Klohn and Pickens, 1970). Since these sands may be less permeable than in the older systems discussed above, the sandstone-to-shale ratios of 1:1 and 4:1 proposed by Grutt (1972) for intermontane basins may be more applicable here than they are elsewhere in South Texas (Quick and others, 1977).

Source of Uranium. There is almost unanimous agreement that the source of uranium in South Texas was the volcanic ash that overlies or is present in all host formations. Although other sources, such as sediments derived from metamorphic rocks intruded by uraniferous pegmatites in the nearby Llano uplift, or uraniferous brines associated with salt domes, could have supplied some uranium, it is unnecessary to call upon these sources. In unexplored areas containing acidic tuffs, the Th/U ratio of the tuffs may be an important indication of whether uranium has been mobilized, since the mobilities of U^{6+} and Th^{4+} are very different. Th/U ratios in excess of 3:1 to 5:1, which are normally associated with rhyolitic-dacitic rocks, may indicate that uranium has been leached from the rocks and transported elsewhere.

Structure. Structure is an important control in the localization of uranium in Texas. Many deposits, especially those in the Duval and Live Oak districts, are associated with down-to-the-coast growth faults. The faults are important in two ways: they may impede groundwater flow in otherwise permeable sandstones and (or) they may provide an avenue for the diffusion of hydrogen sulfide or other gaseous reductants into the host sandstones, causing a relatively uniform reducing environment into which oxidized, uranium-bearing groundwaters diffuse and precipitate uranous minerals. At the Maclean 1 mine (Live Oak County), for example, ore radiates upward from the plane of the Oakville fault.

Iron and molybdenum sulfides are associated with the ore and diminish in abundance with increasing distance from the fault. Strike-oriented faulting, therefore, is an important recognition criterion for Texas roll-type deposits. The presence of faults may explain uranium deposits in sandstones which elsewhere in the U.S. might be considered too permeable to be favorable for uranium deposits.

Alteration. Alteration in Texas roll-type deposits shows an overall similarity to that in Wyoming roll-type deposits; the most obvious characteristic is the destruction of iron sulfides (pyrite and marcasite) and reduced-iron or titanium oxides (magnetite, ilmenite). Goldhaber and Reynolds (1977) report a slight decrease in total iron from oxidized to reduced sides of a Catahoula Formation roll; this is in agreement with the observations of Harshman (1974) for a deposit in Karnes County, but not for the deposit Harshman sampled in Live Oak County, which shows a slight increase in iron down-dip from the roll front. Both papers report a significant increase in FeS_2 down-dip from the roll front for all deposits sampled. Goldhaber and Reynolds (1977) also report an increase in titanium in the fine fraction of sediments relative to the coarse fraction down-dip from the roll. These authors take this to indicate "progressively more intense alteration of precursor iron titanium oxide minerals to fine-grained TiO_2 ." In this case, alteration means sulfidation of the iron to FeS and eventually FeS_2 by H_2S , so that iron is approximately conserved.

Geochemistry and Mineralogy. The reduced ores of South Texas are predominantly the uraninite-coffinite type. Calcite may be present as gangue, at or down-dip from the roll front. Harshman (1974) observed that U, Se, V, Mo, and Fe^{2+} minerals are distributed down-dip from the edge of the altered tongue in the exact order of their oxidation potentials in both Wyoming and Texas deposits. Vanadium, however, does not reach the levels of enrichment that it does in the Salt Wash ores or even in the Gas Hills. The paucity of vanadium in the Texas ores might be an important indicator of the potential for significant reduced deposits down-dip. Uranyl vanadates, such as carnotite or tyuyamunite, are relatively insoluble in water, so vanadium-rich ores would tend to oxidize in place, as in the Colorado Plateau. Vanadium-deficient ores, such as those in Texas and some areas of Wyoming, tend to be dissolved in oxidized groundwaters and migrate down-dip. Radiometric disequilibrium (assays in favor of daughter products) in near-surface autunite-type (oxidized) Texas ores suggests that these deposits are actively undergoing dissolution, and uranium may be migrating down-dip. Slight disequilibrium in favor of chemical U_3O_8 at or near the up-dip side of the reduced rolls supports this contention. It should be stressed, however, that element-distribution studies such as Harshman's are normally conducted within a few tens of feet from the ore zone and are of rather limited utility in wide-scale sampling programs. Although Nichols and others (1977) presented a regional-geochemical-exploration model for sandstone-type deposits, it will not be until the NURE quadrangle-evaluation and Hydrogeochemical and Stream Sediment Reconnaissance programs are well along that valid, empirical, regional geochemical models can be constructed. Molybdenum and selenium (and, of course, uranium) are perhaps the best geochemical indicators of Texas-type reduced rolls.

Goldhaber and Reynolds (1977) stated that the presence of marcasite in the ores indicated formation in an acid medium. This is consistent with observed absence of calcite in the altered tongue, but not with the type of groundwater produced by subaerial weathering of tuffaceous sediments in a semiarid climate (alkaline, carbonate-sulfate type). The marcasite and calcite zonation can be explained without requiring uranium transport in acid solutions. Local concentrations of H_2S (a weak, diprotic acid) introduced along faults or by the sympathetic actions of Thiobacillus ferroxidans and Desulfovibrio desulfuricans can generate local acidic environments; metabolism of organic material or hydrocarbons by D. desulfuricans can add carbonate to the system at the redox zone and cause precipitation of calcite at the roll front and on the down-dip side of the roll (Cheney, 1962).

Reductants. In general, Texas ores are characterized by abundant sulfides and relatively little carbon trash (although logs have been observed associated with some deposits). This indicates that the environment of ore deposition was characterized by significant quantities of reduced sulfur; little adsorption of uranium on humates of humic material occurred. Coaly material, particularly within the Jackson Group, is predominantly lignite, which, although an efficient scavenger, does not have as high an exchange capacity for uranium as lower-rank carbonaceous material. Sour gas is associated with many deposits, petroleum has been produced from some uranium host formations, and the presence of the growth-fault system provides adequate plumbing for migration of H_2S . Carbon trash, of course, is a key recognition criterion for any sandstone-type uranium deposit; however, it need not be present if another reductant can be demonstrated.

Geometry and Size of Deposits. As in the Wyoming-type deposits, ore occurs in approximately crescent-shaped rolls whose apices point down-dip. The ore-bodies are wide in their strike direction (on the order of hundreds of feet). They are normally tens of feet thick and several tens of feet long in the direction of dip. The Felder orebody, a fairly typical reduced-type roll system in Live Oak County, contains on the order of $X.0 \times 10^6$ lb U_3O_8 averaging 0.X percent U_3O_8 (Klohn and Pickens, 1970).

PENECONCORDANT DEPOSITS

Peneconcordant uranium deposits in sandstones are here defined as essentially stratabound deposits which do not normally exhibit the continuous and sharp boundary between altered and unaltered ground commonly found in roll-type deposits. This subclass includes deposits in which altered and unaltered ground may be clearly distinguishable, as in parts of the Uravan Mineral Belt, and those in which the distinction, if it exists, is not readily evident, as at Ambrosia Lake, New Mexico. Nearly all deposits classified here as peneconcordant may show subsidiary features also characteristic of roll-type deposits.

Included in this subclass are the deposits of the Uravan Mineral Belt, Colorado-Utah, which show many roll-like features; channel deposits, as at Monument Valley, Arizona-Utah, and the Red Canyon and White Canyon areas, Utah; and the peneconcordant deposits of Ambrosia Lake and adjacent areas of New Mexico, upon which later fracture- and fault-controlled, redistributed ore (stack deposits) may be superimposed.

The peneconcordant deposits are further broken down (again, for the purpose of resource-assessment calculations) into subclass 243, those hosted by distinct, easily recognized channels (as in Monument Valley-White Canyon, Arizona-Utah); and subclass 244, those deposits in which channel control is not as evident (as in the Uravan Mineral Belt, Colorado-Utah). Because one dimension of the host rock is limited in the channel-controlled deposits, tonnages of individual orebodies of subclass 243 are likely to be somewhat smaller than those of subclass 244.

Peneconcordant Deposits of the Monument Valley-White Canyon Districts, Utah and Arizona (Example of Subclass 243)

Introduction. Copper was first discovered in the White Canyon District in the 1880s, but it was not until 1920 that the first uranium minerals from the area were described (Butler, 1920). The first uranium was produced from the area in the period immediately after World War II, at the Fry no. 4 claim in White Canyon and the Monument no. 2 in Monument Valley (Malan, 1968).

Host Rocks. Uranium in the Monument Valley-White Canyon districts occurs in channels of the Shinarump Member of the Chinle Formation (Upper Triassic) which are incised into the Lower Triassic Moenkopi Formation. The Shinarump is the basal unit of the Chinle in the area and is disconformably overlain by the Monitor Butte and Moss Back Members of the Chinle (Young, 1964). The Shinarump is composed largely of channel-fill sandstones and conglomerates, interbedded with siltstones and mudstones. The mudstones are carbonaceous in places; thin beds of coal may be present locally, indicating local interchannel paludal environments. Individual channels of Shinarump may be tens of feet thick, hundreds of feet wide, and traceable for a mile or more. Johnson and Thorardson (1959) interpret these channels as belonging to an anastomosing system deposited in a broad, shallow basin. Young (1964) has observed that the channels narrow and widen, and that the widening is accompanied by a lithologic change from sandstone to carbonaceous mudstones, signifying a change in gradient of the Shinarump streams. The Shinarump sandstones and conglomerates are composed of clasts of quartz, chert, quartzite, limestone, and siltstone (Thaden and others, 1964), indicating that they were derived from a sedimentary source.

Source of Uranium. The uranium deposits of the Monument Valley-White Canyon districts are an excellent example of the principle that an area cannot be considered unfavorable merely because no obvious source of uranium is present. The mature nature of the sediments all but rules out leaching uranium from either arkosic host rocks or an adjacent granitic highland, because neither source is evident. Overlying or interbedded Chinle mudstones are probably tuffaceous, but the ability to recognize a tuffaceous component in mudstones tends to decrease with the age of the rock (and those deposits are in the oldest

host rock discussed in this paper). A hydrothermal source has been suggested, but Laramide radiometric ages for the ore (Stieff and others, 1953) indicate that the ore probably formed before the emplacement of the nearby middle Tertiary stocks and laccoliths of the Abajo and Henry Mountains. In the absence of compelling evidence for source of uranium other than devitrification of tuffaceous components of the Chinle mudstones, we favor the tuffaceous source.

Structure. Tectonic structure does not appear to be an important ore control in the Monument Valley-White Canyon area. Sedimentary structures, especially scours within the larger Shinarump channels, are an ore control.

Alteration. Limonitic alteration, resulting from oxidation of sulfides, is the type of alteration most commonly visible on outcrop. Even more distinctive, in those deposits rich in copper, are conspicuous, bright blue and green copper minerals, chiefly azurite and malachite, resulting from oxidation of copper sulfides.

Some bleaching due to reduction and (or) removal of iron occurs, chiefly in underlying sediments, but also to some extent in the host formation adjacent to ore. In the Monument Valley area, white, fluorescent opal is associated with some type of ore. Quartz, feldspar, and chert grains are commonly corroded, especially in zones rich in sulfides, vanadium, or calcite. Witkind and Thaden (1963) report intense fracturing of detrital grains on the periphery of distinctive orebodies in Monument Valley termed "rods."

Occurring in the Monument Valley area (but undocumented in the literature) is the penetration of detrital quartz grains by authigenic barite and the subsequent replacement of the barite by quartz in optical continuity with the detrital grain. This is evidenced by the retention of a pattern of inclusions originally in the barite (but not the barite, itself) in the quartz grains, and by the presence of similar inclusions in barite crystals penetrating quartz grains but not replaced by quartz.

Mineralogy and Trace-Element Associations. Uraninite (variety pitchblende) is the dominant primary uranium mineral, but X-ray patterns indicate that coffinite is present in places. In the vanadium-rich ores, secondary uranium minerals are dominantly the uranyl vanadates carnotite, tyuyamunite, and meta-tyuyamunite. Carnotite tends to favor the finer-grained, commonly more-argillaceous sediments and fossil wood, both likely to contain more potassium than coarser, cleaner sandstones, especially if those sediments are not highly feldspathic or arkosic.

The hydrous uranyl oxides, such as schoepite, fourmarierite, and becquerelite, tend to occur in and near uraninite-replaced logs, where oxidation is still in progress, and where uranium is much more abundant than vanadium. The more-stable secondary uranyl phosphates, arsenates, and silicates occur in vanadium-rich deposits only locally, at sites where vanadium is not abundant enough to form vanadates.

Primary vanadium minerals are chiefly montroseite, roscoelite(?), and vanadium clays. Primary vanadium thus tends to favor the finer-grained sediments, where it is adsorbed by and (or) replaces aluminum in the crystal structure of clay minerals. The mineralogy of oxidized, and especially partly oxidized, vanadium minerals is not entirely definitive. However, corvusite and corvusite-like minerals appear to dominate the partly oxidized ores, and hewettite and metaheiwettite are probably the most-abundant minerals of the fully oxidized vanadium-rich zones.

Uraninite and minor coffinite are also the dominant primary uranium minerals in the deposits rich in copper. Secondary uranium minerals are largely the sulfates: zippeite and zippeite-like minerals, uranopilite, and johannite. The dominance of sulfate minerals is probably due to the greater abundance of sulfides in the copper-rich deposits, since the primary copper minerals are the sulfides, and since pyrite and marcasite are also present. Oxidation of the sulfide minerals releases abundant sulfate to combine with the uranium. Of these minerals, only johannite (certainly not the most abundant of the three) contains copper. Other copper-uranium minerals, such as torbernite, metatorbernite, zeunerite, metazeunerite, cuprosklodowskite, and voglite, occur, but are less abundant than the uranyl sulfates.

Chalcopyrite is the most-abundant primary copper mineral, but is less abundant than pyrite in the copper-rich deposits. Other copper sulfides are bornite, chalcocite, covellite, and idaite. Oxidized copper minerals are chalcantite, brochantite, azurite, malachite, and antlerite. Since vanadium and copper are not mutually exclusive in these deposits, copper-vanadate minerals such as volborthite and calciovolborthite occur in deposits rich in both these elements.

Trace elements which are not essential constituents of the minerals previously listed include: molybdenum in jordisite and ilsemannite; zinc in sphalerite; cobalt in erythrite (some bieberite may also be present); cobalt in pickeringite and perhaps wad; lithium and manganese in wad; phosphorus in collophane; lead in galena; and nickel in gersdorffite.

Reductants. The dominant reductant for the ores is carbonized "trash." Trites and others (1959) report that the Shinarump channel fills contain from 1 to 5 percent carbonized logs. Fossil wood is the locus for deposition of uraninite and primary sulfides; secondary sulfides such as marcasite, chalcocite, and covellite are formed from supergene enrichment of the primary sulfides.

Blebs of liquid petroleum have been observed by the senior author in a barren drift at the Happy Jack mine, White Canyon district, but have not been documented in the literature.

Geometry and Size of Deposits. Several types of orebodies have been recognized in the Monument Valley and White Canyon districts (Trites and others, 1959; Witkind and Thaden, 1963; Thaden and others, 1964). Ore occurs as tabular replacements of trash accumulations, as replacements of large individual logs, and as rods, rolls, concretionary masses ("corvusite ore"), and bedded deposits (where sandstone and siltstone are interbedded, generally replacing the siltstone beds). The tabular orebodies are probably the largest and most-important

type, ranging from 50 to 150 feet in length, from 25 to 50 feet in width, and up to 3 feet thick. Total production to date in the White Canyon district has been over 2.0×10^6 tons of ore averaging 0.25 percent U_3O_8 ; Monument Valley has produced 1.3×10^6 tons of ore averaging 0.32 percent U_3O_8 .

Peneconcordant Deposits of the Uravan Mineral Belt (Example of Subclass 244)

Introduction. The Uravan Mineral Belt is the oldest uranium mining district in the United States. The first shipment of ore (10 tons of ore averaging over 20 percent U_3O_8 and 15 percent V_2O_5) was made from the Rock Creek area, Montrose County, Colorado, in 1898 (Coffin, 1921). Ores of the belt were first developed for their radium content, next for their vanadium, and since World War II, when the strategic value of uranium became apparent, for their uranium.

Host Rocks. The predominant host for the uranium-vanadium deposits of the Uravan Mineral Belt is the Salt Wash Member of the Morrison Formation. The Morrison Formation is a series of interbedded mudstones and sandstones, averaging 600-800 feet thick in western Colorado and eastern Utah, that was deposited in a braided-stream or stream-channel and flood-plain environment. The Salt Wash Member has been interpreted as being deposited as a large alluvial fan or system of fans, whose source was near the point where the present Colorado River crosses from Utah into Arizona (Fischer, 1968). In this area, the Salt Wash is composed almost entirely of conglomerate and sandstone and attains its maximum thickness (about 600 feet). The Salt Wash becomes finer-grained and thins northward and eastward from this point. The favorable rocks of the Uravan Mineral Belt occur in an arcuate band where the coarse, proximal facies of the fan grade into the finer, distal mudstones. In the mineral belt, the sandstone-to-mudstone ratio of favorable Salt Wash is approximately 1:1.

Source of Uranium. The source of uranium in the Uravan Mineral Belt is something of an enigma. The mudstones within the Salt Wash and of the overlying Brushy Basin Member of the Morrison Formation are bentonitic and contained a significant component of tuffaceous material which could have supplied uranium to the sandstones. The sandstones themselves are feldspathic, but certainly less so than those of the Wyoming deposits. The least-altered host rocks contain vanadiferous and uraniferous heavy minerals, implying that the host rocks themselves could have supplied uranium to the deposits. The V/U ratio is zoned, decreasing from south to north within the belt, indicating either that the vanadium and uranium came from different sources, or that the two metals came from the same source and the zonation is due to slightly different mobilities of V and U in the ore-forming environment.

Structure. Tectonic structure is not an important ore control in the Uravan Mineral Belt. There is some evidence that the salt anticlines of the Paradox Basin were positive areas during Morrison time; these could have localized stream flow and affected the positioning of the coarser facies of the Salt Wash. Sedimentary structures, such as "festoon solids" (Roach and Thompson, 1964), may be an important ore control, especially in the low-grade ores.

Alteration. Alteration is perhaps a more-useful guide to ore in the Uravan Mineral Belt than in any other major uranium district in the U.S. Readily recognized alteration consists of bleaching of both sandstone host rocks and associated mudstone by removal and (or) reduction of ferric iron. However, ore deposits in the bleached zone may locally contain a larger relative concentration of total iron in the ferrous state (as pyrite and marcasite) than is present in the ferric state in the unaltered ground.

Unaltered sandstone is reddish-brown, and unaltered mudstone is somewhat redder in tone. Altered sandstone is nearly white to gray or buff and commonly oxidized to a darker-buff color or limonitic-brown on outcrop. Altered mudstone is gray to greenish-gray.

Unaltered sediments are considered unfavorable for uranium-vanadium deposits, whereas altered sediments, which contain essentially all the deposits, are considered favorable. However, the presence of at least some reddish, unaltered lenses, especially of mudstone, in the Salt Wash section, is considered more favorable than an entirely altered section. This is probably because here, as in most other districts, primary uranium deposition is controlled in part by the boundary between oxidized and reduced ground.

It is most commonly believed that the host sediments were originally unaltered and reddish in color, and that alteration and bleaching occurred as a result of, or at least in conjunction with, mineralization. It can be argued that the sediments were originally reduced and that those lenses that contained the most reducing material or that were least exposed to oxidizing solutions remained reduced and accumulated uranium. In that case, application of the terms "altered" and "unaltered" would be reversed. However, there is the possibility that some of the bleached sediments now termed "altered" were reduced syngenetically or during early diagenesis.

Mineralogy and Trace-Element Associations. Primary uranium minerals in the Uravan Mineral Belt are uraninite and an unknown but significant amount of coffinite. Primary vanadium minerals are dominantly montroseite, roscoelite(?), and vanadium clays and (or) vanadium-bearing clays. Limited observation by the senior author suggests that low-valence vanadium-oxide minerals such as montroseite do not appear until vanadium has replaced the aluminum occupying essentially all suitable sites in the crystal structures of the clay minerals in the immediate vicinity.

Since the ratio of vanadium to uranium commonly greatly exceeds the approximately 1:1 ratio necessary for the formation of uranyl vanadates, carnotite, tyuyamunite, and metatyuyamunite thoroughly dominate the suite of secondary uranium minerals. Uranyl silicates, such as uranophane and beta-uranophane, and phosphates, such as autunite, meta-autunite, torbernite, and metatorbernite, occur rather sporadically where vanadium is locally deficient.

Partly oxidized vanadium minerals are largely of the corvusite group. Fully oxidized vanadium minerals include pascoite, hummerite, steigerite (all rather similar in appearance), hewettite, meta-hewettite, rossite, and meta-rossite. Several other species occur, but less commonly.

Primary copper minerals such as chalcopyrite occur in copper-rich portions of the district. Secondary copper minerals are azurite and malachite and other blue or green minerals. Lead occurs in clausthalite and galena, and selenium occurs in clausthalite, as well as the red and gray forms of the native element. Zinc is present in sphalerite.

Reductants. The most obvious reductant for the ores of the Uravan Mineral Belt is organic material, especially carbonized wood. The association of high-grade uranium-vanadium ore with carbonized wood is readily observable in most areas, some logs reportedly containing 35 percent U_3O_8 (Stern and Stieff, 1959). The organic material itself may be the locus of uranium deposition (as in replacement of cell walls by uraninite, coffinite, and montroseite), or the organic trash may have provided food for sulfur-reducing bacteria (causing local "islands" of reducing environment in an otherwise oxidized sandstone).

Geometry and Size of Deposits. Orebodies in the Uravan Mineral Belt may show virtually every imaginable shape, but there are two overall types: tabular and discordant. The tabular orebodies are generally aligned normal to the trend of the mineral belt (roughly parallel to depositional trends within the Salt Wash), are roughly concordant with bedding, and may be controlled by sedimentary structures or accumulations of carbon trash. They normally have no obvious front or back and are distributed "like raisins in raisin bread" (Fischer, 1970). The discordant orebodies may be C- or S-shaped rolls; they cut across bedding and show evidence (such as solution banding) of being diffusion phenomena. Typical tabular orebodies may be several feet thick, several tens of feet wide, and hundreds of feet long. Larger individual districts (such as the Slick Rock or Uravan districts) within the mineral belt have produced on the order of 3×10^6 tons of ore, averaging 0.25 percent U_3O_8 .

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URANIUM OCCURRENCES IN AND RELATED TO PLUTONIC IGNEOUS ROCKS

by

Geoffrey W. Mathews

ABSTRACT

The discussion of the geologic characteristics of the eight classes of uranium occurrence in and related to plutonic igneous rocks is subdivided into eight separate categories. These are: (1) tectonic setting, (2) lithology, (3) texture, (4) mineralogy, (5) chemistry, (6) alteration, (7) geometry, and (8) lithologic and structural associations. A discussion of the resource potential of each class is included for quadrangle-evaluation purposes. Except for occurrences of the anatectic class, most occurrences of this classification are either in or closely associated with late-stage, epizonal, postorogenic plutons located in mobile-belt terranes. Textures of the associated plutons are generally porphyritic or hypidiomorphic-granular. Tetravalent uranium and uranium-bearing minerals contain much of the uranium in occurrences of this classification with the exception of occurrences of the authigenic class; authigenic occurrences contain hexavalent uranium minerals. Fluorite is a common accessory mineral in many occurrences of this classification.

Host-rock chemistry is variable. Associated plutons are usually characterized by high SiO_2 , Na_2O , and K_2O contents and low amounts of FeO , MgO , and CaO . A high fluorine content is common; Th/U ratios vary between the different classes. Although no single type of alteration is universally developed in uranium occurrences in and related to plutonic igneous rocks, evidence of albitization is commonly observed. Other varieties of alteration are variable in both kind and extent between the different classes. The geometry of the uranium-enriched zones also varies between the classes. Most occurrences of this classification are discordant; some anatectic occurrences may be concordant.

Associations, whether lithologic or structural, vary between the different classes of uranium occurrences in and related to plutonic igneous rocks. The dominant association is with an igneous intrusive which has an anomalous uranium content. Most occurrences of this classification represent submarginal to paramarginal resources. A few deposits of this classification are recoverable resources and are currently being mined.

INTRODUCTION

Establishment of a comprehensive set of recognition criteria for uranium occurrences in and related to plutonic igneous rocks (Mathews, 1978) depends very heavily upon published descriptions of deposits. The criteria given in this report are compiled from numerous sources. In order that all possibilities be included, the criteria necessarily cover a broad spectrum. Complicating the task of identifying recognition criteria is the fact that published descriptions seldom discuss all aspects of a uranium occurrence in which one might be interested. For example, some reports exclude pertinent chemical characteristics, others omit a discussion of the tectonic setting, and still others ignore or slight discussion of host-rock attributes. This renders difficult the development of a definitive tabulation of recognition criteria common to all occurrences of each class.

However, several themes recur; for example, accessory fluorite is repeatedly described in orthomagmatic occurrences. It is not known whether a characteristic which continually recurs is necessarily a significant recognition criterion for all such occurrences. The recurrence of several characteristics and their consistency with models of uranium behavior in a magma system lead one to suspect that they may be diagnostic.

The lithophile and mobile nature of uranium adds distinctly to the variability in uranium occurrences. This, in turn, adds to the variability and the breadth of tabulated recognition criteria.

Irrespective of inherent drawbacks, uncertainties, and interpretations involved in identifying characteristic recognition criteria for each class of uranium occurrence, a tabulation of criteria has been compiled. These criteria are sufficiently broad that a given deposit will not be omitted.

The tabulated criteria are preliminary and may have to be revised. Continued literature study, field examinations, and data from field geologists will allow necessary revisions.

The purpose of this report is to provide field geologists with a usable summary of recognition criteria for uranium occurrences in and related to plutonic igneous rocks. Tabulation and discussion of these criteria are designed to assist in evaluating the uranium potential of areas underlain by plutonic igneous rocks. Application of these criteria requires a working knowledge of possible environments of uranium enrichment associated with magmatic processes and a familiarity with the various processes of uranium enrichment within a magmatic system.

GENERAL CONSIDERATIONS

Uranium exhibits a predictable behavior in an evolving magma system. Knowledge of the mineralogical, textural, and structural characteristics imparted to the rocks during the differing stages of magmatic evolution and familiarity with the effects of physicochemical environments on the distribution of uranium within the system allow establishment of recognition criteria for associated uranium occurrences. With this background, textural, structural, and compositional attributes of igneous rocks may be used to infer the likelihood of uranium concentrations within the rocks. Similarly, rock attributes might be used to indicate the probability and nature of associated uranium enrichments. Knowledge of a magmatic evolutionary system and its effect on the distribution of uranium allows one to recognize why specific classes of uranium occurrences have specific recognition criteria.

Classification of uranium occurrences in and related to plutonic igneous rocks is based on the theory of behavior of uranium in a magmatic environment (Mathews, 1978). This theory provides the conceptual basis for a genetic classification. Field assignment of given occurrence to a particular class should be based largely on the nature of the enclosing rock, with only secondary reliance on laboratory analytical work. This report is designed to provide sufficient field recognition criteria, so that extensive laboratory analysis is not necessary. By way of review of how both rock properties and the distribution of uranium develop in magmatic systems, a brief discussion of the behavior of uranium in a magmatic environment is given here.

URANIUM IN A MAGMATIC SYSTEM

Uranium, atomic number 92, is the heaviest naturally occurring element. Uranium may exist as either reduced or oxidized ions, U^{+4} and U^{+6} , respectively. The oxidation state of uranium is an important factor in the behavior of uranium in magmatic and postmagmatic environments. Some magmatic and nearly all postmagmatic processes may cause oxidation of tetravalent uranium. Oxidized uranium is readily removed from a magma or plutonic igneous rock. It may become concentrated elsewhere, where reduction promotes precipitation of pitchblende.

Magmatic uranium is almost entirely tetravalent, as shown by the high U^{+4}/U^{+6} ratios in orthomagmatic uraninite, zircon, sphene, and other minerals. The high electrical charge and the moderately large ionic radius (1.05 Å) of tetravalent uranium ions dictate coordination requirements which preclude extensive isomorphous substitution in common rock-forming minerals. Tetravalent uranium displays limited substitution for Ca^{+2} (ionic radius, 1.06 Å; e.g., fluorite, sphene) and Zr^{+4} (ionic radius, 0.87 Å; e.g., zircon) and extensive substitution for Th^{+4} (ionic radius, 1.10 Å; e.g., thorite). (Ionic radii are from Goldschmidt, 1954.) The limited substitution for major constituent cations causes uranium and thorium to become progressively more concentrated in residual fluids during magmatic differentiation. As pointed out by Neuerburg (1956), the uranium content of an igneous rock is not an adequate estimate of the uranium content of the magma from which the rock formed; uranium is more

concentrated in the melt than in coexisting solids. This fact leads to progressively more uranium in younger members of an igneous kindred. The pattern of uranium enrichment in younger differentiates of a comagmatic series has been adequately demonstrated in a number of igneous kindreds (see, for example, Larsen and Gottfried, 1961; Lyons, 1964).

Although isomorphous substitution is severely limited, uranium may be trapped in dislocations and structural defects in major rock-forming minerals (Armstrong, 1974). Such a distribution lacks predictability, however. Although major rock-forming minerals contain low concentrations of uranium (generally <5 ppm), they may account for a large percentage of the total uranium in a plutonic igneous rock.

A magma consists of a single fluid phase during the orthomagmatic stage of the evolutionary continuum. Liquidus crystallization of major rock-forming minerals causes a progressive enrichment of dissolved volatiles and large lithophile elements in the residual melt. When the magma becomes saturated with dissolved volatiles, the pressure of the volatiles exceeds the external pressure which tends to hold them in solution, forcing the volatiles to come out of solution. This process, the second boiling of the magma, forms a separate water-rich magmatic fluid charged with alkalis and large lithophile elements. Uranium is fractionated into the separate aqueous phase. If the f_{O_2} of the system is sufficiently high, some of the uranium may be oxidized and may begin to fractionate from Th^{+4} . Forces acting on the magma at or after the time of saturation govern the fate of the aqueous phase and thus importantly affect the distribution of uranium. The nature of the resultant rocks and the distribution of uranium will depend upon when the uranium-bearing aqueous phase is removed from the magmatic system during continuing crystallization.

Burnham and Jahns (1962) have demonstrated that the amount of water dissolved in a granitic magma increases with increasing confining pressure. A granitic magma under moderately high pressure contains a greater amount of dissolved volatiles than the same magma at lower confining pressures. Therefore, a magma undersaturated with dissolved volatiles will, with upward migration and intrusion, become oversaturated. The second boiling point may be reached, developing the separate aqueous phase.

If the tectonics of the system are such that the magma is tapped soon after separation of the aqueous phase, the silicic, water-rich fluid may penetrate fractures within the parent pluton or may be injected into fissures in the adjacent country rock. Crystallization then produces pegmatites. If, however, the magmatic system remains untapped until most of the silicic phases have crystallized, the separate fluid phase will become still more highly aqueous. Tapping the system at this stage of evolution may give rise to magmatic hydrothermal solutions. Such magmatic hydrothermal solutions may contain a relatively high percentage of lithophile elements of large ionic radius, as well as high percentages of alkalis and halogens. Oxygen fugacity in these solutions is high and promotes oxidation of uranium. Because hexavalent uranium is highly soluble in high-temperature aqueous solutions, and because thorium is not oxidized and tends to remain in the magmatic phase, an effective fractionation of uranium and thorium occurs.

If the magmatic system remains untapped through its evolution, the late-stage, uranium-bearing aqueous phase may permeate either the country rock or the previously crystallized pluton. This may result in metasomatic alterations and enrichment in uranium.

Thus, the amount and partial pressure of water play a significant role in a magmatic system. Water governs the crystallization temperature of minerals. It may strongly influence the species of the ferromagnesian minerals. Water plays a dominant role in the textural development of the rock. Equally important, water governs the oxidation state of uranium and provides a medium for its concentration in the later stages of magmatic evolution.

Concentrations of uranium in and related to plutonic igneous rocks depend on several factors. These include (1) the initial concentration of uranium in the magma, (2) the stage of magmatic evolution during which uranium is either deposited or mobilized, (3) the concentration of uranium-complexing chemical species in the magma, (4) the physicochemical conditions under which differentiation and crystallization occur, (5) the tectonic setting, (6) the behavior of uranium under the conditions prevailing during magmatic differentiation and crystallization, and (7) the postmagmatic chemical environment. These factors do not operate independently. As a consequence, depending upon which of these factors may dominate, uranium may be trapped in common rock-forming minerals (for example, feldspar), be incorporated in trace or accessory minerals (for example, zircon), become concentrated enough to form its own mineral species (for example, uraninite, coffinite), or become concentrated in residual fluids, to be either taken up in uranium and uranium-bearing minerals or remain in fluid inclusions or intergranular fluids (Jahns, 1953; Neuerburg, 1956). Postmagmatic processes may remove labile uranium and concentrate it in specific zones within the pluton or in the adjacent country rock.

CLASSIFICATION

An in-depth discussion of the classification of uranium occurrences in and related to plutonic igneous rocks is beyond the scope of this report; only a brief discussion is given here. The reader is referred to Mathews (1978) for a more complete treatment.

Classification of igneous and igneous-related uranium occurrences is based on the behavior of uranium in magmatic and postmagmatic environments. Time of the uranium mineralization and nature of the host rocks are taken into account. Three major stages of magmatic evolution in which uranium may be deposited are recognized: (1) an orthomagmatic stage, (2) a pegmatitic stage, and (3) a hydrothermal stage. Pegmatitic and magmatic-hydrothermal uranium occurrences represent postsaturation tapping of the magma system. If the magma system remains untapped subsequent to saturation, uranium-bearing magmatic emanations may permeate either the country rock or the previously crystallized pluton and create two metasomatic uranium-occurrence classes. Postmagmatic processes acting at low to moderate temperatures may redistribute uranium into vein-type deposits, either within or near the pluton. Two classes of occurrences formed in this manner are defined on the basis of the host rocks. An additional class, which comprises uranium occurrences formed by anatexis, is included because of similarities with deposits produced by strictly magmatic processes.

Occurrences of this class are a link between occurrences formed by igneous and those possibly formed by metamorphic processes. Thus eight genetic classes of uranium occurrences in and related to plutonic igneous rocks are delineated. These are:

ORTHOMAGMATIC CLASS:	Syngenetic dissemination of uranium and uranium-bearing minerals formed during the orthomagmatic stage of crystallization: disseminations
PEGMATITIC CLASS:	Occurrences formed during the pegmatitic stage of magmatic differentiation: pegmatites/aplites
MAGMATIC-HYDROTHERMAL CLASS:	Occurrences formed during the hydrothermal stage of magmatic evolution: veins
CONTACT-METASOMATIC CLASS:	Occurrences formed by contact metasomatism: disseminations, replacements
AUTOMETASOMATIC CLASS:	Occurrences formed by autometasomatism: disseminations, replacements
AUTHIGENIC CLASS:	Internal occurrences formed by postmagmatic processes
ALLOGENIC CLASS:	External occurrences formed by postmagmatic processes
ANATECTIC CLASS:	Occurrences formed by anatectic processes: pegmatites/aplites

These classes and their mutual relations are pictorially shown on the following chart (Mathews, 1978).

PROCESS

MAGMATIC DIFFERENTIATION

ANATEXIS

STAGE

CLASS

CLASS

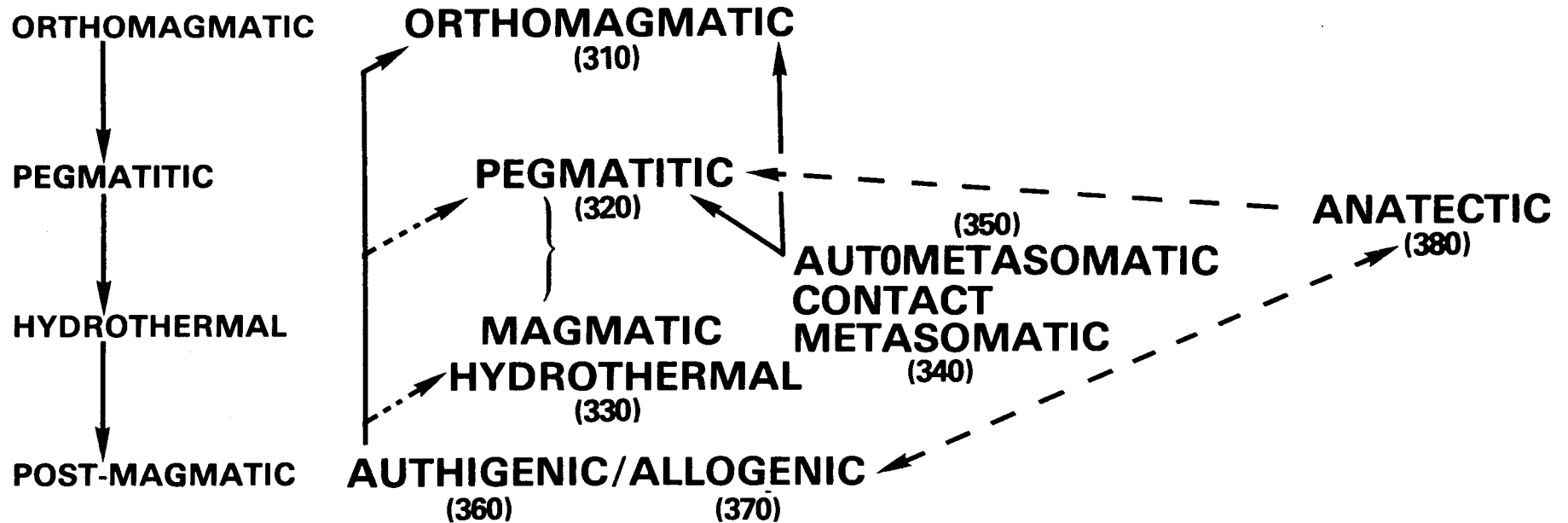


**FIGURE 1. CHART OF GENETIC CLASSES OF URANIUM OCCURRENCES
IN AND RELATED TO PLUTONIC IGNEOUS ROCKS**

ORTHOMAGMATIC CLASS (CLASS 310)

Orthomagmatic uranium occurrences develop by liquidus crystallization of uranium and uranium-bearing minerals in late-stage magmatic differentiates. Uranium exists in uranium minerals per se, as substitutive cations in either fixed or exchange-cation positions in other minerals, as foreign cations in common rock-forming minerals, and dissolved in intergranular fluids or fluid inclusions. Nonlabile uranium exists in small, finely disseminated grains of primary accessory minerals. Occurrences of this class normally develop prior to the volatile-saturation stage of evolution.

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Orthomagmatic uranium occurrences are found in areas marked by extreme crustal mobility, although most are postorogenic. They commonly occur in intracratonic mobile belts, areas underlain by continental crustal material. Strontium-isotope data from a few orthomagmatic-class plutons suggest that the magmas were derived from the continental crust (Beck, 1969). An additional indication of the crustal origin of the magmas comes from the nature of the igneous kindreds. Uraniferous plutons commonly belong to comagmatic sequences which contain small volumetric percentages of mafic intrusive phases. This suggests that the primary magmas were granitic. The cogenetic Laramide intrusives of the Colorado Front Range are a good example.

Uraniferous plutons of the orthomagmatic class are generally epizonal. Epizonal plutons are characterized by sharp, discordant contacts and isochemical thermal metamorphism of the country rock. Some contact aureoles show evidence of contact metasomatism. Synchronous regional metamorphism normally is lacking. Epizonal plutons characteristically have chilled border facies. They are often associated with genetically related volcanics (Kaffo Valley granite, Nigeria, for example). Associated aplites and lamprophyric dikes are common, whereas associated pegmatites are more rare. Roof pendants and xenoliths are generally abundant.

Anomalous uranium concentrations in shallow-seated plutons and hypabyssal rocks are partially explicable in terms of their epizonal character. Jahns and Burnham (1969) have demonstrated that the amount of dissolved fluids in a magma decreases with decreasing pressure. Similarly, Luth and Tuttle (1968) have shown that the composition of dissolved solids in fluids coexisting with granitic melts becomes progressively more restricted with decreasing pressure on the system. These factors cause uranium to tend to remain in the magma ultimately becoming disseminated in the resultant plutonic rock. Uranium in orthomagmatic occurrences is also a function of the uranium content of the initial magma and the degree of differentiation producing the derivative magma. Orthomagmatic occurrences form prior to or nearly contemporaneous with saturation of the magma.

Most uraniferous plutons of the orthomagmatic class are postorogenic. Primary granitic magmas are believed to develop during middle and late stages of tectogenesis (Wyllie, 1971; Hyndman, 1972). Progressive differentiation in a tectonically inactive area and intrusion into high levels of the Earth's crust gives rise to the epizonal and postorogenic character of these plutons. Some subaluminous and peralkaline epizonal intrusions, a few of which have anomalous uranium concentrations, are anorogenic.

Lithology

Plutons comprising occurrences of the orthomagmatic class are normally leucocratic and represent late differentiates of a comagmatic sequence. Alaskites, granites, and quartz monzonites are typical lithologies of quartz-bearing rocks comprising orthomagmatic occurrences. Syenites and feldspathoidal syenites are less common, but probably develop equally late in the magmatic evolutionary sequence.

Texture

Textures of uraniferous plutons are variable, although porphyritic varieties are the most common. Such textures probably reflect the effect that the partial pressure of water has on nucleation rates and crystallization temperatures. Groundmass textures in the porphyries may represent venting or partial venting of the magma. The common association of epizonal plutons with consanguineous volcanics supports this contention.

Plutons comprising occurrences of the orthomagmatic class rarely display any syncrystallization foliation, except perhaps in the immediate contact zone. Nonfoliated textures imply that the magma was quiescent and suggest that tectonic forces which might allow the escape of residual fractions of the magma were not operating during crystallization. The lack of significant tectonic activity during crystallization increases the likelihood of the uranium remaining in the system.

Miarolitic cavities are often prevalent, particularly in the upper reaches of the plutonic body, which suggests that final solidification of the system was roughly synchronous with saturation of the magma and indicates that a contiguous, separate aqueous phase did not develop. Therefore, much of the uranium in the system was not fractionated into a separate aqueous phase. Thus, much of the uranium probably remains in the pluton.

Mineralogy

Leucocratic uraniferous plutons commonly consist of potash feldspar and sodic plagioclase, with either quartz or feldspathoids. Quartz-bearing varieties are the most common. When zoned, the plagioclase exhibits oscillatory zoning, which reflects the quiescence of the magma. Ferromagnesian minerals are often anhydrous or contain a low percentage of water. The most commonly

occurring ferromagnesian minerals are sodic pyroxenes and amphiboles (e.g., aegirine, anhydrous; riebeckite, about 1.86 wt % H_2O). The tendency of the ferromagnesian minerals to be anhydrous is probably a direct function of the low volatile content of a granitic magma in the epizonal environment, as well as a function of possible venting of such a magma. Phair and Jenkins (1975) emphasized reversal of the typical paragenesis of ferromagnesian minerals in uranium-enriched hypabyssal rocks of the Colorado Front Range. They equate this with progressive devolatilization of the magma.

Common accessory minerals include fluorite, hematite (both primary and secondary), sphene, zircon, and apatite. Euhedral to subhedral uranium and uranium-bearing accessory minerals (commonly uraninite, coffinite, uranothorite, zircon, and [or] xenotime) may occur poikilitically enclosed in major rock-forming minerals of the groundmass.

Chemistry

Although mineralogy reflects the chemistry of rock units, some chemical factors should be emphasized. Orthomagmatic uranium occurrences are characterized by high differentiation indices and by high weight percentages of SiO_2 (>66 wt %; Marjanemi and Basler, 1972). The rocks are often subaluminous to peralkaline, as shown by the agpaitic coefficient (>1.0) and the sodic nature of the ferromagnesian minerals. Most uraniferous plutons are alkalic to alkali-calcic. A few uraniferous calc-alkalic, high-level plutons are known (R. Morton, personal communication, 1977).

Uranium-rich plutons are characterized by low weight percentages of MgO , FeO , Fe_2O_3 , and CaO and by relatively high weight percentages of Na_2O and K_2O . In general, the H_2O content is low and the F content is abnormally high. These plutons are characterized by Th/U ratios greater than 1.0 (generally 3-5).

Alteration

Internal and peripheral alkali metasomatism is common to plutons comprising orthomagmatic-class occurrences. Albitization, caused by aqueous fluids developed under low confining pressures during a late stage of magmatic evolution (Phair and Jenkins, 1975), is the most prevalent type of alteration. Deuteric muscovite in a few uraniferous plutons suggests addition of potash to the rock. Alkali metasomatism is a common postsaturation reaction within a quiescent magmatic system. There are varying degrees of contact metamorphism and contact metasomatism. Whereas most epizonal plutons display isochemical metamorphic effects, those comprising occurrences of the orthomagmatic class show wide variations in contact effects. Phair and Jenkins (1975) noted that uranium-enriched hypabyssal intrusives in the Colorado Front Range show contact hydrothermal alterations, whereas the nonenriched hypabyssal rocks are characterized by isochemical thermal metamorphism.

Late-stage metasomatic processes may redistribute and concentrate uranium within either the parent pluton or the adjacent country rock, producing two separate classes of uranium occurrence (see autometasomatic and contact-metasomatic classes, p. 152 and 147, respectively).

Geometry

Most plutons and hypabyssal intrusives containing orthomagmatic deposits are steeply dipping stocks and dikes. Stocks are volumetrically the most important. These intrusive bodies are generally discordant to structures in the surrounding country rocks except where the host-rock structures are nearly vertical (example, the quartz monzonite porphyry of the Midnite mine area, Washington).

Rock Associations

Because plutons containing orthomagmatic occurrences are postorogenic and epizonal, few definitively characteristic rock types are associated with the plutons. First-order associations are with rocks of continental-crust affinities. Uraniferous plutons may be spatially associated with calc-alkalic igneous kindreds, with metasedimentary sequences, and (or) with genetically related volcanics (compare with initial-magmatic class, Pilcher, 1978). The metamorphic grade of associated metasedimentary sequences is generally upper greenschist facies to lower amphibolite facies; the epizonal nature of orthomagmatic-class plutons generally precludes association with granulite-facies metamorphic rocks.

Plutons containing orthomagmatic occurrences are often spatially and genetically related to uranium occurrences of other classes, some of which may be economically significant. The uranium porphyritic quartz monzonite of the Midnite mine area of northeastern Washington, for example, is spatially and genetically related to the economic uranium deposits of the Midnite mine (Nash, 1975, 1977). Orthomagmatic occurrences are likely source rocks of the uranium in some associated deposits.

Resource Potential

No uranium occurrences of the orthomagmatic class currently are being mined. Because presaturation mechanisms of uranium concentration in a magma are ineffectual, and because of the resultant low concentration and fine division of uranium and uranium-bearing minerals in uranium-rich plutons, occurrences formed entirely by liquidus crystallization are submarginal deposits. With improved market conditions and improved mining and metallurgical technology, orthomagmatic occurrences may provide a significant source of low-grade uranium ore in the future. Leaching processes applied to large volumes of uranium-bearing plutonic rocks may be developed and may allow recovery of large quantities of orthomagmatic uranium.

Although orthomagmatic occurrences are currently submarginal resources, postmagmatic processes may concentrate uranium into economic ore bodies of another class (see authigenic and allogenic classes, p. 157 and 161, respectively).

EXAMPLES OF ORTHOMAGMATIC URANIUM OCCURRENCES

Bokan Mountain Granite

The following discussion of the Bokan Mountain orthomagmatic uranium occurrence is taken largely from MacKevett (1958, 1963) and Lanphere and others (1964).

The Bokan Mountain granite is a Late Cretaceous to early Tertiary pluton located in a strongly deformed mobile belt on the southern end of Prince of Wales Island, southeastern Alaska Panhandle. The mobile belt developed along the western margin of North America during Mesozoic time; it may be coincident with an earlier, Paleozoic mobile belt. The nature of the basement underlying the eugeosynclinal trend is unknown. Field and radiometric evidences suggest that this is an area of extensive crustal reworking and multiple orogenic episodes (Nishimori and others, 1977).

The Bokan Mountain granite is an epizonal, circular stock intruded into eugeosynclinal metasediments and an earlier plutonic sequence. Its epizonal character is indicated by contact effects, numerous roof pendants, and association with hypabyssal intrusives. The lack of internal structures, the discordance with structures in the metasediments and the older synorogenic plutonic sequence, and the extensive alkali metasomatism (see autometasomatic class, p. 152) suggest that the Bokan Mountain granite is a postorogenic intrusion. It apparently intruded a strongly deformed mobile belt during a time of quiescence and was generally quiescent during crystallization.

Host rocks for the Bokan Mountain granite comprise two distinct series. The oldest sequence, comprising low- to medium-grade (upper greenschist to lower amphibolite facies), dynamothermally metamorphosed eugeosynclinal sediments and volcanics, is a sequence of graywackes, shales, and conglomerates with minor amounts of overlying carbonates. The metavolcanics range from basic andesites to quartz keratophyres, the predominant lithology. This older meta-sedimentary-metavolcanic sequence was intruded by a synorogenic calc-alkalic kindred comprising pyroxenite, gabbro, diorite, tonalite, and gneissic quartz monzonite.

The postorogenic Bokan Mountain granite cross cuts both older series. It is located predominantly in the gneissic quartz monzonite; the northern margin of the Bokan Mountain intrusive is in contact with slate. Differences in the ages of the Bokan Mountain granite and the older gneissic quartz monzonite preclude a genetic relationship.

The Bokan Mountain mass is a white to light-gray, leucocratic granite which contains less than 10 percent color-index minerals by volume. Minor, local concentrations of ferromagnesian minerals constitute as much as 40 percent of the rock.

Textures of the granite are highly variable. Porphyritic, cataclastic, hypidiomorphic-granular, and allotrimorphic-granular textures are all present in the granite. Porphyritic and cataclastic textures are the most common. Grain sizes varies from coarse to fine.

The Bokan Mountain granite is mineralogically fairly simple, although a complex paragenesis is indicated. Dominant minerals in the granite are potash feldspar, albite, and quartz. The ferromagnesian minerals riebeckite and aegirine are present in minor amounts and often show complex intergrowths. The aegirine contains poikilitically enclosed blebs of hematite which may be products of exsolution. Microcline crystals show sodic microperthite overgrowths. Two distinct generations of quartz and potash-feldspar development are recognized in the porphyritic varieties. This may be explicable in terms of a sudden loss of volatiles from the magma (see Tuttle and Bowen, 1958).

Zircon, xenotime, fluorite, uranothorite, and rare cordierite compose the accessory-mineral suite. Xenotime and uranothorite occur as sparsely disseminated euhedra, whereas fluorite is mainly interstitial and anhedral.

A series of genetically related pegmatites and aplites is found in the peripheral regions of the Bokan Mountain granite. These cut both the granite and the surrounding country rock. The pegmatites and aplite dikes are larger and more numerous near the granite and become progressively smaller and fewer with increasing distance from the contact. The pegmatites consist of quartz and perthite, with accessory albite, hematite, fluorite, and magnetite. Trace amounts of biotite, riebeckite, aegirine, pyrite, sphene, and zircon are found in the pegmatites.

The Bokan Mountain granite is characterized by high contents of SiO_2 , Na_2O , and F. It contains between 20 and 200 ppm uranium. The lack of mica, and the low water content of the rocks, and the associated aplites suggest that the Bokan Mountain magma was intruded "dry."

The Bokan Mountain granite is referred to as peralkaline. Some care must be exercised in using the term "peralkaline." MacKevett (1963) uses the term in describing the Bokan Mountain granite because of its modal and normative aegirine content. Shand (1947) defines peralkaline rocks as those whose agpaitic coefficient is greater than unity. Although sodic ferromagnesian minerals are present in the Bokan Mountain granite, the agpaitic coefficient is less than one (about 0.79; average of five analyses reported by MacKevett, 1963). Therefore, from a modal and normative definition, the Bokan Mountain granite is peralkaline. From a chemical viewpoint, however, it must be considered metaluminous to subaluminous. Regardless of the precise name given to the rock, its sodic character is perhaps most significant. As pointed out by Phair (1952, p. 27), in comparing the bostonite dikes of the Colorado Front Range with the Conway Granite of New Hampshire and the Nigerian riebeckite granites: "The combination of high soda and high silica, and not high soda alone, is apparently prerequisite to, or at least correlative with, the optimum concentration of uranium and thorium in a magma series of this type." The Bokan Mountain granite bears many similarities to these units.

The Bokan Mountain granite is characterized by internal and peripheral albitization. The albitized aureole is as much as 2 km wide. Unlike the bostonite dikes of the Colorado Front Range, in which there is not apparent correlation between degree of alteration and the uranium content, the Bokan Mountain granite shows a moderately strong correspondence between degree of albitization and uranium content. Zones in the pluton characterized by extensive albitic alteration are those with a high uranium content (compare Kaffo Valley granite, Nigeria; see p. 156). This suggests that some of the contained uranium may be a product of a late-stage autometasomatic process.

Laramide Bostonite Dikes of the Colorado Front Range

The following compilation is adapted from Phair (1952, 1957), Phair and Gottfried (1964, Phair and Jenkins (1975), and Wells (1960).

The abundance of uranium and thorium in the Colorado Front Range is approximately twice the generally accepted crustal average. Bostonite, the most uraniferous rock type in this uranium-thorium province, contains as much as 20 times the amount of uranium found in comparable rocks elsewhere. Four varieties of bostonite are present: porphyritic bostonite, garnet-bearing bostonite, quartz-bearing bostonite, and quartz bostonite. Although all four bostonite varieties contain anomalous uranium, quartz bostonite, the youngest and most highly differentiated member of the series, has the highest uranium concentrations; it contains up to several hundred ppm uranium.

Bostonites of the Front Range occur as long (as much as 8 km), narrow dikes, either radiating from stocklike centers or in rectilinear dike networks. The orientation of the dikes in the networks strongly correlates with the regional joint pattern in the enclosing Precambrian hosts. Some dikes display a branching character.

The bostonites are leucocratic. They consist of variable amounts of alkali-feldspar phenocrysts set in an aphanitic groundmass of quartz, feldspar, and a few color-index minerals. The bostonites have a general lavender hue due to the presence of finely divided hematite. Feldspars compose nearly 80 percent of the rock. The alkali-feldspar phenocrysts are perthitic (indicating hypersolvus crystallization), whereas the groundmass displays two distinct feldspars (subsolvus). This texture and mineralogy suggests that the bostonitic magma became saturated with volatiles. Quartz occurs interstitially between feldspar crystals and composes as much as 25 percent of the volume of the quartz bostonites. Lesser percentages are found in other varieties of bostonite. The dominant color-index minerals are aegirine-augite and hematite-magnetite. Maximum color index is less than 7 percent. Minor anhydrous fluorite occurs interstitial to the major rock-forming minerals. Textural relations show that fluorite is a liquidus-crystallization product; it was not added to the system by late-stage or secondary processes. The abundance of fluorite generally corresponds to the amount of uranium present. Uranium in the bostonites is mostly confined to zircons, although some occurs in allanite, thorite, and an unidentified, amorphous, brown, radioactive mineral found as smears along microfractures.

Whereas some Laramide intrusives of the Colorado mineral belt were forcefully injected, as indicated by well-developed intrusion breccias, the bostonites appear to have been intruded passively along tension fractures. The lack of xenolithic fragments and the fact that the bostonite dikes are not deformed suggest intrusion during very late-stage tectogenesis. Their porphyritic textures, the aphanitic groundmass, chilled margins, internal albitization, and ferromagnesian paragenesis characteristic of devolatilization all suggest emplacement at very shallow levels in the Earth's crust.

The Front Range bostonites are highly alkalic, with potash slightly in excess of soda. They are characteristically low in total iron, with a high $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio, and are exceptionally low in MgO and CaO . ZrO_2 is exceedingly high. Regardless of their strong alkalic character, the bostonites possess a "normal" agpaitic coefficient (about 0.6-0.7). Although the Th/U ratio is variable, it is always greater than unity.

Alteration in and around the bostonite dikes is widespread and of three varieties. One variety is deuteric alteration in which the feldspars are partially argillized and the ferromagnesian minerals have been decomposed. Albitization of a few dikes is a second type of alteration. The third type is peripheral hydrothermal alteration. The country rocks are characterized by sericitization and saussuritization of the feldspars and by decomposition of ferromagnesian minerals. The degree of internal alteration does not seem to correspond to the uranium content of the bostonites.

The chemistry and mineralogy of the bostonites show them to be end products of extensive magmatic differentiation of an alkaline magma. The uranium content increases within the bostonite series, culminating in quartz bostonite, with the highest uranium content. The quartz bostonites are extreme products of fractional crystallization.

The quartz bostonite dikes in the Central City area are temporally, spatially, and chemically related to pitchblende-bearing hydrothermal veins. A genetic association is strongly implied. The quartz bostonites in this area constitute the largest bostonite-dike swarm in the Front Range and have a Th/U ratio of 7. The implied genetic association of these dikes with the pitchblende-bearing veins and the relatively high Th/U ratio suggest that some of the uranium from the quartz bostonite magma was concentrated in late-stage, postsaturation hydrothermal fluids and was deposited in the associated pitchblende-bearing quartz veins. The thorium content of the pitchblende veins is extremely low. An increase in PH_2O in the magma at or after saturation (along with the concomitant increase in fO_2) caused oxidation of uranium and resulted in the fractionation of thorium and uranium. The high oxygen fugacity is reflected in the high $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio in the quartz bostonites. Thus, the Th/U ratio in the bostonite may be a crude measure of the amount of uranium lost from the magma.

Another swarm of quartz bostonite dikes, located in the Jamestown-Gold Hill area, has a Th/U ratio of 2. This low ratio implies that thorium and uranium were not fractionated and that all, or at least most, of the uranium is still in the quartz bostonite. Consistent with this interpretation is the fact that no pitchblende-bearing hydrothermal veins are associated with the Jamestown-Gold Hill bostonites.

The bostonite dikes of the Colorado Front Range currently represent a submarginal resource. Phair and Jenkins (1975) estimated that approximately 15 t of uranium could be recovered from each 10 ft of depth mined along the entire length of the Pewabic dike, the most radioactive dike in the Central City area. This is currently uneconomical. Leaching studies show that up to 58 percent of the uranium can be removed in an HCl leach, with a very low

rate of acid consumption. Other trace constituents (Ce, La, Nd, Zr, and Ag) could also be recovered. These leaching studies suggest that the quartz bostonites might become a future source of uranium, as well as other rare elements, with increasing technology in leach-mining processes.

PEGMATITIC CLASS (CLASS 320)

Pegmatitic and aplitic uranium occurrences form from "pegmatitic" fluids derived by saturation during late-stage magmatic evolution. Because uranium does not readily enter common rock-forming minerals during orthomagmatic crystallization, it becomes progressively concentrated in residual melts. The second boiling of the magma may cause uranium to become even more concentrated in a resultant pegmatitic fluid. Thus pegmatitic phases of a comagmatic sequence are normally enriched in uranium relative to the main body of a given pluton.

Features commonly observed in uranium occurrences of the pegmatitic class are adequately explained by considerations of pegmatite genesis. Pegmatites are typified by coarse but variable grain sizes. The high water content of the pegmatitic fluid probably retards nucleation, thereby producing fewer crystals. It decreases the viscosity of the melt and allows more extensive ion migration during crystallization. Retardation of nucleation and decreased viscosity account for the large crystal size in pegmatites.

Uraniferous pegmatites do not differ greatly from nonuraniferous pegmatites; the genesis of the two kinds is virtually identical. The uranium content of the parent magma, the extent of uranium removal prior to saturation, and the degree of concentration in the pegmatitic fluid may be the only significant genetic differences between the two. It is, therefore, difficult to make an a priori prediction whether a given pegmatite will be uraniferous. Field examination is essential.

Uraniferous pegmatites differ from nonuraniferous pegmatites in their contents of fluorite, primary hematite, sodic amphibole, and (or) sodic pyroxene. They are characterized by temporal, spatial, and probably genetic association with plutons having anomalous uranium contents. Uraniferous pegmatites are commonly found within or at the margins of uranium-rich plutons; they may be injected into the country rock. Genetic relations with a given pluton may be difficult to demonstrate in the field, however. Although distributions do not necessarily imply genetic relations, one might infer consanguinity on the basis of the spatial distribution of pegmatites and suspected parental pluton. In general, the size, number, and complexity of pegmatites decrease with increasing distance from the parent pluton.

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Pegmatitic uranium occurrences are found in areas of extreme crustal mobility. They are most common in intracratonic mobile belts; they also occur in marginal mobile-belt terranes associated with deep epizonal to mesozonal plutons. Most pegmatites are either synorogenic or postorogenic. Some minor, anorogenic pegmatites are associated with peralkaline intrusives.

Lithology, Mineralogy, and Texture

Uraniferous pegmatites are normally granitic, consisting of quartz and alkali feldspar close to the compositional minimum in the quartz-orthoclase-albite system. They generally contain few color-index minerals, most notable of which are sodic amphiboles and (or) pyroxenes. Micas are nearly always present. Fluorite, hematite, topaz, zircon, garnet, and apatite are common accessory minerals. Uranium and uranium-bearing minerals (commonly uraninite, allanite, uranothorianite, brannerite) are disseminated throughout the dikes; higher concentrations may occur in quartz-segregation pods. Although disseminated uraninite may be present in pegmatites, much of the uranium is tied up in accessory minerals, such as apatite and zircon. A significant proportion of the uranium may exist either within or on the surface of the major rock-forming minerals.

Although textures are typically pegmatitic, some aplitic varieties of this class exist. Aplitic occurrences are most often associated with shallow epizonal plutons. Aplitic occurrences are not as common as pegmatitic occurrences.

Chemistry

Pegmatitic uranium occurrences are characterized by high SiO_2 , Na_2O , and K_2O contents, intermediate Al_2O_3 contents, and low contents of FeO , Fe_2O_3 , MgO , and CaO . Uraniferous pegmatites are commonly subaluminous to peralkaline. Trace-element chemistry may be more diagnostic than major constituent oxides. Trace constituents which readily form complexes with F and Cl are easily concentrated in pegmatitic melts (Turner and Verhoogen, 1960). Thus uraniferous pegmatites commonly show high values of Li, Be, Mo, W, Th, U, Zr, Sn, Ta, and Nb. The Th/U ratio depends heavily on the degree of fractionation of uranium and thorium in the pegmatitic melt. This, in turn, is a function of oxygen fugacity and the degree of oxidation of uranium. Although the Th/U ratios are variable, they are generally greater than unity.

Alteration

Internal and peripheral alteration is commonly associated with uraniferous pegmatites. Internal mineralogical replacements are commonly observed, particularly in complex pegmatites. Albitization and, less commonly, tourmalinization of the pegmatite and the country rocks are widespread. Albitization and tourmalinization may be genetically related to the internal replacements. Country rocks are often argillically altered; this is probably caused by volatiles escaping from the pegmatitic fluid. The degree and extent of albitization and argillization depend on the permeability and effective porosity of the country rock.

Geometry

Uraniferous pegmatites normally occur as tabular, discordant dikes. Some are elongate pods. Although most uraniferous pegmatites are structurally simple, some may be zoned. Aplitic varieties of pegmatitic-class occurrences are nearly always simple and dike-like in form.

Pegmatites and aplites may be found either in parent plutonic bodies (for example, uranium-rich pegmatites, Wichita Mountains, Oklahoma; Al-Shaieb, 1978) or in the surrounding country rock (for example, Bicroft mine, Bancroft area, Ontario; Satterly, 1956).

Rock Associations

Uraniferous pegmatites are generally associated with mesozonal plutons (for example, pegmatites related to Silver Plume-type granites, Colorado; Sims and others, 1963) and catazonal plutons (for example, Bancroft-Haliburton area, Ontario; Little, 1970). Uraniferous pegmatites associated with epizonal plutons are less common (for example, pegmatites related to the Bokan Mountain granite, Alaska; MacKevett, 1963). Aplitic uranium occurrences are more commonly associated with epizonal plutons and probably reflect devolatilization in the shallow intrusive environment. The association of pegmatites with the more deeply seated plutons is explicable in terms of the confining pressures and, hence, the amount of dissolved volatiles in the magma. High confining pressures increase the density of a separate volatile phase, with a concomitant increase in the solvent capability and chemical activity of the volatiles (Turner and Verhoogen, 1960). These factors increase concentrations of rare constituents in the pegmatitic fluids. This is in contrast to aqueous fluids under low confining pressures, in which components could leave the pegmatitic fluid, perhaps to be deposited in hydrothermal veins (see p. 142, this report).

In accordance with the general association with more deeply seated plutons, associated metamorphics are generally of the amphibolite facies and, more rarely, the granulite facies.

Uraniferous pegmatites may grade laterally into hydrothermal deposits. The distinction between pegmatitic and magmatic-hydrothermal occurrences is made on the basis of mineralogy. The Th/U ratio in pegmatitic occurrences is generally greater than unity, whereas magmatic hydrothermal occurrences usually have Th/U ratios less than unity. Also, hydrothermal occurrences are commonly confined to brecciated veins and vein networks, whereas those of the pegmatitic class exist as distinct dikes.

Resource Potential

Although numerous occurrences of the pegmatitic class are known, grade and tonnage considerations generally preclude economic recovery under current technological and economic conditions. A few occurrences currently are being

explored (for example, Bokan Mountain, Alaska; Crocker Well, Australia), and one (Bancroft, Ontario) has had ore production. Pegmatitic occurrences, therefore, represent paramarginal to recoverable uranium resources.

EXAMPLES OF PEGMATITIC URANIUM OCCURRENCES

Bokan Mountain, Alaska

The following discussion of pegmatitic uranium occurrences at Bokan Mountain, Alaska, is taken from MacKevett (1958, 1963).

Numerous uraniferous pegmatites and aplites are genetically related to and occur in and around the Bokan Mountain granite, southeastern Alaska (see p. 132 for a discussion of the Bokan Mountain granite). Most of the dikes are found within the granitic stock; a few occur in the surrounding country rock. Syngenetic disseminations of primary uranium and thorium minerals are found in both aplitic and pegmatitic varieties of this class.

Steeply dipping dikes and irregular masses of aplite occur both within and near the Bokan Mountain granite; dikes are most common. A few aplites contain small pods and lenticular masses of pegmatitic material. Conversely, minor zones of aplite occur within pegmatitic dikes. Some aplite dikes contain small zones of alaskite.

The white to light-gray aplites are granitic. They consist of quartz, potash feldspar, and albite, with the potash feldspar more abundant than albite. A few aplite samples have nearly equal amounts of potash feldspar and albite. Biotite, riebeckite, fluorite, and pyrite are sparsely scattered through the dikes.

The aplites possess a fine-grained, homogeneous, xenomorphic-granular texture, with the exception of the minor portions of hypidiomorphic-granular alaskite. A few small zones display a cataclastic texture. The feldspars in some of the aplite dikes are argillically altered. Hydrous ferric oxides impart a characteristic rusty color to these altered zones. These altered zones, some of which contain minor secondary pyrite, may represent late-stage deuteric reactions.

Similar to the aplites, most of the uraniferous pegmatites occur within the Bokan Mountain granite. A few extend into the country rock, whereas others are completely isolated within the country rock. Most pegmatites are dikes as much as a few meters wide and 900 m long. Although the dikes have diverse dips, they are normally very steep to vertical. A few pod- or lens-shaped pegmatites have been found.

The pegmatites are light in color and display a wide variety of grain sizes. The bulk of the rock consists of quartz and perthite, accompanied by accessory amounts of albite, hematite, fluorite, and magnetite. Biotite, riebeckite, aegirine, pyrite, and zircon are present in trace amounts.

Uranium occurs in sparsely and erratically disseminated, fine-grained uranorthorite, uranoan thorite, uraninite, xenotime, and brannerite. Quartz is dark-gray and cloudy, and fluorite is dark-purple near the radioactive minerals.

Most of the pegmatites are unzoned; a few have a medium-grained, quartz-feldspar border zone and a coarse-grained, quartz-rich core. Some of the pegmatites are rich in quartz and resemble quartz veins.

Hydrothermal argillic alteration is common in the pegmatites; the altered zones are characterized by hydrous-ferric-oxide staining. Albitization is common. Chemically the pegmatites and aplites are characterized by high contents of U, Th, Na, F, Zr, and REE. Th/U ratio is greater than unity.

Although the pegmatites and aplites of Bokan Mountain contain anomalous syngenetic uranium, postsolidification processes (autometasomatism) may have added significant quantities of uranium.

Bicroft Mine, Bancroft District, Canada

The following discussion of a pegmatitic uranium deposit in the Bancroft area, Ontario, is taken from Robinson and Hewitt (1957), Nishimori and Greenberg (1977), and from the summary provided by Nishimori and others (1977).

The uranium deposits of the Bancroft area occur in the Hastings-Haliburton highlands portion of the Grenville province. Amphibolite- to granulite-facies metasediments and metavolcanics and mantled gneiss domes of catazonal character underlie the area. The metasediments and metavolcanics comprise paragneiss, marble, and amphibolite schist and orthogneiss. The orthogneiss complex consists of migmatitic granite gneiss, leucogranite gneiss, and granite pegmatite.

Pegmatitic uranium deposits are located in or adjacent to three granitic complexes: the Cardiff complex, the Faraday granite, and the Cheddar granite. These granitic complexes are concordant with the mantling metasediments.

Over 100 uranium occurrences have been reported in the Bancroft district. Pegmatitic, metasomatic, and hydrothermal veins are all present; there is a complete gradation between them. Only the pegmatites, primarily from the Bicroft and Faraday mines, have been economic producers.

The Bicroft mine lies within the Cardiff plutonic complex. This complex comprises two gneissic granites and a gneissic syenite, intruded into upper-amphibolite- to granulite-facies metasedimentary rocks. The pegmatites of the Bicroft area are cogenetic with the Centre Lake Granite, a gneissic leucogranite which contains a pegmatitic facies at the contact with the metasediments.

The uranium-bearing pegmatites are located in paragneisses and para-amphibolites adjacent to the Centre Lake Granite. Although four distinct types of pegmatites are found in the area (pyroxene pegmatite, pyroxene granite pegmatite, granite pegmatite, and quartz-rich pegmatite), the

uranium enrichment is largely restricted to the quartz-rich pegmatites. These are the most highly differentiated rocks in the sequence. Ore minerals comprise uraninite, uranothorianite, allanite, pyrochlore, and betafite, set in a gangue of smoky quartz with accessory zircon, molybdenite, amphibole, and anatase. Minor interstitial fluorite and calcite are found in nearly all the uraniferous pegmatites. In general, the amount of uranium minerals is directly proportional to the amount of zircon present.

The pegmatites of this area are thought to be products of differentiation of an anatectically derived, synorogenic granitic magma (Robinson and Hewitt, 1957). Recent work by A. D. Fowler of McGill University (personal comm., 1978) shows that the uraniferous pegmatites in this area are largely post-orogenic and that they are of deep-seated origin rather than anatectically derived. Contact relations with the country rock (alteration halos, sharp contacts, local cross-cutting features, some possibly rotated xenoliths) indicate that the pegmatites were not developed in situ. The uraniferous pegmatites in the area are generally rich in soda and contain peristerite and sodic antiperthite. Nonuraniferous pegmatites in the area are generally rich in potash. This may imply albitization of the uraniferous pegmatites.

Alteration adjacent to the pegmatites is limited. Epidotization, tourmalinization, and scapolitization of the wall rock are common but poorly developed. A few areas of intense alteration make establishment of contacts uncertain. Red staining of quartz and feldspar (hematitization) occurs in the more uranium-rich portions of the pegmatites.

Ore grade within the pegmatites is variable.

MAGMATIC-HYDROTHERMAL CLASS (CLASS 330)

Hydrothermal solutions are generated during final stages of magmatic differentiation. Continued magmatic evolution causes progressive increase in the volatile content in the residuum of a magmatic system and ultimately produces a separate, very hydrous phase. This aqueous phase may contain a wide variety of dissolved constituents, often in greater percentage than in the parent magma. High oxygen fugacity causes oxidation of uranium, allowing it to enter more readily into the hydrothermal solution as a uranium-halogen complex (example: UF_6) or perhaps as a uranyl ion (UO_2^{+2}). These hexavalent uranium complexes are highly soluble in high-temperature aqueous solutions (Gableman, 1977). Because thorium remains tetravalent and does not readily form complexes, an effective fractionation of uranium and thorium is brought about in the magmatic-hydrothermal environment. Some fractionation of uranium in the reduced state may occur because of the differing ranges of thermal stability of uranium and thorium complexes (Gableman, 1977).

An interesting aspect of magmatic-hydrothermal vein deposits is the mechanism whereby tetravalent uranium is deposited from an aqueous solution which transports uranium in its hexavalent state. Reductants in magmatic-hydrothermal vein systems are commonly either absent or paragenetically later than uraninite. Hexavalent uranium may be effectively reduced by a mechanically induced decrease in the oxygen fugacity of the system as the temperature, pressure, and pH of the hydrothermal fluid changes with upward migration into and through dilatant zones (Mathews and Pilcher, in prep.).

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Vein-type uranium occurrences of the magmatic-hydrothermal class exist in areas of crustal instability. An important structural feature of magmatic-hydrothermal occurrences is the nature and distribution of permeable channelways through which mineralizing solutions might migrate. In reference to the uranium-fluorite-molybdenite occurrences in the silicic igneous petrographic province of northwest Queensland, Australia, Bain (1977) points out that permeable fault and fracture zones which have been active throughout long periods and which are of considerable length and depth provide the most favorable sites of deposition (compare with the Schwartzwalder mine along the Rogers breccia reef, Colorado Front Range). Short fractures and breccia pipes are less favorable (for example, the siliceous reefs, northern Boulder batholith, Montana).

Lithology, Mineralogy, and Texture

Magmatic-hydrothermal uranium occurrences generally occur as brecciated veins and vein systems. Multiple stages of brecciation are common. The breccias normally consist of fragments of the enclosing wall rock, although some veins contain "foreign" lithologies.

The mineralogy of the veins is simple. Quartz (commonly smokey) composes the bulk of the vein material. It exists in both massive and cryptocrystalline varieties. Disseminated Fe, Zn, and Pb sulfides, dark fluorite, and carbonate minerals are common accessories. Gold and silver enrichments are present in some veins. Uraninite, the major uranium mineral in magmatic-hydrothermal veins, occurs as finely disseminated euhedra, intragranular coatings, fracture fillings, and as a replacement product in variable concentrations. Ore-grade concentrations are spotty and occur in discrete areas along the veins. Grade tends to be highest along zones of maximum dilatancy.

Chemistry

Silica is the dominant oxide in magmatic-hydrothermal uranium veins. Although other constituents are present in accessory and trace amounts, no readily discernible pattern of their distribution is recognized at this time. Elements typically present are Mo, Se, Ti, Au, Ag, F, Ca, and C. The concentration and distribution vary both within and among veins. Although highly variable, the Th/U ratio is generally less than unity and reflects the effective fractionation of U and Th during the generation of the magmatic-hydrothermal fluid.

Although no generalized pattern of trace-element composition is recognized at this time, there does appear to be a systematic distribution of trace constituents in the uraniferous chalcedony veins in the northern end of the

Boulder batholith, Montana (Wright and others, 1957). Elements present in above-average concentrations in veins containing more than 100 ppm U include Al, Ca, Ti, Ag, and Mo. Conversely, Mg, As, Cr, Cs, Ga, Sn, and Th are present in below-average concentrations. The relatively high concentration of Ca in these veins reflects the presence of calcite.

Alteration

Alteration of the rock adjacent to magmatic-hydrothermal veins is variable in both degree and type. Zoned alteration halos are common. The halos are marked by an inner zone of silicification, followed by successive zones of chloritization and argillization. The argillic zone may comprise subzones of different clay minerals. Any single alteration zone may be absent from a given occurrence. A few veins show little or no peripheral alteration.

Although albitization of the country rock is sometimes apparent, it is generally much less pervasive than in occurrences of the orthomagmatic, pegmatitic, autometasomatic, or contact-metasomatic classes.

Geometry

Magmatic-hydrothermal uranium occurrences are discordant veins and vein systems spatially related to uraniferous plutonic hypabyssal, and (or) pegmatitic units. Multiple-vein systems are more common than solitary veins. The veins appear to occupy very steep to vertical, brecciated fault or fracture zones. Larger, more continuous veins may occupy reactivated basement structures (Schwartzwalder, for example). Magmatic-hydrothermal uranium veins are usually restricted to fractures of a single orientation in areas of multidirectional fracturing. Uranium minerals may be concentrated at fracture intersections.

The veins pinch and swell, depending upon the nature of the enclosing host rocks. Individual veins and vein systems often show a change in thickness and complexity as they pass from one rock unit to another, of different competence.

Rock Associations

Magmatic-hydrothermal uranium occurrences are generally spatially and probably genetically associated with uraniferous leucocratic intrusives of postorogenic or anorogenic and epizonal to hypabyssal character. They are less commonly associated with uraniferous pegmatites. Associated volcanics are common. Some magmatic-hydrothermal veins occur in high-rank metamorphic terranes and appear to be late-stage differentiates of anatectically(?) derived quartzofeldspathic melts (for example in the Bancroft area, Ontario; Satterly, 1956). Association with leucocratic rocks is probably genetic; an associated plutonic unit may have to be inferred. Uraniferous veins in the Colorado Front Range provide good examples of known and inferred plutonic associations. Pitchblende-bearing veins near Central City, Colorado are closely associated with uranium-rich hypabyssal quartz bostonite dikes, which

are well exposed in the immediate vicinity, and are probably genetically related (Phair, 1952, 1957). The Schwartzwalder uranium deposit, however, bears a much less definite relationship to igneous intrusives. The mine is located about 10 mi southeast of the northeast-trending Colorado mineral belt, a region containing numerous Laramide uraniferous igneous units. The age of uranium mineralization is Late Cretaceous (65 m.y. average; Young and Lahr, 1975). Laramide bostonite dikes have been found within a few kilometers of the mine. These considerations and the inference that ore-forming fluids migrated upward along a nearly vertical shear zone, the Rogers breccia reef (Heyse, 1971), lead to the inference of a genetic association with Laramide intrusives. The Schwartzwalder deposit-bostonite dike couple is an example of an inferred epizonal plutonic association.

Resource Potential

Whether or not a magmatic-hydrothermal uranium occurrence is economic depends on the size of the vein or vein system and on the degree of uranium concentration. Some occurrences are too small and (or) of too low grade to be profitable. Others are currently producing. Although an individual vein may contain uneconomic tonnages of U_3O_8 , vein swarms might be economically important. Thus, magmatic-hydrothermal uranium occurrences represent submarginal, paramarginal, and recoverable resources.

EXAMPLES OF MAGMATIC-HYDROTHERMAL URANIUM OCCURRENCES

Radium Hill, Australia

The following discussion of the Radium Hill uranium deposit is taken from Johnson (1958), Parkin and Glasson (1954), Sprigg (1954), and Whittle (1954).

The Radium Hill uranium deposit is located in deeply weathered, highly metamorphosed and migmatized geosynclinal sediments in South Australia. Host rocks are Archean and lower Proterozoic(?) metasediments, consisting of quartzite, migmatitic gneiss, and schistose gneiss. These units have been folded into a gently plunging antiform with very steep to vertical limbs. A nearly concordant orthoamphibolite, whose internal foliation closely parallels that of the metasediments, intrudes the paragneisses. Pegmatites and sodic aplites of possible anatectic origin crosscut all units. There is an apparent spatial and possible genetic relationship between the uranium content of the ore and the distribution of the sodic aplites.

Davidite, intimately intergrown with rutile, ilmenite, and hematite in varying proportions, occurs in brecciated fracture planes oriented subparallel to the foliation and the axial plane of the antiform. Gangue minerals are quartz and biotite. There is an uneven distribution of davidite within the ore zones; the lodes become wider and more enriched in uranium where they crosscut the orthoamphibolite. The lateral distribution of ore within the lodes is thought to be related to the degree of fracturing and brecciation and, hence, to the permeability of the rock. The metasediments around the orebodies are heavily albitized.

Uranium mineralization is believed to have formed by replacement reactions caused by hydrothermal solutions emanating from the sodic aplites and pegmatites (Parkin and Glasson, 1954). The sodic aplites contain a rare-earth-mineral assemblage similar to that found in the ore. Unmineralized metasediments outside the ore zones do not contain this assemblage.

Boulder Batholith, Montana

The following discussion of uraniferous hydrothermal veins in the Boulder batholith was taken from Becraft (1956), Becraft and others (1963), Bieler and Wright (1960), Castor and Robbins (1978), Wright and others (1957), Thurlow (1952), and S. B. Castor (personal comm., 1977).

The Boulder batholith, southwestern Montana, is a composite Cretaceous epizonal intrusive which appears to be the product of two separate but contemporaneous magmas (Tilling, 1973). It intrudes the andesitic Cretaceous Elkhorn Mountain Volcanics and is overlain by the quartz latite Eocene Lowland Creek Volcanics. Post-Lowland Creek rhyolite plugs cut all older units.

Two similar types of uranium-bearing hydrothermal vein deposits, base-metal-sulfide-bearing veins (base-metal veins) and chalcedony veins (siliceous reefs), are found in alaskite and in the Butte quartz monzonite in the northern portion of the Boulder batholith. Although texturally distinct, these two vein types bear many similarities and are probably products of the same pervasive hydrothermal fluids. The distinction between the two is the macrocrystalline character of the quartz and the higher percentage of sulfides in the base-metal veins. Uraninite is the primary uranium mineral in each type. The Butte Quartz Monzonite adjacent to both types of veins is characterized by a zoned alteration halo, which ranges from an internal selvage of silicification through a discontinuous zone of sericitization, surrounded by an outer zone of argillic alteration. Brecciation (sometimes multiple) of the vein material is common. Fractures and brecciated zones were the conduits for the mineralizing fluids. Both types of veins, particularly the siliceous reefs, occur in small, multiple, anastomosing systems.

The source of the uranium-bearing hydrothermal solutions is problematical. Ages of the pitchblende deposits and those of the batholith preclude genetic relations. The postbatholith Lowland Creek Volcanics represent a possible source. However, confinement of the base-metal veins and siliceous reefs to the northern part of the batholith and the widespread distribution of the Lowland Creek Volcanics suggest that they are not genetically related. Post-Lowland Creek rhyolite plugs are restricted to the northern regions of the batholith. Gross ages of the uraniferous veins and the rhyolites are similar. Additionally, at least one of the rhyolites appears to be anomalously radioactive (in a shear zone). On the basis of temporal and spatial relations, it may be tentatively concluded that the hydrothermal veins and the post-Lowland Creek rhyolites are genetically related.

CONTACT-METASOMATIC CLASS (CLASS 340)

Contact-metasomatic uranium occurrences develop by replacement reactions between uraniferous magmatic emanations and mafic or calcareous country rocks, during the late stages of magmatic evolution. Distance of uranium transport in metasomatizing fluids and sites of deposition in the adjacent rock are primarily governed by the temperature gradient and the effective porosity, permeability, and lithology of the host rock.

Some of the uranium in contact-metasomatic occurrences may be derived from the host rock. Finely divided, syngenetic(?) uranium in the host rocks may be remobilized and concentrated by the late-stage magmatic emanations. Similarly, some, and perhaps a large percentage, of the uranium-transporting fluids may originate in the host rocks. Fluids within the country rock may be set in motion and driven away from the intrusive mass by the heat of the intruding magma.

That uranium can be introduced into country rock by metasomatic processes has been strongly implied by Derrick (1977) and demonstrated fairly conclusively by Berezina and others (1976). Berezina and others recognized a systematic increase in uranium content from the outer portions toward the center of a "metasomatizing column." Uranium becomes progressively more concentrated along microfractures, cleavage planes, and crystal defects, particularly in ferromagnesian minerals. Comparison of this distribution with that of nonuraniferous metasomatites in identical host rocks led these authors to conclude that uranium was metasomatically added to the system.

Deposition and concentration of uranium mainly depend upon existence of a suitable host rock. Mafic and calcareous hosts, as well as concentrations of mafic minerals within the host rocks, are ideal sites for uranium deposition by metasomatizing fluids.

Because the same general petrogenetic processes are involved in the formation of metasomatic-hydrothermal deposits (postsaturation, aqueous fluids invading the country rock), distinction between the two may be difficult. By way of a usable operational definition, magmatic-hydrothermal deposits occur in brecciated veins and vein systems, whereas contact-metasomatic occurrences are fine disseminations of uraninite in the host rock. As might be expected from their similar genesis, magmatic-hydrothermal and contact-metasomatic occurrences, as well as some uraniferous pegmatites, commonly may be closely associated in time and space and may grade laterally into one another.

GEOLOGIC CHARACTERISTICS

Tectonic Setting and Rock Associations

Contact-metasomatic uranium occurrences are normally found in middle- to high-rank, dynamothermally metamorphosed rocks adjacent to silicic uraniferous plutonic and (or) pegmatitic rocks in mobile-belt terranes. Reasons for the apparent restriction of these occurrences to high-rank metamorphic host rocks are not known. Restriction to high-rank metamorphic hosts may reflect a more deeply seated environment for the magma, which, in turn, may increase the likelihood of not tapping the magma after saturation. This would allow the uraniferous aqueous solution to permeate the country rock.

One might also expect to find contact-metasomatic occurrences associated with silicic plutons in lower-grade metamorphic terranes, although none have been described in the literature. Perhaps more important than the rank of metamorphism of the host are the composition, effective porosity and permeability of the host, and the spatial relations with a possible source of metasomatizing fluids.

Lithology, Mineralogy, and Texture

Contact-metasomatic uranium occurrences are found in mafic and calcareous rocks and in concentrations of ferromagnesian minerals within the host rocks. Ore minerals may be concentrated by structure and may be related to channelways for the metasomatizing fluids. Areas of uranium concentration often show evidence of retrogressive metamorphism.

Lithology of the host rocks varies. Mineralogical composition of the host rocks is also variable. Common host rocks are mafic and calc-silicate schists, gneisses, and impure marbles.

Primary uranium and uranium-bearing minerals (generally uraninite and thorinite) are finely disseminated in the host rocks. Uranium may be concentrated within individual mafic or calcareous mineral constituents. Uraninite is the dominant uranium mineral in contact-metasomatic occurrences. In the Mary Kathleen, Australia, deposit, uraninite is closely associated with allanite and minor sulfides. Uranium in the Wheeler Basin occurrence is mostly in uraninite, although minor amounts of monazite and zircon contain some of the uranium. Berezina and others (1976) noted higher-than-average concentrations of uranium in aegirine, riebeckite, and biotite in soda metasomatites; Young and Hauff (1975) reported concentrations of uraninite in biotite concentrations in Wheeler Basin, Colorado; Matheson and Searl (1956) noted concentration of uranium in a "belt of granitized diopside granulite." (It should be noted here that Matheson and Searl use the term "granulite" to imply a granoblastic texture, not to imply a high-rank metamorphic facies.)

Chlorite is ubiquitous in contact-metasomatic occurrences, although its relative abundance varies greatly. Much of the chlorite may be attributed to retrogressive metamorphism and may be related to a pervasive magnesium metasomatism (Eupene and others, 1975).

Replacement textures are common in contact-metasomatic occurrences.

Chemistry

Bulk-rock chemistry of contact-metasomatic uranium occurrences is highly variable, both because of the broad spectrum of possible host rocks and because of the possible types of metasomatism. Few generalizations regarding the chemistry of contact-metasomatic uranium occurrences may be made; they cannot be considered universal. The SiO_2 content of the host rocks is generally low and is reflected in the low-silica character of the host rocks of many occurrences. However, metasomatism may add sufficient SiO_2 to the system to mask the original low-silica aspect of the host rocks. Na_2O (and to some extent K_2O) may be anomalously high. This is primarily a function of alkali metasomatism. High

fluorine contents, which probably reflect metasomatic additions to the system, are also common.

Because of possible variations in the oxidation state of uranium in metasomatizing fluids, Th/U ratios may vary among contact-metasomatic occurrences. The bulk of the uranium is probably transported in the hexavalent state; hence, the Th/U ratio is generally less than unity. If a significant proportion of the uranium in metasomatizing fluids is tetravalent, the Th/U ratio could be more typically "igenous" (a range of 2 to 5). Th/U ratios greater than unity are not common. Unfortunately, because of the variability in oxidation state of uranium, Th/U ratios cannot be used as definitive indicators of contact-metasomatic uranium occurrences.

Alteration

Alteration of the country rock containing contact-metasomatic uranium occurrences is extensive. The variable nature of metasomatizing fluids gives rise to several types of alteration in contact-metasomatic aureoles. Albitization is the most common type of alteration, although potassium metasomatism also may be widespread. Chloritization is commonly associated with occurrences of this class. Products of argillization, silicification, and sericitization are often present. These alteration types are not mutually exclusive. No definitive host-rock alteration pattern which might be used as a recognition criterion of contact-metasomatic occurrences has been identified.

Geometry

The geometry of contact-metasomatic uranium occurrences is variable. Geometry depends on many factors, among which are the porosity and permeability of the host rock (as they determine the path taken by metasomatizing fluids), the orientation of major channelways, the temperature gradient, and the orientation of suitable host rocks with respect to the channelways. Most contact-metasomatic uranium occurrences are pod-shaped, which may be a function of the shape of the favorable host rock.

Derrick (1977) noted that the shape of the orebodies at Mary Kathleen may be a result of the retarding action that a dense quartzite layer had on the metasomatizing fluid. Because the quartzite is a massive, coherent unit, with few through-going fractures, and because it was not reactive with the metasomatizing fluid, the fluid tended to "back up" behind it. Where fractures allowed the metasomatizing fluid to pass through the quartzite, the fluid "blossomed out" into a more favorable host, stratigraphically above the quartzite and formed pod-shaped deposits.

Resource Potential

Many variables are involved in the genesis and economic concentration of uranium in contact-metasomatic occurrences, which results in a wide spectrum of sizes and grades. Secondary-enrichment processes may make such occurrences economically important. The Mary Kathleen deposit is a significant producer. Thus, contact-metasomatic uranium occurrences may represent submarginal, paramarginal, or recoverable uranium resources.

EXAMPLES OF CONTACT-METASOMATIC URANIUM OCCURRENCES

Mary Kathleen, Australia

The following discussion of the Mary Kathleen uranium deposit is mainly taken from Matheson and Searl (1956), Hughes and Munro (1968), Hawkins (1975), and Derrick (1977).

The Mary Kathleen uranium deposit is located in metamorphosed and metasomatized sedimentary rocks of the lower to middle Proterozoic Corella Formation, northwest Queensland, Australia. The Corella Formation comprises a series of mixed carbonate and clastic sediments deposited in a near-shore environment. A sedimentary breccia-conglomerate occupies the highest portion of the stratigraphic sequence. This facies, which contains the great bulk of the ore at Mary Kathleen, is interpreted as a cobble beach deposit on the basis of the size, shape, and distribution of clasts and on the basis of the abrupt lateral facies changes in the sequence.

The Corella Formation is exposed in a structurally complex, northward-plunging syncline. A series of north-trending faults and shear zones transects the structure. Two orogenic episodes, each with an associated period of acid magmatism, have affected the Corella Formation. Synorogenic metamorphism converted the sedimentary sequence into a series of schists, slates, quartzites, gneisses, thin-bedded calc-silicate rocks, and calc-silicate breccias of the upper greenschist to lower amphibolite facies. Following the regional metamorphic episode(s), a period of widespread garnetization and alkali metasomatism affected the Corella Formation.

The postorogenic, epizonal(?) Mt. Burstall Granite borders the syncline structure on the east. This multiphase intrusive is in sharp, irregular contact with the metasediments and shows discordant relations with the structures in the metasediments. A finer-grained contact facies of the granite constitutes a slightly chilled margin. The Mt. Burstall Granite represents a differentiation sequence which becomes progressively more silicic (and progressively more uraniferous) toward the Corella Formation. It progresses from diorite in the east (with <1.0 ppm U) through granodiorite and quartz monzonite, to granite in the west (with an average of 7.0 ppm U). Rhyolite and microgranite dikes, which average 12 ppm U, extend westward from the granite toward the Mary Kathleen orebody.

A dominant, north-trending, eastward-dipping shear zone extends through the metasediments toward the Mt. Burstall Granite. This zone is highly garnetized and is thought to be a major channelway for metasomatizing fluids emanating from the residual granite-rhyolite magma (Derrick, 1977).

Uraninite occurs within allanite and andradite crystals in the breccia-conglomerate, near the axial portion of the syncline. Textural relations indicate that allanite and uraninite have selectively replaced andradite. Almandite, the other garnet developed during garnetization, was not extensively replaced. Fluorite is a common accessory mineral in the ore.

Metasomatic minerals in the orebody are also present as primary crystallization products in the rhyolite dikes. These minerals include hedenbergite, garnet, allanite, fluorite, zircon, and sphene.

The Mary Kathleen deposit is a classic example of contact-metasomatic enrichment of uranium. Although some of the uranium may be the result of remobilization of syngenetic uranium in the Corella Formation, the low concentration (<4 ppm) and the even distribution of uranium in the metasediments suggest that remobilization was not a significant process of uranium enrichment. The spatial, temporal, mineralogical, and chemical relations of the orebody to the Mt. Burstall Granite are strong indicators of its contact-metasomatic origin.

Wheeler Basin, Colorado

The following discussion of the Wheeler Basin uranium occurrence is taken from Young and Hauff (1975) and Ludwig and Young (1975), and is also based on analyses, field notes, and verbal information provided by S. Dubyk (1977).

Wheeler Basin is a glacially scoured valley near the continental divide in Grand County, Colorado. Bedrock in the basin comprises metasediments and localized migmatites of the Precambrian Idaho Springs Formation (upper amphibolite facies of metamorphism). A pluton of Silver Plume-type granite shows intrusive relations with, and presumably underlies, the metasediments near the uranium occurrence. Radioactivity of the Silver Plume Granite is three to four times background. One analyzed sample contains 7.2 ppm eU. The Silver Plume Granite is atypical here, in that it is highly variable lithologically (from monzonite to alaskite) and texturally (aplitic to pegmatitic). The dominant phase is porphyritic granite, which shows a slight orientation of plagioclase laths. Numerous discordant perthite-quartz-muscovite-biotite pegmatite dikes and pods, probably related to the Silver Plume Granite, cut the metasediments. These also have above-background radioactivities.

Fine uraninite euhedra are concentrated in titaniferous-biotite segregations within the metasediments. These segregations occur adjacent to pegmatites and along shear zones within the metasediments. They vary in both size and shape. Most are in sharp contact with the pegmatites; a few pegmatites and the Silver Plume Granite display evidence of partial assimilation of the metasediments locally. The uranium-bearing segregations comprise biotite, sillimanite, and quartz, with trace amounts of pyrite, muscovite, monazite, hematite, uraninite, zircon, and fluorite. Iron-rich chlorite is also a common accessory constituent. The Th/U ratio in the biotite segregations is less than unity.

Unit-cell dimensions of the uraninite suggest a magmatic origin for the uranium. Age of mineralization is 1450 m.y., which is well within the generally accepted age range of the Silver Plume Granite.

The finely divided nature of the uranium minerals, their concentration in mafic constituents, the spatial association with radioactive pegmatites, the proximity to the Silver Plume Granite, the unit-cell dimensions of the uraninite, and the corresponding radiometric ages of uranium mineralization and the Silver Plume Granite combine to suggest that contact metasomatism was responsible for at least some of the uranium mineralization. The amount of mineralization caused by either migmatization or remobilization of syngenetic uranium in the metasediments

in response to heat from the Silver Plume magma cannot be evaluated at this time. The apparently even distribution of radioactivity in the Idaho Springs Formation in the area and the lack of reported anomalous uranium concentrations in the Idaho Springs Formation in Wheeler Basin suggest that migmatization and remobilization did not play a significant role in this uranium occurrence.

AUTOMETASOMATIC CLASS (CLASS 350)

Autometasomatic uranium occurrences form by reactions between late-stage aqueous magmatic fluids and previously crystallized plutonic or pegmatitic rocks. The reactions occur during the waning stages of magmatic activity and are most likely in magma systems which have remained untapped subsequent to saturation. Areas of autometasomatic uranium enrichment are generally confined to brecciated (internal) shear, fracture, and fault zones. These altered, porous zones are probably the conduits for the metasomatizing fluids. The uranium in autometasomatic occurrences is transported into the system by autometasomatizing fluids. Some uranium may be remobilized and reconcentrated syngenetic uranium from the host pluton.

As inferred from the mineralogy and chemistry of the rock, autometasomatizing fluids must have been capable of transporting nonfractionated, slightly fractionated, or highly fractionated uranium and thorium, together with high percentages of rare-earth elements. Extensive albitization and the development of phyllosilicates suggest that the fluids were low-temperature aqueous solutions.

Uraniferous autometasomatic zones grade laterally into unaffected rocks of the host plutons. The width and the chemical gradients of the gradational aureole depend in part on the degree of solidification and the extent of cross-fracturing in the host pluton. Gradational aureoles are usually narrow.

Autometasomatic uranium occurrences may be confined to the apical parts of host plutons because of entrapment of upward-migrating autometasomatic fluids. The site of uranium deposition depends on the degree of consolidation of the host rock and (or) the extent and persistence of internal fractures.

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Autometasomatic uranium deposits occur in postorogenic or anorogenic, epizonal plutons bearing orthomagmatic-class uranium deposits. The anorogenic character is important for retaining metasomatic fluids within the system. These deposits occur in mobile-belt and (or) taphrogenic areas. Some autometasomatic deposits are found in association with occurrences of the pegmatitic class.

Lithology, Texture, and Mineralogy

Host rocks of autometasomatic uranium occurrences are usually silicic intrusives formed during late-stage magmatic differentiation. Equivalent feldspathoidal plutons are also possible hosts. Host rocks are commonly porphyritic and contain alkali feldspars and alkali amphiboles and (or) pyroxenes. Autometasomatized zones commonly have the same general texture as the surrounding plutonic rocks. Cataclastic textures are not common. Although relict textures of the host rocks are generally preserved, autometasomatized zones display mineralogical alterations, crystal mantling, and replacement textures. Mirolitic cavities are common and indicate that the magmatic system was not totally tapped after saturation.

High modal percentages of albite characterize zones of autometasomatic uranium enrichment. Albite occurs interstitial to earlier-formed crystals, as reaction rims around major rock-forming minerals, and in patch or injection perthites. It occurs as partial and complete replacement of quartz, potassium feldspar, and plagioclase. A systematic compositional zoning may be developed when albite mantles a more calcic plagioclase crystal. This zoning may be difficult to distinguish from zoning in plagioclase formed during liquidus crystallization. Albite mantles around other mineral species are normally abrupt and are easily recognized in hand sample.

Although fluorite is a common accessory mineral in plutons bearing orthomagmatic deposits, it occurs in higher modal percentages in autometasomatic uranium zones. Reactions between autometasomatizing fluids and the previously formed minerals may release calcium. If some uranium is transported as a uranyl fluoride complex, then reactions between liberated calcium and the fluoride complex might form pitchblende. This process is similar to that proposed for some occurrences of the pneumatogenic class of uranium occurrences (Pilcher, 1978).

Calcite gangue may be present in autometasomatic uranium occurrences, even though it is normally absent from unaltered parts of the host plutons. Calcite deposition might be caused by release of the confining pressure on the upward-migrating metasomatizing fluids. Carbon dioxide comes out of solution as confining pressure decreases and raises the pH of the system into the stability field of calcite.

Aegirine occurs in some autometasomatic uranium occurrences and indicates the highly sodic nature of the mineralizing fluids. If the alumina content of the rock is too low to allow all the soda to be incorporated in albite, aegirine (or perhaps a Na-amphibole) forms.

Uraninite, uranothorite, coffinite, and (or) pyrochlore are the dominant uranium and uranium-bearing minerals in autometasomatic zones. The high thorium content of some occurrences and the fact that mineralized zones contain few reductants suggest that uranium is transported principally in its tetravalent state. Some hexavalent uranium occurs in surficial zones of secondary uranium mineralization.

Chemistry

Host rocks of autometasomatic uranium occurrences are generally subalkaline to peralkaline (see orthomagmatic class, p. 128). Autometasomatic occurrences are chemically dissimilar to unaltered parts of the enclosing plutonic rock. Autometasomatic zones are enriched in Na_2O , and are depleted in SiO_2 and K_2O . These chemical characteristics reflect albitization of quartz and potash feldspar. Occurrences of this class are usually enriched in elements normally concentrated in residual magmatic fractions. These elements include U, Th, Mo, Li, F, Nb, and rare-earth elements. The Th/U ratio is generally greater than unity.

Alteration

Albitization (discussed above) is the most prominent type of alteration in autometasomatic uranium occurrences. Albitization is thought to be a product of a low-temperature, volatile-charged, aqueous solution (Hatch and others, 1961; Phair and Jenkins, 1975). Although few paragenetic data are available, albitization seems to be synchronous with deposition of uranium minerals in autometasomatic uranium occurrences.

The low temperature of metasomatizing fluids is also indicated by internal argillic alteration. Clay minerals are generally restricted to medial parts of the autometasomatically uranium-enriched zones. This is particularly true in zones of autobrecciation. Complete or partial argillization of albite indicates that argillic alteration postdates albitization. Argillic alteration is not found in all occurrences of the autometasomatic class.

Hematitization has affected some autometasomatic occurrences. The position of hematitization in the alteration sequence is not known. Hematitic coatings on uraninite and pervasive red staining in microfractures in albite suggest that hematitization occurs after deposition of uranium minerals and albitization. Hematitization may be synchronous with argillic alteration.

Geometry

The geometry of autometasomatic uranium occurrences is governed by the configuration of the upper margin of the pluton and the conduits used by metasomatizing fluids. Gradational margins around these occurrences make descriptions of the geometry difficult. Autometasomatic uranium occurrences are generally cylindrical or amoeboid. Their geometry may resemble the breccia-pipe shape of some volcanogenic occurrences. Thin, tabular shapes are less common. The areal extent of an autometasomatic uranium occurrence is a function of the depth of erosion and the angle at which topography cross cuts the enriched zone. Because of the gradational margins of such occurrences, the shape of the occurrence is also governed by grade-tonnage relations.

Rock Associations

Rocks associated with autometasomatic uranium occurrences are the same as those associated with occurrences of the orthomagmatic class (see p. 128).

Resource Potential

Autometasomatic uranium occurrences vary in size and grade, which depend on the concentration of uranium in the magmatic residua, the volume of rock which has been metasomatized, and the degree of uranium concentration in the host rock. Initial magmatic composition, the path of magmatic evolution, and the extent of uranium mineralization during either the orthomagmatic or pegmatitic stages of evolution govern the amount of uranium remaining in autometasomatizing residua. Whether concentrations are ore grade is governed by whether metasomatism is pervasive or restricted to specific zones within the host rock. Pervasive autometasomatism may distribute uranium throughout a large volume of rock and may not concentrate it sufficiently for an economic uranium deposit. Such occurrences are submarginal. Where autometasomatism and uranium enrichment are limited to narrow zones, the uranium may be concentrated enough to be economic. Occurrences of this type represent paramarginal to recoverable resources.

EXAMPLES OF AUTOMETASOMATIC URANIUM OCCURRENCES

Ross-Adams Deposit, Bokan Mountain, Alaska

The following summary of the Ross-Adams deposit is taken from MacKevett (1958, 1959, 1963).

The Ross Adams deposit is located in the peralkaline (subaluminous?) Bokan Mountain granite, in the southeastern end of the Alaska Panhandle. It occurs along the southeastern flank of Bokan Mountain, approximately 1,000 ft from the contact between the peralkaline granite and an older quartz monzonite. The ore zone is an intermittent, elongate, north-trending area of uranium enrichment. It extends approximately 400 ft along strike and averages approximately 40 ft wide and 50 ft deep. Some barren zones of granite occur in the orebody.

The orebody consists of a higher-grade medial region surrounded by lower-grade ore. Ore grades decrease from the core into unenriched Bokan Mountain granite. Hematitic alteration, following the same pattern, decreases outward from intense alteration in the higher-grade central region of the orebody.

The autometasomatic ore zone is characterized by closely spaced joints and shears, some of which are marked by a thin zone of iron-stained gouge. A few of the shear zones are brecciated. The ore zone is widest on the south,

near two large fault zones. Although the shears and fault zones offset the ore, they are probably pre-ore structures which were reactivated after mineralization.

Textures of the Bokan Mountain granite in the ore zone are similar to those of the unmineralized portions of the pluton. The rock varies from hypidiomorphic-granular to porphyritic. Replacement textures are common in the ore zone.

The Bokan Mountain granite in the ore zone is mineralogically dissimilar to the main body of the pluton. Within the autometasomatized zone, the granite is characterized by higher modal percentages of albite and aegirine and lower percentages of quartz and potash feldspar. Uranium minerals, uranothorite, uranoan thorianite, and minor coffinite, occur as anhedral to euhedral disseminations and in tiny veinlets within the granite. Accessory fluorite, calcite, pyrite, and galena are present. Although fluorite is present in the main body of the pluton, it is much more abundant and darker purple in the ore zone.

The Ross-Adams uranium deposit is characterized by extensive, zonal alteration. Albitization and hematitization are most prevalent. Minor argillic alteration occurs in the small uranium-bearing veinlets.

Relative to unmineralized portions of the Bokan Mountain granite, the ore-zone granite is enriched in Na_2O , Al_2O_3 , U, Th, Nb, and rare-earth elements and is depleted in K_2O and SiO_2 . The granite adjacent to the ore zone is enriched in both uranium and thorium.

The major fault zones near the southern end of the deposit are thought to be the conduits for upward-migrating, uranium-bearing fluids (MacKevett, 1963). The uranium was apparently distributed into the ore zone along the numerous fractures and shears. The restriction of the uranium concentration to a specific zone; the disseminated nature of the uranium minerals; the associated extensive albitization, hematitization, and fluorite enrichment; the replacement textures; and the chemical modification of the ore zone suggest that autometasomatism was the dominant process of mineralization.

Lireui Complex, Nigeria

The following discussion of the Lireui complex is adapted from Greenwood (1951), Butler and others (1962), and Bowden and Turner (1974).

The Lireui complex, located in the Plateau Province of northeastern Nigeria, is composed of several ring dikes. It occurs near the southern end of a north-trending zone of Jurassic epizonal, anorogenic ring-dike complexes that extends southward approximately 1400 km from central Niger into northeastern Nigeria. The Lireui alkaline complex comprises two early volcanic sequences intruded by fayalite granite porphyry, biotite granite, and peralkaline granite. The Kaffo Valley granite, the youngest intrusive phase in the complex, is a uranium-enriched, albite-riebeckite peralkaline granite. This younger peralkaline unit has a coarse, porphyritic texture, in which large quartz and orthoclase perthite phenocrysts are set in a finer-grained,

hypidiomorphic-granular groundmass of albite, potash feldspar, quartz, riebeckite, and aegirine. Fluorite, topaz, cryolite, pyrochlore, and minor zircon compose the accessory-mineral suite.

The Kaffo Valley granite has been extensively albitized; albite has replaced quartz and orthoclase in the groundmass and has developed extensive reaction rims around the phenocrysts. Aegirine displays a complex replacement relationship with riebeckite. Uranium enrichment is represented by high percentages of disseminated and replacement pyrochlore. Uranium is most abundant in the highly albitized zones.

Chemically, the Kaffo Valley granite is characterized by anomalously high concentrations of rare-earth elements, F, Zr, Nb, Sn, U, Rb, and Li. The high agpaitic coefficient (>1.3) is also characteristic. The Kaffo Valley granite has an exceptionally low K/Rb ratio. Although Taylor and others (1956) interpret low K/Rb ratios as indicative of highly differentiated granites produced late in the magmatic evolutionary sequence, Bowden and Turner (1974) suggest that Rb (together with Nb, Sn, and U) may have been added to the system by the late-stage fluids responsible for the albitization of the unit. This, together with the lack of associated pegmatites, is consistent with the anorogenic character of the ring-dike complex.

Extensive albitization, anomalous trace-element concentrations, and the low K/Rb ratios all suggest postsolidification modification of the Kaffo Valley granite (autometasomatism). Albitization and the formation of pyrochlore occurred when fluids enriched in albite and aegirine constituents separated from the evolving magma and permeated the peralkaline granite during the very late stages of magmatic differentiation. In addition to albitizing the granite, this metasomatizing fluid caused extensive recrystallization of alkali amphibole, generation of aegirine, and an enrichment in uranium.

The Kaffo Valley granite is similar to the Bokan Mountain granite at the Ross-Adams mine in several respects: mineralogical and chemical composition, uranium enrichment in highly albitized zones, anomalously high concentrations of selected trace elements (Nb, Zr, rare-earth elements), and enrichment of the uranium-rich zones in fluorine.

AUTHIGENIC CLASS (CLASS 360)

Authigenic uranium occurrences are postmagmatic, secondary uranium enrichments formed by leaching and subsequent redeposition of labile uranium in shears and fracture zones within source plutons. Redistribution and enrichment of uranium occurs in the near-surface environment. Authigenic occurrences are shallow and may be related to the ground-water table.

Authigenic uranium occurrences are probably uncommon, because uranium leached from plutonic igneous rocks is usually transported away from the source. Therefore, many of the recognition criteria presented here are

based on considerations of the geochemical behavior of magmatic uranium in a postmagmatic environment. Thus, many of the recognition criteria are speculative. These criteria assume an internal source for the uranium, although externally derived uranium could be an integral part of authigenic uranium occurrences.

An intraplutonic source is suggested by high thorium contents and high Th/U ratios in surficial portions of the host plutons and anomalous uranium contents in deeper, unmineralized, and unaltered regions of the pluton. High Th/U ratios imply postsolidification removal of uranium; liberated uranium may be concentrated in authigenic occurrences within the pluton. An extraplutonic source of uranium is possible. Country rocks for plutons containing authigenic uranium occurrences generally have low uranium contents and are therefore unlikely uranium sources. Country rocks are normally better depositional sites for secondary uranium minerals than they are sources for uranium.

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Authigenic uranium occurrences are restricted to postorogenic, epizonal plutons that are end products of magmatic differentiation. Such plutons are normally the most uraniferous phases of a magmatic system; they are the most likely sources for internally derived uranium. Postorogenic, epizonal plutons are more likely to retain uranium than are synorogenic plutons; synorogenic intrusives generally form in mesozonal and catazonal environments and are more likely to lose uranium-bearing aqueous fluids during orogenesis. Authigenic uranium occurrences may form in deep-seated plutons or in anatectically derived units if the uranium has not been driven away from the pluton during orogenesis (see discussion of Rossing deposit, p. 167). In general, authigenic occurrences are less likely in mesozonal and catazonal plutons than they are in epizonal plutons.

Lithology and Texture

Plutons containing authigenic uranium occurrences are products of late-stage magmatic evolution; they are generally granitic and porphyritic. Although no authigenic uranium deposits in subsilicic, feldspathoidal plutons are known, the genesis of authigenic uranium occurrences does not preclude their discovery.

Lithologic and textural characteristics of host rocks for authigenic uranium occurrences are described in the recognition criteria for the orthomagmatic and autometasomatic classes (p. 128 and 152).

Mineralogy

Mineralogical characteristics of host plutons for authigenic uranium occurrences have been discussed above (p. 129). Zones of enrichment in authigenic uranium minerals are characterized by autunite and (or) other secondary

uranium minerals, finely disseminated along and adjacent to shear and fracture zones within the parent pluton. Hexavalent uranium minerals also occur along cleavage traces within the major rock-forming minerals. Small percentages of contemporaneous gangue minerals, principally quartz and calcite, may accompany the secondary uranium minerals.

Chemistry

Unmineralized surficial exposures of plutons hosting authigenic uranium occurrences are characterized by high Th/U ratios; these ratios reflect remobilization and removal of uranium. Other chemical characteristics of host plutons have been discussed above (see orthomagmatic class, p. 130).

The zones within host plutons which have been authigenically mineralized are characterized by low Th/U ratios. These ratios reflect the fractionation of thorium and uranium in the authigenic environment. Authigenically mineralized zones may show anomalous concentrations of SiO_2 and CaO .

Alteration

Unlike other classes of uranium occurrences in and related to plutonic igneous rocks, authigenic uranium occurrences are not associated with any specific type of alteration. Host plutons may show evidence of albitization, hematitization, autometasomatism, and (or) argillic alteration. Surficial weathering characteristics, exemplified by decomposition of ferromagnesian minerals and feldspars, may prevail. Limonitic staining and argillic alteration of feldspars may occur along fracture zones. Evidence of hydrothermal alteration is generally lacking in zones of secondary uranium enrichment.

Geometry

Authigenic uranium occurrences comprise concentrations of secondary uranium minerals in veinlike bodies along and adjacent to major fracture systems within the parent pluton. The major fractures and joint systems may be expansion features caused by deroofing the pluton. Shear intersections are particularly favorable sites for secondary-uranium-mineral deposition. Thus, the ore zones are commonly lenticular to pod-shaped.

Resource Potential

Because of the mobility of uranium in the near-surface environment, and because of the low probability of retaining remobilized uranium within the parent pluton, authigenic uranium occurrences are generally small and low grade. Authigenic uranium occurrences probably represent submarginal to paramarginal resources.

Authigenic uranium occurrences may be guides to occurrences of other classes of uranium deposits related to plutonic igneous rocks. An authigenic occurrence may be a surface expression of a more deeply buried orthomagmatic or autometasomatic uranium deposit.

EXAMPLE OF AN AUTHIGENIC URANIUM OCCURRENCE

Daybreak Mine, Washington

The Daybreak mine is the largest of several authigenic uranium occurrences in pegmatites and alaskites on Mount Spokane, northeast of Spokane, Washington. These occurrences consist of meta-autunite crystals along fractures, microfractures, and cleavage traces in the pegmatitic and alaskitic phases of Cretaceous porphyritic quartz monzonite. The quartz monzonite is an epizonal plutonic body emplaced into a complex sequence of highly metamorphosed Beltian sedimentary rocks.

Plutonic rocks of the Daybreak mine consist of a series of subhorizontal, alternating bands of garnet-bearing, muscovite-biotite pegmatites and hypidiomorphic-granular alaskite. Each rock type composes approximately 50 percent of the rock. The individual bands range from 1 to 5 m thick and are nearly parallel to a set of subhorizontal, arcuate joints. A few small pegmatites are discordant to this orientation.

The dominant structure of the mine area is a major horizontal shear zone and is marked by bleached fault gouge and breccia. The shear zone itself is largely mylonitic. Widely spaced, vertical, northwest-trending shears occur in the hanging wall.

Secondary uranium minerals, mostly meta-autunite, are restricted to the near-surface environment and are concentrated in shear zones. Maximum concentrations occur at the intersections of the northwest-trending vertical shears with the major horizontal structure. Meta-autunite also occurs along fractures and microfractures which trend away from the vertical shear zones; plates of meta-autunite also occur along cleavage planes of the larger feldspar and biotite crystals within the pegmatite. Some meta-autunite masses, as much as 40 cm in diameter, have been found in open spaces in the fault breccia.

Although feldspars in the alaskite and pegmatite are partially altered, the biotite is fresh. Evidence of extensive hydrothermal alteration is lacking.

These observations and the fact that unmineralized portions of the alaskite possess high Th/U ratios (8) suggest removal of uranium from the host rock itself. Deposition of uranium as meta-autunite resulted from in situ remobilization and concentration of the uranium along channelways within the source-host plutonic rocks.

ALLOGENIC CLASS (CLASS 370)

Allogenic uranium occurrences form in a manner similar to occurrences of the authigenic class. The difference between the two is the site of uranium deposition. Whereas authigenic uranium occurrences are restricted to the parent pluton, allogenic uranium deposits occur in rock units surrounding the source pluton.

Allogenic occurrences form by remobilization and deposition of orthomagmatic, pegmatitic, and (or) autometasomatic uranium. The uranium is deposited in suitable host rocks adjacent to the source pluton, in the near-surface, postmagmatic environment. Uranium transportation and redeposition may be a continuous process.

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Because allogenic uranium derived from shallow-seated plutons is concentrated in near-source depositional sites, the general geologic setting of allogenic uranium occurrences is usually the same as that of orthomagmatic occurrences (see p. 128). Low- to medium-grade metamorphic rocks adjacent to postorogenic, uraniferous epizonal plutons in mobile-belt areas are likely environments for allogenic uranium occurrences.

Lithology and Texture

Plutons of the orthomagmatic class, which may have been autometasomatized, are the principal source of the uranium in allogenic occurrences. Petrographic aspects of these source plutons are discussed above (see p. 129).

Allogenic uranium deposits commonly occur in low- to medium-grade meta-sedimentary rocks. Because allogenic uranium is transported in the hexavalent state, potential host rocks must be capable of reducing the uranium in order to promote pitchblende deposition. Ideal host lithologies are carbonaceous slates, graphitic schists, and calc-silicate rocks. Foliated, hornfelsic, and (or) granoblastic textures prevail.

Host rocks which were originally of medium to high metamorphic rank are commonly retrogressively metamorphosed; this may reflect the epizonal environment of the source pluton. Retrogressive metamorphic effects may be either regional or confined to aureoles around the source plutons.

Mineralogy

The mineralogy of source plutons has been discussed above (p. 129). The dominant mineralogical aspect of host rocks of allogenic uranium occurrences is a high modal percentage of minerals capable of reducing hexavalent uranium. Sulfides and graphite are most prevalent. Ferromagnesian minerals also may serve as reductants.

Pitchblende is the principal uranium mineral in allogenic occurrences; secondary uranium minerals may occur in the near-surface portions of the deposit. Contemporaneous gangue minerals, mainly calcite and (or) quartz, are minor.

Chemistry

Chemical aspects of source plutons have been discussed above (see orthomagmatic and autometasomatic classes, p. 130 and 154, respectively). Associated plutons may not show anomalous uranium contents, because some (most?) of the uranium may have been leached. Inference of an initially anomalous uranium content may be made on the basis of a high thorium content and a high Th/U ratio. A high Th/U ratio suggests removal of labile uranium, and although it does not indicate where the leached uranium is deposited, it might be used to infer an associated allogenic uranium occurrence.

Host rocks of allogenic uranium occurrences have variable chemical characteristics. Except for anomalous concentrations of reduced elements (carbon and sulfur, for example), rocks hosting allogenic uranium occurrences have no definitive chemical characteristics. Host rocks may show disproportionately high contents of FeO and MgO; this is not a universal characteristic, however.

Alteration

No diagnostic alteration patterns or types characterize allogenic uranium occurrences. Allogenic deposits generally lack evidence of hydrothermal alteration and may or may not show evidence of retrogressive metamorphism. Contact metamorphic and (or) metasomatic effects may occur near the source pluton. Poorly developed argillic alteration may occur along fractures and shear zones within the host rocks in some allogenic occurrences.

Geometry

The geometry of allogenic uranium occurrences reflects the near-surface remobilization and deposition of uranium. The occurrences are generally amoeboid and shallow and consist of pitchblende in veins and vein systems along fractures and shears in the host rocks. Finely disseminated pitchblende may also occur adjacent to the veins.

Rock Associations

Allogenic uranium occurrences are found in metasedimentary rocks associated with plutonic igneous rocks which are (or were) anomalously rich in uranium. Metavolcanic rocks may be associated with allogenic uranium occurrences. Except for the reducing nature of the host rocks, allogenic occurrences have no apparent restricted association with particular types of metamorphic rocks.

If the source pluton is not exposed, a given allogenic uranium occurrence might be confused with a magmatic-hydrothermal or contact-metasomatic occurrence. The lack of hydrothermal and metasomatic effects, the common restriction of uranium minerals to shear zones, and the shallow depth of the occurrence should serve to distinguish allogenic uranium occurrences from contact-metasomatic and magmatic-hydrothermal occurrences.

Resource Potential

Sizes and grades of allogenic uranium occurrences depend on many factors which include the quantity of leachable uranium in the source pluton, amount of uranium leached and transported, effectiveness of the host rocks in reducing and concentrating the uranium, and the volume of the rock in which a given amount of uranium is concentrated. For these reasons, allogenic uranium occurrences may represent submarginal to recoverable resources.

EXAMPLE OF AN ALLOGENIC URANIUM OCCURRENCE

Midnite Mine, Washington

The Midnite mine, approximately 40 mi northwest of Spokane, Washington, consists of primary uranium minerals concentrated in a roof pendant of the Beltian Togo Formation, adjacent to a late Cretaceous porphyritic quartz monzonite. The orebodies are roughly tabular, have nearly horizontal upper surfaces, and are bordered on at least one side by unmineralized porphyritic quartz monzonite. They are thickest over depressions in the subjacent pluton.

The Togo Formation, the host rock of the uranium deposits, comprises a series of steeply dipping, low-grade, metamorphosed black shales (metapelites) with interbedded, discontinuous lentils of calcareous material. Minerals include quartz, muscovite, biotite, potash feldspar, and minor andalusite. Iron sulfides, principally pyrite, compose up to 2 percent of the rock. Graphite is present throughout.

The porphyritic quartz monzonite is an epizonal, postorogenic intrusive. It displays sharp, generally concordant contacts with the Togo Formation. Contact-metamorphic effects are limited. The quartz monzonite consists of

large, pink potash feldspar phenocrysts (up to 5 cm long) set in a hypidio-morphic-granular groundmass of quartz, potash feldspar, plagioclase, and biotite. Accessory minerals include muscovite, sphene, zircon, apatite, and fluorite. The quartz monzonite contains an average of approximately 12 ppm uranium.

Primary uranium minerals, chiefly pitchblende and coffinite, are concentrated along a series of small step faults and shears in the metasediments. The uranium minerals occur as replacement products, disseminations along foliation planes, and minor-fracture fillings. Typical vein geometry is lacking. The postintrusive shears and fractures closely associated with the uranium mineralization within the Togo Formation are barren where they extend into the porphyritic quartz monzonite.

Ore-deposit location is not strongly controlled by stratigraphy, although more ore occurs in the metapelitic facies than in the metacarbonate units. The orebodies crosscut lithologic contacts within the Togo Formation. Ore zones seem to be principally controlled by the distribution of permeable channelways. A high sulfide and (or) graphite content and proximity to the porphyritic quartz monzonite seem to be prime requisites for uranium reduction and deposition within the Togo Formation.

The origin of the ore in the Midnite mine is speculative. Lehrman (1977) favored a hydrothermal origin, on the basis of the restricted geographical distribution of the ore. Nash (1977) discussed three possible origins for the Midnite mine ore: (1) syngenetic deposits within the Togo Formation accompanied by later metamorphic concentration, (2) hydrothermal emplacement by fluids derived from the quartz monzonite magma, and (3) supergene emplacement of uranium derived from the deroofed porphyritic quartz monzonite pluton.

The lack of anomalous uranium concentrations in the Togo Formation in areas removed from the Midnite mine suggests that metamorphic enrichment of syngenetic sedimentary uranium in the Togo Formation is an unacceptable hypothesis. The proximity to the anomalously uranium-rich quartz monzonite and the low thorium content of the ore in the Midnite mine suggest that the uranium was removed from the quartz monzonite and deposited in favorable localities within the Togo Formation.

An allogenic origin for the ore is inferred from the geometry of the orebodies and the lack of gangue and hydrothermal effects. Nash and Lehrman (1975, p. 2) noted: "Economic zones of uranium are interpreted to have been secondarily enriched in late Tertiary time by downward and lateral migration of uranium into permeable zones where deposition was influenced by groundwater control and minerals that could reduce or neutralize uranium-bearing solutions." They concluded (p. 29): "It is possible that pitchblende ores have been deposited over a span of time from immediately following intrusion of the porphyritic quartz monzonite (Cretaceous?) to recent."

ANATECTIC CLASS (CLASS 380)

Uranium liberated from sedimentary and igneous rocks by ultrametamorphic processes may become concentrated in anatectically derived quartzofeldspathic melts. Liquidus crystallization of these uranium-enriched melts produces occurrences of the anatectic class.

The source of uranium in anatectic melts is speculative. Prograde metamorphism generally drives labile uranium out of sedimentary and igneous rocks. The amount of uranium remobilized in anatexis is governed by the nature of the ultrametamorphic environment. Uranium tends to be retained in a reducing, closed metamorphic system, whereas an open, oxidizing metamorphic environment allows uranium to escape with the fugitive constituents. Because water is the principal fugitive constituent evolved during prograde metamorphism, it is the most likely transporting medium for remobilized uranium.

The manner in which uranium is held in premetamorphic rocks also affects the uranium concentration in paligenetic melts. Uranium adsorbed on the surface of crystals, along crystal boundaries, in crystal defects, and trapped in intragranular fluids readily escapes during prograde metamorphism. Therefore, uranium in anatectic melts probably comes from uranium and uranium-bearing minerals and from major rock-forming minerals which have incorporated spurious uranium in their crystal lattices.

Source rocks of anatectic melts may not be near the site of crystallization and the resultant occurrence.

GEOLOGIC CHARACTERISTICS

Tectonic Setting

Anatectic uranium concentrations occur in structurally complex, highly metamorphosed and migmatized terranes, in deep mesozonal and catazonal regions of mobile belts. These are characterized by steeply plunging, tight, isoclinal folds.

Lithology, Mineralogy, and Texture

Anatectic uranium occurrences comprise pegmatites, alaskites, and, to a lesser extent, aplites. These units are mineralogically simple; alkali feldspars and quartz are the major minerals. A small amount of biotite is usually present. Ferromagnesian minerals in anatectic alaskites and pegmatites may be similar to those in the surrounding host rocks, although their relative abundance is generally lower in the anatectically derived units.

Ferromagnesian minerals in anatectic units usually have alteration rims and show evidence of partial replacement. Muscovite is a common accessory mineral; it may be a major constituent in some occurrences. Garnet is often present in accessory to trace amounts.

Euhedral to subhedral primary uranium minerals, principally uraninite and uranothorite, are finely disseminated throughout alaskites and pegmatites of the anatectic class. Similar to occurrences of the pegmatitic class (see p. 137), quartz-rich zones and pods may contain localized concentrations of uranium minerals. Secondary uranium minerals may be present in either the palinogenetic rocks or the host rocks near the upper margins of the occurrences (authigenic and allogenic occurrences, respectively).

The strongly foliated and migmatized rocks surrounding anatectically derived units vary in lithology and mineralogy. They may be granitized. Host rocks adjacent to anatectic units which have crystallized in place are commonly deficient in quartz-feldspathic constituents. If the anatectic melt has migrated away from its site of generation, the surrounding host rocks may not be depleted in quartz and feldspar.

Anatectic uranium occurrences are characterized by hypidiomorphic-granular and pegmatitic textures. Some aplites may be present, but, because of the mesozonal or catazonal environment of crystallization, aplitic textures are not common.

Chemistry

Rock units containing anatectic uranium occurrences are characterized by high percentages of silica, alumina, and alkalis. Alumina and potash may be highly anomalous if the muscovite content of the unit is high. Anomalous uranium is characteristic. Although the concentration of trace constituents is variable, anatectic units are generally enriched in Li, Be, Mo, and rare-earth elements compared to the country rocks. Although the Th/U ratio is variable, it is generally greater than 1.0. Th/U ratios depend on the Th/U ratios of the rock units from which the anatectic melts were derived and on the oxidation-reduction potential of the ultrametamorphic environment. Palinogenetic melts derived from Archean rocks have Th/U ratios that are greater than unity because of the nonfractionation of uranium and thorium in sediments deposited under the Archean anaerobic atmosphere. Anatectic melts derived from sedimentary rocks formed in an oxygenated atmosphere have Th/U ratios less than unity.

The chemical composition of rocks adjacent to uraniferous anatectic units is variable and depends on the initial composition of the rocks, the degree of chemical modification during metamorphism and (or) granitization, and the extent of anatexis. Host rocks for anatectically derived units which have formed in place have disproportionately high percentages of FeO, MgO, and CaO; they are generally low in alkalis and silica.

Alteration

Alteration in and adjacent to anatectic uranium occurrences is negligible. The host rocks may show minor, poorly developed, retrogressive thermal metamorphic and (or) metasomatic effects. Contact aureoles are generally narrow.

Geometry

Anatectic uranium occurrences are tabular and (or) lenticular, quartzofeldspathic bodies and generally show sharp contacts with the host rocks. The dike-like pegmatites and alaskites are usually conformable to foliation; they may be locally discordant in the axial regions of folds.

Rock Associations

Anatectic uranium occurrences are associated with dynamothermally metamorphosed (upper amphibolite to granulite facies), eugeosynclinal sedimentary and volcanic rocks. They may be associated with foliated synorogenic granitic intrusives. Association with uraniferous metasedimentary rocks may be essential, although these latter rocks may not be exposed, particularly in cases where the palingenetic fluid has migrated away from its site of generation.

Resource Potential

Several factors govern the size and grade of anatectic uranium occurrences. These include the uranium content of the source rocks, the degree of concentration of uranium in the palingenetic melts, and the extent of uranium retention during subsequent crystallization. Because so many factors are involved, anatectic uranium occurrences range from submarginal to recoverable resources.

EXAMPLE OF AN ANATECTIC URANIUM OCCURRENCE

Rossing Deposit, South-West Africa

The Rossing uranium deposit is a large, low-grade occurrence situated along the southwestern flank of a major domal structure in the central region of the northeast-trending, late Precambrian Damaran orogenic belt, South-West Africa (Namibia). Uranium minerals are concentrated in syntectic alaskites within steeply dipping isoclinal folds of the migmatized Kahn and Rossing Formations.

The Kahn and Rossing Formations consist of highly metamorphosed and migmatized pyroxene and hornblende gneisses, amphibolites, schists, and marbles. At least three stages of dynamothermal metamorphism and associated structural deformation have affected these host rocks. A younger, superimposed thermal-metamorphic event is recognized adjacent to the alaskite in these units. Thermal metamorphism is particularly evident in the marbles.

Syntectic alaskites range from small, secretory lenses to large, intrusive and replacement bodies. They display concordant, discordant, and replacement relations with the complexly folded metasedimentary rocks of the Kahn and Rossing Formations. The alaskitic rocks have been emplaced along shears, fractures, bedding planes, and axial planes of tight, isoclinal folds within the country rock. The alaskites are predominantly pegmatitic, although hypidiomorphic-granular textures are common. Small zones of graphitic textures are also present in the alaskite. The alaskites comprise quartz, microcline, and microcline perthite, together with accessory amounts of zircon, fluorite, molybdenite, apatite, biotite, and sphene.

Uraninite is the dominant ore mineral in the alaskites. It occurs as small euhedra poikilitically enclosed in quartz and feldspar and as finely disseminated euhedra interstitial to and along microfractures within the major rock-forming minerals. Interstitial uraninite is often closely associated with zircon.

Secondary uranium minerals, principally beta-uranophane, are concentrated in the upper portions of the deposit and constitute nearly 45 percent of the ore. They occur principally within the alaskitic rocks, either as replacements of primary uraninite or as thin films along microfractures. Fewer secondary uranium minerals occur in the surrounding country rocks and in a discontinuous, intermittent layer of overlying limestone. Such a high percentage of secondary uranium minerals in the ore emphasizes the significance of secondary enrichment and retention of mobilized uranium.

The origin of the uranium ore is speculative. On the basis of field, petrologic, and chemical data, Berning and others (1976) suggested that the alaskites were paligenetically derived from early Precambrian units now exposed in the core of the adjacent domal structure. The fact that the alaskites within the ore zone are uraniferous, whereas similar alaskitic units outside the ore zone are barren, is attributed to localization of uranium in the source units of the paligenetic alaskites. Secondary factors, such as vertical zonation caused by chemical fixation of hexavalent uranium in areas of Eh and pH changes, may have played a significant role in the location of the ore deposit.

RECOGNITION-CRITERIA SUMMARY

+ = Strong criterion

- = Weak criterion

o = Unevaluated criterion

RECOGNITION CRITERIA		ORTHOMAGMATIC	PEGMATITIC	MAGMATIC-HYDROTHERMAL	CONTACT-METASOMATIC	AUTOMETASOMATIC	AUTHIGENIC	ALLOGENIC	ANATECTIC
TECTONIC SETTING	page	128	137	143	147	152	158	161	165
Mobile belt		+	+	+	+	+	+	+	+
Synorogenic		-	+	-	-	-	-	-	+
Postorogenic		+	+	+	+	+	+	+	
Anorogenic		+	+	+	+	+		-	
Epizonal		+	-	+	+	+	+	+	
Mesozonal		-	+	-	-	-	-	-	-
Catazonal			-		o		-	-	+
HOST-ROCK LITHOLOGY	page	129	138	143	148	153	158	161	165
Granitic (incl. qtz. monz.)		+	+			+	+	+	+
Syenitic		+	+			-	-	-	
Acidic		+	+	+		+	+	+	+
Intermediate		-			-				-
Basic					+				
Breccia		-		+	+	+	-	-	-
Leucocratic		+	+			+	+	+	+
HOST-ROCK TEXTURE	page	129	138	143	148	153	158	161	165
Granitic		+				+	+		+
Porphyritic		+				+	+		+
Pegmatitic			+				-		+

RECOGNITION-CRITERIA SUMMARY

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RECOGNITION CRITERIA	ORTHOMAGMATIC	PEGMATITIC	MAGMATIC-HYDROTHERMAL	CONTACT-METASOMATIC	AUTOMETASOMATIC	AUTHIGENIC	ALLOGENIC	ANATECTIC	
HOST-ROCK TEXTURE (continued)									
Aplitic		+				-		-	
Cataclastic	-	-	+	+	-	-	+	+	
Miarolitic	+				+	-		o	
Variable	+		-	+	+	+	+	-	
MINERALOGY									
	page	129	138	143	148	153	158	162	165
U ⁺⁴ minerals		+	+	+	+	+		+	+
U ⁺⁶ minerals		-	-	-	-		+	-	-
Quartz		+	+	+	-	+	+	-	+
Alkali feldspar		+	+	-		+	+	o	+
Feldspathoid		+	-			-	-		
Muscovite		-	+			-	-		
Biotite		+	+			+	-		+
Riebeckite		+	+	-		+			-
Aegirine		+	-			+			
Fluorite		+	+	+	+	+	+	+	+
Sulfides		-	+	+	+	+	-	+	-
Carbonate			-	+	-	-	+	-	o

RECOGNITION-CRITERIA SUMMARY

+ = Strong criterion
 - = Weak criterion
 o = Unevaluated criterion

RECOGNITION CRITERIA	ORTHOMAGMATIC	PEGMATITIC	MAGMATIC-HYDROTHERMAL	CONTACT-METASOMATIC	AUTOMETASOMATIC	AUTHIGENIC	ALLOGENIC	ANATECTIC
CHEMISTRY	page 130	138	143	148	154	159	162	166
High SiO ₂	+	+	+	o	+	+		+
High Na ₂ O	+	+	-	+	+	+		+
High K ₂ O	+	+	-	+	+	+		+
High F	+	+	+	+	+	+	+	+
High Fe ₂ O ₃ /FeO	+	+		o	+			o
High Na ₂ O+K ₂ O/Al ₂ O ₃	+	+		o	+	+		o
Th/U >1	+	+						
Th/U <1						+	+	
Low MgO	+	+		o	+	+		+
Low CaO	+	+		o	+	+		+
ALTERATION	page 130	138	144	149	154	159	162	167
Silicification	o	o	+	-	-	o	-	
Sericitization	-	+	+	o	-	o	-	
Albitization	+	+	-	+	+	o	-	o
Argillization	-	+	+	-	-	-	-	
Hematitization	-	-	+	-	-	-	-	-

RECOGNITION-CRITERIA SUMMARY

+ = Strong criterion
 - = Weak criterion
 o = Unevaluated criterion

RECOGNITION CRITERIA		ORTHOMAGMATIC	PEGMATITIC	MAGMATIC-HYDROTHERMAL	CONTACT-METASOMATIC	AUTOMETASOMATIC	AUTHIGENIC	ALLOGENIC	ANATECTIC
GEOMETRY	page	131	139	144	149	154	159	162	167
Stock		+				+			-
Pod			-		+	+	-	-	+
Tabular			+	+	-	-	+	-	+
Concordant								-	+
Discordant		+	+	+	+	+	+	+	-
ASSOCIATIONS	page	131	139	144	147	155	158	163	167
Greenschist facies		+	-	+	+	+	-	+	
Amphibolite facies		-	+	-	+	-		-	+
U-bearing pluton			+	+	+	+	+	+	
Prograde contact metamorphism		-	-	-	-	-	o	-	o
Retrograde metamorphism		-	+	+	+	+	o	+	-
Pegmatites		-		-	o	-	-		+
Aplites		+	-	-	o	+	-		-
Volcanics		o		o	o	-	o		
Shear zones				+	+	+	+	+	-

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VOLCANOGENIC URANIUM OCCURRENCES

by

R. C. Pilcher

ABSTRACT

Discussion of the geologic characteristics of the four classes of volcanogenic uranium occurrences is subdivided into eight separate categories. These are: tectonic setting, lithology, texture, mineralogy, chemistry, alteration, geometry, and rock associations. A discussion of the resource potential of each class is included for quadrangle-evaluation purposes. All occurrences of this classification are found in volcanic rocks that have high agpaitic coefficients, and in their sedimentary derivatives. These rocks originate from eruptive centers located in taphrogenes. The taphrogenes may be either basin-and-range relaxation features or rift systems.

Host-rock chemistry is variable. Associated rocks are usually characterized by high SiO_2 , Na_2O , and K_2O contents and low amounts of FeO , MgO , and CaO . Silica-undersaturated late-stage differentiates are also known to be uraniferous. High fluorine content is common. Anomalous concentrations of Be, Mo, Li, and Hg are sometimes associated with anomalous uranium contents. Th/U ratios vary between classes. Tetravalent uranium and uranium-bearing minerals are characteristic of the occurrences in the initial-magmatic and pneumatogenic classes. Hydroauthigenic and hydroallogenic occurrences characteristically contain hexavalent uranium minerals.

Textures and alteration of the host rocks are variable and complex, due to overprint of postdepositional processes not necessarily related to uranium mineralization. Geometry of volcanogenic uranium occurrences is also variable. Generally pneumatogenic occurrences are discordant, whereas the mineralization associated with other classes of occurrences is not.

Lithologic and structural associations are those characteristic of caldera evolution and the volcanogenic system. The dominant association is with soda-rich, highly differentiated volcanic rocks. The associated rocks often contain anomalous concentrations of uranium.

Deposits with economic reserves are known from the pneumatogenic, hydroauthigenic, and hydroallogenic classes.

INTRODUCTION

The geologic characteristics presented in this paper are an outgrowth of field and laboratory observations and the merging of several recent systems studies of volcanic fields throughout the world. They are to be used in conjunction with the author's classification of volcanogenic uranium deposits (Pilcher, 1978).

Although literature on the petrogenesis of volcanic rocks and volcanic systems is voluminous, data on uranium occurrences and their genesis are scarce and incomplete.

The following discussion of volcanogenic-uranium-occurrence recognition criteria is divided into three sections: 1) a discussion of theoretical considerations and the framework of caldera evolution, 2) a summary of the recognition criteria, and 3) a series of examples. The examples emphasize the volcanogenic system and type of occurrences that may develop during different stages of evolution of the system. Each example of a volcanogenic system contains at least one class of uranium occurrence. A chart summarizing the recognition criteria is included at the end of this paper; it is designed as both an index and a ready comparison of the different volcanogenic uranium classes.

THEORETICAL CONSIDERATIONS

It is commonly recognized that alkaline-rock provinces are anomalously enriched in uranium and other trace elements, such as F, Mo, Be, and Li. Uraniferous alkaline volcanic rocks occur in taphrogenic zones. These taphrogenes may be found flanking orogenically uplifted areas, such as the Basin and Range Province, or they may represent foundered rift systems, such as the Trans-Pecos rift. Effusive activity within taphrogenes can produce a comagmatic sequence of alkaline volcanic rocks and their sedimentary derivatives. These genetically related rocks and the igneous and sedimentary processes responsible for their formation are considered a volcanogenic system. Prediction of the locale and type of uranium deposition within a volcanogenic system requires an understanding of the genesis of the host-rock environment and the behavior of uranium within this environment.

Studies of igneous systems throughout the world have shown that late-stage differentiates, alkali-rich rocks, tend to have higher concentrations of uranium than do rocks formed earlier in the differentiation sequence. Distribution patterns of the alkaline rocks vary, but, in general, there is an increase in abundance of alkaline rocks as one moves onto the continent from a subduction zone.

Dewey and Bird (1970) proposed a model for the subduction of an oceanic plate beneath a continental plate; they described the mechanisms and distribution of structural elements and associated rock types resulting from mountain building and subsequent relaxation tectonics. The model proposes that igneous rocks become more alkaline and more differentiated with increasing distance onto the continent from the subduction zone.

Deep-seated magmas arise from the melted zone of the oceanic plate being subducted beneath the continental plate. A magma has more time to differentiate with increased depth of the subducted and melted plate. As the magma migrates to the surface, the proportion of volatiles within the magma chamber increases.

Zentilli and Dostal (1977) noted a general enrichment in alkali metals and uranium with increased distance onto the continent from the subduction zone.

However, they noted that there appeared to be a maximum in the potassium content centered over the thickest segment of the continental crust; this implies that crustal contamination is an important process in the increase of alkali elements. Uranium tends to increase away from the subduction zone onto the continent and appears to be independent of the thickness of the crust.

Civetta and Gasparini (1972) noted a progressive enrichment of volcanic rocks in uranium with distance from the west-northwestward subduction of the oceanic plate in the southeastern Tyrrhenian Sea. As might be expected, this increase in uranium is coincident with increased differentiation. The rocks become progressively less silicic (from sodic rhyolites to trachyphonolites) and more uraniferous (from 15 ppm U to 40 ppm U) from the Island of Pantelleria northward to the Vico volcano. Similar distribution patterns have been recognized throughout the world and throughout geologic time.

In order for a magma to undergo sufficient differentiation to concentrate the elements necessary for the deposition of uranium, it must reside at a relatively shallow depth, undisturbed by tectonic activity. Premature release of pressure on the magma can rid the chamber of volatiles and uranium in a manner that will not result in significant uranium mineralization. Continual or intermittent tapping of the magma chamber may result in deposition of low-grade deposits of finely disseminated uranium.

Taphrogenes are structural regimes in which shallow-seated magmas may evolve without being disturbed. When taphrogenic zones develop on the flanks of orogenically uplifted areas, magmatic activity is often controlled by intersection of structural lineaments within the taphrogene. Large volcanic piles often develop on the margins of the taphrogene, where the boundary is likely to be highly deformed by large-scale, deep-seated faulting. Structural deformation of this type allows a large-volume magma chamber to develop and persist for several million years. A magma in this environment may go through many cycles of uranium concentration and volatile saturation during differentiation. The result is a massive accumulation of volcanic and intrusive rocks that may be uranium-enriched.

Physicochemical properties of the magma are greatly affected by the alkali-element and volatile content. These properties are responsible for the eruptive style of an effusive center and, ultimately, such lithologic characteristics as texture, porosity, permeability, and mineralogy. The eruptive style of highly differentiated magmas differs from the quiet eruptive style of mafic magmas. In most cases, eruption of silicic magmas is one of high-energy. The energy of eruption is due to the viscosity of the magma and the amount of volatiles that exsolve as the magma reaches saturation. Viscosity depends on the major-constituent composition, particularly the alkali metals; as the alkali-metal content increases, the solubility of silica increases. Addition of sodium to a silicic melt lowers the melting temperature, but the viscosity remains relatively high. Addition of water to the melt lowers the viscosity. The high volatile content of alkali-element-rich magmas allows a high eruptive velocity and a high energy of emplacement. Viscosity is also time-dependent in that, as volatiles in the magma exsolve at saturation, bubble growth in the upper portions of the magma chamber lowers the viscosity of the magma. Thus the first eruptive event is highly fluidized. Sparks (1978) showed that in viscous magmas, an average rhyolite for example, both bubble growth and coalescence are retarded by viscosity. At saturation, bubbles grow, coalesce,

migrate to the surface, and begin to accumulate as a froth. This accumulation represents an increase in the internal pressure of the volatiles, and as the pressure increases and surpasses the lithostatic pressure, eruption proceeds. The disruption front (interface of the magma and froth) moves downward in the magma chamber. The froth on the upper surface freezes and is often seen as pumice fragments in initial flows.

Thus, eruption of magmas is a result of an overall release of gaseous constituents in the upper region of the magma chamber. This release is explosive. If, however, the major part of the magma chamber is resident below the disruptive layer, then most of the effusives from this source will be of much higher viscosity and lower volatile content and tend toward lava flows or injection dikes rather than ignimbrites or pyroclastic falls.

TECTONIC CONTROL OF URANIFEROUS-MAGMA GENERATION

To more completely understand the timing and spatial associations of alkaline-magma evolution and eruptive style, one must consider the tectonic environment, its ability to persist through time, and its role in the evolution of the magmas. The following discussion of the tectonic setting of the Blue Ribbon lineament and the Pioche mineral belt is intended to demonstrate that prediction of uranium mineralization within a given volcanic environment is not merely a function of various characteristics that can be observed in an outcrop or even within a single volcanic field; to a large extent predictions of uranium mineralization may be based upon presence of much larger-scale features. Recognition of large-scale features has been greatly assisted by high-altitude photography and satellite imagery.

East-trending mineral belts are recognized throughout the Great Basin, a taphrogenic east of the Sierra Nevada batholith. These east-trending belts are described as lineaments; they may owe their existence to large, east-trending faults, associated with Basin and Range rifting, that may be as old as early Tertiary. The Blue Ribbon lineament, an east-trending structural zone described by Rowley and others (1978), is one such zone within the southern Pioche mineral belt of southwestern Utah and eastern Nevada. These authors concluded that the Blue Ribbon lineament is a fault zone; it is identified by alignment and coincidence of topographic features, major high-angle faults, and aeromagnetic contours. The lineament dies out eastward, toward the Wasatch front.

Stewart and others (1977) suggested that these east-trending zones are due to east-trending warps in subducting mantle plates. Rowley and others (1978) suggest that the lineament may be the surface expression of a major, east-trending, intracontinental transform fault.

Regardless of the mechanism of its generation, large volumes of volcanic rocks were erupted along the Blue Ribbon lineament within the Pioche mineral belt. The Pioche mineral belt contains some of the richest metal deposits in the Great Basin. Other such lineaments have been inferred for many parts of the Great Basin. (For an excellent review, see Rowley and others, 1978.) All have several features in common, among which are:

- 1) surface expression of east-trending, high-angle faults,
- 2) aeromagnetic "ridges",
- 3) alignment of intrusive and effusive systems,
- 4) often markedly alkaline volcanism, and
- 5) parallelism with worldwide patterns (Moore, 1973).

Work of Rowley and others (1978) points to the control of alkaline volcanism by mechanisms which may be related to global tectonics. Volcanic centers containing anomalous uranium are often associated with deep-seated structural elements. They are also characterized by anomalous concentrations of other economic commodities, such as precious metals, base metals, Be, W, Li, Mo, Hg, and fluorite. The Pioche mineral belt may have had locally persistent igneous activity, as seen in the volume and length of activity documented in the Marysvale volcanic pile (10 m.y. from the first eruptions of the Bullion Canyon volcanics to the last eruptions in the western source area). Lipman and others (1978) demonstrated that early, intermediate-composition lavas were erupted in the San Juan volcanic field about 30-35 m.y. ago, and that the eastern basaltic and rhyolitic eruptions ceased about 5 m.y. ago.

Persistence of volcanic eruptions suggests that the magma source was large and remained relatively undisturbed throughout the eruption history. Migration to the surface of a large magma body could be facilitated by rifting. Lipman and others (1978) and Cunningham and Steven (1978) suggested that the San Juan volcanic pile and the Marysvale volcanic pile are associated with large batholiths at depth. Lipman and others (1978) suggested that differences in magma composition and eruptive style between calderas within a single caldera system are due to differences in stage of differentiation within different cupolas supplying magma to the various eruptive centers. Duration of volcanic activity and volume of effusives are determined by the size and volatile content of the derivation magmas within the cupolas involved.

In addition to lineaments that cut across the Basin and Range, other tectonic features seem to control the location of large, mineralized volcanic piles. Three volcanic centers known for their well-preserved volcanic history and pervasive mineralization are the San Juan volcanic field, the Marysvale volcanic field, and the McDermitt caldera. These volcanic piles are products of persistent magmatic activity that occurred along margins of major tectonic features. The Marysvale volcanic field and the McDermitt caldera lie along the margin of the Great Basin subprovince of the Basin and Range province. Marysvale is on the easternmost margin, just west of the Wasatch front, marking the transition between the Colorado Plateau and the Basin and Range. The McDermitt caldera is on the northern margin of the Basin and Range and close to the southern edge of the Snake River downwarp. The San Juan volcanic field is on the northeastern edge of the Colorado Plateau and lies within the Rio Grande rift. All these volcanic centers lie in a transition zone between a more-stable tectonic feature and a taphrogene. Development of the taphrogene may be contemporaneous with the volcanism.

Areas around the taphrogene may be zones of deep-seated deformation, including high-angle faulting. Structural disturbances of this style would be suitable localities for migration and emplacement of large magmatic bodies. Such bodies could supply large amounts of volcanic material through time and, with time, they could become highly differentiated. Derivative magmas may be distributed peripherally around the larger, batholith-sized magma chamber by cupolas.

MODEL OF CALDERA DEVELOPMENT AND MINERALIZATION

Many different events may take place after emplacement of the large body of magma. One obvious possibility is the emplacement of intrusives with no surface venting. (Behavior of uranium in an intrusive environment is treated by Mathews elsewhere in this volume.) Many eruptive styles may occur. A comprehensive treatment of eruptive characteristics of silicic and subsilicic volcanogenic systems is given by Smith and Bailey (1968), although not all of Smith and Bailey's stages of evolution must occur in a given system. The evolution of the magma and its attendant structural deformation may be halted at any stage of development, thus determining the environments most favorable to uranium deposition. However, any system, regardless of the stage at which it is aborted, has particular structural, lithological, and mineralization characteristics that may be predicted from a generalized model of the evolution of a volcanogenic system.

To understand the causative interplay of magma evolution, its volatile and major-constituent content, and the tectonophysical setting, uranium migration and concentration will be discussed through a stepwise description of the behaviour of uranium in the magmatic and posteruptive history of a silicic to subsilicic, caldera-forming eruption, using Smith and Bailey's model of evolution.

Smith and Bailey recognized seven distinct evolutionary stages of caldera evolution and resurgence. These are:

- 1) regional tumescence and generation of ring fractures,
- 2) caldera-forming eruptions,
- 3) caldera collapse,
- 4) preresurgence volcanism and sedimentation,
- 5) resurgent doming, intrusion, and effusion,
- 6) major-ring-fracture volcanism, and
- 7) terminal solfatara and hot-spring activity.

Each of these stages is related ultimately to the size and stage of evolution of the magma source(s). It is likely that through the influence of the tectonic setting or magma composition a given magma source will not complete the idealized evolutionary model of caldera formation and resurgence. For example, the magma chamber may be disturbed and drained such that there is only one caldera-forming eruption. A continuum of eruptive styles exists, depending on many factors. But the most important factors are tectonic setting and magma composition and size of the magma chamber. Caldera evolution among the Basin and Range volcanic centers and the volcanic centers that lie within rift systems may appear to be very different. Also, there are apparent differences in eruptive styles among individual calderas if individual rift systems are compared. The Trans-Pecos rift system contains some calderas that have undergone the entire sequence of caldera evolution proposed by Smith and Bailey, whereas other calderas of this region have not undergone resurgence. The Trans-Pecos rift system has an abundance of silica-undersaturated rocks, and with some volcanic centers that had highly silicic magma sources. The San Juan volcanic field, lying within the Rio Grande rift system, has relatively few silica-undersaturated rocks; resurgent doming is prevalent. The Oslo rift system contains abundant silica-undersaturated rocks; resurgence in cauldrons is rare. Oftedahl (1978) suggests that the intermediate-composition magmas

are responsible for the notable lack of resurgence. The less-viscous intermediate magmas stopped their way up through the subsided cauldron block rather than doming the block, as a more viscous, silicic magma would do. Composition of the magma affects the eruptive style and the probability of uranium concentration, but the size of the caldera and the span of time in its evolution depend on the size of the magma chamber feeding the system. However, size of the caldera is not necessarily related to favorability of the system. The ultimate factors controlling favorability are the stage of differentiation and the amount of volatiles resident in the system at the time of eruption.

Feeder stocks for long-lived caldera complexes may be cupolas related to a central batholith. For this reason, uranium occurrences in one part of a volcanic field increase the likelihood of uranium deposition for the entire system. Cunningham and Steven (1978) related the contemporaneous rhyolitic eruptions of the Red Hills Caldera and rhyolitic eruptions from a western source area to a large, elongated magma chamber with two small cupolas forming distinct eruptive centers. Flows from both centers were highly silicic and gas-charged. Rhyolite dikes originating from the Red Hills caldera are responsible for uranium mineralization in the Bullion Monarch area (see example p. 198).

Lipman and others (1978) showed that a gravity anomaly about 50 by 100 km in the San Juan volcanic field is probably caused by a subvolcanic batholith. They explain the transition in eruptive style from early calc-alkalic eruptions to a later, bimodal, rhyolitic silicic-basaltic suite as a result of the batholith intruding to a shallower level in the crust. Transitions from silicic to mafic composition within are explained by tapping the chamber from the top down, draining the upper, more-silicic fractions first. Differences in the composition of effusives and the eruptive style of small calderas are due to differences in composition and size of feeder magma chambers. Further compositional variations may be caused by tapping the magma(s) at different levels.

Bearing in mind the obvious deviations from an idealized model of caldera evolution, the following discussion is based on the concept of structural evolution and rock formation and their relationship to uranium mineralization. Migration of volatiles and the distribution of uranium is related to fluid mechanics. Through observable effects of petrogenesis and their relation to magma evolution and emplacement one can predict the behavior of uranium during the effusive and intrusive events and the post-crystallization phases of rock formation. Each stage of Smith and Bailey's model of caldera evolution is discussed below with regard to deposition of uranium in each environment.

Regional Tumescence and Ring-Fracture Development

The first stage of caldera development is regional tumescence accompanying migration of the magma into the near-surface environment. Ring fracturing occurs when intrusive pressure overcomes the tensile strength of the overlying rocks. As ring fractures develop, magma intrudes the lower-pressure environment of the newly fractured rocks.

Uranium in the magma is in the U^{+6} state and is progressively concentrated in the liquid as the magma undergoes liquidus crystallization. If the magma is left undisturbed for a time, most of the uranium will be concentrated in the

relatively silicic residual magma. However, a study of various volcanic piles in which anomalous uranium concentrations occur has shown that most early eruptions tend to be of intermediate compositions (Cunningham and Steven, 1978; Lipman and others, 1978; Greene, 1976). Intermediate compositions suggest that the magmas were not highly differentiated before fracturing became extensive enough for eruptions to occur.

Intrusive bodies frozen at this stage contain uranium in major-constituent minerals; in discrete, finely disseminated uranium minerals; and in intergranular spaces and fluid inclusions. Hydrothermal activity may occur as the intrusive invades the country rocks and drives water away from the invaded zone. This water may be caught in convective cells, which may remain active throughout the thermal life of the pluton. Mineralization of the country rock may take place and may vary from uranosilicates to major pitchblende mineralization caused by escape of uranium-rich volatiles into environments of lower temperature and pressure (TP).

Caldera-Forming Eruptions

The second stage of caldera evolution is marked by the issuance of voluminous pyroclastic debris. This eruption stage is the first major energy expenditure during caldera development. Eruptions take place through the ring fractures formed during the stage of regional tumescence.

The mechanism for eruption of ash falls and flows is that described above; with the supersaturation of volatiles, the upper portion of the magma chamber reaches a pressure higher than the lithostatic-hydrostatic pressure, resulting in a violent disruption of the upper magma surface (Sparks, 1978). The upper surface becomes a frothing, fluidized mass and rushes toward lower-TP environments (in this case the atmosphere) in the form of an eruptive column.

Sparks and Wilson (1976) developed a quantitative model that describes the behavior of the eruptive column. In general, two processes are at work as eruption ensues:

- 1) Initially, the lower part of the eruptive column acts as a high-velocity gas jet which decelerates rapidly as it mixes with the surrounding air. If the eruption has sufficient energy, eruptive gases will continue to heat the surrounding air and, through convection, a large Plinian column develops.

- 2) If the density is not reduced sufficiently, the column collapses and the host material flows away from the volcano as a density current. It is postulated that, as the material flows, the trapped, gas-rich pumice will be reduced to finer material and cause fluidization of the lower portions of the ash flow, perpetuating the ability of the pyroclastic material to flow. During this process fine material and gas continue to escape.

It is likely that most eruptions which are preserved as ash flows were accompanied by co-ignimbritic ash falls derived from the Plinian column. The ash fall may form an apron about the margins of the ash flow and may produce thin, distinctive layers of ash-fall material interbedded with ash flows. The realization that ash flows are accompanied by air-fall tuffs may solve some

of the discrepancies between caldera volume and calculated volume of ash flows. The combined volume of ash falls and ash flows more closely approximates true eruptive volume (Sparks and Walker, 1978).

During this stage of caldera evolution at least three vehicles for transportation of uranium out of the magmatic environment are active:

1) Gases erupted during the collapse of the column and the formation of the ash flow may be enriched in uranium-bearing volatiles, such as UF_6 .

2) Vitric material that is part of the ash flow also may have constituent uranium compounds. Rosholt and others (1971) postulated that UF_6 is one of the volatiles that escapes upon devitrification and during cooling and rupture of gas vesicles.

3) Uranium may also be transported in solution as UO_2^{+2} . Uranium concentration and deposition is dependent upon either the dissociation of UF_6 and reduction of U^{+6} to the U^{+4} state, or simply the reduction of UO_2^{+2} to the stable UO_2 state.

Reduction of f_{O_2} (oxygen fugacity) will reduce the uranyl ion. Significant drops in f_{O_2} can be effected by sudden drops in temperature or release of pressure. The release of pressure is particularly effective at and near the temperature at which water is a supercritical fluid, because a small drop in pressure can allow a sudden drop in temperature (Mathews and Pilcher, in prep.).

Fluids are probably not supercritical after they leave the magmatic environment. Reduction due to decrease in temperature and release of pressure can be effective if the UF_6 complex dissociates into U^{+6} and F^{-1} ions. This is easily done, since Ca^{+2} is abundant in most alkaline rock systems and may react with F^{-1} and form fluorite (CaF_2). Calcium ion has a higher chemical activity than does U^{+6} ; consequently fluorine ions will preferentially react with calcium.

Ash-flow cooling units were recognized by Smith (1960) as efficient heat-conserving units. Furthermore, they are isolated chemical cells in which both trapped volatiles and volatiles generated by crystallization (devitrification) can migrate and react in the manner described above. Efficiency of this process is affected by texture and postdepositional deformation. Texture depends on both the composition of the magma and the heat of eruption. Viscosity, porosity, and permeability are all affected by heat of eruption and nearness to source. Viscosity is important in that it is the principal control on migration and accumulation of gases throughout the unit. Variations in viscosity and the temperature of the erupted material are reflected in the rock by differing degrees of welding and attendant flow foliation. Welding and crystal and lithic content affect porosity and permeability throughout the unit. In general, crystal and lithic contents are directly proportional to porosity and permeability.

Rate of migration of the gases is important. Rapid migration through a unit does not allow time for accumulation of uranium-rich volatiles; concentration of uranium is negligible. Abundant tumuli or fumaroles on the upper surface of an ash-flow sheet are an indication of rapid migration. Thick units

having high viscosity are more likely to trap volatiles than are thin, less-viscous units. Subflow topography may affect thickness locally, as in the intracaldera moat or, in the case of extracaldera flows, in valleys or canyons on the flanks of the eruptive center.

Mineralization style in ash-flow cooling units depends on porosity and permeability, which also control the migration of uranium-bearing fluids. If porosity and permeability changes are rapid, reduction in temperature and pressure may be an effective mechanism in reducing hexavalent uranium, and deposition of pitchblende is likely. If porosity and permeability changes are slow, cooling of the silica-saturated, uranium-enriched fluids may result in the precipitation of uranosilicates.

In summary, ash-flow cooling units formed in this stage of caldera evolution act as thermally isolated, chemically active cells; they undergo postdepositional alteration which is contemporaneous with and responsible for uranium migration and concentration.

Caldera Collapse

The next stage of caldera evolution recognized by Smith and Bailey is caldera collapse. Caldera collapse is thought to be a response to the rapid draining of the upper portion of the magma chamber. In an ideal caldera, the caldera floor responds much like a plunger in a cylinder and subsides evenly. However, violent eruptions may fragment the floor and cause uneven subsidence; the caldera floor block may be fragmented into a series of concentrically arranged horsts and grabens, the outer graben forming an intracaldera moat.

Smith and Bailey suggested that most subsidence occurs after the massive eruptions of the second stage. They concluded that some subsidence might occur continually and that small, thin dikes would be intruded from the magma chamber into and around the subsiding block.

Lipman and others (1978) reported that ash-flow-tuff accumulations in the San Juans were at least an order of magnitude thicker up the caldera wall than on the surrounding volcanic plateau. This stratigraphic relation indicates that subsidence is contemporaneous with or earlier than the caldera-forming eruptions.

Caldera collapse is not a uranium-concentrating mechanism in itself. However, because of ponding of ash flows in a subsided block, the ash flows are thickened. Thickening conserves heat and promotes welding in the ash flows, inhibiting the escape of volatiles into the atmosphere and trapping uranium-enriched volatiles in porous and permeable zones. Uraniferous fluids may also invade interbedded sediments and lava flows.

Preresurgence Volcanism and Sedimentation

Surface processes begin to erode the volcanic edifice following caldera collapse. As magmatic pressure is regained, renewed volcanism may occur. This event may either mark the end of the caldera evolution or a period of relative

quiescence before the next stage (resurgent doming) begins as magmatic pressure increases.

Uranium-concentrating mechanisms are much the same as in the first stage; magmatic differentiation progressively concentrates uranium in the residual liquid. If this stage of volcanism is the final stage of evolution of a given caldera, concentration of uranium depends on 1) the extent to which the magma was differentiated at the time of eruption of the ash-flow tuffs during the first stage of evolution, and 2) the size of the magma chamber. If the magma chamber is small the most silicic fraction may have been erupted. Deep tapping of the chamber may cause a more mafic eruption which is less rich in uranium. If the magma chamber is large and highly differentiated, silicic ash-flow eruptions and collapse may be followed by eruption of additional uraniferous silicic magma differentiated from the enriched parent magma. This volcanic event typically comprises small-scale doming, lava flows around the margins of the caldera, and attendant fracture-filling dikes.

The small Red Hills caldera region (1200 m diameter) was the source of the Red Hills Tuff. This caldera did not undergo resurgence; it did have partial collapse and volcanic activity in the form of rhyolite domes and dikes.

Lacustrine sediments which may fill a significant portion of the intracaldera moat may be contemporaneous with the volcanic activity. Lacustrine sediments and coarse alluvial debris derived from slumping caldera walls may be intercalated with numerous ash falls, ash flows, and (or) lava flows.

Facies favorable for uranium deposition which develop during this stage include the sedimentary fill that is interbedded with volcanic flows or that is invaded by volcanic intrusives. These sedimentary facies are favorable because of the likelihood of remobilization and concentration of uranium in the sediments with the addition of heat and attendant hot, uranium-bearing volatiles. Mineralization may be either in form of vein-like pitchblende or haloes of uranosilicates, usually occurring near the contact of rhyolitic intrusives. The volcanic intrusives may also be favorable sites for the deposition of uranium. The typical mode of mineralization is pitchblende deposition along shears and breccia zones within the intrusive body.

Resurgent Doming, Intrusion, and Effusion

Establishment of magmatic pressure may cause renewed doming and reactivation of intrusive and effusive activity. Renewed differentiation and concentration of uranium in the silicic fraction coincides with renewed volcanic activity.

Resurgent doming reactivates faulting and localizes intrusion and effusion. This stage of caldera evolution may be considered as transitional between re-establishment of the differentiation of the magma and the resumption of generation of magmatic pressure.

Many documented resurgent events show that doming has taken place through lakes (Smith and Bailey, 1962). Deformed lacustrine sediments may be silicified by the initial flows and (or) the percolation of magmatic fluids. Favorable environments for uranium deposition are similar to those of previous stages.

Major Ring-Fracture Volcanism

Voluminous volcanic material erupts when magmatic pressure overcomes lithostatic pressure. Eruption at this stage is an important determinant in the likelihood of concentrating uranium within the volcanogenic system. Ring-fracture volcanism usually indicates that renewed differentiation has produced additional silicic fractions and high magmatic pressure. Ash flows from this stage are usually highly gas-charged and may be enriched in uranium. Because magmatic activity is rejuvenated, there is a possibility of remobilizing and recycling uranium through convective hydrothermal systems. It is important to note that uranium may be more concentrated in the silicic melt of this stage than it was in the first ash-flow eruptions.

Favorable environments are much the same as in earlier stages; however, the likelihood of economic uranium deposits is increased due to the more-concentrated uranium-bearing fraction.

Terminal Solfatara and Hot-Spring Activity

Solfatara and hot-spring activity is the final stage of caldera evolution. Smith and Bailey recognized that solfataras, fumaroles, and geothermal activity are present throughout the cycle; they are likely to continue for several tens of thousands of years after the cessation of volcanic events. Smith and Bailey noted that long periods of geothermal activity following volcanic activity may be responsible for the disparity between ore-forming minerals formed at a given temperature and pressure and the alteration of the associated wall rocks at a different temperature and pressure.

They also noted that silicic volcanic centers are more likely to have extensive posteruption hydrothermal alteration than nonsilicic volcanic centers. Both observations are consistent with the concept of high volatile content in the upper magma chamber. Volatiles will continue to accumulate if magmatic pressure never exceeds lithostatic pressure. The volatiles migrate into the surrounding rock and may remobilize uranium. Meteoric water invading the upper portions of the rocks surrounding the subvolcanic intrusive is likely to mix. A convective cell may be formed about the margins of the magma chamber. The likelihood of a well-established geothermal system surrounding a subvolcanic intrusive core, as modeled by Austin (1978), is very high. Mineralization is likely to produce secondary uranium minerals in fractures and porous zones in the surrounding country rock.

In accordance with the TP-release theory proposed earlier, uranium may be oxidized by the downward-migrating meteoric waters and redeposited in the upward-migration portion of convection cells. Zones most likely for uranium deposition are those which are effective heat sinks, such as brecciated zones with large available surface area.

INITIAL-MAGMATIC CLASS (CLASS 510)

GEOLOGIC CHARACTERISTICS

Initial-magmatic occurrences form by liquidus crystallization of uranium and uranium-bearing minerals in late-stage magmatic differentiates. Uranium may exist as discrete uranium minerals, as substitutions in fixed or exchange-cation positions in other minerals, as foreign cations in the major rock-forming minerals, or as a dissolved component of interstitial and intragranular fluids. Occurrences of this class develop prior to volatile saturation of the magma and may be preserved as hypabyssal intrusives or they may be preserved as extrusives which are erupted after volatile saturation of the magma.

Tectonic Setting

In a given comagmatic sequence, intermediate-composition rocks and their associated late-stage differentiates were probably emplaced in or erupted onto stable crust; the silicic-basaltic volcanic suite was erupted during the extensional faulting such as in the Basin and Range Province of the U.S., or the Trans-Pecos rift system. Eruption of calc-alkalic magmas from a deep source (the melted subducted plate) and eruption of silicic-basaltic, bimodal suites as evolution of the taphrogene progresses are contemporaneous with the upward migration of large magmatic sources (Lipman and others, 1972). Typical sequences exemplifying this process are represented by the San Juan volcanic field in southwestern Colorado (Lipman and others, 1978) and the Marysvale volcanic field in southwestern Utah (Cunningham and Steven, 1978). Both sequences have initial-magmatic uranium occurrences in plutonic and associated volcanic rocks.

Lithology

Intrusives associated with volcanic centers are typically leucocratic, late-stage differentiates of a comagmatic sequence which are enriched in alkali metals. Granites and quartz monzonites are the most common plutonic rocks containing occurrences of this type; however, syenites and feldspathoidal syenites may also contain initial-magmatic occurrences.

Effusives are silicic or subsilicic, late-stage differentiates and often occur with cogenetic plutons, as described above. Typical effusives are: rhyolites, rhyodacites, alkali trachytes, trachytes, latites or their subsilicic equivalents, phonolites, tephritic phonolites, and phonolitic tephrites.

Texture

Textures of uraniferous volcanogenic rocks are highly variable. In general, subvolcanic intrusives are porphyritic, often with quartz and plagioclase phenocrysts. The granites may have graphic intergrowths of quartz and orthoclase which suggests crystallization at or about the time of volatile (H₂O) saturation. Textures of effusive rocks are much more complex and variable.

Ash-flow tuffs may be crystal-rich to crystal-poor and may have a well-developed basal vitrophyre with abundant lithophysae. (Abundant lithophysae are characteristic of ash flows with a high volatile content generated by high-temperature devitrification.) Ash flows generally have a high glass-shard content. Flow-age and welding may be so strong locally that the rock closely resembles a lava flow. Crystalline patches may show granophyric or spherulitic devitrification textures. Lava flows and silicic dikes may show highly contorted foliation (typical of sodium-rich, high-silica rocks) and abundant gas cavities. Vapor-phase crystallization within lithophysae and other pore spaces and devitrification textures are common.

Mineralogy

Uraniferous plutons consist of potash feldspar, sodic plagioclase, and quartz (or feldspathoids). Ferromagnesian minerals include biotite, sodic pyroxenes, and (or) sodic amphiboles. Accessory minerals are magnetite, apatite, sphene, zircon, rutile (often in quartz), and (or) ilmenite. Uranium-bearing zircon and (or) xenotime may be euhedral to subhedral, whereas uraninite, coffinite, uranothorite, and uranium-bearing minerals often occur poikilitically enclosed by major rock-forming minerals.

Uraniferous effusives commonly have a high glass content and contain phenocrysts of sanidine, aegirine, arfvedsonite, sodic plagioclase (albite and oligoclase), and, occasionally, magnetite, biotite, and zircon. Most of the uranium is in the glassy fraction of the rock, although a significant portion may also be present in uranium-rich accessory minerals (Dostal and Capredi, 1975).

Chemistry

Rocks hosting initial-magmatic occurrences are typically subaluminous to peralkaline; they have a high weight percentage of silica (> 72 wt. percent) and often a high Na₂O content (comenditic or pantelleritic). Alkali rhyolites may be derived from a calc-alkalic series or an alkalic series; anomalous uranium contents may occur in both. The volatile content of these magmas is high; H₂O and F are extremely high in some, as indicated by abundant lithophysae and spherulites. Uranium content is high, averaging 10 ppm in rhyolites and 50 ppm in some trachyphonolites. Th/U ratios are greater than unity (generally 2-6; higher ratios are typical of subsilicic late-stage differentiates).

Alteration

Alteration of plutonic rocks of this class is much the same as that described for deposits of the orthomagmatic class (Mathews, this volume). Albitization occurs during and after saturation by volatiles. Hydrothermal alteration may be more extensive in the initial-magmatic class than in deposits of the orthomagmatic class, due to venting and association with the long-lived geothermal circulation associated with caldera development. Contact metasomatism and metamorphism are likely, because invasion of high-silica, alkali-rich fluids is extensive in this environment.

Geometry

Geometry of these occurrences is highly variable and depends on the size and shape of the eruptive center. Geometry of ash-flow sheets depends on the volume of the eruption and the topography of the underlying terrain. No generalizations hold.

Rock Associations

Rock associations run the whole gamut of possible rock types. Typical associations are characteristic of continental volcanic centers. Rocks are of crustal origin, comprising intermediate volcanic suites and bimodal basalt-rhyolite suites. Volcaniclastic sedimentary sequences may also be closely associated with initial-magmatic occurrences.

Resource Potential

No uranium occurrences of the initial-magmatic class are currently being mined. Low concentration and fine dissemination of uranium throughout the rock body make these occurrences submarginal. Escalation of market prices and improvement of mass-leaching techniques might make some initial-magmatic occurrences low-grade deposits.

Although initial-magmatic uranium occurrences are economically submarginal, they may be the sources for economic sedimentary uranium deposits (see Austin and D'Andrea, this volume) and (or) sources of hydrothermal fluids which might mineralize subjacent or superjacent volcanogenic rocks (see hydroallogenic class, p. 206).

Example of Initial-Magmatic Occurrence

In order to emphasize the relation between initial-magmatic occurrences and other volcanogenic occurrences, the example of the initial-magmatic class is combined with the example for the hydroallogenic class.

PNEUMATOGENIC CLASS (CLASS 520)

GEOLOGIC CHARACTERISTICS

Pneumatogenic occurrences of pitchblende form during primary degassing of newly emplaced intrusives or erupted effusives as uranium-enriched volatiles equilibrate with near-surface or surface temperatures and pressures. These volatiles form in the upper portion of the magma chamber as the magma moves closer to the surface and the lithostatic pressure decreases. If the magma erupts as an ash flow, much of the volatile fraction will be trapped and will eventually equilibrate with atmospheric conditions. If equilibration is rapid, the quick loss of heat and pressure can result in deposition of pitchblende

in veins or in brecciated zones along faults, shears, breccia pipes, and (or) stockworks. Slower equilibration can result in deposition of uranosilicates (see hydroauthigenic class).

Tectonic Setting

The tectonic setting of pneumatogenic uranium deposits is much the same as that of the initial-magmatic class. Pneumatogenic occurrences are associated with discrete eruptive or intrusive events in the evolution of a volcanic sequence. Known pneumatogenic occurrences are associated with ash flows formed during the caldera-forming eruptions and with late-stage ring-fracture volcanism. They are also known in ring-fracture intrusions, rhyolite dikes and domes and hypabyssal, subvolcanic intrusives. Pneumatogenic occurrences are related to eruption of the most highly differentiated magmas during caldera evolution.

Lithology

Host rocks for pneumatogenic deposits are likely to be the same as those for occurrences of the initial-magmatic class. Known pneumatogenic occurrences are found in alkali-rich, porphyritic quartz monzonites, porphyritic quartz syenites, granites, and alkali rhyolites.

Texture

Although textures of the host rocks are much the same as those of the initial-magmatic class; there are several particular textures closely associated with pneumatogenic occurrences. Subvolcanic intrusives may be porphyritic and show abundant miarolitic cavities. Extrusives also may be porphyritic; they are commonly glassy, and glomeroporphyritic. Ash-flow tuffs may be crystal-poor, with crystals confined largely to devitrified zones. Granophyric texture, the interpenetration of groundmass alkali feldspar and quartz phenocrysts, indicates rapid and efficient evacuation of volatiles from the rock during high-temperature devitrification. Many times this texture is not found throughout the rock, but occurs only in the glomeroporphyritic zones in thin streaks along fractures or shears. The prevalence of granophyric textures may be so distinct that a glassy rhyolitic dike may appear to grade into a "fine-grained felsite."

Textures associated with vapor-phase alteration may also be present in ash-flow tuffs. Vapor-phase minerals such as quartz, alkali feldspars, and alkali amphiboles occur extensively in lithophysae. Although spherulitic devitrification occurs, spherulitic texture may not be as common as granophyric texture, because volatile escape is too rapid and efficient in host rocks of pneumatogenic occurrences.

Welding in ash-flow tuffs is dense; it may be so dense that the ash flows resemble lava flows. This high degree of welding may be due to high eruptive temperatures, high volatile content, and (or) high alkali-metal contents.

Less-welded tuffs may exhibit a eutaxitic structure. Lava flows and rhyolite domes may show a strong foliation and brecciation of the upper surface, with abundant stretched and contorted gas cavities.

Mineralogy

The mineralogy of the host rock is much the same as those of the initial-magmatic class. However, additional minerals may occur. These minerals are: pitchblende, fluorite (black and [or] purple), magnetite, pyrite, quartz, jordanite, and ilsemanite; oxidized uranium minerals may be present where veins are exposed to surface processes. Sodic amphiboles, either in the groundmass of plutonic or volcanic intrusives or in the vapor-phase zones of ash-flow tuffs, may be abundant.

Uraniferous volcanic intrusives may have high glass contents and contain few phenocrysts, except where high-temperature devitrification has occurred.

Chemistry

Host rocks for pneumatogenic deposits are usually highly silicic (> 70 wt. percent silica) and are essentially the same as in the initial-magmatic class. Rocks containing occurrences of the pneumatogenic class may have a higher volatile content than those of the previous class. They often have higher fluorine and water contents, as shown by abundant fluorite and the ropy and frothy character of some ash-flow cooling units.

Alteration

Alteration about a pneumatogenic occurrence may be extensive. The deposits may occur in heavily brecciated zones and may be surrounded by extensive argillic alteration associated with postdepositional hydrothermal activity. Chlorite, illite, kaolinite, smectite, and sericite are commonly present. Products of secondary biotitization and carbonatization may be found.

Geometry

Pneumatogenic pitchblende may occur in discordant veins as a network of veins, as a stockwork system, or in and along brecciated zones. Veins may occur in subvolcanic intrusives and the invaded country rock. Stockworks may develop in an extremely brecciated zone within and surrounding an intrusive. Brecciated zones that taper with depth to knife-like fractures may appear as breccia-pipes. Shear zones parallel to flow-foliation may contain pitchblende and, therefore, may appear to be concordant with the host rock.

Rock Associations

Known occurrences of this class are restricted to alkalic rhyolite ash-flow tuffs, alkali-rhyolite intrusives, porphyritic quartz monzonite, porphyritic

quartz syenites, and porphyritic granites. These latter rocks are comagmatic with rocks of the related volcanic sequence. They may be associated with basalts that are part of a rhyolite-basalt bimodal suite.

Resource Potential

Occurrences of the pneumatogenic class are likely to be economically recoverable. Pitchblende veins in these occurrences have had as much as 27 percent U_3O_8 . They have been mined relatively easily by both underground and open-pit methods.

DESCRIPTION OF PNEUMATOGENIC DEPOSITS RELATED TO THE RED HILLS CALDERA

The uranium-bearing veins of the Bullion Monarch mine and the Freedom No. 2 mine in the Marysvale, Utah, area are related to rhyolite dikes intruding quartz monzonite and fine-grained granite. Although deposits were discovered independently, later consolidation of workings established that the oxidized uranium vein in the Bullion Monarch mine is related to the veins discovered in the Freedom No. 2 mine. Both mines are in the central mining district, near the eastern volcanic source area. The vein in the Bullion Monarch mine contains weathered fluorite and oxidized uranium minerals. Uranium minerals in the Freedom No. 2 mine are less altered and are restricted to pitchblende in brecciated wall rock and fluorite (Kerr and others, 1957). The following description relates the veins and their mineralogy to the evolution of the Red Hills caldera. Much of the following description is a synopsis of work done by Cunningham and Steven (1977) and Kerr and others (1957).

Tectonic Setting

The Red Hills Caldera is a small caldera (1200 m diameter) in the eastern portion of the Marysvale volcanic pile, along the eastern bank of the Sevier River. The Marysvale volcanic pile lies west of the Wasatch front; it may be in the transitional boundary between the Colorado Plateau and the Basin and Range Province.

History of Effusive Center

The local tectonics and history of the Red Hills Caldera area are governed by the long evolution of the Marysvale volcanic complex, which began with eruption of the Bullion Canyon Volcanics of intermediate composition. Intrusion of the core of the effusive centers followed at about 23 m.y. ago. Beginning 21 m.y. ago, domes, lava flows, and ash flows of alkali rhyolite erupted from the eastern source area of the Mount Belknap Volcanics. A fine-grained granite intruded the eastern source area about 20 m.y. ago; between 19 and 18 m.y. ago, volatile-rich ash flows erupted from the Red Hills caldera, which subsequently subsided. Related rhyolite dikes were emplaced in an older quartz monzonite and fine-grained granite of the central mining district. Final activity in the eastern source area was extrusion of viscous flows and domes between 19 and 18 m.y. ago.

Activity in the western source area was restricted to voluminous eruptions at about 19 m.y. ago and subsequent collapse of the Mount Belknap caldera. Less-voluminous ash flows continued to issue from the Mount Belknap caldera until about 17.4 m.y. ago; somewhat later, rhyolite plugs were emplaced about the margin of the caldera.

Lithology and Mineralogy

Three rock types are involved in the central mining district: quartz monzonite, fine-grained granite, and glassy and felsic rhyolite dikes (petrographic descriptions are from Kerr, 1957).

The bulk of the quartz monzonite in the central mining district is a porphyritic border phase that grades into a nonporphyritic medial phase. It is equigranular, greenish-gray, and medium- to coarse-grained. Major mineral constituents are calcic andesine, orthoclase, quartz, biotite, augite, and minor hornblende. Magnetite, apatite, sphene, zircon, rutile, and ilmenite are accessory minerals, listed in order of decreasing abundance.

The granite in the central mining district varies in color from brown to gray. The brown coloration noted in Marysville Canyon is due to oxidation of pyrite; it is uniformly gray in the subsurface workings of the Bullion Monarch mine. Quartz and orthoclase compose the bulk of the groundmass, with phenocrysts of feldspar and quartz. Some oligoclase is present; biotite is rare. Chlorite, apatite, fluorite, and pyrite are present.

Gray rhyolite dikes intrude brecciated zones in the porphyritic quartz monzonite and fine-grained granite. Although the rhyolite is largely glassy, there are a few microlites and sanidine crystals aligned along flow foliation. The glassy dike may be devitrified; it grades into "felsite" dikes locally. The felsite dikes are white to buff and are commonly limonite-stained. They are microcrystalline to porphyritic and contain quartz and potassium feldspar, along with minor amounts of oligoclase and biotite.

Textures

The only textures noted by Kerr (1957) are the porphyritic and myrmekitic textures in the quartz monzonite. These textures suggest that the pluton cooled at its volatile-saturation point. The "felsite" dikes were found to exhibit micrographic intergrowths of quartz and potash feldspar. Since these dikes grade into a glassy portion, one wonders if the felsite portion represents a completely devitrified zone that has undergone evacuation of most of its volatiles. The glassy portions of the dikes exhibit spherulitic and granophyric devitrification textures.

Mineralogy of the Deposits

Uranium mineralogy at the Bullion Monarch mine is limited to secondary uranium minerals and abundant weathered fluorite. The secondary minerals reported by Kerr (1977) are autunite, uranophane, torbernite, and schroekingerite.

Veins in the Freedom No. 2 mine contain pitchblende and abundant fluorite (which increases with depth), along with some pyrite, quartz, magnetite, sericite, clay minerals, and alunite. Also present are the molybdenum minerals jordisite and ilsemanite. Secondary uranium minerals are also present. These are: uranopilite, uranophane, β -uranophane, schroeckingerite, autunite, meta-autunite, meta-torbernite, and phosphuranylite.

Chemistry

Pertinent data on rock chemistry are not available. The important chemistry to consider is that of the rhyolite dike which intrudes the wall rock in the Freedom No. 2 and Bullion Monarch mines. From description of the mineralogy, it is apparent that the rock is alkali-rich and highly silicic. Because it is related to the red rhyolite, it was also one of the last eruptive events of the Marysville volcanic pile and is presumed to have been from a highly differentiated magma. Such a magma would be favorable for enrichment in uranium.

Alteration

The following discussion of alteration is a combination of the description of alteration at the Freedom No. 2 mine and the Bullion Monarch mine given by Kerr (1957).

Pitchblende ore in the Freedom No. 2 mine occurs in an argillic sheath extending from the rhyolite dike intrusion through the brecciated quartz monzonite and granite. Most of the pitchblende ore occurs in the rhyolite dikes or the invaded wall rock, and not in the highly altered and brecciated core of the vein. The alteration halo widens in areas of concentrated pitchblende deposition. The alteration minerals nearest the mined portion of the pitchblende vein are sericite in the lower mine levels and kaolinite, dickite, and halloysite in the upper mine levels. The next zone outward consists of smectite and illite extending the length of the vein. The last zone of argillic alteration is a smectite-allophane zone, present only in the upper portions. The outermost alteration zone sheathing the vein consists of chlorite and carbonate.

Devitrified portions of the rhyolite dike in the Bullion Monarch mine have undergone extensive alteration to clay. The dike remains glassy at its contact with the quartz monzonite wall rock. Devitrification has occurred next to the glassy portion; the center of the dike has first undergone devitrification, then incipient silicification.

Geometry

Geometries of the veins in the Bullion Monarch and Freedom No. 2 mines are generally the same, although along the length of the adit connecting the two mines are rhyolite dike and, consequently, the veins pinch and swell. The vein tapers to a couple of feet in the Freedom No. 2 mine above the rhyolite dike and expands to nearly twice that width in its upper extent in the quartz monzonite. The interior breccia zone reaches into the rhyolite flow above the quartz monzonite, but does not extend through the flow to the surface.

Rock Associations

The rocks described above are the only rocks found associated with the vein in the mines.

Classification and Resource Potential

The Bullion Monarch-Freedom No. 2 deposit belongs to the pneumatogenic class. Its characteristic mineral assemblage and geometry suggest that the fluids were seeking a low T and P regime, such as that which might be afforded by a breccia zone. The uranium-hexafluoride transfer mechanism proposed in the classification of volcanogenic deposits by Pilcher (1978) may be applicable to this occurrence, in that there is abundant fluorite, which increases with depth.

These mines were economic producers of uranium in the early and mid-fifties. Higher ore prices have resulted in renewed exploration in the central mining district.

HYDROAUTHIGENIC CLASS (CLASS 530)

GEOLOGIC CHARACTERISTICS

Hydroauthigenic deposits form during high-temperature devitrification. They are known mainly from ash-flow tuffs of Sierra Peña Blanca and the Trans-Pecos volcanic field. These deposits are characterized by uranosilicates in lithophysal cavities, altered pumice fragments, corroded meta-stable phenocrysts, and small fractures. They form from uranium-enriched volatiles which evolve during high-temperature devitrification and escape into lower-TP environments.

Tectonic Setting

The tectonic setting is the same as in previously described classes. However, hydroauthigenic occurrences are less influenced by intracaldera tectonics and associated geochemical processes; they are most likely to occur in outflow facies of ash-flow tuffs. Intracaldera tuffs are likely to be much thicker and subject to longer periods of heating and circulation of hydrothermal solutions.

Lithology

All known occurrences of this class are associated with soda-rich alkali rhyolite (peralkaline) ash-flow sheets. The ash-flow sheets are crystal-poor and may have a greenish-black basal vitrophyre.

Texture

Although textures are much the same as described before, spherulitic devitrification (cristobalite and alkali feldspars) and an abundance of large lithophysae predominate. The upper zones of the ash-flow units may exhibit eutaxitic texture. The ash-flow cooling units may show striking flow patterns and abundant tumuli. Tumuli are less abundant in the zone of mineralization. Well-developed and persistent flow banding and the occurrence of tumuli both suggest that there was a high volatile content in the ash flow. Compactional foliation is well developed.

Vapor-phase alteration is very extensive. Shards are completely obliterated. Porous zones contain vapor-phase tridymite and alkali feldspars. Vapor-phase sodic amphiboles are often present in rocks that are highly enriched in sodium.

Mineralogy

Uranosilicates occur in lithophysae and in other porous and permeable zones. Lithophysae may also be partially filled with magnetite, hematite, and other metallic minerals. Metallic minerals are preceded by several stages of quartz growth; the quartz varies from high-temperature forms to microcrystalline and amorphous forms. Traces of clinopyroxenes have been noted.

Chemistry

All known host rocks of this class display pronounced peralkaline affinities with high silica contents (> 72 percent). These rocks are usually crystal-poor. Where crystals are present, they are usually alkali feldspar and are indicative of high Na₂O and K₂O contents.

Alteration

Modification of the rock is predominantly by vapor-phase alteration, as described above; however, alteration associated with uranium mineralization is commonly a pervasive yellow-brown coloration due to invasion of iron-rich fluids into the zones surrounding lithophysae. Many of the alkali-feldspar phenocrysts undergo argillic alteration. Late-stage calcite infilling of lithophysae is common; it is probably not related to uranium mineralization.

Geometry

Geometry of hydroauthigenic occurrences is controlled by the size and distribution of the ash-flow tuffs and by lateral changes in porosity and permeability. No generalizations can be made about the geometry of these occurrences at this time.

Rock Associations

Rock associations are not diagnostic. Host rocks may be emplaced early in the eruptive history of the sequence and may be underlain by totally unrelated rock types. Conversely, they may be intercalated with cogenetic volcanogenic rocks.

Resource Potential

Some hydroauthigenic deposits are economically recoverable resources. These deposits may also be the source of uranium in hydroallogenic deposits (see discussion, p. 206).

EXAMPLE OF A HYDROAUTHIGENIC DEPOSIT: THE BUCKSHOT IGNIMBRITE

Tectonic Setting

The Buckshot Ignimbrite crops out in the Trans-Pecos volcanic field of west Texas. The volcanic field lies within the Trans-Pecos magmatic province of west Texas and New Mexico. Barker (1977) found that the alkalic rocks of the province are analogous to rocks in the Kenya Rift, East Africa. This, together with similarities in tectonic style, led Barker to propose that the Trans-Pecos magmatic province is an evolved remnant of a rift system.

The main fault trend in the area is north-northwest, subparallel to Basin and Range structures. King (1965) and Twiss (1970) have proposed that some of these faults are reactivated Precambrian and Paleozoic structures. Local structural patterns are due to intrusive and volcanic events, with attendant smaller-scale deformation.

Eruptive History

The source area of the Buckshot Ignimbrite is not known. The Chinati caldera complex to the east has been proposed as the source. However, Anderson (1975), using ramp structures, determined that flow direction was from the southwest. The only known part of the eruptive history of the Buckshot is the cooling unit and a coignimbritic ash fall that overlies it in the southern part of its outcrop. The following descriptions are taken from Anderson's thesis (1975); the reader is referred to this report for an excellent and more-detailed description.

Lithology

The Buckshot is a simple cooling unit erupted during the late Eocene or early Oligocene. It is a comenditic ash-flow tuff. The unit shows distinct zonation, with a zone of dense welding in the lower portion, a middle, partially welded zone, and an upper zone of no welding. A basal vitrophyre is present in some areas.

The crystal- and lithic-fragment content is variable. The unit contains colorless phenocrysts of alkali feldspar, glass shards, fragments of intermediate volcanic rock, and various secondary minerals in cavities. Lithophysae are abundant and conspicuous and look like buckshot (hence the name). The partially welded zone has undergone extensive vapor-phase crystallization.

Texture

Textural characteristics are related to the degree of welding, vapor-phase crystallization, and devitrification.

The welded zones show distinct flow features. Eutaxitic structures are common in some parts of the densely welded tuff; some relict shard structures are present. High-temperature devitrification textures are mostly spherulitic. The size of the spherulites is inversely related to rate of cooling; consequently, smaller spherulites are found lower in the units.

During spherulitic devitrification, released gases produced lithophysae. A gradation from small, gash-like pockets to well-rounded lithophysae may be seen in the densely welded zone of the cooling unit near the Mammoth uranium prospect in Presidio County, Texas.

Mineralogy

The only descriptive mineralogy discussed here is from observations made from examination of the Mammoth Prospect by Anderson (1975). Uranium mineralization occurs in densely and partially welded zones of the Buckshot Ignimbrite. The Buckshot Ignimbrite at the Mammoth prospect has a densely welded basal vitrophyre approximately 1 m thick. This zone contains 2 to 3 percent crystals and 2 percent volcanic-rock fragments, set in a glassy groundmass. Overlying the basal vitrophyre is a 0.5-m zone of pink spherulites (averaging 2 to 3 mm in diameter), set in a brown, densely welded matrix. Vesicles up to 10 cm in diameter are present in this zone. Overlying the spherulitic zone is a 2-m-thick, reddish-brown, densely welded tuff containing abundant lithophysal gashes near the top. Densely welded tuff 1.5 m thick forms the upper portion of the unit and is characterized by numerous gashes and well-formed lithophysae. The matrix in this zone consists of sanidine and quartz. "Uranophane occurs in the Buckshot as acicular crystals filling lithophysal cavities, pore space filling in volcanic rock fragments, and in flattened vesicles in pumice lapilli within the zones of partial welding" (Anderson, 1975, p. 106). Ore grade in this deposit is 0.27 percent U_3O_8 .

Chemistry

Anderson (1975), on the basis of whole-rock analyses, classified the Buckshot as a peralkaline rock, specifically a comendite. He noted that four of eight analyses showed the rock to be peralkaline, and the remaining four showed it to be nearly peralkaline. The variation in the analyses may be due to post-eruptive devitrification and volatile evacuation. Several lines of evidence suggest that the ash flow was volatile-rich and that posteruptive chemical

processes were active:

1. Tumuli (blister cones) on the upper surface of the ash flow suggest escape of large volumes of volatiles.
2. Pervasive vapor-phase crystallization of tridymite is evidence of migration of silica-rich volatiles through the cooling unit.
3. Pervasive lithophysae are evidence of large volumes of volatiles released during high-temperature devitrification.
4. Well-formed flow folds are present, which suggests that the unit had enough volatile content to remain plastic during emplacement.

Alteration

The matrix surrounding the mineralized lithophysae at the Mammoth prospect is "altered to a yellow to yellow-brown crumbly rock. This alteration persists laterally to the west about a hundred meters..." (Anderson, 1975, p. 195). The altered material was found to be a mixture of quartz and sanidine.

Geometry

This deposit is tabular and parallel to the densely welded zone. Cores from the Buckshot imply that the mineralization may be in a thickened portion of the unit. However, data are poor, since only 2 of 20 cores drilled are preserved; the core samples are ambiguous regarding how much of it is Buckshot.

Rock Associations

The Buckshot is in contact with the Gill Breccia (a series of flow breccias with a maximum thickness of 90 m), the Colmena Tuff (interbedded sandstone, conglomerate, and mudstone, with fragments of carbonate rock; maximum thickness 135 m), and the Chambers Tuff (a volcanogenic sedimentary wedge; maximum thickness 256 m).

Classification and Resource Potential

The Mammoth Prospect is a hydroauthigenic occurrence, formed by the internal entrapment of released uranium-bearing volatiles and subsequent precipitation of uranophane.

The Mammoth Prospect was economically submarginal in the mid-50s; renewed interest in the prospect occurred in the early 70s. The extent of the mineralized zone must be the determining factor, since a grade of 0.27 percent U_3O_8 could be economic.

HYDROALLOGENIC CLASS (CLASS 540)

GEOLOGIC CHARACTERISTICS

Hydroallogenic occurrences form from uranium-enriched fluids released from volcanic effusives and injected into subjacent volcanogenic and country rocks, and (or) by remobilization of syngenetic uranium by ground water. Mineralization is characterized by epigenetic concentrations of uranosilicates, uraniferous microcrystalline silica, and uraniferous amorphous silica in porous and permeable host-rock environments within the volcanogenic system.

Tectonic Setting

The tectonic setting is the same as for previously discussed classes. Both intracaldera and extracaldera lithologies may be favorable for these occurrences.

Lithology

Lithologies are highly variable; however, porosity and permeability are major determining parameters. Intracaldera and extracaldera sediments which are directly associated with peralkaline ash flows, lava flows, or intrusives are the most favorable host rocks for uranium minerals.

Texture

Textures are determined by the depositional environment of the host rock. Secondary alteration, such as diagenetic growth of zeolites, calcite, and silica, may alter the textures significantly. New and thorough work pertaining to textures and diagenesis of these rocks is under way (Walton and Henry, in prep.).

Mineralogy

Uranium mineralogy is variable. The most common uranium and uranium-bearing minerals are uraniferous silica (opal, chert), uranosilicates, and (or) other epigenetic minerals, such as autunite, torbernite, soddyite, and carnotite.

Chemistry

Although remobilization of silica and alkalis may be important, little information regarding the lower-temperature chemistry of these deposits is available. Many of these data will be supplied by ongoing research, being done by subcontractors, on the diagenesis of volcanogenic rocks.

Alteration

Host rocks for hydroallogenic deposits are usually highly silicified. Silicification is accompanied by widespread zeolitization and calcification.

Geometry

Hydroallogenic deposits occur in two major forms. The first form is an aureole of uranium minerals around the contact of the host rock with the intrusive or effusive body from which the mineralizing fluids originate. The second is a tabular or lenticular unit which follows bedding and permeable zones within the sedimentary host rocks.

Rock Associations

Rock associations are not particularly diagnostic. Occurrences of this class are restricted to rocks that are a part of the associated volcanogenic system. Most reported deposits are associated with fluvial and lacustrine rocks and interbedded effusives within the intracaldera moat, or with the sedimentary apron and outflow effusives surrounding the volcanic edifice.

Resource Potential

These occurrences are highly variable in size and concentration. They range from radioactive opal or chert to concentrations of epigenetic minerals which may contain as much as 1-2 percent U_3O_8 .

EXAMPLE OF INITIAL-MAGMATIC AND HYDROALLOGENIC OCCURRENCE: THE HARTFORD HILL RHYOLITE AND THE INFERRED CALDERA

Uranium occurrences in the Hartford Hill Rhyolite and the Truckee Formation were examined and an evaluation of favorability was made by Cupp and others (1977). A model of the caldera development, collapse, and resurgence was applied, and convincing evidence for the existence of a caldera was given in their report. The following discussion of the Hartford Hill Rhyolite and the Truckee Formation relies heavily on their description and concept of caldera evolution. This discussion is an attempt to relate the concept of caldera evolution to the formation of uranium-enriched source rocks (initial-magmatic occurrence) and to the development of environments favorable for epigenetic uranium mineralization within the Truckee Formation (hydroallogenic occurrences).

Eruptive History of the Hartford Hill Rhyolite

The following history is taken directly from Cupp and others (1977); it uses Smith and Bailey's (1968) model for caldera development, resurgence, and collapse to explain field relations of the Hartford Hill Rhyolite and the Truckee Formation.

Stage I: Regional tumescence and propagation of ring fractures produced initial ash-flow eruptions, the most basic of the sequence (cooling units 1a and 1b). These may have been the caldera-forming eruptions.

Stage II: Major ash-flow eruptions followed a period of erosion and produced cooling units 2 and 3 and the Rainbow Canyon Member. All three units are silicic, which indicates tapping of the magma chamber after considerable differentiation.

Stage III: In response to the eruption of the ash flow, the caldera collapsed. The resultant arcuate feature can be seen on Sky Lab photos.

Stage IV: During this time of relative quiescence, intracaldera lava and pyroclastic material was the extent of volcano activity. During this stage, avalanche deposits of the Maue-McCray Member and lava flows associated with intrusions of the Kate Peak intrusions at Mullen Pass formed in the ring-fracture zone on the caldera walls.

Stage V: A resurgent structural dome formed while Truckee Formation sediments and volcanics began to fill the intracaldera moat. Parts of Warm Springs Valley, Hungrey Valley, Lemmon Valley, and Long Valley are physiographic remnants of the moat.

Stage VI: Ring Fractures were re-opened, and the Cascade Member was erupted while the Truckee Formation was being deposited.

Stage VII: Hydrothermal activity may have been responsible for mobilization of uranium into the ground-water system (see description of this process, p. 192).

Posteruptive deformation occurred during Basin and Range faulting.

Tectonic Setting

The inferred caldera is located approximately 10 km north of Sparks, Nevada. It has an average diameter of nearly 40 km and is situated in a structural transition zone between the Sierra Nevada batholith on the west and the Basin and Range Province on the east (Bonham, 1969). It is located on the northwest end of the Walker Lane, a series of north- and northeast-trending, large-magnitude normal faults. Structures related to caldera formation also occur in the area. The Hartford Hill Rhyolite and the Truckee Formation are quaquaversally dipping units, around a center of breached-basement granitic rocks. The Hartford Hill Rhyolite is unconformably overlain by the Truckee Formation. The 10-20° difference in dip between the two units may reflect active resurgent doming prior to or during deposition of the Truckee Formation.

Lithologies

For the purpose of this description, only three lithologies will be examined: the two lower cooling units (1a and 1b) and the Truckee Formation. The following descriptions are adapted from Cupp and others (1977); for more details, see their report.

Cooling Unit 1a

Cooling unit 1a is a vitric to vitric-crystal tuff, 175 ft thick. It is rhyodacitic to andesitic, with a phenocryst content of 4 to 18 percent. The phenocrysts are quartz, potash feldspar, plagioclase, and biotite. It is non-welded at the base and moderately welded at the top.

Cooling Unit 1b

Cooling Unit 1b is a vitric to vitric-crystal tuff that is up to 425 ft thick. It is rhyolitic and andesitic, with approximately 4 percent phenocrysts. The phenocrysts are quartz, potash feldspar, plagioclase, and biotite. Volcanic rock and pumice fragments and glass shards are abundant. Welding is variable; the unit is generally nonwelded at the base and contains a zone of dense welding near the center of the flow. The upper portion of the flow is moderately welded and contains some nonwelded zones.

Truckee Formation

The Truckee Formation comprises a series of sand, silt, and clay beds and contains abundant plant detritus. It was deposited in the intracaldera moat. The Truckee Formation probably represents a wide variety of paleoenvironments, which include fluvial, lacustrine, and marsh environments. More-detailed information is not available. However, for the purposes of this description, the recognition of the paleoenvironments is sufficient for a discussion of uranium deposition.

Mineralogy

Uranium mineralogy of the deposits in the Hartford Hill Rhyolite and the Truckee Formation is varied and will be discussed in terms of the deposit type. Cupp and others (1977) recognized three types of deposits in the Hartford Hill Rhyolite:

1. Deposits related to fracture systems in cooling units 1a and 1b. The uranium minerals are disseminated gummite, uranophane, and autunite in iron-stained, silicified veinlets. Data are insufficient to classify these deposits.
2. Deposits related to intrusion of basalt dikes into the ash-flow cooling units of the Hartford Hill Rhyolite. The dikes trend NNE through the Hartford Hill Rhyolite. The uranium minerals are concentrated in fractured wall rock; the fractures are filled with greenish-gray opal, dark-reddish-brown hematite, and thin clay seams. Uranium minerals include autunite, sabugalite, phosphuranylite, and cleveite.
3. Deposits in the Truckee Formation are related to a humus-rich paleosol of post-Truckee Formation age. The only reported uranium mineral was sabugalite.

Chemistry

Data on whole-rock chemistry of the ash-flow cooling units are not available.

The Hartford Hill Rhyolite has an average equivalent U_3O_8 content of 5.6 ppm, an average thorium content of 18.8 ppm and an average Th/U ratio of approximately 4.

Uranium and thorium values of individual prospects are not recorded here, because they were taken in areas obviously enriched in uranium. Without comparison with a statistically selected background sample, they have little meaning.

Alteration

Alteration in the deposits related to fracture systems is limited to silicification and hematitization(?). Alteration in the deposits related to the basalt dikes includes kaolinization of the wall rock, opalization, hematitization, and argillization. The only alteration reported in the Truckee Formation occurrences is hematitic staining.

Geometry

Data on geometry are discussed for each deposit type:

1. Deposits related to fracture systems are thin stringers of epigenetic uranium minerals in and along the fracture systems. The deposits are erratic, and geometry is highly variable.
2. Deposits related to the basalt dikes are localized in zones $\frac{1}{2}$ to 2 m on either side of the basalt dikes and are within the altered zones. The occurrences are discontinuous; ore occurs in pods and stringers.
3. Geometry of the deposits in the Truckee Formation is difficult to discern. Ore appears to be related to carbonaceous trash or organic-rich paleosols, and the distribution of weathered surfaces is unpredictable.

Rock Associations

Associated rocks are restricted to those formed during the evolution of the caldera, namely, silicic ash flows and intrusions and intracaldera sediments.

Type of Occurrences

There are at least two distinct classes of occurrence and one which cannot be classified because of insufficient data. Deposits related to fracture systems need to be studied in more detail to determine their classification. Deposits spatially related to the basalt dike appear to be caused by the intrusion

of the dike; the heat of the intrusion could have remobilized uranium in the uranium-enriched acidic ash flows. These interpretations fit some of the recognition criteria of the hydroallogenic class, but further investigation is needed before classification is made. Some ore was removed in the 50s and these deposits could again be considered economic in the future. These deposits must be considered paramarginal resources.

Deposits in the Truckee Formation appear to be hydroallogenic occurrences, because they probably were formed by remobilization of the uranium contained within the volcanic sequence. The remobilized uranium was deposited in reducing environments in the intracaldera moat. Although these deposits are not now being mined, the Truckee has high potential.

The second kind of occurrence belongs to the initial-magmatic class, and one might consider the small deposits found thus far as indications of uranium available for remobilization and concentration. Deposits in the Truckee Formation emphasize the possibility of low-temperature diagenesis of the volcanics and concentration of the mobile uranium in cogenetic, porous and permeable sediments.

RECOGNITION-CRITERIA SUMMARY

+ = strong criterion
 - = weak criterion
 o = unevaluated criterion

RECOGNITION CRITERIA		INITIAL-MAGMATIC	PNEUMATOGENIC	HYDROAUTHIGENIC	HYDROALLOGENIC
TECTONIC SETTING		page 193	196	201	206
Taphrogenic:	Extensional	+	+	+	+
	Rift Systems	+	+	+	+
HOST-ROCK LITHOLOGY		page 193	196	201	206
	Granites/Rhyolites	+	+	+	+
	Syenites/Trachytes	+	+	-	-
	Intermediates	-	+	+	+
	Silica-Undersaturated	+	+	-	-
HOST-ROCK FACIES		page 195	197	203	207
	Subvolcanic Intrusive	+	+	-	+
	Ring-Fracture Intrusive	+	+	+	-
	Outflow Facies:				
	Ash Flows	+	+	+	+
	Lava Flows	+	-	+	+
	Sediments				+

RECOGNITION-CRITERIA SUMMARY

+ = strong criterion

- = weak criterion

o = unevaluated criterion

RECOGNITION CRITERIA		INITIAL-MAGMATIC	PNEUMATOGENIC	HYDROAUTHIGENIC	HYDROALLOGENIC
Intracaldera Facies:					
Ash Flows		+	+	+	+
Lava Flows		+	-	+	+
Sediments					+
HOST-ROCK TEXTURES	page 193	196	202	206	
Granitic		+	+	+	+
Porphyritic		+	+	+	+
Granophyric		+	+	-	-
Spherulitic		+	-	+	-
Lithophysae		+	+	+	+
Pumiceous		+	+	+	+
Welded Tuffaceous		+	+	-	-
Non-Welded Tuffaceous		+	-	+	+
MINERALOGY	page 194	197	202	206	
Uranium Oxides		-	+		
Uranosilicates		-	-	+	+

RECOGNITION-CRITERIA SUMMARY

+ = strong criterion
 - = weak criterion
 o = unevaluated criterion

RECOGNITION CRITERIA	INITIAL-MAGMATIC	PNEUMATOGENIC	HYDROAUTHIGENIC	HYDROALLOGENIC
Quartz	-	-	-	-
Alkali Feldspars	+	+	+	+
Sodic Pyroxenes	+	+	+	+
Sodic Amphiboles	+	+	+	+
Fluorite	+	+	-	-
Sulfides	-	+	-	-
CHEMISTRY	page 194	197	202	206
High SiO ₂	+	+	+	+
High Na ₂ O	+	+	+	+
High K ₂ O	+	+	+	+
High F	+	+	+	
Na ₂ O + K ₂ O / Al ₂ O ₃ > 1	+	+	+	+
Th/U > 1	+	+	+	
Th/U < 1				+
Low MgO	+	+	+	+
Low CaO	+	+	+	+

RECOGNITION-CRITERIA SUMMARY

+ = strong criterion
 - = weak criterion
 o = unevaluated criterion

RECOGNITION CRITERIA		INITIAL-MAGMATIC	PNEUMATOGENIC	HYDROAUTHIGENIC	HYDROALLOGENIC
ALTERATION	page 194	197	202	207	
Silicification		+	+	+	+
Sericitization		-	+	+	+
Albitization		+	+	o	-
Argillization		-	+	+	+
Hematitization		-	+	o	o
GEOMETRY	page 195	197	202	207	
Veins			+	+	
Pipes			+		
Stockworks			+		
Tabular/Conformable				+	+
Stratiform				+	+
EXAMPLES AND PAGE NUMBERS					
Red Hills Caldera, Utah			198		
Buckshot Ignimbrite (Mammoth Prospect), Texas				203	
Hartford Hill Rhyolite, Nevada	207				207

RECOGNITION-CRITERIA SUMMARY

+ = strong criterion
 - = weak criterion
 o = unevaluated criterion

RECOGNITION CRITERIA	INITIAL-MAGMATIC	PNEUMATOGENIC	HYDROAUTHIGENIC	HYDROALLOGENIC
ADDITIONAL EXAMPLES FROM PILCHER (1978)				
Vico Volcano, Italy	+			
Sabatini Volcano, Italy	+			
Zletovska Reka, Yugoslavia	+			
Sierra Peña Blanca, Mexico	+	+	+	+
Spancevo Deposit, Yugoslavia				+
Virgin Valley, Nevada				+

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URANIUM OCCURRENCES OF UNCERTAIN GENESIS

by

Geoffrey W. Mathews

ABSTRACT

Geologic characteristics of the three classes of uranium occurrences of uncertain genesis are subdivided into eight separate categories: (1) tectonic setting, (2) lithology, (3) texture, (4) mineralogy, (5) chemistry, (6) alteration, (7) geometry, and (8) lithologic and (or) structural associations. A discussion of the resource potential of each class is included for quadrangle-evaluation purposes. Because the origin(s) of these deposits is not known, and because of the different geologic settings in which they occur, few recognition criteria are common to all classes. Unconformity-related deposits and vein-type deposits in metamorphic rocks bear many general similarities; vein-type deposits in sedimentary rocks are dissimilar to the first two classes.

Unconformity-related deposits and vein-type deposits in metamorphic rocks commonly occur in brecciated, foliated metamorphic rocks in Precambrian-shield areas. Graphite, chlorite, and, to a lesser extent, hematite are common minerals in unconformity-related deposits and vein-type deposits in metamorphic rocks. These minerals are not common in vein-type deposits in sedimentary rocks. Vein-type deposits in both metamorphic and sedimentary rocks commonly show evidence of silicification and carbonatization. Tetravalent uranium minerals, sulfides, and (or) sulfarsenides occur in deposits of all three classes.

Most deposits of these classes are tabular; some are amoeboid in plan. Deposits of all three classes are associated with faults and (or) shear zones. Unconformity-related deposits are closely associated with major regional unconformities where coarse continental clastic sediments overlie variously metamorphosed basement rocks. The genetic significance of the associated unconformities is not known.

Uranium occurrences of uncertain genesis represent submarginal to recoverable resources. Much of the world's known uranium occurs in deposits of these classes.

INTRODUCTION

Uranium deposits of uncertain genesis are divided into three classes: unconformity-related deposits, vein-type deposits in metamorphic rocks, and vein-type deposits in sedimentary rocks (Mathews, 1978). The origin of these deposits is speculative and is a matter of continuing controversy. Among the unsolved problems regarding their genesis are the source of the uranium and its mode of transport, the source of the mineralizing solutions, the role of reductants, and the extent of lithologic and structural controls on the deposition of uranium. Too many questions remain unanswered to establish acceptable genetic models for the several classes of uranium deposits of uncertain genesis.

Without adequate genetic models, recognition criteria cannot be based on hypothetical, systematic evolutionary patterns. Consequently, recognition criteria must be based on empirical data from first-hand study of a few deposits and from published descriptions of numerous additional deposits. Not every criterion is present in all deposits of a given class, nor does any single deposit possess all the recognition criteria for that class.

The recognition criteria discussed in this chapter are preliminary. They are designed to assist field geologists in recognizing likely environments of uranium concentrations and to aid in the evaluation of quadrangles for the National Uranium Resource Evaluation (NURE). The preliminary and general nature of these criteria is unavoidable; not enough is known about these deposits to be more definite. Further study and data from field geologists involved in the NURE program are necessary to make a more definitive tabulation of recognition criteria.

The recognition criteria for each class of uranium deposits of uncertain genesis are discussed in several broad categories: (1) tectonic setting, (2) lithology, (3) texture, (4) mineralogy, (5) chemistry, (6) alteration, (7) geometry, and (8) lithologic and structural associations. The type of deposit (submarginal, paramarginal, or recoverable) is discussed for each class. Although the type of deposit is not a recognition criterion, it is included here as a possible aid in evaluating the uranium potential of the quadrangles. A summary chart is included at the end of this chapter; it is designed to provide a ready comparison of the characteristics of the different classes of uranium deposits of uncertain genesis.

UNCONFORMITY-RELATED URANIUM DEPOSITS (CLASS 710)

Unconformity-related uranium deposits compose a newly discovered class of deposits which contain a significant proportion of the world's known uranium reserves. Known unconformity-related uranium deposits are very large and range in grade from a few hundredths to over 50 percent U_3O_8 . Although no deposits of this class are known in the United States, several large deposits have been discovered in northern Australia and around the Athabasca rim in northern Saskatchewan.

Unconformity-related uranium deposits are epigenetic concentrations of primary uranium minerals in vein and stratabound deposits spatially associated with major regional unconformities. Known deposits of this class are associated with unconformities of Proterozoic age (basal Helikian in Canada; basal Carpentarian in Australia).

With the exception of the deposits at Cluff Lake, northern Saskatchewan, unconformity-related deposits in Australia and northern Saskatchewan are located near the erosional edge of the sedimentary units overlying the unconformity. The existence of additional deposits under the thicker sections of the overlying rocks in the center of the depositional basin is conjectural. Ojakangas (1978) speculated that such deposits might be found basinward from the erosional edge of the unconformably overlying sedimentary rocks.

Unconformity-related veins are confined to the immediate vicinity of paleoerosion surfaces where terrestrial sediments overlie variously metamorphosed igneous and sedimentary rocks. They are commonly associated with faults and breccia zones which transect both the basement rocks and the overlying sedimentary units. The faults and breccia zones may be reactivated basement structures.

The origin of unconformity-related uranium deposits is not known, nor is it known whether all unconformity-related uranium deposits have the same genesis. Whether unconformity-related uranium deposits are supergene or hypogene has not been established. A major question is: are the deposits genetically related to the spatially associated unconformity surfaces? Although spatial associations do not necessarily imply genesis, the restriction of deposits of this class to the vicinity of major regional unconformities suggests that the associated unconformities had a genetic influence on the deposits. Regardless of genetic inferences, spatial associations are undeniable and have become an important part of uranium-exploration programs. Even if one accepts a hypothesized genetic relationship, the nature of the relationship is still in question. Do unconformity surfaces represent channelways for uranium-bearing supergene fluids? Do rocks overlying the unconformity cause localization and precipitation of uranium from hypogene solutions? In either case, questions regarding the source of the uranium, the mode of transportation, the cause(s) of deposition, and the role of reductants in the deposition of pitchblende remain unanswered.

Uranium in unconformity-related deposits exists in concentrations of pitchblende in veinlets along faults, in brecciated zones, and secondary parasitic structures associated with the major structure. It also occurs as fine disseminations within specific horizons in the country rock. Although mineralization straddles the unconformity in some deposits, it is generally confined to the underlying metamorphic rocks. The associated major structures apparently antedate the unconformity and seem to have been reactivated subsequent to deposition of the sedimentary rocks over the unconformity.

Unconformity-related uranium deposits rarely extend more than 100 m below the unconformity and characteristically have large horizontal projections.

The mineralization nearly always postdates the unconformity. This contradicts the concept that the upper parts of the orebodies have been removed during the erosion cycle marked by the unconformity; the limited vertical extent of these deposits cannot be explained by erosion.

Host rocks of known unconformity-related uranium deposits are universally of Precambrian age. They are characterized by extensive chloritization adjacent to associated fault zones; the degree of chloritization decreases with increasing distance from fault zones. High-rank metasedimentary units below the unconformity are often retrogressively metamorphosed to the greenschist facies in the vicinity of the deposits. The overlying terrestrial sediments also have been chloritized in some deposits.

Hematitic alteration is a characteristic of the host rocks for unconformity-related deposits. The distribution of hematite around the orebodies follows, and sometimes extends beyond, the chlorite. In general, the degree of hematitization is directly proportional to the grade of uranium ore. Paragenetic relations show that hematitization often follows chloritization and precedes pitchblende deposition.

Base-metal sulfides and sulfarsenides are common associates of pitchblende and constitute a valuable resource in the polymetallic subclass. Sulfide deposition follows pitchblende deposition in most unconformity-related uranium deposits.

Carbonates and quartz, which are normally paragenetically younger than pitchblende, commonly cement the breccia fragments in the fault zones.

Pitchblende is largely confined to graphite-bearing schists or chlorite schists within the ore zones. Large, high-grade concentrations of primary uranium minerals commonly occur beneath graphite and (or) chlorite horizons. Carbonates are favorable host rocks in some deposits. Thus, unconformity-related uranium deposits seem to be controlled by lithology, at least in part.

The distribution of uranium with respect to associated structures suggests that unconformity-related deposits may be at least partially controlled by structure. As noted above, the genetic influence of the associated unconformity is not known. Langford (1974) suggested that the unconformity provided a channelway for lateral migration of uranium-bearing ground waters; the associated fault and breccia zones were merely adequate receptacles for uranium deposition. The limited vertical extent of these deposits lends credence to Langford's hypothesis. Conversely, the associated faults and fault zones may have acted as conduits for upward-migrating uranium-bearing aqueous solutions.

Many unconformity-related uranium deposits show evidence of remobilization and reconcentration of uranium subsequent to its initial deposition. Temperatures of uranium mineralization, as determined by fluid-inclusion studies and the coexistence of mineral pairs, range from 60° to 260° C.

Some of these deposition temperatures are higher than might be expected from simple ground-water percolation, unless either a very thick sedimentary sequence lay above the unconformity at the time of mineralization or the geothermal gradient was exceptionally steep. High-temperature alteration products, which commonly occur immediately adjacent to the deposits, decrease in abundance with increasing distance into the country rock. The distribution of alteration products around some deposits and the concentration of pitchblende below graphitic units suggest deposition by ascending hydrothermal fluids.

Thus, the question of the origin of unconformity-related uranium deposits remains unanswered.

GEOLOGIC CHARACTERISTICS

Because the origin(s) of unconformity-related uranium deposits is not known, recognition criteria cannot be based on a genetic model; recognition criteria cannot be predicted without a logical, systematic genetic framework. Therefore, the recognition criteria included here are empirical; they are a tabulation of observations and generalizations derived from the study of several examples of unconformity-related uranium deposits. Few generalizations can be made about all unconformity-related uranium deposits. Deposits of this class differ in the metamorphic grade of the enclosing host rock, the nature of associated minerals, or the degree and type of alteration. The recognition criteria discussed in this section are purposefully general. The reader is urged to study specific examples of unconformity-related uranium deposits so that variations in recognition criteria might become apparent.

Tectonic setting

All known unconformity-related uranium deposits have been found in stable Precambrian-shield areas. These areas are marked by moderate to intense deformation and metamorphism prior to the development of the associated unconformity surface. Little or no deformation has occurred since the erosion interval.

The sedimentary units overlying the unconformity are flat-lying or very gently dipping; locally they have been faulted in the vicinity of the orebodies.

Lithology

The lithologies of two sequences must be considered here: the sedimentary rocks overlying the unconformity and the metamorphic rocks below the unconformity. Orthoquartzitic to feldspathic fluvial sandstones are the common rock types above the unconformity. These sedimentary rocks are commonly marked by a high degree of textural and mineralogical maturity and show varying degrees of induration. They are more poorly sorted and are mineralogically more immature near the base of the sequence; they may contain local polymictic conglomerate lenses near the unconformity. The sandstones may contain intercalated lenses of shales and siltstones, although the percentage of the rocks is generally low near the basal unconformity.

Metamorphosed sedimentary and igneous rocks underlie the unconformities and contain most of the uranium minerals in unconformity-related uranium deposits. Both the degree of metamorphism and the extent of pre-unconformity structural deformation are variable. Some metasedimentary units are only slightly metamorphosed and deformed, whereas others are highly metamorphosed and strongly deformed. The grade of metamorphism and structural complexity of the host rocks do not appear to correlate with the uranium content of unconformity-related deposits. For example, unconformity-related uranium deposits in the Alligator River area of northern Australia are contained in a single rock unit, the Cahill Formation; both the degree of metamorphism and the extent of structural complexity of the Cahill Formation change across the region and between the various deposits.

Most deposits of this class are confined to, or are concentrated below, reducing horizons within the metasedimentary host rocks. Graphite- and chlorite-bearing schists are the most common host lithologies for these concentrations. Quartzites, sericite schists, chloritic gneisses, calc-silicate rocks, and marbles are also present, but generally contain smaller concentrations of uranium minerals.

Texture

Because of the wide variety of host rocks in which pitchblende is concentrated, the textures of the host rocks for unconformity-related deposits are highly variable. Primary uranium minerals are often concentrated in cataclastic and mylonitic zones along shears and fracture systems. They also occur in schistose, gneissic, and granoblastic rocks. The rocks overlying the unconformity commonly exhibit mature, clastic sedimentary textures.

Because of the wide textural spectrum of host rocks, texture cannot be considered an adequate recognition criterion for unconformity-related uranium deposits.

Mineralogy

Because both the metamorphic grade and the premetamorphic composition of host rocks are variable, the mineralogy of the host rocks for unconformity-related uranium deposits is also variable. Graphite, chlorite, and biotite are very common and are generally accompanied by quartz, feldspars, and muscovite. Higher-rank metamorphic minerals such as garnet, kyanite, and sillimanite may be present, depending on the composition of the rock, the degree of metamorphism, and the extent of retrogressive modification. Calc-silicate minerals are common in some unconformity-related uranium deposits.

Sedimentary rocks above the unconformities consist almost entirely of quartz. Feldspar is present in some of the fluvial sandstones.

Pitchblende is the dominant uranium mineral in unconformity-related deposits. Coffinite may also be present, although it generally is less abundant than pitchblende. Secondary uranium minerals may be locally abundant, particularly near the surface of the deposits. Gangue minerals contemporaneous with pitchblende, principally quartz and carbonates, are often present in low concentrations.

Other associated minerals are variable in both type and abundance; they govern whether an individual deposit belongs to the monometallic or polymetallic subclass. Sulfides are generally present in variable quantities. Polymetallic deposits may contain a wide variety of associated minerals.

Chemistry

The chemical composition of host rocks for unconformity-related uranium deposits is as variable as the mineralogy. The ore zones, however, possess more definite and regular chemical characteristics. The most dominant chemical aspect is an anomalously low thorium content and, hence, a very low Th/U ratio. This characteristic reflects the transposition of uranium to the deposit in the hexavalent state. It may also explain why the uranium minerals are most concentrated in reducing rocks, such as graphite schists.

Other chemical characteristics are governed by whether the deposit is monometallic or polymetallic. Polymetallic unconformity-related uranium deposits may have highly anomalous concentrations of Ni, Cu, Ag, Au, or Bi, whereas monometallic deposits possess only uranium in economic concentrations. It is not known why certain unconformity-related uranium deposits are polymetallic and others are monometallic. The metallic character of a deposit may reflect the nature of the source rocks, the efficiency of the transporting medium, and (or) the tectonic setting of the deposit.

Alteration

Hematitization and chloritization are the most common types of alteration found in host rocks of unconformity-related uranium deposits. Hematitization commonly occurs prior to uranium mineralization in the paragenetic sequence. In general, higher grades of uranium ore are associated with more pronounced degrees of red alteration.

Chloritization, a common process affecting host rocks of unconformity-related uranium deposits, is generally restricted to the immediate vicinity of the ore zone. It may precede or it may be synchronous with uranium mineralization. In most instances, magnesian chlorite is the major product of this alteration. One deposit (Key Lake, northern Saskatchewan) is associated with iron chlorite. The genetic significance of iron chlorite at Key Lake is not known.

Evidence of hydrothermal alteration and propylitization is generally lacking from unconformity-related uranium deposits.

Geometry

The geometry of individual unconformity-related uranium deposits probably depends upon which factor is dominant in localizing pitchblende deposition, lithology or structure. Unconformity-related uranium deposits vary in size and shape. They are confined to within 100 m of the unconformity surface and have fairly large horizontal projection areas. Deposits controlled principally by structure tend to be elongate, whereas those governed largely by stratigraphy are often amoeboid.

Lithologic and Structural Associations

Two major associations are paramount to unconformity-related uranium deposits. The first, and most prominent criterion, is the spatial association with a regional unconformity in which coarse terrestrial, sedimentary rocks overlie metasedimentary and (or) metavolcanic rocks. In all known major deposits of this class the unconformity is of Proterozoic age (Paleohelician in Saskatchewan and pre-Carpentarian in Australia). Because the origin of unconformity-related uranium deposits is not known, and, in particular, because the genetic relationship, if any, between the associated unconformity and the mineralization is not known, the apparent restriction of deposits of this class to Precambrian unconformities cannot be explained. Unconformity-related uranium deposits may be present below Phanerozoic unconformities.

The second essential association of unconformity-related uranium deposits is a major fault or shear zone near the orebody. These associated structures commonly are cataclastic and (or) mylonitic zones; they may be basement structures which have been reactivated after deposition of the sedimentary rocks above the unconformity. They are commonly steeply dipping and show reverse-fault characteristics. The structures are probably conduits for the mineralizing solutions, regardless of whether the solutions migrated downward in a supergene environment or upward in a hypogene environment.

Uranium minerals are not always concentrated along and within the associated structures. In some unconformity-related uranium deposits, the uranium minerals are either in the headwall or the footwall block. In some deposits the orebodies lie athwart the structure. Uranium minerals in some occurrences are concentrated in specific lithologic units adjacent to the structures and give the impression that the shear zones truncate the mineralized rock. This may not be the case, however, because the suitable host rock is present only on one side of the structure. Thus, although the structure appears to truncate the orebody, it more likely was the conduit for mineralizing solutions as they migrated to a favorable lithology. The prime factors in concentrating pitchblende are the lithology of the host rock and its spatial relation to the structure.

Lithologic associations of unconformity-related uranium deposits are variable. Most known deposits are associated with metamorphosed shelf-facies sedimentary rocks, and fluvial sandstones. The deposits are not related to the grade of metamorphism of the rock units below the unconformity. Lithology of the host rocks may be a dominant factor in controlling the site of uranium deposition.

Resource Potential

Unconformity-related uranium deposits probably contain more of the world's uranium than any other single class of uranium deposit. They are large, moderately high-grade deposits. Small, low-grade occurrences of this class are possible, but none are known. Because of these factors, unconformity-related uranium deposits must be considered paramarginal to recoverable resources.

EXAMPLES OF MONOMETALLIC UNCONFORMITY-RELATED DEPOSITS (SUBCLASS 711)

Koongara, Northern Australia

The following synopsis of the Koongara uranium deposit is taken from Dodson and others (1974), Crohn (1975), Foy and Pederson (1975), and Morton (1976).

The Koongara uranium deposit is located in intensely folded lower Proterozoic metamorphic rocks of the Pine Creek geosyncline, Northern Territory, Australia. The host rocks for the deposit comprise retrogressively metamorphosed amphibolite-facies metasedimentary rocks. Quartz-chlorite schist, which locally contains muscovite and (or) garnet, is the dominant lithology in the vicinity of the ore zone. One unit of graphite-quartz-chlorite schist is interlayered with the graphite-free schists. Flat-lying, coarse quartz sandstones of the middle Proterozoic Kombolgie Sandstone unconformably overlie the metasedimentary units.

A steeply dipping reverse fault, which places the basal quartz-chlorite schists on top of the Kombolgie Sandstone, is the dominant structure in the vicinity of the orebody. The fault has a stratigraphic throw of up to 600 m and is marked by a 7-m-thick zone of highly brecciated and mylonitized material. Several smaller, parasitic shears occur in the schists of the hanging wall. They are subparallel to the major fault zone and are especially numerous within the interlayered graphitic-schist horizon.

Chloritization is the dominant type of alteration found in the ore zone. It is most intense within the mylonitized fault zone and becomes progressively less pronounced with increasing distance into the hangingwall metasedimentary units and the footwall Kombolgie Sandstone.

Crystalline uraninite and minor amounts of sulfides occur in veinlets both parallel and transverse to the foliation of the metasedimentary rocks. Sooty pitchblende coats minor-fracture surfaces. The largest concentrations and the highest grades of ore are located immediately below the graphite-quartz-chlorite schist horizon in the metasediments. This concentration below the reducing horizon emphasizes the lithologic control on mineralization and suggests that the uranium was deposited by ascending solutions. Minor amounts of uranium minerals are found in the Kombolgie Sandstone adjacent to the fault.

The Koongara deposit is a steeply dipping wedge; it pinches out at a depth of approximately 100 m. Most primary uranium mineralization occurs within 50 m of the fault zone. Extensive oxidation and secondary uranium minerals, principally hydrous uranium silicates and phosphates, are found in the upper part of the orebody. This zone of secondary uranium mineralization extends to a depth of approximately 25 m.

Primary uranium minerals at Koongara are thought to be of hydrothermal origin (Morton, 1976). Their association with retrogressive chloritization along the major fault zone, and the concentrations of higher grades of ore immediately below the graphitic-schists horizon, suggest emplacement by ascending hydrothermal solutions. If the uranium mineralization was indeed caused by ascending solutions, then the spatial relation with the pre-Carpenterian unconformity may have little, if any, genetic significance.

Rabbit Lake, Northern Saskatchewan, Canada

The following summary of the Rabbit Lake uranium deposit was adapted from Little (1970), Knipping (1974), Hoeve and Sibbald (1976), and McMillan (1977).

The Rabbit Lake uranium deposit is located in Aphebian metasedimentary rocks of the northeast-trending Wollaston fold belt, along the eastern erosional edge of the unconformably overlying Helikian Athabasca Formation. The top of the Rabbit Lake deposit is less than 50 feet below the eastward-projected basal Athabaskan unconformity.

Aphebian host rocks comprise a series of metamorphosed, impure shelf- to miogeosynclinal-facies sedimentary rocks. Meta-arkose composes the bulk of the Aphebian rocks in the Rabbit Lake area. Lesser amounts of biotite paragneiss, plagioclase-rich calc-silicate rocks (termed plagioclasites by Hoeve and Sibbald, 1976), and marble are present. These rocks were tightly folded and metamorphosed to the cordierite-amphibolite facies (Abukuma facies series) during the Hudsonian orogeny. Subsequently they have been retrogressively metamorphosed and heavily chloritized. The Athabasca Formation, which consists of a thick series of quartz sandstones and conglomerates, rests unconformably on a well-developed regolith on the truncated edges of the Aphebian metasedimentary rocks.

The Rabbit Lake uranium deposit occurs in a steeply dipping, highly chloritized breccia zone in the metasedimentary rocks. Dolomite, calcite, and quartz cement the breccia fragments. Both massive and sooty pitchblende occur in veinlets and as fracture fillings and are associated with minor amounts of galena, sphalerite, pyrite, marcasite, and chalcopyrite. The mineralized breccia zone is truncated at depth by a low-angle thrust fault (the Rabbit Lake fault) which placed the Aphebian metasediments on top of the Athabasca Formation. The breccia zone is interpreted as a pre-Athabasca fracture zone which was reactivated by the Rabbit Lake fault. The Rabbit Lake fault plane, marked by a thin zone of mylonite and soft gouge, is the footwall of the ore zone. Only minor mineralization occurred in the metamorphic rocks and the Athabasca Formation below the Rabbit Lake fault.

Chloritic alteration is pervasive and zonal around the Rabbit Lake deposit. The most intensely altered rocks are in the middle of the ore zone, where the breccia fragments consist almost entirely of chlorite and quartz. The rocks become progressively less chloritized outward from the center of the ore zone. Both alteration and uranium mineralization decrease with depth and become virtually nonexistent below a depth of approximately 350 ft.

Two stages of uranium mineralization have been recognized in the Rabbit Lake deposit. The first stage was the deposition of massive pitchblende; it preceded the extensive chloritic alteration. Subsequent oxidizing solutions leached some of the primary uranium during a "red alteration" (hematitization) stage and redeposited it as sooty pitchblende and coffinite during a reducing or "green alteration" stage. The second generation of pitchblende deposition was contemporaneous with the extensive chloritic alteration.

The radiometric age of initial pitchblende deposition is 1,100 m.y., compared to the 1,350[±] m.y. age of the Athabasca Formation. Fluid-inclusion studies on gangue minerals associated with the initial stage of pitchblende deposition suggest a minimum temperature of formation between 160° and 225° C.

Age, temperature of deposition, and the fact that chloritic alteration postdates the Rabbit Lake fault all suggest that the uranium deposition was not genetically related to the weathering interval that formed the basal Athabaskan unconformity. Nevertheless, uranium may have been deposited by ground water which percolated along the unconformity surface after deposition of the Athabasca Formation.

EXAMPLES OF POLYMETALLIC UNCONFORMITY-RELATED DEPOSITS (SUBCLASS 712)

Key Lake, Northern Saskatchewan, Canada

The following discussion of the Key Lake uranium-nickel deposit was taken from Dahlkamp and Tan (1977) and McMillan (1977).

The Key Lake uranium-nickel deposit consists of two elongate orebodies and is located along the southeastern margin of the Athabasca basin, in northern Saskatchewan. Basement rocks comprise strongly deformed and highly metamorphosed (amphibolite to granulite facies) Archean metasedimentary rocks of the Wollaston fold belt. They have been retrogressively metamorphosed to the greenschist facies. Graphite schist, chlorite-sericite schist, biotite gneiss, calc-silicate gneiss, and meta-arkose compose the basement rocks in the Key Lake area. A well-developed regolith marks the upper limit of the metasedimentary units. A few small, concordant quartz-feldspar pegmatites have been encountered by drill holes. The Archean metasediments and regolith are unconformably overlain by flat-lying to gently dipping quartz arenites and conglomerates of the Helikian Athabasca Formation.

The two orebodies which make up the Key Lake deposit were probably part of a single depositional system prior to being breached by Pleistocene erosion. They have a combined strike length of over 3000 m, range in thickness from 10 to 100 m, and extend to a depth of 150 m below the base of the Pleistocene overburden.

The orebodies are confined to a steeply dipping, highly brecciated zone which transects both the metasedimentary units and the unconformably overlying Athabasca Formation. The breccia zone marks the location of a high-angle reverse fault whose stratigraphic throw is approximately 25 m.

Uranium (in pitchblende and coffinite) and nickel (in gersdorffite, millerite, and niccolite) are present in roughly equal amounts. They are most concentrated in and immediately below the graphite-schist horizon in the highly altered breccia zone (compare with the Koongara deposit, p. 229). Less-extensive mineralization occurred in the chlorite schist. Paragenetic relations indicate that initial pitchblende deposition preceded deposition of nickel sulfides and arsenides and was synchronous with the nickel sulfarsenide gersdorffite.

Chloritization is ubiquitous in the Key Lake deposit. In contrast to chloritization in other unconformity-related uranium deposits, the chlorite at Key Lake is an iron-rich variety. Genetic implications of iron-rich chlorite are not known.

Too few data are available to formulate an acceptable hypothesis regarding ore-forming processes. Although the Key Lake deposit is known only through drill cores, several facts may bear on a genetic model. Deposition of uranium and nickel postdates the Athabasca Formation. Geothermometry of the bravoite-uraninite mineral pair suggests a depositional temperature of approximately 135° C. Mineralization was controlled principally by structure and lithology. Although genetic relations with the basal Athabaskan unconformity have been postulated, the nature of the relationship is not yet known.

Jabiluka II, Northern Territory, Australia

The description of the Jabiluka II uranium-gold deposit given below is summarized from Dodson and others (1974), Rowntree and Mosher (1975), Smart and others (1975), and Morton (1976).

The Jabiluka II uranium-gold deposit, located in the East Alligator River district, Northern Territory, Australia, occurs in brecciated metasedimentary rocks beneath 20 to 70 m of the gently dipping, unconformably overlying Kombolgie Sandstone. Brecciated amphibolite-facies metasediments are the host rocks for the deposit; they have been retrogressively metamorphosed to the greenschist facies. These lower Proterozoic rocks, the Cahill Formation, comprise pyritic quartz-chlorite-graphite schist, chlorite-graphite schist, chlorite schist, and some minor interlayered calc-silicate rocks. They have been folded into a gently plunging, open, asymmetrical syncline. Small, unmineralized pegmatite and phonolite dikes cut the Cahill Formation. A thrust fault is the major

structural element in the vicinity of the Jabiluka II deposit. The fault truncates the basal Kombolgie unconformity, has placed the Kombolgie Sandstone in fault contact with the footwall metasediments, and has thickened the sandstone section over the orebody.

Pitchblende is the principal uranium mineral at Jabiluka II, in both massive and disseminated forms. It occurs as coatings on breccia fragments and in veinlets up to 2mm wide. Native gold, which assays 0.44 oz/st, is associated with the pitchblende in one part of the deposit. Minor amounts of sulfides (pyrite and chalcopyrite) are associated with the uranium minerals. Hematite is a common associate of the ore.

Uranium is generally confined to extensively chloritized and brecciated zones at Jabiluka II. It is most concentrated within and beneath graphite-schist and chlorite-graphite-schist horizons within the Cahill Formation. This distribution of maximum pitchblende concentrations may have significant genetic implications. Some uranium occurs in the Kombolgie Sandstone where it has been chloritized and silicified.

The mineralized zones at Jabiluka II are characteristically enriched in MgO and are depleted in alkalis compared to unmineralized parts of the same units. This suggests that extensive magnesium metasomatism of the Cahill Formation and the Kombolgie Sandstone may have at least partially controlled the location of the ore deposit. Chloritization, silicification, and mineralization appear to be directly related. Pre-existing uranium concentrations (possibly in the Cahill Formation) may have been mobilized and reconcentrated in favorable structural zones and favorable host-rock units by hydrothermal solutions. The distribution of the most highly concentrated ore within and beneath reducing horizons suggests deposition by ascending solutions (compare with the Koongara deposit, p. 229). The genetic significance of the spatially associated basal Carpentarian unconformity is not known.

VEIN-TYPE DEPOSITS IN METAMORPHIC ROCKS (CLASS 720)

GEOLOGIC CHARACTERISTICS

The origin(s) of vein-type uranium deposits in metamorphic rocks is not known. Both the source of the uranium and the nature of the mineralizing solutions are speculative. The uranium in deposits of this class may be transported and precipitated by metamorphic-hydrothermal solutions. Subsequent reworking and redistribution of the uranium during later orogenic and (or) taphrogenic episodes is possible. Regardless of uncertainties concerning their origin, vein-type uranium deposits in metamorphic rocks possess several empirical recognition criteria which might be used in evaluating the potential for economic concentrations of uranium within metamorphic terranes. Like recognition criteria for all classes of uranium deposits of uncertain genesis, the criteria for vein-type deposits in metamorphic rocks are generalized. They are not based on a genetic model. No single criterion fits all known occurrences and, conversely, no single occurrence possesses all the generalized recognition criteria.

The major distinctions between deposits of this class and unconformity-related uranium deposits are the lack of association with a major regional unconformity, the geometry of the orebodies, and the vertical extent of the deposits.

Vein-type uranium deposits in metamorphic rocks are closely associated with brecciated major fault systems. Uranium minerals may not occur in the major fault plane itself; instead, they are commonly found in related secondary faults, fractures, and breccia zones. Most known large veins and vein systems occur in Proterozoic metamorphosed igneous and sedimentary rocks.

Pitchblende is the principal uranium mineral in vein-type deposits in metamorphic rocks; it occurs as open-fracture fillings and as fine disseminations adjacent to the fractures. Other uranium minerals (for example, coffinite and brannerite) may be present, but their overall volume and economic significance is minimal. Chlorite, hematite, and pyrite are commonly associated with uranium minerals in deposits of this class.

Vein-type uranium deposits in metamorphic rocks are usually elongate and steeply dipping; they have very long strike lengths compared to their thickness and generally extend to great depths. Long, deep fracture systems which have been active during long periods of geologic time may be important factors in the development of vein-type deposits (Bain, 1977). Such deep structures may provide access to and sporadically open channelways for mineralizing solutions. They are readily accessible conduits which may collect large volumes of deeply circulating uranium-bearing fluids. This concept may lend credence to hypogene models of many vein-type deposits in metamorphic rocks. Deep structures are not necessary for supergene models.

Structure appears to be the principal controlling factor for veins and vein systems of this class. The actual location of pitchblende deposition within the veins is probably strongly influenced by lithology. Carbonaceous slates, chloritized schists and gneisses, graphitic units, and metacarbonates are favorable host rocks.

Many deposits of this class are in anastomosing vein systems associated with, and probably controlled by, cymoid structures related to a major fault system.

Host rocks containing vein-type deposits are characterized by retrogressive chloritization. The role of chloritization in the genesis of uranium-bearing veins is not known; it may prepare the rocks for pitchblende deposition. Chloritization may be produced by the same fluids which transport and deposit the uranium, although it commonly occurs prior to uranium deposition, as indicated by the common occurrence of pitchblende-coated, chloritized breccia fragments.

Hematite, a common alteration product in vein-type uranium deposits in metamorphic rocks, occurs in alteration halos of variable widths. Although the concentration of uranium is generally proportional to the degree of hematitization, some areas of extensive red alteration contain no pitchblende; other areas which have little or no hematitic alteration may contain large

quantities of pitchblende. Paragenetically, hematite usually precedes pitchblende. It forms during the initial stages of hydrothermal activity and may represent the initial oxidizing nature of the transporting solution. As the solution becomes progressively more reducing, hematite development ceases and pitchblende is deposited.

Evidence of carbonatization and silicification is found in many vein-type deposits in metamorphic rocks. Carbonates and quartz, which normally follow pitchblende in the paragenetic sequence, may reflect temperature and pressure decreases and an increase in pH in upward-migrating hydrothermal solutions.

Vein-type deposits in metamorphic rocks are divided into monometallic and polymetallic subclasses on the basis of the metal content of the veins (Mathews, 1978). Monometallic veins contain only uranium in economic concentrations, whereas polymetallic deposits contain economic concentrations of at least one additional metal. The reasons why some vein-type uranium deposits in metamorphic rocks are monometallic and others are polymetallic are not known. The metal content of a given deposit may be a function of the metal content of the source rocks, the nature of the transporting solution, the geochemical character of the depositional site, and the location of the depositional site with respect to major tectonic elements, as suggested by Bedham (1976).

Tectonic Setting

Vein-type uranium deposits in metamorphic rocks occur in Precambrian metamorphosed igneous and sedimentary rocks in shield areas. Both the degree of deformation and the intensity of metamorphism vary among deposits of this class. Because of the unknown genesis of vein-type deposits in metamorphic rocks, the reason why these deposits are apparently restricted to Precambrian shield areas is not known. They might be encountered in Phanerozoic metasedimentary and meta-igneous units in the axial regions of younger fold belts. If the uranium-concentrating mechanism is the metamorphic process itself, restriction to the Precambrian is not essential. Whether deposits of this class are necessarily restricted to Precambrian shields is conjectural. L. Tremblay of the Canadian Geological Survey, at a seminar on uranium-ore genesis held at McGill University in January 1978, speculated that the size and grade of vein-type deposits in metamorphic rocks (referred to as Beaverlodge-type veins by Tremblay) might increase toward the center of the Canadian Shield. He seems to suggest that restriction to shield areas is essential. Further work on grade-tonnage-location relations is necessary before this hypothesis might be adequately tested.

Lithology

Host rocks containing vein-type deposits of this class are variable. They range from high-rank (amphibolite to granulite facies) to low-rank (zeolite facies) metasedimentary and meta-igneous rocks. Host rocks have been severely granitized in some regions (Beaverlodge area, Saskatchewan, for example). Other areas are marked by varying grades of dynamothermal metamorphism. Rock types include metapelites, meta-arkoses, metacarbonates, and metamorphosed intermediate and silicic volcanics.

Because vein-type deposits in metamorphic rocks do not appear to be lithologically restricted, host-rock lithology is probably not an adequate recognition criterion.

Texture

Host-rock textures vary from hornfelsic and granoblastic to highly foliated. Because vein-type uranium deposits in metamorphic rocks are closely associated with major structural zones (see below), cataclastic and mylonitic textures are common. However, uranium minerals are not necessarily confined to zones of cataclasis.

Mineralogy

Most vein-type uranium deposits in metamorphic rocks are mineralogically simple. Pitchblende is the only significant uranium mineral. It occurs in thin smears along minor fractures and as fine disseminations in the wall rocks adjacent to the fractures. Minor amounts of brannerite and (or) coffinite may be associated with the pitchblende. Secondary uranium minerals are minor.

Gangue minerals in vein-type deposits in metamorphic rocks are variable, both in mineralogy and amount. Some deposits of this class are associated with only minor amounts of gangue, principally calcite and (or) quartz. Other vein-type deposits have a high percentage of gangue minerals, such as in the quartz-vein deposits in the Port Radium area, Canada.

Sulfides and sulfarsenides are associated with pitchblende in vein-type deposits in metamorphic rocks. Percentages of these minerals vary. Polymetallic vein-type deposits in metamorphic rocks contain anomalous percentages of other economically important minerals, including, but not restricted to, argentite, galena, chalcopyrite, and sulfarsenides of cobalt and nickel. Native silver, gold, bismuth, and selenium are found in some polymetallic deposits.

Some deposits, particularly those of the polymetallic subclass, show a mineralogical zonation within the vein systems. Zonation occurs not only with respect to the metallic minerals, but also with respect to gangue and pitchblende. Recognition of patterns in the zoning and formulation of zoning systematics have not been accomplished.

Chemistry

The chemistry of vein-type uranium deposits in metamorphic rocks is variable and indistinctive. The only important chemical characteristic that these veins share is a very low Th/U ratio, which implies a separation of Th and U during the transportation process. Other chemical characteristics depend on the composition of the pre-metamorphic rock, the degree of metamorphism, and the extent of retrogressive metamorphism. Uranium is the dominant metal in monometallic vein-type deposits, whereas polymetallic vein-type deposits in metamorphic rocks may contain significant percentages of Cu, Ni, Co, Bi, Ag, Au, or Se.

As noted in the classification of vein-type deposits in metamorphic rocks (Mathews, 1978), the reasons for different elemental compositions of uranium veins in metamorphic rocks are not known. Composition may be a function of the source rocks, the ability of the transporting medium to either transport the elements together or to fractionate them, and the setting with respect to major tectonic elements.

Alteration

Although the extent and types of alteration associated with vein-type uranium deposits in metamorphic rocks are variable, chloritization and hematitization predominate. Both these alteration types are present in varying degrees in most deposits of this class. Hematitization is common and often widespread. There is a gross correlation between the degree of hematitization and the amount of uranium. In general, the more extensive and pervasive the hematitization, the more enriched is the uranium deposit. There are, however, local areas within these deposits which are relatively rich in uranium and which show no evidence of hematitization. Conversely, other areas which are heavily hematitized contain no uranium. Hematitization is often distributed peripheral to the associated major structures.

Chloritization is the second major type of alteration associated with vein-type deposits in metamorphic rocks. Retrogressive metamorphic effects of chloritization are found along and in rocks adjacent to the major structures. The extent of chloritization varies along the structures and seems to be dependent on the type of rock being altered. Chloritization does not appear to have the gross relationships with pitchblende concentrations that hematitization does.

Some vein-type deposits in metamorphic rocks show evidence of hydrothermal alterations including propylitic alterations of some intermediate metavolcanic rocks. Argillic alteration along some of the fracture systems may also be encountered.

Geometry

Vein-type uranium deposits in metamorphic rocks are steeply dipping, tabular bodies; they are generally narrow and have long horizontal extents. They generally extend to several hundreds of meters below the surface. This is in contrast to unconformity-related deposits, which are usually confined to within 100 m of the unconformity surface. Vein-type deposits in metamorphic rocks may occur as individual veins (in the Port Radium area, for example) or as a series of complex, anastomosing veins and veinlets whose overall width may be up to 50 m.

Some vein-type deposits in metamorphic rocks become thicker with depth. Surface expression of these veins may be very minimal, and they may appear as only a single, thin, knife-edge seam of pitchblende in the host rock. The hematitized aureole around the thin seam on the surface might also be very narrow. Deposits of this type could easily be overlooked in the field.

Lithologic and Structural Associations

Lithologic associations of vein-type uranium deposits in metamorphic rocks have been discussed above (p. 235).

Vein-type uranium deposits in metamorphic rocks are associated with large, steeply dipping structural zones which are marked by cataclasis and mylonitization. Pitchblende mineralization does not always occur within the major structures, however. In some deposits, the major structural zone is devoid of pitchblende; instead, the pitchblende occurs as veinlets in minor, parasitic fractures adjacent to the major structures and as finely disseminated crystals in host rocks between the fractures. Pitchblende may be concentrated in wide mylonite zones or in closely spaced fracture systems. In the Beaverlodge area of northern Saskatchewan, pitchblende seems to be most highly concentrated along minor cymoid fractures within a larger cymoid complex. Intersections of cymoid fractures are the most favorable sites for uranium deposition in the Beaverlodge area. Other vein-type deposits in metamorphic rocks have not been described as being associated with cymoid structures, particularly quartz-vein-type deposits.

Resource Potential

Vein-type uranium deposits in metamorphic rocks vary from small shows to large, economically important deposits. One cannot ascertain the tonnage of a given deposit from the surface expression; drilling is necessary for grade-tonnage relations. Therefore, vein-type uranium deposits in metamorphic rocks must be considered submarginal to recoverable resources. Polymetallic vein-type deposits in metamorphic rocks may economically yield uranium as a by-product.

EXAMPLE OF A MONOMETALLIC VEIN-TYPE DEPOSIT IN METAMORPHIC ROCKS (SUBCLASS 721)

Beaverlodge Area, Northern Saskatchewan, Canada

The following synopsis of the Beaverlodge area is adapted from MacDonald and Kermeen (1956), Beck (1970), Morton and Sassano (1972), Sassano and others (1972), and Tremblay (1970, 1972, 1978).

The Beaverlodge area is located on the north shore of Lake Athabasca in northern Saskatchewan. It is perhaps the most extensively studied area of pitchblende vein deposits in North America. The regional geology, vein mineralogy and paragenesis, and the structural setting of the veins have been well established. The origin of the pitchblende in the veins is still conjectural, however.

The Beaverlodge area is underlain by highly metamorphosed and granitized orthogneiss and paragneiss of the amphibolite facies of metamorphism (the Tazin Group). These rocks were strongly deformed, metamorphosed, and granitized during the Hudsonian orogeny. They are unconformably overlain by taphrogenic, continental red beds of the Martin Formation.

Pitchblende, associated with calcite gangue, occurs in veins and multiple-vein systems within the Tazin Group; minor amounts of pitchblende occur in the overlying Martin Formation. The uranium-bearing veins are closely associated with a major fault (St. Louis fault) and have an overall strike length of more than 15,000 ft; they extend to a depth of at least 5,400 ft. Two modes of pitchblende occurrences are present: (1) distinct veins and (2) disseminations in the rocks adjacent to the veins. Although the pitchblende veins are in close proximity to the St. Louis fault, no uranium minerals are found in the fault plane itself. Most of the ore is located in closely spaced shears and fractures and in highly brecciated zones within a few hundred feet of the St. Louis fault. Pitchblende appears to be confined to a specific stratigraphic interval within the Tazin Group (the Fay complex). A small amount of brannerite occurs in the lower levels of the Fay-Ace-Verna mine complex.

Several different types of alteration have been noted in the Beaverlodge area. Feldspathization, which may be related to granitization of the Tazin Group, is very widespread. Chloritic and hematitic alterations are also very common, particularly in areas of disseminated pitchblende.

Two distinct generations of chlorite development have been recognized. The first and most pervasive episode of chloritization is reflected in the widespread retrogressive metamorphism of the Tazin rocks. It preceded pitchblende deposition. The second episode of chlorite development was contemporaneous with initial pitchblende deposition. Hematitic alteration is common, although it is not universally associated with pitchblende concentrations. Some highly hematitized rocks contain little or no uranium. Conversely, some small pitchblende veins have no associated red alteration.

At least two episodes of uranium mineralization have been recognized in the Beaverlodge area. Initial pitchblende deposition occurred 1,780 m.y. ago. Uranium was remobilized and redeposited during a thermal event 1,140 m.y. ago. Temperatures of mineralization ranged from 80° to 440° C.

Some debate exists in the literature regarding whether the Beaverlodge deposit is a vein-type deposit in metamorphic rocks or an unconformity-related deposit. The large vertical extent, the high initial deposition temperatures, and the relation to the St. Louis fault and its associated cymoid structures all suggest hydrothermal deposition of pitchblende in structurally and lithologically favorable areas. A block of rock, which has been tentatively identified as a horse of Martin Formation caught up along the St. Louis fault, occurs deep in the mine. If this rock is indeed the Martin Formation, then the criterion of close proximity to a major unconformity is met; the deposit may be unconformity-related. However, some workers believe the block of "Martin Formation" is a highly brecciated and altered block of Tazin Group rocks, in which case the vein-type deposit at Beaverlodge may not be unconformity-related.

EXAMPLE OF A POLYMETALLIC VEIN-TYPE DEPOSIT IN METAMORPHIC ROCKS (SUBCLASS 722)

Echo Bay/Eldorado Mines, Northwest Territories, Canada

The following summary of the Echo Bay/Eldorado deposit is taken from descriptions given by Ruzicka (1971), Robinson (1972), and Robinson and Ohmoto (1973).

The Echo Bay and Eldorado uranium-silver mines are in the same vein system in the Bear Province of the Northwest Territories, Canada. The veins containing U, Ag, Ni, and Cu are located in roof pendants of Aphebian sedimentary and volcanic rocks (the Echo Bay Group) within a Hudsonian granitic intrusive. The margins of the roof pendant have been affected by thermal metamorphism to varying degrees; the centers of the roof pendants, in which the Echo Bay/Eldorado deposit is located, have been only slightly deformed and metamorphosed (lower zeolite facies).

The Echo Bay Group is a thick series of tuffs, porphyritic andesite flows, and interlayered clastic sedimentary rocks. The mineralized veins occur in green-and-red-banded andesitic tuffs near the base of the Echo Bay Group.

Three steeply dipping veins constitute the Echo Bay/Eldorado deposit. They have an average thickness of 0.5 m and a strike length of about 1,500 m; they have been mined to a depth of 400 m. The veins are surrounded by an alteration halo of feldspathization, hematitization, chloritization, and carbonatization. The alteration halo is up to 3 m wide. The veins contain pitchblende and native silver and bismuth, accompanied by smaller percentages of base-metal sulfides and Co-Ni arsenides. Gangue minerals include quartz, chlorite, and carbonate.

Several stages of minerogenesis have been recognized in the Echo Bay/Eldorado deposit. Hematitization and silicification preceded pitchblende deposition, which was followed by deposition of Co-Ni arsenides, native silver, and native bismuth. A sulfide-carbonate-mineralization stage came next and was followed by a second episode of native-silver deposition.

Temperatures of mineralization, as determined by geothermometry of mineral pairs, oxygen-isotope studies, and fluid-inclusion data, show an increase from 120°C in the early stages, to approximately 200°C in the middle stages; the final episode of mineralization occurred at about 95°C. Oxygen- and sulfur-isotope data, in addition to the occurrence of hematite early in the paragenetic sequence suggest an initial high oxidation potential of the hydrothermal solutions. The paragenetic sequence indicates that the transporting solution became progressively more reducing through time. The origin of the hydrothermal solutions is unknown. Isotope data suggest that saline surface waters may have composed a significant percentage of the solutions.

VEIN-TYPE DEPOSITS IN SEDIMENTARY ROCKS (CLASS 730)

In contrast to other classes of uranium occurrences in sedimentary rocks (Jones, 1978), vein-type deposits in sedimentary rocks are mainly controlled by structure. They are epigenetic deposits in brecciated, tabular bodies and pipe-like structures oriented transverse to stratification. The source of the uranium, its mode of transport into the system, and the mechanism by which it is deposited are not known. The fact that these deposits contain low concentrations of thorium suggests that the uranium was transported into the system in the hexavalent state. Because tetravalent-uranium minerals contain the bulk of the uranium in deposits of this class, it is essential that the uranium be reduced at the depositional site. The mechanism by which reduction occurs is speculative. It may be partly due to temperature, pressure, and pH changes during the upward migration of uranium-bearing solutions (Mathews and Pilcher, in prep.). It is possible that the very low Th/U ratios were inherited from the source rocks.

Not all uranium-bearing structures in sedimentary rocks show a discernible relationship to other, larger-scale structural elements. Whereas some pipe-like structures are spatially associated with folds (Temple Mountain, Utah, for example), others, such as the Orphan Mine, Arizona, have no apparent structural associations. Tabular vein systems may be related to a regional fracture pattern.

The origin of some of the structures containing vein-type deposits is conjectural. Several deposits occur in pipelike structures in areas which lack evidence of significant volcanic activity. These areas are structurally stable and underlain by massive carbonate and (or) evaporitic units. The roughly cylindrical, pipelike structures may terminate at depth in a carbonate unit; they may have formed by solution collapse and may represent multiple stages of development. Other possible origins for these structures are cryptovolcanic explosions and (or) pipe-drilling by gases evolved from an underlying magma. There is no evidence supporting these latter hypotheses.

GEOLOGIC CHARACTERISTICS

Because the origin of vein-type uranium deposits in sedimentary rocks is not known, establishment of definitive recognition criteria cannot be based on a genetic model. The criteria discussed below are empirical and are based on published descriptions.

Tectonic Setting

Vein-type uranium deposits in sedimentary rocks occur in areas of thick sedimentary sequences and moderate structural deformation. Structurally stable areas are more likely to develop solution-collapse structures than are areas of extreme deformation, because of the necessity of a suitable hydrologic system. Highly deformed and faulted areas often contain structurally controlled channelways for ground-water percolation and, therefore, provide less containment of ground-water flow in specific stratigraphic horizons.

Tabular vein-type deposits may be associated with regional fractures, shear systems, and (or) growth faults.

Lithology

Vein-type deposits in pipelike collapse structures consist of a wide variety of rock types. The nature of the rocks composing a collapse structure depends on the rock units overlying the structure at the time of its development, the amount of underlying material removed by solution, and the vertical stratigraphic section affected by the resultant collapse. Blocks of sandstone, siltstone, shale, and carbonates may occur in the collapse structure. Sandstone and, to a lesser extent, siltstones are important sites of uranium mineralization.

Breccia fragments within tabular vein-type deposits in sedimentary rocks are usually limited to blocks of the host-rock units(s). Little evidence of either downward collapse of superjacent or upward transport of subjacent lithologic units is encountered.

Texture

Vein-type uranium deposits in sedimentary rocks are characterized by brecciated, cataclastic textures, in which fragments of varying size and lithology are set in a matrix of finer-grained material. Mylonitization is minimal. Pipelike structures consist of a chaotic complex of breccia fragments of stratigraphically higher lithologic units. Tabular vein-type uranium deposits consist of fragments of the surrounding host rock unit(s).

Mineralogy

The mineralogy of the matrix and the down-dropped blocks within pipelike structures containing vein-type deposits in sedimentary rocks is variable. It depends on the nature of the rocks affected by the collapse, the type and extent of alteration, and the cementation.

Pitchblende is the principal uranium mineral in deposits of this class. It occurs in small veinlets along fractures within and surrounding the structures and as finely disseminated crystals in porous breccia fragments within the structures. Pitchblende concentrations may be zonally distributed within the ore; it is often more concentrated in the upper levels of the structures.

Epigenetic minerals accompanying pitchblende are variable; they depend on the composition of the source, the nature of the mineralizing solutions, and the paragenetic sequence of mineral development. Polymetallic varieties of vein-type deposits in sedimentary rocks may contain several associated minerals. Sulfides and sulfarsenides are commonly associated with pitchblende. Associated minerals may be partially segregated from pitchblende and may show a crude, ill-defined zonal distribution within the deposit.

Calcite and quartz are common gangue minerals associated with pitchblende, sulfides, and sulfarsenides in deposits of this class. Asphaltite is associated with pitchblende in the Temple Mountain, Utah, occurrence.

Chemistry

Because of the wide mineralogical and lithologic variability in vein-type deposits in sedimentary rocks, chemical composition is not an adequate recognition criterion. Chemistry varies as a function of the composition of the rocks involved in the uranium-bearing structures, the elements associated with uranium, and the type and extent of alteration. Perhaps the only significant chemical characteristic in deposits of this class is the very low Th/U ratio. Trace-element contents are highly variable. There may be a correlation between trace-element abundances within the deposits and those in the sedimentary rocks elsewhere in the district. If this can be demonstrated, it might suggest a fairly local source for the uranium.

Alteration

Various types of alteration are common in vein-type uranium occurrences in sedimentary rocks. They are often zonally distributed, with the most intensely altered rocks within the ore deposit and less-altered rocks in adjacent sedimentary units. The roughly circular fracture zone surrounding pipelike structures often marks an abrupt change in the degree of host-rock alteration. Tabular vein-type deposits generally have a more gradual decrease in alteration intensity with increasing distance into the host rocks.

Bleaching of normally red host rocks is perhaps the most universally observed alteration associated with vein-type deposits in sedimentary rocks. Porosity and permeability of the affected host rocks appear to govern the width of the bleached aureole around the deposits; the bleached zone is narrowest in siltstones and shales and widest in sandstones. Breccia fragments within the pipelike structures and tabular vein systems are commonly highly bleached. The cause(s) of the bleaching of the host rocks is not known. It may be a function of a gradual increase in the reducing nature of the uranium-transporting solution. Evidence of hydrothermal alteration and argillization is either lacking or is very minimal.

Silicification and carbonatization may affect sedimentary host rocks containing vein-type deposits. Paragenetic relations indicate that deposition of silica and carbonate minerals is normally either synchronous with or follows deposition of pitchblende. Argillic alteration, although not pronounced, has been noted in the Temple Mountain, Utah, occurrence (Hawley and others, 1965).

Geometry

Vein-type uranium deposits in sedimentary rocks occur in two general forms: pipelike and tabular. Pipelike structures have the general shape of cones which become progressively narrower with depth. These structures have a limited vertical extent and appear to terminate in a specific stratigraphic unit. The vertical extent of the pipes rarely exceeds a few hundred feet. They are roughly circular in plan. The pipes consist of an inner zone of brecciated, down-dropped blocks, surrounded by a steep, inward-dipping, circular fault system.

Tabular orebodies comprise veins and vein systems whose lateral extent greatly exceeds their thickness. Breccia fragments of the surrounding host rocks compose the ore zones. Primary uranium minerals occur as finely disseminated grains within the breccia fragments and as coatings on the fragments.

Lithologic and Structural Associations

Vein-type uranium deposits in sedimentary rocks have no specific rock associations. The pipelike structures may be associated with soluble rock at depth. Such an underlying rock, commonly a massive carbonate body and the cause of the solution collapse, is not generally exposed.

The dominant association of vein-type deposits in sedimentary rocks is with structure. Pipe structures are ringed by a series of concentric normal faults. Minor faults and collapse structures may be found within the pipes. Uranium and other epigenetic minerals are often concentrated along the concentric fracture zones. A vertical, subpipe fracture might be postulated; such a fracture might be a conduit for upward-migrating mineralizing solutions. However, such an associated feature would not be generally exposed, it must be inferred, and, therefore, it is not an adequate recognition criterion.

Resource Potential

Vein-type uranium deposits in sedimentary rocks are currently of little economic importance. Although some have produced small amounts of uranium (Temple Mountain, Utah, for example), most vein-type deposits in sedimentary rocks are of submarginal economic value. Uranium might be recovered as a by-product from deposits containing economic concentrations of associated metals.

EXAMPLE OF A VEIN-TYPE DEPOSIT IN SEDIMENTARY ROCKS

Orphan Mine, Arizona

The following description of the Orphan mine is summarized from Gornitz and Kerr (1970).

The Orphan mine, Grand Canyon National Park, Coconino County, Arizona, is located in a roughly cylindrical, vertical, pipelike structure, which consists of brecciated, down-dropped fragments of upper Paleozoic sedimentary rock units. The margins of the pipe are marked by circular fractures, which may be tensional features formed during collapse. The uranium-bearing structure appears to terminate in the underlying Redwall Limestone and probably developed by solution collapse. Alternative hypotheses for the origin of the pipe are: (1) collapse caused by magma withdrawal, (2) a deep-seated volcanic explosion which did not vent at the surface, and (3) explosive drilling by magma-derived gases. Gornitz and Kerr found no evidence in the Orphan mine area to support these latter hypotheses.

Uraninite is the principal uranium mineral in the deposit. It is associated with paramarginal concentrations of chalcocite, chalcopyrite, and tennantite, and with calcite gangue. Uraninite is most concentrated in the circular fracture zones around the margins of the pipe; it also occurs as finely disseminated, irregular masses within porous breccia fragments in the pipe core. Some uraninite is found in the matrix between the breccia blocks.

Uraninite deposition was controlled largely by structure; no pre-uranium reductants are found in the host rocks. Blocks of porous sandstone contain more uraninite than do blocks of siltstone or shale. Therefore, uranium deposition was at least partially governed by lithology.

A general lateral and vertical zonation of the ore minerals has been recognized. Uraninite concentrations increase upward and outward toward the margins of the pipe. Copper mineralization is most intense in the lower levels of the pipe.

Alteration associated with the uranium and copper mineralization consists in bleaching of the normally red sandstones, development of hematitic halos around uraninite crystals, and calcite cementation of the pipe matrix and porous breccia fragments. No argillic alteration has been recognized.

Depositional temperatures of between 60° and 110°C have been determined through fluid-inclusion studies on the calcite gangue. Since the calcite formed late in the paragenetic sequence, these temperatures may be lower than the temperature of the preceding uraninite deposition.

Uranium-bearing solutions are hypothesized to have traveled upward along a subpipe fracture system. They eventually entered the concentric marginal fractures and the brecciated core of the pipe. Reduction of uranyl ions by bacterially generated H₂S caused simultaneous precipitation of uraninite and copper sulfides and sulfarsenides.

RECOGNITION-CRITERIA SUMMARY

+ = Strong criterion

- = Weak criterion

o = Unevaluated criterion

RECOGNITION CRITERIA	UNCONFORMITY-RELATED	VEIN-TYPE, METAMORPHIC	VEIN-TYPE, SEDIMENTARY
TECTONIC SETTING	page 225	235	241
Shield area	+	+	
Stable platform			+
HOST-ROCK LITHOLOGY	page 225	235	242
Metamorphic	+	+	
Sedimentary	-		+
TEXTURE	page 226	236	242
Foliated	+	+	
Granoblastic	-	+	
Clastic	-		+
Brecciated	+	+	+
Crystalline	+	+	+
MINERALOGY	page 226	236	242
U ⁺⁴ minerals	+	+	+
U ⁺⁶ minerals		-	-
Chlorite	+	+	-
Graphite	+	-	
Hematite	-	+	-
Carbonate	-	+	+
Sulfides/sulfarsenides	+	+	+

RECOGNITION-CRITERIA SUMMARY

+ = Strong criterion

- = Weak criterion

o = Unevaluated criterion

RECOGNITION CRITERIA

	UNCONFORMITY-RELATED	VEIN-TYPE, METAMORPHIC	VEIN-TYPE, SEDIMENTARY
GEOMETRY	page 228	237	244
Tabular	+	+	+
Amoeboid	+		
Pipe			+
ASSOCIATIONS	page 228	238	244
Unconformity	+		
Faults/shears	+	+	+
Pipe			+
ALTERATION	page 227	237	243
Hematitization	+	+	-
Chloritization	+	+	o
Argillization	-	-	-
Silicification	-	+	+
Carbonatization	-	+	+

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