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Notes on the Geology of Uranium

GEOLOGICAL SURVEY BULLETIN 1046-F

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By M. R. KLEPPER *and* D. G. WYANT

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By M. R. Klepper and D. G. Wyant

ABSTRACT

These notes concerning the geochemistry of uranium and its behavior during orogeny, the types, size, grade, and distribution of uranium deposits, and the discernment of broad areas in which different types of uranium deposits are to be sought, are the product of a survey of much of the pertinent world literature available by 1954; the survey is supplemented by the results of unpublished work by colleagues and by their views as well as the authors' views. The paper is incomplete and contains generalizations that are probably based on insufficient facts. Because of the rapid developments in uranium geology, some parts of the paper are almost certain to be dated before publication. It can justly be criticized for these and other shortcomings, but if it is of some help in the search for and evaluation of uranium deposits it will have served its purpose.

Igneous processes tend to concentrate uranium in late-phase differentiates of magmas, notably in carbonatites, pegmatites, small alkalic plutons, and in veins and other epigenetic deposits. The concentrations in igneous rocks are syngenetic. Some relatively small plutons or dikes rich in soda or potash in the apical and peripheral parts of larger intrusive masses or surrounding wall rock contain millions of tons of rock that may average as much as 0.01 percent uranium, along with small quantities of thorium, niobium, and tantalum. No concentrations of this type have yet been exploited successfully. Many zoned pegmatites in uranium provinces contain specimen quantities of some or many of the complex four-valent uranium minerals and their six-valent uranium alteration products. Few contain or have yielded significant amounts of uranium, although some in Saskatchewan, Canada, contain large tonnages (1,000 tons per vertical foot) of ore grading 0.08 to 0.2 percent uranium oxide. Carbonatites, peculiar calcite-bearing pegmatites or pegmatitic veins, are commonly uraniferous and some may constitute low-grade uranium "ore." With the exception of a few large, low-grade uraniferous pegmatites, the syngenetic uranium deposits in igneous rocks are likely to be important mainly as source material for exploitable placer deposits of refractory uranium minerals, and for soluble uranium. These uraniferous igneous rocks are to be sought among the acidic and alkalic igneous rocks of ancient shields and massifs or within more recent orogenic belts.

Vein and other epigenetic deposits formed by igneous or metamorphic processes are generally relatively small, but some are of high grade. Most of the world production of uranium, until about 1954, came from vein deposits of pitchblende. For discussion, pitchblende veins may be divided into those containing few associated minerals, those containing cobalt and nickel sulfides and sulfosalts, and those containing base-metal sulfides. Many, if not most important deposits, are mesothermal fissure fillings in thin units of competent rock within structurally

complex shields and massifs containing metamorphic rocks and highly differentiated alkalic or silicic rocks. Ore shoots are commonly discontinuous and irregular in shape. Deposits commonly contain from a few tens to a few thousands of tons of uranium in ore grading a few tenths to several percent uranium. Many, and perhaps most of the important epigenetic deposits of undisputed igneous crigin are of the pitchblende-cobalt-nickel type, are characterized by hematitic alteration, and are in uraniferous provinces.

Weathering and sedimentary processes may either disperse or concentrate uranium, depending primarily on climate. Some primary and relatively insoluble uranium minerals accumulate in placers, which are syngenetic deposits. Placers, either beach or stream, commonly contain only weakly uraniferous minerals; consequently, even large placers are likely to yield only small amounts of uranium as a byproduct of gold, tin, titanium, and other valuable placer minerals. Uraniferous placers are to be sought in, or where streams flow through, areas of acidic or alkalic igneous rocks in deformed and intruded belts of shields and massifs. Other primary uranium minerals are dissolved and the uranium is tranported by ground and surface water, from which it may be precipitated in favorable receptors to form epigenetic deposits. The most important deposits so-formed are the many uraniferous lignite and low-rank coal deposits. In many deposits of uraniferous lignite and coal, hundreds of thousands of tons contain 0.005 to 0.01 percent uranium, and smaller but richer deposits are known. Such deposits should be sought in structural basins containing or bordered by acidic igneous rocks, especially volcanic rocks; they are generally in areas of arid or semiarid climate.

Some uranium in solution reaches the sea and may be precipitated to form large low-grade syngenetic accumulations in phosphorite or black shale. Only those phosphate deposits of marine origin, or those of other origin exposed to sea water at some time, contain more than 0.01 percent uranium. The richest and largest deposits are bedded or plate phosphorite containing less than 2 percent CO_2 and more than 25 percent P_2O_5 that were deposited on the slope between the platform and the geosyncline before orogeny. The richest and largest deposits of uraniferous marine carbonaceous shale are laminated, black, carbon-rich, relatively thin units of Paleozoic age; they contain lenses, nodules, or disseminations of pyrite and commonly small quantities of rare earths, titanium, copper, vanadium, manganese, nickel, chromium, cobalt, molybdenum, and phosphorus. They were deposited slowly on the marginal part of platforms adjacent to geosynclines.

Metamorphic processes may affect concentrations of uranium either by converting preexisting rocks to magma, which subsequently may form uranium-rich differentiates, or by "sweating" uranium out of large volumes of weakly uraniferous rocks and concentrating it in favorable geologic settings.

Sandstone-type uranium deposits and uraniferous conglomerates have supplied the bulk of world production of uranium since about 1954 and probably constitute the world's largest resource of uranium ore. Most geologists agree that these deposits are epigenetic, but the source of the uranium and of the transporting solutions is controversial. Uranium deposits of the sandstone-type commonly comprise lenticular ore bodies localized in stratigraphic traps or organic-rich parts of favorable formations. Favorable formations comprise dominantly permeable, nonmarine, partly red, clastic rock units composed largely of clayey sandstone, and subordinately of mudstone, siltstone, conglomerate, and limestone. Most deposits contain from a few tons to perhaps 100,000 tons of ore ranging in grade from 0.2 to 0.4 percent uranium but some are richer; several deposits of this type contain millions of tons of ore. Uranium deposits of the sandstone-type should be sought within the broad areas containing the gently folded and faulted consolidated debris derived from secondary orogenic mountains that were cored by acidic and alkalic igneous rocks.

Conglomerates of the Witwatersrand, South Africa, and in the Blind River district of Ontario, Canada, contain millions, possibly billions, of tons or ore ranging in grade from a few hundredths to 0.1 percent uranium. The deposits are in widespread, thin units of well-sorted quartz-conglomerate in Precambrian quartzite sequences. Uraninite and coffinite(?), associated with carbonaceous material, gold, monazite, brannerite and other refractory placer minerals are typically concentrated in elongate, braided, ore shoots. They are in the marginal parts of Precambrian shields.

Most of the world's important uranium deposits are clustered in a few areas or provinces that perhaps represent uranium-rich portions of an originally inhomogeneous crust. These uranium-rich provinces seem to persist through long periods of geologic time. Within them, some types of uranium-rich rocks and uranium deposits may be relatively short lived, depending on the geologic history and climate; but as they are destroyed by erosion or metamorphism others in equilibrium with the prevailing environment may form. Indicators of a uranium province are the presence of a variety of types of uranium deposits and of uranium-rich rocks and waters. A strong clue to the existence of a uranium province would be a single epigenetic deposit in a geologically favorable area. Once an area is known or suspected to be a uranium province every possible setting in which uranium might be localized should be searched.

INTRODUCTION

Prior to about 1940 uranium was a commodity of slight importance and little was known about its occurrence or its geochemical behavior. Since 1944, however, this element has been studied more exhaustively than any other, and a great deal of information on the geology of individual deposits and type of deposits and on geochemistry and distribution or uranium has been published. The present report is an attempt to synthesize this great volume of diverse information and to point out features that may be important in searching for and appraising uranium deposits. The report deals with processes that concentrate uranium; describes types of uranium deposits; and discusses the clustering of uranium deposits within provinces, and provides some clues for prospecting and appraisal.

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GEOCHEMISTRY OF URANIUM

The formation of exploitable uranium concentrations depends on many geologic factors and in some places on climate as well. The geochemical processes involved are to a large extent actuated by orogenic events. Accordingly, a review of the geochemical behavior of uranium and the tectonic settings that seem to be favorable for uranium concentration is pertinent. To provide a basis for the discussion some data on the abundance and distribution of uranium are summarized as follows:

ABUNDANCE AND DISTRIBUTION OF URANIUM

Data on the uranium content of rocks and fluids are relatively sparse, and consequently estimates of the abundance and distribution of this element in the earth's crust are approximations, though probably of the correct order of magnitude. Estimates of Urey and Brown (*in* Urey, 1952, p. 233) indicate that uranium is the least common element in the earth, having an atomic abundance of 0.0002 (silicon=10,000). However, the abundance of uranium in the earth's crust is estimated by Fleischer (1953, fig. 2) to be 0.0002 percent, or about the same as that of tungsten and tantalum. Estimates of the uranium content in various materials of the earth's crust are listed on the following page.

MINERAL PHASES OF URANIUM

According to Frondel and Fleischer (1955, p. 170), about 103 minerals may contain uranium as a major component (more than 1 percent uranium). In about one-quarter of these minerals the uranium is tetravalent and in about three-quarters of them, hexavalent. Fifteen of these uranium minerals are simple oxides or hydrated oxides, 20 are complex titanates and niobates, 14 are silicates, 17 are phosphates, 10 are carbonates, 6 are sulfates, 8 are vanadates, and 8 are arsenates (Frondel and Fleischer, 1955, p. 171–173). Unidentified uranium compounds occur in some marine carbonaceous shale, lignite, and coal, and possibly as intergranular films in igneous rocks. The principal uranium minerals in the larger ore deposits are the oxides pitchblende and uraninite, the silicate coffinite, the vanadates carnotite and tyuyamunite, and the complex titanates brannerite and davidite. Uranium is not known in nature as a native element or as a simple sulfide, arsenide, or telluride.

Estimates of uranium content in materials of the earth's crust, in percent

[Data from the following sources, weighted or averaged by the authors: Green, 1953; Fleischer, 1953; Rankama and Sahama, 1950; Davidson, 1951; Davis and Hess, 1949; Tomkieff, 1946; Senftle and Keevil, 1947; Evans and Goodman, 1941]

	Typical uranium content	*Maximum uranium content in exploitable deposits*
Meteorites:		
Iron meteorites	0.0000001	----------
Silicate meteorites	.00004	----------
Rocks:		
Ultrabasic igneous rocks	.0001	----------
Basic igneous rocks [1]	.0001	----------
Intermediate igneous rocks [1]	.0002	----------
Acidic igneous rocks [1]	.0004	----------
Limestone	.0001	----------
Shale	.000X	----------
Sandstone	.0001	----------
Water:		
Sea water [2]	.00000013	----------
River water [2]	.0000001	----------
Ground water [3]	.0000005	----------
Abnormally rich rocks and ore deposits:		
Marine phosphorite [4] [5]	.01	0.02
Marine black shale [5] [6]	.00X	.02
Placer deposits [5] [7]	.001	.005
Lignite and coal [5] [8]	.00X	.X
Pegmatite [5] [9]	.00X	.2
Nigerian riebeckite-albite granite [10]	.01	.01
Vein deposits [5] [11]	.X	1.0
Sandstone-type deposits [5] [12]	.X	1.0
Uraniferous conglomerate [13]	.1	.1-.2

[1] In general the uranium content of plutonic rocks may be a little lower than the figure listed and that of volcanic rocks of comparable composition a little higher.

[2] Koczy *in* Faul, 1954.

[3] R. L. Nace, written communication.

[4] McKelvey and Nelson, 1950; Barr, 1954.

[5] Ruch, 1954; Bain, 1950; Butler, 1952; U. S. Geological Survey, 1953, 1954a, 1954b, 1954c, 1955.

[6] Gott, Wyant, and Beroni, 1952; Duncan, 1954.

[7] Anonymous, 1954a, Bain, 1950; and miscellaneous published and unpublished data.

[8] Davidson and Ponsford, 1954 and miscellaneous published and unpublished data.

[9] Page, 1950 (and written communication); Mawdsley, 1952.

[10] Mackay and Beer, 1952.

[11] Lang, 1952; McKelvey, 1955; Everhart and Wright, 1953; Bain, 1950; and many articles and notes in Engineering and Mining Journal and other technical journals.

[12] Fischer, 1942, and many articles and notes in technical journals.

[13] Traill, 1954; MacKay, 1954; Stokes, 1954; and many other articles and notes in various technical journals.

PROCESSES THAT CONCENTRATE URANIUM

The concept of the geochemical cycle (Goldschmidt, 1922b; Rankama and Sahama, 1950, p. 189–190, 243–263, 636–638; Mason, 1952, p. 247–254), though idealized and imperfectly known, provides a means of relating the processes that concentrate uranium to the geologic history of an area and thus perhaps predicting where concentrations of uranium are likely to occur and what the potential of a particular area may be. It is convenient to think of the geochemical cycle as consisting of three phases that grade into one another: one in which igneous processes prevail, one in which weathering and sedimentary processes prevail, and one in which metamorphic processes prevail. During the igneous and metamorphic phases of the cycle magma is generated, emplaced, and consolidated; preexisting rocks are metamorphosed; and uranium deposits of igneous and metamorphic origin are formed. During the weathering and sedimentary phase preexisting rocks and ore deposits are weathered and eroded, uranium is transported, and may be concentrated in the sediments that are accumulated and lithified.

IGNEOUS PROCESSES

The generation of a magma, its upward movement and crystallization, and the exposure of the resulting igneous rock is a part of the orogenic cycle. How a magma forms cannot be considered here, but its formation is the first step in concentrating uranium. The uranium content of rocks crystallized from a magma increases rather constantly from the oldest to the youngest and thus in a general way uranium follows the same path as silica, the alkalis, and a number of rare elements such as thorium, beryllium, niobium, tantalum, and the rare earths (Rankama and Sahama, 1950; Larsen and Gottfried *in* U. S. Geological Survey, 1953; Billings and Kevil, 1946; Adams and Saunders, 1953).

The earliest magmatic differentiates consist chiefly of olivine, pyroxene, and calcic plagioclase—minerals that tolerate only negligible quantities of uranium in their crystal lattices. Consequently, rocks composed of these minerals generally contain less than 1 part per million of uranium. Later differentiates contain significant amounts of biotite and accessory minerals. Some of these minerals, for example zircon, xenotime, and monazite, can accommodate in their crystal lattices from 10 parts per million to a few percent uranium, and the rocks containing them, such as granodiorite, syenite, and granite, commonly contain from 2 to 6 parts per million of uranium. The progressive increase in uranium content of rocks of the Southern California batholith from gabbro, the oldest, to granite, the youngest, is clearly demonstrated by Larsen and Phair (*in* Faul, 1954, p. 83). The youngest rocks in some alkalic and calc-alkalic series, for example albite-rich riebeckite granite in Nigeria (Mackay and Beer, 1952), quartz bostonite in Colorado (Larsen and Phair, *in* Faul, 1954, p. 87), and pegmatites from many widely scattered localities (L. R. Page, oral communication), contain from 10 to 100 parts per million (0.001 to 0.01 percent) of uranium, and a pegmatite in western Canada contains large tonnages of rock averaging 0.2 percent uranium (Mawdsley, 1952).

Recent investigations suggest that effusive rocks tend to be more uraniferous than their intrusive equivalents, possibly by a factor of 1½ or 2. Data assembled by Adams (*in* Faul, 1954) indicate a range from 0.8 to 15.4 and an average of 5.6 parts per million of uranium in about 50 volcanic rocks ranging from basaltic to rhyolitic composition and taken from many localities over the world. The data show that uranium increases directly as potassium increases and becomes progressively higher in more acidic rocks. Perhaps the best explanation of the higher average uranium content of effusive rocks is that most or all of the uranium is trapped in dispersed form during the crystallization of effusive magmas, whereas a significant part of the uranium in plutonic magmas is concentrated in residual fluids from which pegmatities and veins may form. This interpretation, if correct, substantiates the generally held belief that the most favorable settings for hydrothermal deposits of uranium are in the vicinity of plutons of acidic and alkalic rock.

In some of the relatively uraniferous igneous rocks most of the uranium is in the rather common accessory minerals, notably xenotime, zircon, monazite, and allanite (Billings and Keevil, 1946; Larsen and Gottfried *in* U. S. Geological Survey, 1953; Larsen *in* U. S. Geological Survey, 1954c) and in biotite. In others most of the uranium is in relatively uncommon uranium-rich accessory minerals such as uraninite, thorite, thorianite, brannerite, and euxenite.

Most igneous rocks also contain uranium in a form that is readily soluble in weak acids. Hurley (1950) found that as much as 90 percent of the total radioactive elements of some granites could be removed by leaching the granulated rock with weak acid. He postulated that leachable radioactive elements along fractures and on grain surfaces may have been due to "supergene enrichment" but he did not estimate what part of the total radioactivity might be due to uranium. Larsen and Phair (*in* Faul, 1954, p. 80) note that "commonly, as much as 40 percent of the uranium in most fresh-appearing igneous rocks is readily leachable." They suggest that

> this leachable radioactivity [uranium] may occur (1) in metamict phases of primary silicates [presumably such accessories as zircon, allanite, and thorite], (2) as interstitial material derived from late magmatic, deuteric, or hydrothermal solutions, (3) in certain non-metamict partly soluble radioactive accessories, such as apatite, and (4) as adsorbed ions in disseminated weathering products such as iron oxide.

Bowie (in Davidson, 1951, p. 330) using autoradiographs found that ". . . in an unaltered granite the heavy minerals [accessories] account for nearly all the radioactivity, . . ." but, "in rocks slightly altered by pneumatolysis or by ground waters the radioactive elements become distributed along cracks within and as coatings to the feldspars and quartz."

The origin and nature of this acid-soluble material is not yet established, but its presence has several important implications. First, it suggests that significant quantities of uranium can be leached from igneous rocks by acidic ground water and perhaps later be concentrated as secondary deposits in coal or other sedimentary rocks. Secondly, the possibility that some of this acid-soluble material may be a sample of the last-crystallized fraction of a magma suggests that a close relationship may exist between the acid-soluble uranium in igneous rocks and uranium in veins and other types of epigenetic deposits.

Veins and other epigenetic uranium deposits of igneous origin are believed to have formed from the late differentiates of uranium-rich magma where structural conditions were favorable. Thus, much of the uranium-rich residual fluid probably drained off to form veins and other epigenetic deposits if through-going fractures tapped the magma chamber at the proper time. If fractures did not tap the chamber at an opportune time, most of the uranium in the residual fluids probably was trapped in the last igneous rocks to crystallize, partly in specific uranium-rich minerals and partly as soluble intergranular films in plutonic rocks, and perhaps partly in the glassy matrix of effusive rocks including volcanic ash as suggested by Koeberlin (1938, p. 458–61).

Information on the relationship of abnormally uraniferous igneous rocks and hydrothermal deposits of uranium is meager. Bain (1950, p. 282) noted a lack of hydrothermal uranium deposits in areas containing uraniferous pegmatites, but examples can now be cited of close spatial and close temporal association of abnormally uraniferous igneous rocks, including pegmatites, and hydrothermal uranium deposits. Some examples are:

(1) In the Colorado Front Range Late Cretaceous or early Tertiary pitchblende veins are intimately associated and probably genetically related to uraniferous quartz bostonite (Phair, 1952). Some pitchblende veins of the same age also occur in the vicinity of uraniferous Precambrian pegmatites.

(2) In the Erzgebirge and Riesengebirge of Saxony, Silesia, and Czechoslovakia uraniferous granite, uraniferous pegmatite, and pitchblende veins all considered to be about the same age, are closely associated (Kohl, 1942; Teuscher, 1936a and b; Hoehne, 1936; Klockmann, 1882).

(3) In the Goldfields region and at Stack Lake on the east arm of Great Slave Lake, both near the western margin of the Precambrian shield of Canada, uraninite-bearing pegmatites and pitchblende veins are in close association (Lang, 1952, p. 63, 71), though they may not be of the same age; furthermore, the important uraniferous pegmatite

at Charlebois Lake (Mawdsley, 1952) is only about 100 miles east of the Goldfield's pitchblende veins. In the Grenville subprovince, uraniferous pegmatites are abundant, and there are pitchblende veins, though none of them are commercially important at present. Important uraniferous carbonatites (calcite-fluorite pegmatites) also occur near Bancroft in this subprovince (Lang, 1952, p. 136–151).

Though these examples are too few to support a generalization, the writers are inclined to agree with Lang (1949, p. 5) that abnormally radioactive igneous rocks may be indicators of nearby hydrothermal uranium deposits. However, they are not necessarily so, for as noted above, tectonic events during the late stage of magmatic consolidation probably determine to a large extent whether most of the uranium in the residual magmatic fluids crystallizes in late-stage igneous rocks, such as pegmatites, or in veins, or in both. If most of the uranium was drained off at a late stage to form veins, the associated igneous rocks may not be abnormally uraniferous.

WEATHERING AND SEDIMENTARY PROCESSES

Weathering and erosion of uranium-rich igneous rocks and veins and uranium concentrations in sedimentary and metamorphic rocks releases uranium that may be either flushed out of the area or reconcentrated nearby in suitable environments.

Whether uranium is retained or exported from an area appears to depend largely on the climate, topography, and lithology of the area. Probably climate is the most important factor. In a humid climate the water table is high, weathering is intense, and the products of weathering tend to be clay minerals. As the drainage is to the sea, the uranium, whether in solution or adsorbed on particles of clay minerals, tends to be permanently removed from the area.

Conversely, in an arid climate, the water table tends to be relatively far below the surface, and in places is essentially nonexistent. Weathering tends simply to disaggregate existing rocks, and drainage is either intermittent toward the sea or centripetal. In such an environment the uranium brought near the surface by igneous activity cannot be readily exported from the area. Rain that extracts uranium from outcrops of igneous rocks or veins soon sinks deep into the soil or subsoil and may follow subterranean channels for great distances. In so doing the uraniferous water may traverse favorable lithologic types and uranium may be redeposited in new and perhaps much richer concentrations. Clay minerals do not form in great quantities and little uranium is lost by adsorption on clay particles. Certainly the western United States and the Fergana-Kara Tau area of the Soviet Union owe many of their secondary uranium concentrations to arid climatic conditions that have prevailed for millions of years.

Soluble uranium in ground and surface waters is concentrated in several ways: it may be extracted by organisms and incorporated in their tissues (Cannon, 1952); it may be precipitated as secondary minerals such as carnotite and schroeckingerite (Stugard, Wyant, and Gude, 1952); or adsorbed or absorbed by certain clays, organic and phosphatic material, and colloidal silica (McKelvey and Nelson, 1950); or it may be extracted to form organouranium compounds in petroleum (Gott, Wyant, and Beroni, 1952; Erickson, Myers and Horr, 1954). The deposits so formed probably include most uraniferous peat, lignite, coal, and petroleum residue and many deposits of secondary uranium or complex metal-uranyl phosphates, carbonates, vanadates, sulfates, arsenates, and others. (Denson and others 1952; Stugard, Wyant, and Gude, 1952).

Whether useful concentrations of uranium are precipitated from migrating fluids is probably largely dependent on the amount of uranium in the carrier, the continuity of flow within a restricted area over a long enough period of time, and the presence of suitable receptors or reagents, or favorable physical conditions such as alternate wetting and drying, or an interface between fluids, as well as the proper condition of Eh and pH, to remove uranium from solution.

Depths beneath the ground surface at which these uranium-bearing fluids may still actively migrate are unknown. The occurrence of deep oil pools, however, suggests that helium, carbon dioxide, petroleum and its gaseous derivates, and ground water move at depths of 15,000 feet or more.

At still greater depths these fluids probably are essentially stagnant unless activated by changes in temperature or pressure. Such changes might be brought about, for example, by heat from magma or by folding and faulting.

Many minerals that contain small to moderate amounts of uranium, such as monazite, zircon, xenotime, brannerite, samarskite, and euxenite, are relatively resistant to chemical and mechanical attack. These resistant minerals locally are concentrated in fluviatile or marine placer deposits in the vicinity of the source rocks, but the bulk of them are dispersed in terrestrial and near-shore marine sediments without significant concentration. Typically placers are ephemeral, but a few persist and become lithified. Some geologists contend that the uraniferous Witwatersrand and Blind River conglomerates of Africa and Canada are ancient placer accumulations that have been subsequently modified and perhaps enriched by hydrothermal solutions (Geological Society of South Africa, 1931), others contend that the deposits cannot be placers (Davidson, 1953; Traill, 1954), and some strongly advocate a hydrothermal origin (Graton, 1930).

Soluble uranium that is not extracted from ground and surface waters is carried to the sea. Apparently most of this uranium does not remain in solution long, for Goldschmidt (1937) and Russell (1945) have shown by different lines of evidence that nearly all the uranium that could have been eroded from the land throughout geologic time is in the sediments rather than in the sea water (McKelvey and Nelson, 1950, p. 44). Uranium may be extracted from sea water by organisms and incorporated in their tissues (Burkser, Shapiro, and Bronstein, 1929; Neuman, 1947), or it may be adsorbed or absorbed by certain clays and organic and phosphatic material (McKelvey and Nelson, 1950; Piggot, 1944). Part of the uranium removed by these processes is very sparsely dispersed in large volumes of sediment, but some is concentrated to a rather high degree (0.005 to 0.02 percent) in thin units of marine phosphorite and black organic shale that accumulated very slowly.

METAMORPHIC PROCESSES

When sedimentary rocks are deeply buried, generally during the deformation of geosynclines, they are transformed to a rock or liquid that is in equilibrium with its surroundings. At different depths and under the influence of different temperatures and pressures, either hydrostatic or directed, the rocks are metamorphosed to gneiss, schist, hornfels, and other rocks, and under extreme conditions are probably liquified to magma. As a result of these processes, fractionation and concentration of uranium may take place. In the melting of rocks the first liquid to form tends to resemble the last liquid fraction of a magma and be rich in silica, potash, alumina, and water, and probably also in uranium and other minor elements that tend to concentrate in residual granitic fluids. If this is so, some magmas produced by ultrametamorphism should be relatively rich in uranium, and, because of their relatively high water content, might be especially likely to yield uranium-rich hydrothermal solutions. Some support for this suggestion is the fact that most of the world's important vein deposits of uranium and many uraniferous pegmatites are in ancient shields or massifs (Bain, 1950, p. 289) where rocks probably have been subjected to at least one episode of ultrametamorphism.

It seems likely that migration of uranium, and perhaps its concentration also, may take place under less severe conditions of metamorphism (Sullivan, 1954). Many marine black shales contain appreciable quantities of syngenetic uranium, whereas few graphitic slates have been reported to contain abnormal quantities, though several examples of epigenetic concentrations in or near such rock can be cited. In the Rum Jungle area of northern Australia, deposits of uraninite and secondary uranium minerals with copper minerals occur in carbonaceous slate and graphitic schist (Sullivan and Matheson, 1952, p. 754); in Middle Asia, U. S. S. R., local concentrations of uraniferous turquoise, kolovratite, volborthite, and secondary uranium-vanadium minerals occur in graphitic Silurian slate (Sosedko, 1933; Adelung, Kushnar, and Chikhachev, 1937; Fersman, 1928) and in Cambrian chert and carbonaceous shale (Tyurin, 1944); in the iron ranges of the Great Lakes region abnormal concentrations of uranium occur locally in Precambrian graphitic schists and associated iron deposits (Vickers, R. C., *in* U. S. Geological Survey, 1953 and 1954c). It is possible that such deposits as well as other types are due to the "sweating out", migration, and local concentration of syngenetic or preexisting epigenetic uranium under conditions of moderate to weak metamorphism rather than to introduction of uranium from an igneous source.

INFLUENCE OF OROGENY ON CONCENTRATION OF URANIUM

Uranium can be concentrated by various processes and in many geologic environments. The environments that exist and the processes that are active from time to time are largely determined by the orogenic history of a region. The world's important deposits of uranium, excluding low-grade deposits in phosphorite and black shale, are all in or adjacent to orogenic belts as might be expected, for magmas, the primary sources of uranium, are generated and emplaced or extruded in orogenic belts. Though the histories of different orogenic belts differ in detail, many of them seem to have evolved through four general stages (Cady, 1950, p. 780–785; Stille, 1940, p. 4–23; Cady, McKelvey, and Wells, 1950): the primary geosynclinal stage, the primary mountain-building stage, the secondary mountain-building stage, and a stage of final differential uplift and local subsidence.

In the primary geosynclinal stage arcuate belts of subsidence form between major stable elements. Graywacke, argillite, chert, and submarine volcanic rocks, principally spilite, accumulate in the primary geosyncline. Shale and limestone, that grade laterally in the direction of the stable block into first-cycle quartz sandstone, accumulate on the mobile shelf adjacent to the primary geosyncline. In stage 2 the primary geosyncline is strongly deformed and intruded by synorogenic batholiths ranging from ultrabasic to intermediate in composition, and secondary geosynclines are formed. The debris from the mountains, consisting of graywacke and shale and, locally, arkose and second-cycle quartz sandstone accumulates in the geosyncline. In the third stage the geosynclinal belt is again strongly deformed, intermediate to acidic and alkalic plutons and volcanic rocks are emplaced and extruded, and continental sediments accumulate within and adjacent to the mountains. Highly differentiated small granitic and syenitic intrusives that may be rich in uranium are emplaced at or near the end of this stage, mainly in the secondary geosynclines and adjacent parts of the continental block but locally in the area of the primary geosyncline. The fourth stage is characterized by block faulting and commonly by the extrusion of plateau basalt.

There is little likelihood that important concentrations of uranium form during the primary geosynclinal and primary mountain-building stages. The sediments accumulate too rapidly for syngenetic concentrations to form and the magmas, mainly of simatic origin and ranging from ultrabasic to intermediate in composition, generally are not sufficiently differentiated to be important carriers of uranium. The apparent lack of important uranium deposits in primary geosynclinal belts and basic volcanic chains such as the Coast Ranges in Oregon and California, the Philippine Islands, the eastern Caribbean region, the Aleutian and Kamchatka arc, and much of eastern New England and the piedmont belt to the south seems to support the general validity of this reasoning.

The optimum opportunity for concentration of uranium is during and following the secondary mountain-building stage. Uraniferous marine black shale and phosphorite may accumlate in the marginal parts of secondary geosynclines and on adjacent parts of the continental block. The highly differentiated granitic and syenitic intrusives that are emplaced during this stage may be important bearers of uranium that may crystallize in the last-formed igneous rocks or, if structural conditions are favorable, in veins and other types of epigenetic deposits.

During the latter part of the stage of secondary mountain building and the succeeding stage, which is characterized mainly by block faulting and locally by extrusion of plateau basalts, the earlier formed primary concentrations of uranium are subject to weathering and erosion and, if climatic conditions are favorable, a variety of types of secondary deposits may form. Noteworthy examples are placer deposits and lignite and coal containing uranium that was apparently derived from the leaching of acidic volcanic rocks by ground water.

Many of the enigmatic sandstone-type deposits—for example, those on the Colorado Plateau (Fischer, 1942; Fischer and Hilpert, 1952; Weir, 1952; Finch, 1953)—also seem to be closely related to the latter part of the third stage in both time and space, though their origin is a subject of heated controversy. Most deposits of this type are in predominantly nonmarine sequences that are the erosional debris of orogenic mountains. It is not clear how these deposits were formed but the following two hyptheses seem most compatible with the available evidence: 1, by secretion and fractionation of uranium originally dispersed in the sedimentary prism at a time when the energy level of the crust was rather high owing to the sinking of the sedimentary basin and widespread local penetrations of magma, as suggested by Burbank (oral communication) or, 2, by hydrothermal solutions of igneous origin. Uraniferous Precambrian conglomerate deposits (Abraham, 1953; Traill, 1954; Union of South Africa Geologic Survey, 1940; Davidson and Bowie, 1951) are in some respects similar to deposits of the sandstone type and may have a similar origin.

The tectonic stages in such idealized form as that briefly described in the preceding paragraphs are shown in only a few places on the earth. In many places the stages are obscured or the various belts are wide and overlap in both space and time.

In the more ancient parts of the crust, particularly in Precambrian shields and massifs, successive periods of deformation, intrusion, and metamorphism have provided a number of opportunities for accentuation of any original differences in the uranium content of the crust. Such areas are believed to be particularly favorable sites for uraniferous igneous rocks and uranium deposits of igneous or metamorphic origin but obviously certain types of secondary deposits are not likely to occur.

TYPES OF URANIUM DEPOSITS

The classification of uranium deposits here used (see following table) attempts to focus attention on features that may be helpful in recognizing geologic settings in which deposits of different types are likely to be found and in evaluating the potential of such settings. Deposits are divided into four major groups: those formed by igneous or metamorphic processes, those formed by sedimentary processes, those formed by weathering processes, and those of uncertain origin. Deposits formed by igneous or metamorphic processes are subdivided into syngenetic and epigenetic types. Deposits of sedimentary origin are syngenetic and those formed by weathering processes are epigenetic. The deposits of uncertain origin are believed to be mainly and perhaps entirely epigenetic.

Classification of principal types of uranium deposits

Type of deposit	Distinctive features	Size and grade*	Tectonic setting	Origin
Deposits formed by igneous or metamorphic processes				
Syngenetic deposits: Acidic and alkalic rocks	Most of uranium is in sparsely and uniformly disseminated refractory accessory minerals such as monazite, zircon, allanite, and xenotime with relatively low uranium content, and less commonly in uraninite, pyrochlore, brannerite, and other minerals with a relatively high uranium content.	Low grade, but may be very large. A few igneous rocks, generally small bodies or parts of small bodies, contain 0.008 to 0.015 percent U (Butler, 1952, p. 12). Millions of tons of a pyrochlore-bearing albite-riebckite granite in Nigeria average about 0.01 percent U with appreciable Nb and Th (Mackay and Beer, 1952).	Shields and massifs in or marginal to orogenic belts.	Late-stage differentiate of acidic and alkalic magmas or products of metasomatism.
Pegmatite	Generally mineralogically complex; may contain uraninite, pitchblende, or any of a large number of refractory uranium-bearing minerals with a varied suite of uncommon minerals; most are zoned, and much of the uranium is localized in one or a few zones. Different radioactive minerals tend to favor different zones.	Small to large, but with a few notable exceptions low grade. Some pegmatites may contain as much as a few million tons of rock, averaging 0.005 percent U and a few contain as much as 50,000 tons of rock in zones averaging >0.01 percent U (Page, 1950, Bain, 1950, p. 290, 296). Exceptional pegmatites in Charlebois Lake area, Canada, may contain a few million tons of rock containing 0.08–0.2 percent U (Mawdsley, 1952, p. 373). From some pegmatite districts a few tons or tens of tons of uranium could probably be recovered as byproducts.	Shields and massifs in or marginal to orogenic belts. Typically clustered in marginal parts of large acidic or alkalic intrusives or in adjacent wall rock.	Late-stage differentiate of acidic and alkalic magmas or products of metasomatism.
Carbonatites	Typically dikelike bodies of carbonate and silicate minerals. May contain uraninite, pyrochlore, and other radioactive minerals.	Little information available; probably similar to pegmatites in size and grade.	In complexes of hyperalkalic igneous rocks, generally at margins of orogenic belts.	Late-stage igneous, hydrothermal, or metamorphic.
Epigenetic deposits: Fissure veins	Filled fissures in igneous and metamorphic (rarely unmetamorphosed sedimentary) rocks. Many examples of several mineralogic types, most of which contain pitchblende or uraninite as the principal uranium mineral.	Broad range in size and grade. Typically short narrow ore bodies of rather small vertical extent containing tens or hundreds of tons of uranium in ore averaging hundredths or tenths of a percent uranium. A few unusually large and rich ore bodies may contain thousands of tons of uranium in ore averaging several percent (Bain, 1950, p. 290, 296, 301).	Principally in shields, massifs, and strongly deformed and intruded areas.	Late-stage product of magmatic differentiation; in part may be due to assimilation and metasomatism.

See footnote at end of table.

Classification of principal types of uranium deposits—Continued

Type of deposit	Distinctive features	Size and grade*	Tectonic setting	Origin
Deposits formed by igneous or metamorphic processes—Continued				
Epigenetic deposits—Con. Replacement lodes, disseminations, and impregnations.	Selective replacements along cleavage and bedding in carbonaceous and graphitic slates and schists (Rum Jungle, Australia); veinlets or disseminations of pitchblende in walls of uranium veins (Erzgebirge) or unrelated to known major veins (Gunnar); disseminated (?) uraninite in copper ore (Northern Rhodesia).	Individual replacement lode ore bodies may contain hundreds of tons of uranium in ore averaging a few tenths of a percent; large tonnages of ore in disseminations and impregnations average from a few hundredths (?) of a percent uranium (Erzgebirge) to about 0.25 percent uranium (Gunnar).	Principally in shields, massifs, and strongly deformed and intruded areas.	Late-stage product of magmatic differentiation; in part may be due to assimilation and metasomatism.
Deposits formed by sedimentary and weathering processes				
Syngenetic deposits: Marine carbonaceous shale.	Uranium is rather uniformly distributed in widespread thin dark-colored highly carbonaceous very fine grained units; typically pyritic and noncalcareous; may be phosphatic. Uranium content is roughly proportional to content of organic matter. Products of very slow accumulation in reducing environment. Most examples are of Paleozoic age.	Low grade but may be very large. Few inches to few tens of feet thick; hundreds of square miles in extent. Local nodules, very thin beds, and lenses of bitumens may contain 0.1 percent U or more, but minable thicknesses are not likely to to exceed 0.02 percent U and most average 0.01 percent U or less (Bain, 1950, McKelvey and Nelson, 1950).	Pre-orogenic deposits, typically in marginal part of platform adjacent to a geosyncline.	Uranium extracted from sea water by organic (carbonaceous) matter and possibly by clay.
Marine phosphorite	Uranium rather uniformly distributed in thin widespread units that may contain interbedded chert or dark carbonaceous shale or limestone; most of the uranium is in the highly phosphatic beds. Uranium content roughly proportional to phosphate content and inversely proportional to CO_2 content. Reworking in marine environment may have enriched some deposits. Examples of Paleozoic, Mesozoic, and Tertiary age are known.	Low grade but may be very large. Individual phosphate deposits of minable grade are typically less than 10 feet thick but may cover hundreds of square miles. Probable highest average grade of minable thickness or of a concentrate: 0.015 to 0.02 percent U (McKelvey and Nelson, 1950, p. 35, 37–40; Bain, 1950, p. 292, 297).	Generally deposited on slope between platform and geosyncline during stable period prior to orogeny. Some may have accumulated on platform. May occur in same areas and same sequences as uraniferous black shales.	Uranium extracted from sea water, largely by proxying for calcium in phosphate minerals.

Placers	Stream and beach placers may contain refractory uranium-bearing minerals (commonly monazite, locally or sparsely thorite, thorianite, brannerite, euxenite, etc.) generally associated with titanium minerals, tin, gold, or other valuable metals or minerals. May be at considerable distance from source area.	Generally low grade, but may be large. Stream and beach deposits: thickness measured in feet; volume of individual deposits as large as millions of cubic yards; districts may contain tens of millions of yards. Though placers are the only important source of thorium, few contain enough uranium to be of interest except as a minor byproduct (Bain, 1950, p. 292–293, 315–319; Mertie, 1953).	Shields, massifs, and strongly deformed and intruded belts; especially in or near areas of crystalline rocks or metallic mineral deposits.	Product of disintegration of igneous and metamorphic rocks and less commonly of mineral deposits.
	Eluvial deposits: no important examples known.	----------	----------	Eluvial deposits at or near outcrop of pegmatites or mineral deposits in favorable topographic or climatic environments.
Epigenetic deposits: Uraniferous lignite and coal and associated carbonaceous shale.	Most deposits are in lignite, some in low-rank bituminous coals. Uranium generally is concentrated in only one or two relatively thin zones, most commonly at the top and less commonly the bottom of a bed or a sequence of beds. Some radioactive peats are known. Uranium content variable within mineralized bed or zone.	May be large and relatively high grade. In many places hundreds of thousands or millions of tons of lignite or coal in beds of minable thickness contain 0.005–0.01 percent U. Unusually rich deposits or parts of deposits contain as much as several tenths of a percent uranium (McKelvey, 1955, p. 42; U. S. Geol. Survey, 1953, p. 17–20, 114–119, 123–144; 1954a, p. 15–16, 116–125; 1954b, p. 8, 100–121).	In structural basins containing or bordered by acidic igneous rocks, especially volcanic rocks; generally in areas of arid or semiarid climate.	Uranium, in most places, believed to have been leached by ground water from overlying, interbedded, or adjacent acidic volcanic rocks and to have been precipitated by carbonaceous material. In some places source of uranium may have been acidic intrusive rocks or hydrothermal solutions. In few cases, the uranium may be syngenetic.
Others	Typically consist of colorful secondary uranium minerals along fractures.	Generally small and low grade	Diverse, but generally in arid or semiarid areas with abundant acidic igneous rocks.	Most are probably due to leaching by and precipitation from ground water.

See footnote at end of table.

Classification of principal types of uranium deposits—Continued

Type of deposit	Distinctive features	Size and grade*	Tectonic setting	Origin
Deposits of uncertain origin				
Sandstone-type deposits (including uraniferous asphaltite).	Commonly lenticular deposits in dominantly nonmarine, partly red, clastic sequences consisting chiefly of muddy sandstones and siltstones but including impure carbonate rocks. Ore bodies typically localized in sedimentary traps or organic-rich portions of favorable formations. Uranium minerals tend to migrate along fractures and other structural features during oxidation; many mineralogic types known.	Deposits contain hundreds, less commonly thousands or tens of thousands and rarely millions of tons of ore, averaging a few tenths (generally 0.2 to 0.5) of a percent uranium. Some contain recoverable vanadium or copper (Fischer, 1942, McKelvey, 1955, Steen, 1954).	Late-orogenic deposits in weakly or moderately deformed continental sedimentary rocks in broad structural basins. The host rocks are the erosional debris of nearly orogenic mountains in which acidic crystalline rocks are generally exposed.	Primary ore bodies may have been deposited from hydrothermal water of igneous origin, ground water (including mixtures of various natural gases and petroleum), or both. Many secondary ore bodies are products of oxidation in situ; some may have been deposited by ground waters that leached uranium from preexisting ore bodies or disseminated uranium minerals.
Uraniferous conglomerate	Known deposits are in widespread thin units of well-sorted quartz conglomerate in Precambrian quartzite sequences. Uraninite, uraniferous hydrocarbon, and (or) complex uranium-bearing minerals such as brannerite typically concentrated in elongate ore shoots or "pay streaks" with pyrite and gold and trace amounts of other metallic minerals.	Deposits of millions of tons of ore, contain a few hundredths to 0.1 percent uranium. Uranium is main metallic element in Ontario deposits and gold in Witwatersrand deposits (Bain, 1950, p. 286, 322).	The few known deposits are in marginal parts of Precambrian shields.	Uranium probably deposited in permeable zones in conglomerate by hydrothermal solutions. Uncertain whether uranium is of igneous origin or whether it is redistributed from preexisting uraniferous placers.

*Estimates based largely on many anonymous short articles and notes in various United States, Canadian, South African, Australian, and British mining journals.

Syngenetic deposits are those in which uranium accumulated with, or consolidated with, the enclosing rocks. In most syngenetic deposits, the uranium tends to be rather uniformly dispersed through large volumes of rock. Most deposits of this type contain millions of tons of rock, but some pegmatite and placer deposits are much smaller. Syngenetic deposits generally are of low grade. The uranium content of large volumes of rock is generally 0.01 percent or less, but in a few cases may be as much as a few hundredths of a percent. Nodules, lenses, or very thin layers in sedimentary rocks or zones in pegmatites may contain as much as a few tenths of a percent uranium, but the volume of rock of this grade is generally small. Epigenetic deposits are those in which the elements were introduced, or redistributed within a rock after its consolidation or lithification. Consequently, they tend to be localized in relatively small structural or stratigraphic traps within the host rock. Most epigenetic deposits are small, commonly in the range of thousands to hundreds of thousands of tons of rock, but in a few places, millions of tons. The uranium is erratically distributed within them, but individual deposits or parts of deposits commonly contain as much as 1.0 percent uranium, and a few contain several percent.

DEPOSITS FORMED BY IGNEOUS OR METAMORPHIC PROCESSES

Igneous processes or closely related metamorphic processes result in both syngenetic and epigenetic uranium deposits. Syngenetic deposits are generally late-stage differentiates of acidic or alkalic magmas, for example, pegmatites and the albite-riebeckite granite of Nigeria; some may be rocks of igneous appearance that were formed by metamorphic processes. Epigenetic deposits are veins, replacement lodes, and disseminations. The uranium in most epigenetic deposits has probably been introduced with hydrothermal solutions that are late-stage products of magmatic differentiation, but in some cases uranium originally present in the host rock may have been redistributed and concentrated either by hydrothermal solutions of igneous origin or by metamorphic processes.

SYNGENETIC DEPOSITS

ACIDIC AND ALKALIC IGNEOUS ROCKS

Few acidic and alkalic igneous rocks contain enough uranium to constitute potential low-grade ore, but some have been important as sources of resistant radioactive minerals for placer concentrations and some may have provided soluble uranium for the formation of epigenetic deposits. Ultrabasic and basic igneous rocks are only slightly radioactive; none constitute potential ores, or significant sources of resistant radioactive minerals, or soluble uranium.

Small highly differentiated plutons or dikes intruded at a late stage of a magmatic cycle are generally more radioactive than the earlier crystallized batholiths or large stocks with which they are generally associated. These small radioactive bodies are in ancient shields and massifs and in the marginal parts of more recent orogenic belts or on the margins of platforms adjacent to them. These bodies, as well as veins and pegmatites, tend to be in the peripheral, and especially the apical, parts of large intrusive masses or in wall rock adjacent to or between exposed parts of large plutons. Accordingly they are most likely to be found in areas where erosion has been deep enough to uncover small outlying plutons or possibly the apical parts of large acidic or alkalic intrusives but not to strip away the upper part of the batholith and any small late-stage plutons that might have formed in or around it.

So far as is known to the authors, the only igneous rocks that have been seriously considered, to date, as sources of uranium are small bodies of albite-riebeckite granite in Nigeria, millions of tons of which average about 0.01 percent uranium, 0.01 percent thorium, and 0.26 percent $(Nb, Ta)_2O_5$ (Mackay and Beer, 1952). This very radioactive igneous rock is a late-stage differentiate of a suite of biotite and riebeckite granite and is characterized by the rare accessory minerals pyrochlore (a niobate of the cerium metals, calcium, and other bases, with titanium, fluorine, thorium, and uranium) and astrophyllite, a complex titanosilicate (Mackay and Beer, 1952; Beer, 1952). The uraniferous rock is of special interest because virtually all of the uranium is in grains of pyrochlore, which could be mechanically concentrated. Riebeckite granite in the United States and Madagascar also is abnormally radioactive, though less so than the Nigerian rocks. Davidson (1951, p. 330) reports that as much as 0.02 percent U_3O_8 occurs in "exceptional granitic phases in Rhodesia and elsewhere in Africa." More recently several other similar deposits, some containing millions of tons of rock, have been reported in Tanganyika, Kenya, Uganda, and Northern Rhodesia (Spalding, 1954). Other acidic and alkalic igneous rocks in Africa, India, Indonesia, Canada, and the United States are abnormlly radioactive, containing between 0.01 and 0.02 percent equivalent uranium. If the radioactivity is caused by thorium and uranium in a ratio of 3.4 to 1, which was reported as an average for acidic igneous rocks (Senftle and Keevil, 1947), the uranium content of these rocks is between 0.005 and 0.01 percent.

Although no broad generalizations are warranted concerning what petrographic types and geologic settings of acidic and alkalic rocks are most likely to contain abnormally large quantities of uranium, several clues are suggested:

1. Igneous suites that have a large variety of rock types are more likely to have strongly radioactive members than simple suites.

2. In any igneous sequence the late-stage differentiates are the most radioactive.

3. Known, highly radioactive, late-state differentiates are commonly rich in soda, less commonly in potash; few contain more than 1 percent CaO.

4. Biotite-bearing granitic rocks may be more radioactive than hornblende-bearing rocks.

Evidence accumulated by several investigators (Davidson, 1951; Hurley, 1950; Larsen and Phair, *in* Faul, 1954, p. 80–81) indicates that as much as 40 percent of the total uranium content of some granular igneous rocks can be removed by leaching with dilute hydrochloric acid (6 *N*). Judging from these experiments it might be possible, using weak acid, to leach as much as 40 tons of uranium and possibly equal or greater quantities of some other elements from 1 million tons of igneous rock containing 0.01 percent uranium. It is also likely that under favorable conditions over a long period of time ground water will leach a large amount of uranium from uraniferous igneous rocks, for a cubic mile of "average" granite or rhyolite probably contains about 50,000 tons of uranium, much of it in a relatively soluble form. Two implications of these findings may be important: (1) in lieu of other sources of uranium and at a high cost it might be possible to extract large tonnages of uranium from some igneous rocks; (2) ground and surface water draining areas of abundant acidic or alkalic igneous rocks, including tuffs, may be relatively highly charged with uranium, which would tend to be fixed by or in favorable receptors, such as peat, lignite, petroleum, or continental-sandstone sequences, and under favorable climatic conditions might be deposited as secondary uranium minerals in fractures in the host rock itself.

PEGMATITES

Pegmatites are common associates of acidic and alkalic igneous rocks and consequently are localized in ancient shields and massifs and in more recent orogenic belts. Most pegmatites are probably late magmatic differentiates but some may be wholly or in part of metamorphic (metasomatic) origin. Typically pegmatites are most abundant in the peripheral parts of batholiths or large stocks and in the adjacent country rocks, where they form dikes, sheets, or irregular bodies from a few feet to rarely a few hundred feet thick and from a few hundred to, rarely, a few thousand feet long. In uranium provinces, pegmatites that are zoned, mineralogically complex, and rich in potash feldspar, are likely to contain uranium minerals. No peculiar mineral assemblages or structural features are known, however, that can be used to predict successfully which pegmatites are likely to be radioactive and

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which are not. Pegmatites have generally been considered of little consequence as potential sources of uranium (Bain, 1950, p. 290, 296; Page, 1950, p. 27, 34), but recently described uraniferous pegmatites in the Lake Charlebois (Mawdsley, 1952) and Lac La Ronge (Anonymous 1954b and c; Mawdsley, 1954) areas of Saskatchewan show that there are exceptions to this generalization.

Though many uranium-bearing minerals have been found in pegmatites, the quantity of these minerals in most pegmatites is very small. Some pegmatites contain uranium-rich primary minerals such as uraninite, pitchblende, and thorianite and alteration products such as gummite, autunite, and uranophane, but in most radioactive pegmatites uranium is a subordinate component of refractory minerals of titanium, niobium, tantalum, and the rare earths, such as samarskite, euxenite, pyrochlore, fergusonite, monazite, and microlite (Page, 1950, p. 16–19). Betafite is the chief uranium mineral in the Madagascar alkali feldspar pegmatites, the only pegmatites from which a significant production of uranium has been reported—at least 100 tons of combined betafite and euxenite concentrate, probably containing at least 10 and possibly as much as 20 tons of uranium (Hess, 1923 and 1926). Smaller quantities of uranium minerals have been recovered from a number of pegmatites elsewhere in the world, mostly as a byproduct of other minerals.

Virtually all uraniferous pegmatites that might be of any economic importance may be divided into internal structural units or zones on the basis of texture and mineralogy (Page, 1950, p. 15, 20–21). These units are either shell-like or lenticular and roughly parallel the contact of the pegmatite and the wall rock. In most pegmatites, the subsurface size and shape of the units or zones are predictable from a detailed geologic surface map. Zoned pegmatites may have from 2 to about 11 zones, some of which may be discontinuous. The thickness of a zone, except the core, rarely exceeds 10 feet; the other dimensions are commonly a few hundred feet and rarely as much as a thousand. The outside selvage generally is called the border zone, the next zone is the wall zone, the central zone is the core, and any zones between the core and wall zone are called intermediate zones. Page (1950) points out that uranium minerals may be in any zone—for example, uraninite is localized in the upper selvage of a markedly zoned sill and the adjacent mica schist wall rock in the Lac La Ronge district of Saskatchewan (Mawdsley, 1954)—but they are most common in intermediate zones. Different uranium minerals are likely to occur in different intermediate zones (Page, 1950): uraninite in the muscovite-rich part of perthite-rich intermediate zones, samarskite in perthite-plagioclase-quartz zones, euxenite in the perthite-rich parts of zones in which large crystals of perthite are surrounded by quartz, and microlite in zones rich in lepidolite or cleavelandite. In the Charlebois Lake area, Saskatchewan, (Mawdsley, 1952) calcium-rich pegmatites in migmatite are replaced locally by fine-grained uraninite.

Most of the uranium in a pegmatite is likely to be concentrated in one or two zones, within which its distribution will be spotty and unpredictable. Consequently, the entire zone or zones, must be mined or at least prospected. In most pegmatites the individual zones do not exceed a few feet in thickness and several hundred feet in length and breadth. An unusually large and rich zone might contain 100,000 tons of rock averaging 0.05 to 0.1 percent uranium. The cores of some large pegmatites may contain as much as a few million tons of rock, but the large cores are unlikely to average as much as 0.01 percent uranium. Some recently described pegmatites in Saskatchewan appear to be unusually large and rich. A flat-lying pegmatite sill in the Lac La Ronge district is reported to average 162 feet in thickness and to contain about 1.7 pounds of uranium per ton or 0.085 percent uranium (Anonymous 1954b and c). In the Lake Charlebois area "six widely separated bodies * * * in the aggregate contain at least 1,000 tons per vertical foot of 'ore' grading possibly 0.20 percent uranium oxide" and "the amount of material, now indicated, with an average grade of 0.08 percent uranium oxide is many times 1,000 tons per vertical foot." (Mawdsley, 1952, p. 373.)

Though pegmatites never have been significant sources of uranium and though most of the world's pegmatites will yield little more than specimen amounts of uranium minerals, the recent discoveries in Saskatchewan point out that some pegmatites contain large low-grade uranium resources that can, perhaps, be profitably exploited.

CARBONATITES

Carbonatites are a group of silicate-carbonate rocks that are genetically associated with hyperalkalic igneous complexes. Typically they consist of calcite and (or) dolomite, pyroxene and (or) biotite, alkali feldspar, and a varied suite of accessory minerals including apatite, magnetite, olivine, and (or) monticellite, and accessory minerals containing titanium, niobium, tantalum, rare earths, uranium, and thorium (W. T. Pecora, oral communication). They are commonly veinlike or dikelike and in some respects resemble pegmatites. Masses as much as 1 square mile in area have been reported. The origin of carbonatites is controversial. Different investigators have ascribed magmatic, hydrothermal, and metamorphic origins either to individual masses or to the group as a whole. Davidson (1951, p. 331) notes that carbonatites "* * * in Norway, Uganda, and Nyasaland contain interesting amounts of pyrochlore and sometimes monazite and possess a radioactivity as must as 0.02 percent eU_3O_8." [1]

[1] eU_3O_8 is a symbol for equivalent U_3O_8 and is determined by measuring rock radioactivity and comparing the amount with that emitted by a standard containing a known amount of uranium. Equivalent uranium content of a rock will equal chemical uranium content if the uranium in both rock and standard is in secular equilibrium with its decomposition or daughter elements, and if there are no other radioactive elements in the rock.

Uraninite and other uranium minerals occur in peculiar calcite-bearing granite pegmatites and pegmatitic carbonatite veins in the Haliburton-Bancroft area of southern Ontario (Ellsworth, 1932, p. 213–217). These bodies are in a terrane of strongly metamorphosed rocks cut by granite and alkalic igneous intrusives. They may be of metamorphic origin (Chayes, 1942, p. 505–510). Perhaps the most significant deposits are a series of veinlike bodies in Cardiff township. They are composed chiefly of interbanded sheared calcite and purple fluorite with variable amounts of feldspar (chiefly plagioclase), hornblende, apatite, and magnetite. In some places, uraninite, allanite, zircon, molybdenite, and sphene also occur. Some of these deposits may constitute low-grade uranium ore. These occurrences indicate that carbonate-bearing igneous or pseudoigneous rocks should be carefully scrutinized as possible sources of low-grade uranium.

EPIGENETIC DEPOSITS

VEINS

Although the great bulk of the uranium in the earth's crust is in low-grade syngenetic disseminations in certain types of igneous and sedimentary rocks, most of the world production has come from a few relatively small but much higher grade epigenetic concentrations. Veins containing pitchblende have accounted for the bulk of the output in the past, but deposits of the sandstone type and uraniferous conglomerate depsits have become the most important sources in the last few years. Small amounts of uranium occur in many veins, but few veins contain enough uranium to constitute an important source.

A survey of the world literature on uranium deposits suggests several generalizations that may be helpful in focusing the search for important vein deposits (summarized mainly from Everhart and Wright, 1953, and references cited in that paper): (1) most of the known important deposits are mesothermal fissure fillings that contain pitchblende and are characterized by symmetrical banding, crystal-lined vugs, open brecciated character, and lack of replacement features; (2) most deposits are in structurally complex terrane containing metamorphic rocks and highly differentiated alkalic or silicic rocks (shields or massifs) and few, in any, are reported in areas of undeformed or slightly deformed sedimentary rocks, areas of plateau basalts, or in basic volcanic rocks of Tertiary age; (3) many and perhaps most are in areas where other types of uranium deposits or abnormally radioactive rocks or waters are known, that is, in uraniferous provinces; (4) many of the more important deposits contain a complex mineral assemblage, including minerals of cobalt and nickel; (5) many are characterized by hematitic alteration or by hematite-stained vein matter; (6) many are in relatively thin units of competent rock that will support open fractures; and (7) many of the more important vein deposits of uranium are in districts in which important deposits of other metals are not known.

No consistent relationship between vein deposits of uranium and mineral zoning or telescoping has been recognized; some deposits or groups of deposits appear to conform to a local or regional zonal pattern (Colorado Front Range), some may be in a telescoped environment (Erzgebirge, Germany; Kara-Mazar, U. S. S. R.), but many have no features that suggest either zoning or telescoping.

None of these features nor any combination of them is certain to indicate the presence or absence of uranium in a vein. Nevertheless it is believed that they do constitute useful guides and that the greater the number of favorable factors that apply, the greater will be the likelihood that a vein or group of veins contains worthwhile quantities of uranium.

Pitchblende-bearing veins are here arbitrarily divided into three types based on mineral associations; pitchblende veins with few accessory minerals, veins with cobalt and nickel sulfides and sulfosalts, and veins with base-metal sulfides. The types are not sharp and distinct but rather tend to grade into one another and also into uraniferous fluorite deposits. Nevertheless, the authors feel that this compartmentation may be useful to emphasize features that may be of value in attempting to recognize and evaluate deposits.

PITCHBLENDE VEINS WITH FEW ACCESSORY MINERALS

Some veins contain pitchblende alone or with hematite, pyrite, or less commonly magnetite in a gangue of quartz or carbon minerals or both and, in at least one locality—Marysvale, Utah—fluorite. Other primary metallic minerals are sparse or absent. This type of vein is found in the Marysvale deposits (Everhart and Wright, 1953, table 12), the chalcedonic veins in the Boulder batholith (Roberts and Gude, 1953), the giant quartz veins of the Northwest Territories of Canada (Lang, 1952, p. 16), the deposits in the Montreal River district in Ontario (Everhart and Wright, 1953, table 9), and many of the deposits in the Goldfields region of Saskatchewan (Lang, 1952, p. 16, 68–106). Until 1954 only the Marysvale deposits have had a significant production, but important production is anticipated from the Goldfields region. Veins tend to be narrow and discontinuous, and pitchblende is erratically distributed in them. Stockwork deposits are not uncommon. Grade of large tonnages of ore in the richest deposits known probably does not exceed a few tenths of a percent uranium. Most deposits probably contain only a few hundreds or thousands of tons of ore averaging 0.1 percent uranium or better, but a few (Goldfields region, Marysvale) contain hundreds of thousands and perhaps a few million tons of ore, averaging a few tenths of a percent uranium.

VEINS WITH COBALT AND NICKEL SULFIDES AND SULFOSALTS

Most veins that have yielded important quantities of uranium, in the aggregate accounting for perhaps 90 percent of the total world production from veins, are characterized by the association of pitchblende with minerals of cobalt and nickel. Though individual deposits of this type differ considerably in detail, certain features appear to be sufficiently typical to provide clues for recognition. Everhart and Wright (1953, tables 1–3, 6, 7, 13) list them as follows: (1) complex mineralogy including one or more precious metals (commonly silver) and sulfides and sulfarsenides of cobalt, nickel, copper, lead, and less commonly native bismuth or bismuth sulfide; (2) wall rocks commonly are metamorphosed sedimentary or volcanic rocks, less commonly plutonic rocks; (3) deposits are filled fissures, but locally impregnations or disseminations occur in wall rock adjacent to a vein; (4) carbonate minerals typically are more abundant than silica in the gangue; and (5) hematite-stained rock or gangue minerals are common.

Tin-bearing veins and pitchblende-bearing cobalt-nickel veins are associated at Cornwall (Rumbold, 1954) and in the Erzgebirge (Beyschlag, Vogt, Krusch, 1916). Irrespective of whether the association is a result of zoning—as many geologists believe (Babanek, 1889; Oelsner, unpublished notes; Bateman, 1950, p. 551)—or of telescoping, or of different periods of mineralization, the association, nevertheless may provide a useful clue to recognition of possible favorable deposits or districts. Mineralogically complex deposits of the so-called "Tien Shan" type in the Kara-Mazar-Taboshar area of the Fergana district, U. S. S. R. (Nasledov, 1935; Komlev, 1938), and similar deposits at the Băita mine in the Transylvanian mountains of Rumania were probably formed during more than one period of mineralization.

Many cobalt-nickel veins contain little or no uranium (Bastin, 1939). Nickel-copper deposits of the Sudbury type that are associated with basic rocks and have a very high ratio of nickel to cobalt are notably devoid of uranium.

The principal deposits of the pitchblende-cobalt-nickel type are at Shinkolobwe, Belgian Congo; Great Bear Lake, Canada; Cornwall, England; Carrizal Alto, Chile; in the Erzgebirge, East Germany and Czechoslovakia; and a few in the Goldfields, Lake Athabaska district of Canada. Precambrian, late Paleozoic, and Tertiary ages are represented, but the known Tertiary deposits seem to be relatively unimportant. The Shinkolobwe deposit, by far the richest and largest uranium vein deposit in the world, has yielded thousands of tons of uranium (Bain, 1950, p. 298–299) from ore that probably averaged several percent uranium. Most pitchblende-cobalt-nickel veins are relatively small by comparison, and the uranium in them is erratically distributed. Ore shoots are as much as a few hundred feet in length and depth and commonly do not exceed a few feet in thickness. The maximum grade of ore across minable thicknesses is as much as a few percent uranium in parts of some ore shoots, but the bulk of the ore in most shoots probably averages only tenths of a percent uranium (Bain, 1950, p. 290, 296, 303, 307), and most uraniferous veins, as a whole, probably contain only hundredths of a percent uranium. Individual deposits commonly contain a few tens or hundreds of tons, and rarely more than a few thousands of tons of uranium.

VEINS WITH BASE-METAL SULFIDES

In many veins widely scattered over the western United States (Butler, 1952, p. 14–16) and probably in other parts of the world where vein deposits of base and precious metals are abundant, pitchblende, secondary uranium minerals, or unidentified radioactive materials are associated with variable amounts of the common sulfide minerals (especially of copper) and precious metals. There is no peculiar or diagnostic feature of the group.

In the best-known group of deposits, those in the Colorado Front Range, pitchblende is associated with variable quantities of pyrite, common base-metal sulfides, and silver minerals in quartz and quartz-carbonate veins that cut Precambrian gneiss and schist and early Tertiary intrusive rocks (King, Moore, and Hinrichs, 1952, p. 8–9). Production from two deposits totalled nearly 200 tons of uranium and from a number of deposits as much as a few tens of tons of uranium. Reserves of individual deposits range from tens of tons to a few tens of thousands of tons of ore, most averaging only a few tenths of a percent uranium. Uraniferous veins in the Coeur d'Alene district in Idaho (Thurlow and Wright, 1950) are somewhat similar to those in the Colorado Front Range.

Most deposits of this type may yield a few tons or tens of tons of uranium and a few may yield a hundred tons or more of uranium from ore averaging a few tenths of a percent uranium. From some deposits it may be feasible to recover uranium as a byproduct or coproduct with other metals.

DISSEMINATIONS AND IMPREGNATIONS

The Gunnar deposit in the Goldfields district of Saskatchewan is perhaps the most important example of pitchblende in disseminations or impregnations described to date. The deposit, in paragneiss and granite gneiss, is about 120 feet thick, more than 800 feet long, and contains several million tons of ore that may average as much as 0.2 percent uranium, judging from a statement by La Bine (1954) that the

"A" zone alone is valued at over $130 million and ore averages $38 per ton. Hoiles (1953) states that

> The uranium occurs as hard, black, lustrous, botryoidal pitchblende in fractures, most of which are barely visible to the naked eye, and disseminations; and as soft sooty pitchblende in small fractures.

Uranophane also is abundant (Fraser and Robertson, 1954). The ore is associated with hematite, specular hematite, and red feldspar; the gangue consists of carbonates, dolomite, and quartz. Chalcopyrite, galena, and pyrite occur in trace amounts.

Impregnations of pitchblende are also associated with some veins in the Erzgebirge of Germany and Czechoslovakia. Bain (1950, p. 303–304) states that some pitchblende occurs along microfractures in the schists at Schneeberg, Johanngeorgenstadt, and Joachimsthal, and Babanek (1889) reports that scapolite schist in the eastern part of the Joachimsthal district averages 0.265 U_3O_8. Though Babanek's figure is almost certainly much too high to be accepted as an average, it does suggest that impregnations in the Erzgebirge may constitute a large low-grade resource.

Impregnations similar to those in the Erzgebirge might be expected to accompany vein deposits in strongly shattered rocks elsewhere, but none have been reported. Nevertheless, the fact that they do occur in one region must be considered in evaluating the potential of other vein deposits or districts, for if pitchblende is disseminated through large volumes of wall rock adjacent to veins, a large resource of low-grade ore may be present.

REPLACEMENT LODES

Uranium deposits of replacement origin seem to be relatively uncommon. Perhaps the most important deposits of this type are in the Rum Jungle area of northern Australia (Sullivan and Matheson, 1952), where uraninite, with or without copper minerals, selectively replaces contorted Precambrian carbonaceous slate and graphitic schist along bedding and cleavage surfaces. The slate and schist are interbedded with quartzite, and carbonate rock. Quartz veinlets that intersect these rocks contain chalcopyrite, pyrite, and uraninite. The deposits in the Rum Jungle area are probably comparable in size and grade to some of the more important fissure vein and sandstone-type deposits. Some deposits in the Kara Tau region of the U. S. S. R. (Sosedko, 1933; Adelung, Kushnar, and Chikhachev, 1937; Fersman, 1928; Tyurin, 1944) may also be replacements in carbonaceous shale or slate. The fact that replacement deposits seem to favor carbonaceous rocks indicates that the chemistry of carbonaceous rocks may be an important factor in localizing uranium. If this is correct, replacement deposits of uranium might be expected in carbonaceous rocks in areas that contain uraniferous vein deposits in more brittle but inert rocks.

Small quantities of uraninite are disseminated in or otherwise associated with large copper ore bodies in the Northern Rhodesia copper belt (McNaughton, 1953; Davidson, 1953 and 1954). Some of the deposits probably contain enough uraninite with the copper, or adjacent to it, to permit commercial uranium production (Nininger, 1954, p. 58). Nininger points out that the type of mineralization is strikingly similar to that at Rum Jungle. The origin of the copper is controversial. Some geologists believe that it was introduced by hydrothermal solutions of igneous origin and deposited along permeable beds; others believe that it was deposited with the enclosing sedimentary rocks or prior to their consolidation and was later redistributed by hydrothermal solutions. The origin of these deposits and of the equally controversial Witwatersrand deposits is the subject of papers by Garlick (1953), McNaughton (1953), and discussions of these papers in Institute of Mining and Metallurgy, London, Bulletins 564, 567, 569, 570, 573, 574.

URANIFEROUS FLUORITE DEPOSITS

Fluorite deposits at Wolsendorf, Germany, (Everhart and Wright, 1953, p. 80, table IV), Marienbad, Czechoslovakia, and at various places in the western United States (Wilmarth and others, 1952, p. 13–18), contain uranium. Deposits are simple veins, stockworks, and breccia "pipes." Characteristically, the uranium is spottily distributed within a fluorite deposit. With few exceptions it is associated with deep-purple to black fluorite. In some deposits, uranium occurs as finely divided pitchblende. In others no uranium mineral has been recognized, and uranium is thought to be held in the fluorite structure. Grade of ore typically is only a few hundredths of a percent uranium, but some deposits contain as much as several thousand tons of fluorite averaging 0.1–0.2 percent uranium. Production of uranium from fluorite deposits has been very small and probably will not be much greater in the future.

A close relationship of uranium and fluorite is also indicated by the commonness of fluorite as a gangue mineral in pitchblende-bearing veins.

DEPOSITS WITH REFRACTORY URANIUM MINERALS

Refractory uranium-bearing minerals are common as accessories in pegmatites and other acidic igneous rocks but, so far as known, are rare in hydrothermal deposits.

Davidite, a uraniferous mineral related to titanomagnetite and containing as much as 4.4 percent uranium (Frondel and Fleischer, 1955, p. 178), is reported from at least two deposits of probable high-temperature hydrothermal (quasi-pegmatitic) origin. At Radium Hill, Australia, davidite is intergrown with rutile, ilmenite, hematite, and some magnetite in irregular replacement lodes (Mawson, 1944; Parkin

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and Glasson, 1954) or veins. The lodes occupy fracture planes near the axial plane of a regional fold in Precambrian gneiss cut by granite plutons. The ore forms irregular shoots within the lodes. Whittle (*in* Parkin and Glasson, 1954, p. 824) suggests a

paragenetic sequence that commences with hematite, ilmenite, and rutile associated with biotite gangue. This is followed by the period of soda aplite intrusion which concludes with the introduction of davidite. Finally, there is a period of sulfide mineralization—pyrite and chalcopyrite— * * *. The deposit is a significant producer of uranium ore.

In the Tete district of Mozambique davidite, rutile, sphene, magnetite, ilmenite, apatite, and molybdenite occur in narrow bands and stringers in scapolitized and carbonatized shear zones in norite and anorthosite (Davidson and Bennett, 1950). The deposits are not sources of significant amounts of uranium.

Uraniferous lodes in a Precambrian complex in the Mount Painter area of Australia contain monazite, fergusonite, uraniferous ilmenite, and secondary uranium minerals along with quartz, stilbite, fluorite, barite, and hematite (Mawson, 1944). The lodes probably are not an important source of uranium.

Brannerite, a rare calcium-uranium titanate containing as much as 40 percent uranium, accompanies molybdenite, chalcopyrite, pyrite, gold, and silver in a quartz-calcite vein and in disseminations in a brecciated quartz diorite at Bou-Azzer in French Morocco. The brannerite occurrences are in or near veins or massive ore bodies of cobalt-nickel-iron arsenides and sufarsenides; some are in serpentine (Jouravsky, 1952). The uranium-molybdenum mineralization is thought to be older than the cobalt-nickel-iron mineralization. The ore is of low grade and probably does not constitute an important source of uranium.

DEPOSITS WITH URANIFEROUS CARBONACEOUS MATERIAL

Uraniferous carbonaceous material of probable hydrothermal origin occurs in veins in Precambrian rocks in Australia, Canada, and Scandinavia (Mawson, 1944; Ellsworth, 1932; Davidson and Bowie, 1951) and in Permian and Mesozoic rocks in Colorado (U. S. Geological Survey, 1953, p. 16, 17, 107, 198). None of the described deposits are likely to be significant sources of uranium, but they may be important as indicators of a uranium province, and certainly indicate areas that are favorable for prospecting. A more complete treatment of uraniferous carbonaceous material is given elsewhere in this paper.

DEPOSITS FORMED BY SEDIMENTARY PROCESSES

Many marine carbonaceous shale and phosphate rocks and some fluvial and marine placers contain abnormal amounts of uranium that were deposited along with the enclosing sediments and form an integral part of them. These syngenetic deposits are invariably of low and relatively uniform grade (<0.02 percent uranium). Marine phosphorite and black shale constitute very large low-grade resources of uranium and some placers contain enough uranium to be of interest, at least as a coproduct or byproduct of other minerals.

PHOSPHATE ROCK

Phosphate is concentrated in several types of deposits, principally in igneous apatite, marine phosphorite, residual phosphorite, river pebble, phosphatized rocks (limestone, volcanic rocks, or clay), and guano (McKelvey and others, 1953). No guano or igneous apatite and few, if any, nonmarine phosphorite deposits contain as much as 0.01 percent uranium, but some marine phosphorite deposits contain 0.01 to 0.02 percent uranium (McKelvey and Nelson, 1950, p. 35) and constitute large low-grade resources. Some of the larger fields of uraniferous phosphorite contain a few hundred thousand tons of uranium in rock of this grade.

The thickest and richest phosphate deposits, and the most uraniferous, are those of the geosynclinal facies deposited on or near the edge of submarine slopes of platforms at depths generally believed to have been between 200 and 1,200 feet, rather than on the platforms themselves or in the deeper parts of geosynclines. Consequently, they are to be sought in moderately thick sequences of miogeosynclinal rocks. Their facies consist of bedded or plate phosphorite associated with chert and carbonaceous mudstone and minor amounts of limestone (McKelvey and others, 1953, p. 12–16).

The platform phosphorite deposits (McKelvey and others, 1953, p. 15) are generally nodular rather than bedded. Some are associated with black shale, and they are generally somewhat uraniferous. Most of the platform phosphorite, however, is associated with limestone, sandstone, and glauconite, and is not appreciably uraniferous. An exception is the phosphorite in the Bone Valley formation of Florida, which was reworked from an older phosphatic limestone of platform type and concentrated in a marine platform environment (McKelvey and others, 1953, p. 23).

Several fundamental relationships between uranium and marine phosphorite permit estimation of the uranium content of marine phosphorite if sufficient data are available. These relationships are:

1. Uranium in the phosphorite is part of the phosphate mineral, which is generally carbonate-fluorapatite, and probably substitutes for calcium in the mineral lattice.

2. The amount of uranium in the lattice of the phosphate mineral varies widely but is relatively constant for a given type of deposit, such that the uranium content of a phosphate rock generally increases with increasing phosphate content.

3. Phosphates rich in CO_2 or those enclosed in limestone are not appreciably uraniferous (McKelvey and Nelson, 1950, p. 41), but some uraniferous phosphates contain thin lenticular interbeds of limestone.

4. Only phosphate deposits formed in or exposed to sea water at some time during their history are appreciably uraniferous.

In thousands of samples of marine phosphorite from several fields in this country and abroad, phosphate particles that do not contain more than about 25 percent P_2O_5 do not average as much as 0.01 percent uranium. It should be emphasized that this refers to averages, not to single analyses, and to the particles, not the rock. The phosphate rock in Florida, for example, contains only 10 to 20 percent P_2O_5, but the phosphate particles, which can be separated mechanically, contain as much as 35 percent P_2O_5 and are as uraniferous as phosphate beds of that grade in Idaho (0.01 to 0.02 percent) (V. E. McKelvey, written communication, 1953).

Few samples of western phosphate rock that contain more than 0.005 percent uranium contain more than about 2 percent CO_2 (McKelvey and Nelson, 1950, p. 41). This negative relationship between carbonate and uranium is further attested to by the fact that phosphatic limestone is only weakly uraniferous, even though the phosphate mineral particles in some limestone beds may contain more than 25 percent P_2O_5.

Phosphorite of residual origin that forms on decomposed phosphatic limestone does not contain much uranium. River-pebble deposits that are transported residual phosphorite are also poor in uranium as are phosphatized rocks that develop when residual phosphate rock decomposes, enters into ground-water solution, and replaces another rock at a lower horizon. Residual phosphorite deposits that are reworked by marine waters, however, may be uraniferous, and river-pebble and phosphatized rock derived from them may be also. Thus, the phosphorite particles in the marine limestone in the Hawthorn formation in Florida contain only 0.005 to 0.008 percent uranium, but those in the overlying Bone Valley formation, derived in large part from residuum of the Hawthorn and reworked in a marine platform environment, contain 0.015 percent uranium or more.

Nonmarine phosphatic limestone and fossil bone locally are uraniferous, but important deposits are not known.

MARINE CARBONACEOUS SHALE

Marine carbonaceous shale is a general term here adopted to include fine-grained argillaceous rocks of marine origin referred to by different authors as black shale, bituminous (sapropelic) shale, phosphatic shale, alum shale, graphitic shale or slate, oil shale, and combustible shale. Uraniferous marine carbonaceous shale deposits typically are several feet thick, cover tens or hundreds of thousands of square miles, and contain millions of tons of uranium in rock whose uranium content ranges from a few thousandths percent to perhaps as much as 0.02 percent (Bain, 1950, p. 291; McKelvey and Nelson, 1950, p. 35). Some marine carbonaceous shale deposits are siliceous and many contain kerogen, iron sulfide, and significant amounts of certain trace metals.

Uraniferous shale is the product of slow accumulation in a marine environment during a period of crustal stability. Some of the richest deposits seem to have accumulated at or near platform margins. The uranium is believed to have accumulated with the sediments, and the deposits are, therefore, regarded as syngenetic.

Most and perhaps all uraniferous shale deposits are dark colored and have a high content of organic material. Generally, the uranium content of a deposit seems to increase with increasing content of organic matter (McKelvey and Nelson, 1950). For example, the organic content of the Chattanooga shale is about 14 percent (Breger and Deul *in* U. S. Geological Survey, 1954c, p. 180), and the average uranium content of the shale ranges between 0.006 and 0.008 percent (Ruch, 1954), whereas selected samples from small pods rich in coalified wood and spores contain as much as 0.71 percent uranium (V. E. Swanson, oral communication). The *Peltura minor* zone of the Swedish alum shale contains about 30 percent organic matter and about 0.02 percent uranium, whereas within the shale, nodules of kolm (a coaly substance containing 79 percent organic matter), contain as much as 0.4 percent uranium (Davidson, 1951, p. 333; Bain, 1950, p. 320).

Two other characteristic features of uraniferous black shale are the presence of pyrite or marcasite in thin lenses, nodules, or disseminated particles and the absence or sparsity of calcium and magnesium carbonate (McKelvey and Nelson, 1950, p. 39) though thin beds of carbonate may be interbedded in the same sequence with the shale beds. Conversely, Ponsford (unpublished notes) attributes the lack of radioactivity in some British Rhaetic-Lias black shale deposits to their silty and (or) calcareous nature.

Most uranium-rich marine black shale contains small quantities of other metals including rare earths, titanium, copper, vanadium, manganese, nickel, chromium, cobalt, molybdenum, and phosphorus (McKelvey and Nelson, 1950; Bain, 1950, p. 286; Leutwein, 1951; Hundt, 1940). These metallic elements, as well as uranium and such other components as organic matter and pyrite, are commonly evenly disseminated throughout shale beds, and many beds contain phosphatic nodules or phosphate-rich layers. In most places the nodules are richer in uranium than the enclosing shale, but in some they are poorer (Davidson, 1951, p. 333; Gott, Wyant, and Beroni, 1952, p. 31; Russell, 1944, p. 205, 208). The tendency for phosphatic parts of a formation to be more uraniferous than the associated organic-rich beds is shown by the Phosphoria formation where the phosphate beds are more uraniferous than the shale beds (V. E. McKelvey, written communication, 1953).

Most uraniferous marine carbonaceous shale is laminated, dense, and tends to break with a conchoidal fracture when fresh. Different beds or units in a black shale sequence generally contain different quantities of uranium, but the grade of individual beds or units and of the sequence as a whole is commonly very uniform over broad areas. In the *Dictyonema* shale of Estonia and the Soviet Union and the Tomon shale of Venezuela the uranium content is higher where laminae are more closely spaced. Sparse information suggests that within a uraniferous marine carbonaceous shale, beds of the finest grain size are richest in uranium. Sandy layers in the Chattanooga, for example, are consistently less uraniferous than finer grained beds (V. E. Swanson, written communication), and sandy layers of the *Dictyonema* shale are only weakly radioactive.

Uraniferous marine carbonaceous shale beds are thin and widespread stratigraphic units that accumulated very slowly on or adjacent to stable platforms. In general the thickest of the relatively highly uraniferous beds seem to have been deposited near the platform margin. Some uraniferous marine carbonaceous shale beds are associated with unconformities, and most represent a considerable period of time. The entire Chattanooga shale is only 5 to 100 feet thick yet it represents all the material deposited during much of Late Devonian time (McKelvey and Nelson, 1950, p. 38). The layers richest in uranium range in thickness from 2 to 9 feet and can be traced for at least several tens of miles and with fair certainty for 100 miles.

Similarly the Swedish alum shale, 100 to 200 feet thick, represents all the material deposited during Middle and Late Cambrian time (Westergard, 1944), and the layers richest in uranium, the *Peltura minor* zone, range in thickness from 3 to 20 feet and can be traced over broad areas.

Most uranium-rich marine carbonaceous shale units are interbedded with other shale and limestone beds; some are interbedded with, or overlain by, phosphorite, chert, novaculite, or bentonite; some are themselves siliceous. Some of the uraniferous Pennsylvanian shale units of Oklahoma, Kansas, and other western states are rhythmic or cyclic deposits of shale, sandstone, and limestone (Gott and Hill, 1953, p. 73). Some of the siliceous shales, for example the Cambrian shale of the Kara Tau region of Siberia (Tyurin, 1944) and the alum slate of Thuringia in Germany (Leutwein, 1951), may in part be lateral equivalents of contemporaneous siliceous volcanic rocks. Other uraniferous shale units, such as the alum shale of Sweden and the *Dictyonema* shale of Estonia and the Soviet Union, were deposited marginal to granitic terrane (Glebov, 1941).

All the richer and larger known deposits of uraniferous marine carbonaceous shale are of Paleozoic age: the Swedish alum shale and the *Dictyonema* shale are Cambrian and Ordovician, the Chattanooga is Devonian, the Domanik in the Soviet Union is Upper Devonian, and the shungite in Karelia, U. S. S. R., is now thought to be post-Devonian, probably Lower Carboniferous.

From the above-mentioned characteristic features of the richer and larger deposits of uraniferous marine shale the following inferences regarding origin have been made: very fine grained clastic material, colloids, organic material, pyrite, and in many places phosphate, accumulate very slowly on sea bottoms deficient in oxygen (Conant, 1953). Contemporaneously, uranium and other metals are extracted from sea water by organic matter (McKelvey and Nelson, 1950, p. 39–40), phosphate, and possibly by colloidal clay or pyrite (Davidson, 1951, p. 333) and incorporated into the sediment. Tectonic stability within and adjacent to the site of deposition seems to be essential. Abnormal uranium content of the sea water may also be a significant factor. If so, an abnormal uranium content may have been furnished by volcanoes in adjacent areas or by abundant granitic rocks in the source area. The most favorable environments seem to have been local areas near margins of platforms during the Paleozoic.

PLACERS

Placers are products of the sedimentary part of the geochemical cycle. As rocks weather, the minerals that are resistant to solution are released and carried away by streams. During transportation minerals that are heavy and resistant to solution, abrasion, and impact may be concentrated by wave and current action into stream placers or, after they reach the sea, beach placers. Many placers contain weakly uraniferous minerals and a few contain moderately to strongly uraniferous minerals, but the uranium content of most placers is too small to be of interest, except perhaps as a minor byproduct of gold, tin, titanium minerals, and other common placer minerals.

Eluvial deposits are the result of deep decay and are gradational between weathered outcrops and stream placers. Deposits formed on gentle slopes commonly overlie the bedrock source and are of about the same grade as the bedrock source. On steeper slopes, the material tends to creep, and some concentration may result as lighter components tend to be dissipated by rain wash or wind. On the other hand, impoverishment will occur if the valuable mineral is relatively soluble. Because most uranium minerals are relatively soluble and because the conditions that favor the formation of eluvial deposits are likely to result in the complete or partial elimination of soluble minerals, important eluvial deposits of uranium are probably rare. They are most likely to occur in areas where veins, pegmatites, or other igneous rocks that contain uranium are exposed to a climatic environment that favors rock disintegration with a minimum of chemical decomposition.

Few minerals that contain much uranium are sufficiently resistant to impact, abrasion, and solution to be concentrated in stream placers.

Most of those that do are either very sparsely distributed or only locally concentrated within bedrock sources. Monazite is a notable exception, for it is a rather common accessory mineral in acidic and alkalic igneous rocks and it resists both chemical decomposition and physical disintegration. However, most monazite contains only 0.1 to 0.4 percent uranium though it may contain as much as 10.6 percent thorium (Frondel and Fleischer, 1955, p. 185). Resources measured in tens of thousands of tons of monazite are found in parts of the world where there are stream placers. They constitute small very low grade resources of uranium. A placer containing samaraskite, euxenite, and brannerite in Bear Valley, Idaho (Armstrong in U. S. Geological Survey, p. 221) is a potentially important resource of uranium. No other large or rich stream placers of radioactive minerals other than monazite have been reported, but some large placers that are worked primarily for tin or gold contain subordinate quantities of radioactive minerals (monazite, xenotime, thorite, thorianite, fergusonite, and others) that might be recovered as byproducts. Important stream placers of radioactive minerals are to be expected only along streams that head in or flow through areas of acidic or alkalic igneous rocks or silicic gneiss.

No beach placers that contain significant amounts of strongly uraniferous minerals are known, but beach placers in India and Brazil contain several hundred thousand tons of monazite (Bain, 1950, p. 315–318) and, therefore, constitute a large but very low grade resource of uranium.

Placers are ephemeral deposits and most of them are ultimately destroyed, but a few persist and become lithified. Such monazite placers have been recognized in Michigan (Vickers *in* U. S. Geological Survey, 1953, p. 203–204), Wyoming (Nininger, 1954, p. 100), Australia (Sullivan and Matheson, 1952), and in the U. S. S. R. (Chernov, 1938). Some geologists believe that uraniferous conglomerates, such as those in the Witwatersrand of Africa and the Blind River district of Canada, are buried placers that have been somewhat modified by hydrothermal solutions. (See p. 129–131.)

DEPOSITS FORMED AS A RESULT OF WEATHERING PROCESSES

Some uranium deposits seem to have formed as a result of weathering processes. Preexisting deposits that contain refractory uranium minerals (igneous rocks and placers) or uranium in unidentified but relatively insoluble form (shale and phosphorite) are not greatly affected by supergene processes. Deposits that contain pitchblende or uraninite with sulfides, however, are very susceptible to solution, and the uranium content of parts of many such deposits that are above the water table has been redistributed and perhaps, in some cases, completely dissipated. Obviously the amount of redistribution is dependent upon climate, topography, permeability, geologic structure, type of deposit, and composition of the ground water and host rock. In general, however, the net effect of these factors seems to result in dispersal rather than concentration of uranium. In some places, generally in arid or semiarid climates, the dispersal, or impoverishment, is not great, and the oxidized parts of primary deposits are minable (Shinkolobwe, Marysvale, and many sandstone-type deposits). In others, the oxidized zone does not constitute ore, but it may contain colorful and easily recognized uranium minerals and, thus, may provide a clue that workable primary deposits might be found at depth. In still others, however, the uranium removed by oxidation and solution is transported to favorable environments to form new deposits. Perhaps the most important deposits are the many uraniferous lignite and low-rank coal deposits, which apparently extracted uranium from percolating meteoric waters. Many deposits of uranium arsenates, vanadates, carbonates, silicates, and phosphates, most of them relatively small and unimportant, and some larger but very low grade deposits of uraniferous aluminum phosphate also appear to have been formed by weathering processes.

URANIFEROUS LIGNITE AND COAL

Coal, lignite, and associated carbonaceous shale deposits are generally among the least uraniferous rocks (Butler, 1952, p. 20; Davidson, 1951, p. 332), but locally such rocks contain enough uranium to constitute exploitable resources (Gill *in* U. S. Geological Survey, 1954c, p. 149–155). A fundamental difference between uraniferous marine and nonmarine carbonaceous rocks is that the uranium in the marine rocks generally is syngenetic and coextensive with a particular bed or group of beds whereas in the nonmarine rocks, the uranium generally seems to be epigenetic and is erratically distributed within a bed or group of beds. Uraniferous nonmarine carbonaceous rocks are generally much less extensive than uraniferous marine black shale. Individual deposits of uraniferous lignite and coal in the United States range in area from a fraction of a square mile to about 100 square miles and contain from less than 100 tons to more than 10,000 tons of uranium in rocks ranging from a few thousandths of a percent to as much as 0.76 percent uranium (U. S. Geological Survey, 1953, p. 17–19, 123–142; 1954a, p. 15–16, 116–123; 1954b, p. 18, 120–141; 1954c, p. 21, 149–156; 1955). Because most or all of the uranium remains in the ash or retort char of combustible carbonaceous rocks, low-grade material of this type may be sufficiently upgraded by burning or retorting to constitute ore. For example, a sample of coal containing 10 percent ash and 0.02 percent uranium would contain 0.2 percent uranium after ignition.

Nonmarine carbonaceous rocks rich in uranium have certain features in common:

(1) They are thin discontinuous beds or parts of beds. The uraniferous part of a lignite or coal bed generally ranges from a few inches

to a few feet in thickness, although the Bullion Butte lignite bed in North Dakota is weakly uraniferous across its full thickness, which is as much as 26 feet.

(2) Most of them contain a suite of other metals in addition to uranium, including titanium, rare earths, nickel, cobalt, molybdenum, tin, and vanadium (Erickson and others, 1954, p. 2208), but the suite and ratio of metals differ from one deposit to another. No suite has been recognized that is especially indicative of the presence of uranium or that would permit an estimation of the content of uranium. In most deposits of this type recognizable uranium minerals are sparse or absent. Studies of weathered coal indicates that the uranium is held in substances very similar to humic acids in composition, probably as the ionic compounds, uranyl humates (Breger and Deul *in* U. S. Geological Survey, 1954c, p. 171).

(3) Most of the uraniferous coal in the United States is interbedded with or overlain by acidic tuff and tuffaceous sedimentary rocks (Miller and Gill, 1954, p. 36–39), but some radioactive peat and other radioactive coaly deposits are not. These latter deposits are, however, within the drainage area of rocks that are known or likely to be uraniferous, as for example, the uraniferous Sungol peat of the Urals (Baranov and Novitskaya, 1943), in an area of acidic intrusive rocks and metalliferous deposits.

Radioactive nonmarine carbonaceous rocks as old as Silurian and as young as Recent are known; most of the larger and richer deposits are of Tertiary age. The deposits listed below are representative:

Age	*Deposits*	*Character and reference*
Silurian	"Coal" (bituminous material) in central Asia.	Radioactive, possibly uraniferous (Fersman, 1930).
Carboniferous	Carbonaceous (coaly) shale, northern Spain.	As much as 0.12 percent uranium (Judd, De Sanctis, and Brown, unpublished notes.
	Many localities in the central United States.	As much as 0.004 percent uranium (Gott, Wyant, and Beroni, 1952, p. 31).
Permian	Coal in Kuznetsk and Minusinsk coal basins, U. S. S. R.	As much as 0.014 percent uranium (Labazin, 1930).
Mesozoic	Many localities in western United States.	Exceptionally as much as 0.5 percent uranium in small deposits, but generally less than 0.01 percent. (U. S. Geological Survey, 1953, 1954a, 1954b, 1954c, 1955).
Tertiary	Many localities in western United States.	Locally as much as 0.76 percent uranium, but commonly less than 0.01 percent. (U. S. Geological Survey, 1953, 1954a, 1954b, 1954c, 1955).
Quaternary	Sungol peat, Ural Mountains.	Radioactive (Baranov and Novitskaya, 1954).

Several hypotheses have been formulated to account for the origin of uranium in lignite, coal, and other nonmarine carbonaceous rocks (Burkser and others, 1929 and 1934; Denson and others, 1952; Hoffmann, 1943; Wyant and others, unpublished notes). The abnormal amount of uranium in many uraniferous coal beds seems to have been deposited by ground water, after coalification, though it is possible that part or all the uranium in some coaly rocks may have been concentrated by growing plants or, more likely, by decaying plant material before coalification. At many deposits in the western United States there is evidence that uranium was leached from weakly uraniferous overlying or interbedded acidic tuffs, transported along permeable beds in the coal-bearing formation by subsurface water, and fixed in the coal as an organic-uranium compound or complex (Denson and others, 1952, p. 8, 9; Miller and Gill, 1954, p. 37–38; Breger and others *in* U. S. Geological Survey, 1953, p. 121).

This explanation seems to account satisfactorily for the origin of most of the uraniferous Upper Cretaceous and Tertiary coal and lignite in the western United States, but there are some deposits to which it does not apply. For example, the geologic setting of some uraniferous coal is such that leaching of acidic tuff could not have provided the uranium but that leaching of acidic or alkalic intrusive rocks, uraniferous marine sedimentary rocks, arkose, or veins and other deposits of higher grade of uranium could have. The uranium in some coal, notably at the Leyden coal mine in the Colorado Front Range (Gude and McKeown, 1953), probably was introduced by and precipitated from hydrothermal solutions of igneous origin.

In summary, in prospecting for nonmarine carbonaceous rocks that are likely to be uraniferous, one should probably assign first priority to coaly rocks that are interbedded with or overlain by acidic volcanic rocks but should not overlook coaly rocks that are closely associated with or are in the same drainage basin with abnormally uraniferous igneous intrusive or sedimentary rocks or hydrothermal deposits, especially if in, or suspected to be in, a uranium province.

SECONDARY URANIUM MINERALS

Many deposits of secondary uranium minerals, such as sulfates, arsenate, vanadates, carbonates, and silicates, are formed as a result of weathering processes. Some are clearly the result of oxidation of preexisting deposits with more or less dispersal of the uranium (Stugard, Wyant, and Gude, 1952); such deposits are not included here. Many of the others are associated with acidic tuffs or tuffaceous sedimentary rocks of Tertiary age (Hewett, 1923 and 1925; Walker, 1953; Walker and Lovering, 1956); some are in coarse-grained acidic igneous rocks. Typically they consist of secondary minerals erratically distributed on fractures or along bedding planes. Some deposits of this type may have a hydrothermal origin (Duncan, 1953a), but in most cases the uranium seems to have been leached from the host rocks and redeposited along fractures or in favorable rocks by ground water, as suggested by Gill and Moore (1955) for carnotite-bearing tuffaceous sandstone in South Dakota. Most known deposits of this type are in areas where the climate is arid or semiarid. With few exceptions, the deposits are small and minable thicknesses generally contain less than 0.2 percent uranium (McKelvey, 1955).

Uraniferous aluminum phosphate is a distinctly different type of deposit resulting from the weathering of phosphorite in a tropical or subtropical climate (McKelvey, 1955). Deposits of this type in Florida constitute a large very low grade resource of uranium.

DEPOSITS OF UNCERTAIN ORIGIN

SANDSTONE-TYPE DEPOSITS

Continental sandstone and, less commonly, siltstone, shale, and limestone are hosts to a variety of mineralogic types of uranium deposits that collectively are called sandstone-type deposits and constitute the principal source of uranium in the United States.

In most deposits of the sandstone type, uranium is associated with vanadium or copper, and with carbonaceous material. Some deposits contain black or dark-colored minerals of tetravalent uranium, such as pitchblende; some contain minerals of brightly colored hexavalent uranium, such as carnotite or autunite, that are probably the oxidation products of tetravalent uranium minerals; and some contain minerals of both tetravalent and hexavalent uranium. Deposits are most abundant in fluviatile sandstone, although many occur in finer grained clastic rocks and some occur in limestone. The host rocks are typically permeable units in sequences of continental dominantly clastic rocks, commonly including red beds, carbonaceous rocks, and acidic tuffs, that were deposited in broad basins and are the erosion products of surrounding highlands. The ore-bearing rocks typically are not strongly deformed or intruded, but in many places they are gently warped, block-faulted, and (or) cut by a few dikes, sills, and laccoliths, which commonly are moderately alkalic types. Many of the important sandstone-type deposits are in rocks that contain at least traces of petroleum or asphaltite.

A number of theories have been advanced to explain the origin of uranium deposits in sandstone and related rocks (summarized in McKelvey, 1955; see also Stieff, Stern, and Milkey, 1953; and Osipov, 1941), but no single theory satisfactorily explains the significant features of all types of ore bodies (Wright, 1955, p. 151). Recent determinations of the age of ore minerals have apparently established that the uranium in sandstone-type deposits in the Colorado Plateau was deposited during Late Cretaceous or early Tertiary time, long after the host rocks of Paleozoic and Mesozoic age accumulated (Stieff, Stern, and Milkey, 1953). Though the ultimate source of the uranium has not been established, it was almost certainly deposited from migrating fluids. It may have been introduced by hydrothermal solutions or it may have been concentrated by secretion and fractionation from original sparse disseminations within the sedimentary rocks by percolating fluids, for the ore-bearing sequences, or rocks that overlie them, commonly contain syngenetic uranium, mainly in acidic volcanic ash or tuffaceous material but also in accessory radioactive minerals.

W. S. Burbank (oral communication) has pointed out that during the Late Cretaceous and early Tertiary the energy level of the crust was rather high in an area that includes the Colorado Plateau, owing to the sinking of the sedimentary basin and widespread local penetrations of magma. This observation may also hold true for other areas containing sandstone-type deposits such as the Fergana valley in the Soviet Union, and the west-central part of Argentina. It supports both hypotheses of ultimate source, though perhaps more strongly that of the lateral secretion and fractionation of uranium from materials dispersed in the sedimentary prism.

The fluid most commonly postulated as the uranium carrier is ground water, but others such as brine, petroleum, and natural gases, including carbon dioxide, or combinations of several of these earth fluids also may have carried uranium.

Irrespective of the ultimate source of the uranium and the nature of the transporting medium, most of the deposits are localized by sedimentary features, but some are localized, at least in part, by structural features.

Most sandstone-type deposits seem to have consisted initially of pitchblende or uraninite with variable amounts of coffinite (a hydrous uranium silicate), pyrite, other sulfide minerals, and dark-colored vanadium oxides, such as montroseite, doloresite, lumsdenite (Weeks, and Thompson, 1954; Weeks, 1955). Many deposits have been oxidized in situ to colorful sulfates, hydrous oxides, phosphates, carbonates, vanadates, and silicates of uranium, copper, and other metals.

Oxidized sandstone-type deposits composed of secondary uranium minerals are most likely to be found where the prevailing climate is arid to semiarid, or continental with long dry summers because, in regions of great rainfall, the soluble uranium minerals tend to be leached from the permeable host rocks, and the uranium tends to be flushed from the area in ground and surface water.

The Colorado Plateau and vicinity may be considered the type locality of sandstone-type uranium deposits. Deposits there have been studied and sporadically exploited for 40 years. The bulk of the production from this area until 1954 was from carnotite ore bodies (oxidized vanadium-uranium ore bodies), but copper-uranium, uranium-carbon, uranium, and unoxidized vanadium-uranium ore bodies now contribute a significant and increasingly important part of the total. Most of the deposits are impregnations in sandstone that contains carbonaceous material, but some deposits are in carbonate rocks—for example, those in the fetid Todilto limestone near Grants, N. Mex.

Although ore bodies in and around the Colorado Plateau occur in 32 rock units ranging in age from Pennsylvanian to Tertiary (Isachsen, Mitcham, and Wood, 1955, p. 127; Finch, 1955), most of the ore in a given area is restricted to a few formations or members and normally to a few strata within the favored formations, such as the basal part of the Shinarump member of the Chinle formation (Triassic) and the upper part of the Salt Wash sandstone member of the Morrison formation (Jurassic). Most of the known ore bodies are in fluvial sediments, but some are in rocks of lagoonal and lacustrine origin (Craig and others, 1955; Isachsen, Mitcham, and Wood, 1955, p. 134). Ore bodies of either primary or secondary uranium minerals are generally flat lenses of irregular shape and size that, in general, follow the bedding of the enclosing rocks and are elongated in one horizontal dimension. Most of them are localized by sedimentary features, principally by ancient stream channels or by interfingering lenses of sandstone in mudstone. Some are localized by carbonized wood and carbonaceous trash. Disseminations of hexavalent uranium minerals are common along near-surface fractures near either primary or secondary ore bodies, but they rarely constitute ore themselves.

The carnotite deposits in the Salt Wash sandstone member of the Morrison formation, in what up to 1954 was the principal producing area of the Colorado Plateau, are grouped in clusters within a broad arcuate mineral belt (Fischer and Hilpert, 1952; Wright, 1955), within which the long axes of individual deposits characteristically trend inward, like the spokes of a wheel. Recent data indicate an additional clustering around the flanks and axes of major anticlines that transect the mineral belt (Cater *in* U. S. Geological Survey, 1953, p. 28–29), and there is some evidence that the primary deposits in this area are similarly clustered.

Elsewhere on the plateau, deposits of different types in several formations tend to be localized around major anticlinal structures (Wright, 1955, p. 147), but this may be a result of present exposure rather than of origin. Similar deposits in South Dakota, however, are clearly related to major anticlines and minor structural terraces (U. S. Geological Survey, 1954c, p. 99–101).

Most ore deposits contain from a few tons to perhaps a hundred thousand tons of ore. One of the largest ore bodies known, that at the Mi Vida mine, is reported to contain a few million tons of minable ore (Steen, 1954). Average grade of ore in most ore bodies is 0.2 to 0.4 percent uranium (Ruch, 1954), but some ore approaches 1 percent uranium in grade (Fischer, 1942, p. 367). In addition many ore bodies on the plateau commonly contain 1 to 5 percent V_2O_5. Examples of ore bodies that are partly oxidized are too few to indicate whether grade of ore typically increases, decreases, or remains about the same during oxidation. However, one of the largest vanadium-uranium deposits, the Mi Vida body of primary ore, is higher grade than most carnotite deposits, averaging 0.45 percent U_3O_8 according to Steen (1954), and the primary ore at the Happy Jack mine, the largest copper-uranium deposit now known, is somewhat richer than the secondary ore (Dodd, 1950, p. 18–20).

Several empirical clues have been established to describe ground favorable for prospecting (Wier, 1952; Witkind and Thaden, in preparation). The presence of several of the following features indicates favorable ground: brown sandstone speckled with limonite, abundant carbonaceous materials including accumulations of plant debris and petroleum residues, channels in underlying shale or mudstone filled with porous sandstone or conglomerate, interbedded sandstone and mudstone near the margins of thick sandstone lenses, mudstone altered from red to gray, and abundant copper stains.

The likelihood that deposits of sandstone type occur in any particular area can be estimated from rather general geologic information. For example, sequences of continental rocks, including permeable sandstone units, that cover broad areas, may be considered potential hosts for uranium deposits. If other types of uranium deposits or uraniferous waters occur in or adjacent to an area of such rocks, that is, if there is evidence of a uranium province, the likelihood of finding deposits of sandstone type is good. The degree of likelihood that such deposits occur is considered to increase as more of the following favorable features are present; climate is arid to semiarid, potential host beds are gently folded and faulted; volcanic ash of acidic composition is interbedded with or overlies host beds; minor igneous intrusions, especially those of moderately alkalic composition, cut or dome the potential host beds; host beds contain petroleum, asphalt, carbonized plant remains, and disseminated copper, vanadium, silver, or cobalt-nickel minerals.

URANIFEROUS CONGLOMERATE

The gold-bearing conglomerate of the Witwatersrand of South Africa is becoming increasingly important as a source of uranium and perhaps constitutes the largest single resource of low-grade uranium ore that can profitably be exploited under present conditions. Judging from many articles in several mining journals the reserve of gold ore containing several hundredths of a percent uranium that can be recovered as a byproduct may be of the order of a billion tons. Millions of tons of ore averaging about 0.1 percent uranium are already indicated in similar deposits in the Blind River district of Ontario (Browning, 1955, p. 85–86), even though the deposits were discovered only a few years ago. The known deposits are of Precambrian age and are similar in habit, mineralogy, type of host rock, and probably in origin.

The Witwatersrand deposits, the world's most important source of gold, have been described by many investigators (Young, 1917; Reinecke, 1930; Union of South Africa Geological Survey, 1940; Graton, 1930; Geological Society of South Africa, 1931). Pyrite, gold, uraninite (or pitchblende), and small amounts of many other minerals and metals together with carbonaceous material (thucholite) are localized in thin quartz conglomerate beds, called reefs, in the middle part of a 25,000-foot thickness of conformable sediments resting on crystalline basement rocks. The beds are folded into a broad syncline, broken by many faults of small to moderate displacement, and cut by dikes, mainly of diabasic composition. Ore occurs in elongated shoots or pay streaks as much as 5,000 feet long and 1,000 feet wide and from 1 to 10 feet thick. According to Reinecke the richest parts of the gold deposits coincide with volumes of well-sorted pebbles, large pebbles, alined pebbles, and with the thickest parts of a reef. The pay streaks are roughly parallel but form a braided pattern, which has been interpreted as a series of channels on a gigantic piedmont alluvial fan (Union of South Africa Geological Survey, 1940, p. 127). Quartz veinlets cut the conglomerate and adjacent rocks but are not common. Some contain pitchblende (Davidson, 1953 and 1954). The gold deposits consist of 70 to 90 percent quartz, 10 to 30 percent sericite (including some pyrophyllite, chloritic material, and chloritoid), 1 to 3 percent pyrite, and traces or small fractions of a percent of pentlandite, pyrrhotite, chalcopyrite, galena, cobaltite, sphalerite, niccolite, gersdorffite, arsenopyrite, marcasite, altaite (AuTe), hydrocarbon, uraninite, iridosmine, zircon, magnetite, chromite, leucoxene, goethite, ilmenite, tourmaline, rutile, and gold.

The deposits at Blind River have been described briefly by Traill (1954) and Abraham (1953). They occur in quartz conglomerate at or near the base of a sequence of sedimentary rocks of the Huronian resting unconformably on a complex of metamorphic and igneous rocks. They are generally similar to the deposits of the Witwatersrand but differ in containing brannerite and relatively abundant monazite in addition to uraninite, more uranium than gold, and less carbonaceous material.

The origin of uraniferous conglomerates, like the origin of the sandstone-type deposits that they resemble in many respects, is a subject of heated controversy. The evidence presented in the literature, in the present authors' opinion, is insufficient to demonstrate conclusively whether the uranium and gold are of igneous origin and were deposited in permeable channelways by hydrothermal solutions or whether much or all of the uranium and gold was originally of placer origin and was merely reconcentrated by migrating waters of meteoric, hydrothermal, or mixed origin.

URANIUM IN PETROLEUM AND ASPHALTITE

From the few data available on the trace-element content of petroleum it is probable that most petroleum accumulations contain only a small fraction of a part per million uranium (Erickson, Myers, and Horr, 1954; Russell, 1945). The highest uranium content reported in available literature is 0.02 part per million in crude oil from Wyoming. However, partly oxidized residual oil extracted from petroliferous rock near Golden, Colo., contains 50 parts per million uranium (Erickson, Myers, and Horr, 1954). As crude oil volatilizes, the uranium content of the residue increases, but data are insufficient to permit an estimate of the ratio of concentration from liquid petroleum to solid hydrocarbon. Petroleum coke and flue dust have for many years been a minor source of vanadium. Some of the residues also contain uranium, but the amount that could be recovered is probably too trivial to be of interest, for even if the average uranium content of domestic crudes is 0.01 part per million, half the maximum reported by Erickson, Myers, and Horr, the total uranium content of the annual output of crude oil in the United States (roughly 300 million tons) would be only 3 tons, and the total uranium content in the estimated reserve of crude oil in the United States (4 billion tons) would be only 40 tons. This, however, is probably only part of the story, for as petroleum migrates through porous rock, heavy "dead oil" residues containing appreciable uranium and other heavy metals may be trapped in the rock.

Though many oil-field brines are strongly radioactive, most of the radioactivity is due to radium and other disintegration products of uranium (Bell, Goodman, and Whitehead, 1940), and consequently few, if any, brines are likely to constitute exploitable low-grade resources of uranium. Oil-field brines, petroleum, and natural gas that contain uranium or decay products of uranium (radium, radon, helium) are chiefly of interest in that they may provide supporting evidence for the existence of a uranium province and perhaps even indicate uranium ore deposits (Gott and Hill, 1953).

Although the uranium content of petroleum is very low, that of some solid hydrocarbons is relatively high. Uraniferous hydrocarbons have been reported from a variety of geologic settings in many countries and under a number of names—asphaltite, bitumen, thucholite, carburan, anthraxolite, and others (Davidson and Bowie, 1951; Erickson, Myers, and Horr, 1954). For simplicity all these hydrocarbons are herein referred to as asphaltite, even though this is not conventional. Many asphaltites, including all that have been mined for their asphaltite content, are believed to be natural petroleum residues formed from crude oil by oxidation, polymerization, and volatilization. Some others are thought to be coal extracts (I. A. Breger and M. Deul, written communications). Most petroleum residues contain too little uranium to be of interest, but locally botryoidal pellets, grains, impregnations or veinlets of asphaltite contain from a fraction of a percent to as much as 20 percent uranium (Hill and Beroni *in* U. S. Geological Survey, 1954a). Botryoidal pellets particularly tend to be strongly uraniferous (Arthur Pierce and J. W. Mytton, oral communication). The content of 28 samples of asphaltite from the Panhandle field, Texas and Oklahoma, ranges between 0.1 and 10.0 percent uranium (Gott *in* U. S. Geological Survey, 1953, p. 256–258). Typically these pellets, grains, impregnations, or stringers, even though they contain moderate amounts of uranium, are too sparsely dispersed to constitute an exploitable resource. A notable exception occurs, however, in the Temple Mountain district, Utah, where minable bodies of uraniferous asphaltite are associated with typical sandstone-type (including carnotite) deposits and are of comparable habit, size and grade (Wyant, unpublished notes). Uraniferous asphaltite is present in a number of sandstone-type deposits on the Colorado Plateau, and in Wyoming, and has been found at a number of localities in north Texas and Oklahoma (Hill *in* U. S. Geological Survey, 1953, p. 200–203; U. S. Geological Survey, 1954a, p. 256–258; 1954c, p. 217–218).

Uraniferous hydrocarbons also occur in pegmatites, in uraniferous conglomerate, and in veins in crystalline rocks, both alone and with metallic and gangue minerals. Most occurrences of these types are in rocks of Precambrian age (Lang, 1952, p. 11, 12). The uranium content of these hydrocarbons ranges from little more than a trace (0.003 percent) in the anthraxolite veins of the Canadian shield to as much as 45 percent in the ash of some samples of thucholite (Frondel and Fleischer, 1955).

In some and perhaps in all asphaltites, most of the uranium is in uraninite, coffinite, and perhaps other primary minerals that occur as discrete and generally microscopic grains within the asphaltite (Davidson and Bowie, 1951; Kerr, Rasor and Hamilton, 1951). Some may occur as a metallo-organic compound (Kerr, Rasor and Hamilton, 1951). Recent study of polished sections of uraniferous pellets by Pierce (*in* U. S. Geological Survey, 1954c, p. 274–276) shows that the major part of the trace metal content (about 5 percent of the pellet) can be accounted for by inclusions of mineral arsenides and sulfides.

The uraniferous hydrocarbons in pegmatites, veins, and metamorphosed uraniferous conglomerate deposits are generally considered to be of igneous origin (Ellsworth, 1932)), but the origin of uraniferous hydrocarbons in sedimentary rocks is a subject of controversy and probably is not the same for all occurrences. Several theories of origin have been advanced: 1, the uranium was originally a minor constituent of petroleum and was greatly concentrated during the conversion of the petroleum to asphaltite (Gott, Wyant, and Beroni, 1952, p. 35; Erickson, Myers, and Horr, 1954); 2, petroleum extracted uranium from the rocks through which it migrated or from uraniferous ground water or perhaps from hydrothermal solutions of igneous origin, and the uranium was greatly concentrated by adsorption during mixing with the aqueous solutions and consequent conversion of oil to asphaltite pellets (A. Pierce and J. W. Mytton, oral communication); 3, the hydrocarbons formed around preexisting grains of uraninite and perhaps in some cases other strongly uraniferous minerals as a result of polymerization of crude oil or natural gas (methane) by alpha radiation (Davidson and Bowie, 1951); and 4, the uranium- and vanadium-bearing solutions extracted organic matter from degraded plant debris in the sediments and this mixture of carbonaceous material, uranium, and vanadium was subsequently deposited in porous sandstone (A. Breger and M. Deul, written communication). Available data on the uranium content of petroleum indicate that an improbably high ratio of concentration would be required to produce strongly uraniferous asphaltite by the first mentioned theory (Breger and Deul *in* U. S. Geological Survey, 1954c, p. 172–174), without modification. The fragmental "jigsaw" pattterns of the mineral inclusions in black lustrous pellets examined by Pierce and Mytton (*in* U. S. Geological Survey, 1954c, p. 274–276) suggest that the included minerals were formed prior to solidification of the asphaltite from a liquid stage and not from a gas.

Uraniferous asphaltite of possible commercial interest is most likely to be found in the same areas as sandstone-type uranium deposits or in areas that would be judged favorable for the occurrence of such deposits according to the guides listed in the section on sandstone-type deposits. In fact, in some deposits of sandstone-type part of the uranium is in an organouranium compound and part is in pitchblende (uraninite or other low-valent oxides) or secondary uranium minerals, or both. Some deposits consisting entirely or almost entirely of uraniferous asphaltite, especially if in pellets, might be much larger than typical deposits of sandstone-type, but the average grade is likely to be lower, though perhaps high enough to be of interest (A. Pierce, and J. W. Mytton, oral communication). In other geologic environments asphaltite deposits of minable size will in general probably contain too little uranium to constitute ore, and uraniferous pellets will in general probably be too sparsely or sporadically distributed to constitute ore.

Hydrocarbons in igneous and metamorphic rocks, other than the mildly metamorphosed uraniferous conglomerate deposits, and in veins, though rarely present in commercial quantities, are favorable indicators for the presence of uraninite or other strongly uraniferous minerals that might occur in exploitable concentrations in veins, pegmatites, and other rocks nearby.

URANIUM PROVINCES

Geologic and geochemical evidence indicates that parts of the earth's crust, called provinces in this report, are richer in one or more elements or exploitable concentrations of these elements, than other parts. Parts of the North American continent, the Mississippi Valley area in particular, are richer in lead and zinc deposits than others; Arizona and parts of New Mexico and Nevada are unusually rich in copper deposits; and parts of Idaho and Arkansas are rich in niobium. Similarly, certain areas are richer in uranium deposits than others. Some of the areas seemingly poor in uranium deposits are geologically similar to areas relatively rich in uranium deposits. Uranium provinces may reflect differences in composition of the primordial earth or they may have originated and been maintained solely by geochemical processes activated by cyclic tectonic forces. In any event the recognition of a province may lead to new discoveries of uranium ore.

DEFINITION AND EXAMPLES

A uranium province is here defined as a broad and generally indefinitely bounded area in which uranium deposits and uranium-rich rocks are relatively abundant. Commonly the deposits are of several types and of more than one age. Most of the important uranium deposits are clustered in a few such areas; notably the broad belt in and adjacent to the Rocky Mountains, extending from New Mexico and Arizona to the Dakotas and Montana; the western and southern parts of the Canadian shield; the northeastern part of the South African shield, parts of the Australian shield; the Erzgebirge and vicinity in central Europe; and the Fergana-Kara Tau region in Russian middle Asia. Outside of uranium provinces significant uranium deposits are sporadically distributed, sparse, or lacking.

In contrast there are broad areas in which uranium deposits, other than low-grade syngenetic concentrations in phosphorite, black shale, or pegmatites, are sparse or lacking. For example, in the eastern third of the United States in and adjacent to the Appalachian Mountains, no important uranium deposits have been reported, though there are low-grade syngenetic concentrations in black shale and scattered pegmatites and a few small epigenetic deposits of carnotite in sandstone. The main geologic features of the seemingly uranium-poor Appalachian region are in many respects similar to those of the uranium-rich Erzgebirge region. Both of these areas are strongly deformed geosynclinal belts, intruded by granitic plutons, and flanked and in part covered by erosional debris from orogenic mountains. The Triassic basins and the plateaus underlain by Pennsylvanian nonmarine rocks in the Appalachian region are comparable to the Triassic and younger basins and plains marginal to the Erzgebirge. Nevertheless, in the Appalachian region, known uranium concentrations are few, low-grade, and mostly of syngenetic origin (black shale and pegmatite), whereas in the Erzgebirge region veins have been an important source of uranium for many years (Bain, 1950, p. 302–305) and strongly uraniferous coal has recently been reported (Davidson and Ponsford, 1954).

Similarly, the geologic history and features of the Canadian shield, the South African shield, the Fennoscandian shield, and the Brazilian shield are roughly similar, but the first two contain important uranium deposits whereas virtually none are known in the second two.

These observations suggest that parts of the earth's original crust were richer in uranium than others. Differences in metal content of the original crust would be expected if the earth formed by accretion of planetesimals and other cosmic material and never was completely molten (Goldscmidt, 1922a, 1937; Urey, 1952). Whether significant differences existed or not, the interplay of geochemical and tectonic processes, which tend to be cyclic, redistributed the uranium in the earth's original crust and in part concentrated it in exploitable deposits, most of which are clustered within broad and poorly defined areas or provinces that have persisted for long periods of geologic time. As deposits of one type are destroyed, others in equilibrium with the existing environment are formed. The province persists so long as the geochemical processes that tend to concentrate uranium preponderate over the geochemical processes that tend to dissipate uranium.

RECOGNITION OF A URANIUM PROVINCE

At our present level of knowledge the only positive indicator of a uranium province seems to be the presence of a variety of types of abnormal concentrations, regardless of the amount of uranium concentrated in any particular deposit. However, the presence of a single epigenetic deposit in a geologically favorable area is sufficient to suggest that a uranium province may exist, and if several deposits of a single type are known the chance is very good that other deposits will be found. All the concentrations in a province may be of about the same age, but because of the high degree of mobility of uranium, deposits of more than one age are typical. The boundaries of uranium provinces are controlled by the interplay of many geologic and climatic factors and consequently are likely to be rather indefinite. These criteria for the recognition of a province are perhaps obvious and undoubtedly incomplete. Almost certainly they will be sharpened as new discoveries are made and as the viewpoints of geologists change as a result of increased geologic and geochemical knowledge.

APPLICATION OF THE PROVINCE CONCEPT TO PROSPECTING

The province concept is valuable in roughly appraising the potential of an area in which uranium deposits are known and in pointing out settings within a province in which exploitable concentrations might profitably be sought. If an area is known or suspected to be a province, every possible setting in which uranium might be localized should be investigated. These include acidic and alkalic igneous rocks and mineralized structures in the vicinity of such rocks; placers or sites where placers might occur; sequences of continental sandstone and shale, particularly those that contain abundant carbonaceous material, mixed with tuffaceous material and petroleum residues, or those cut by small acidic or alkalic intrusives; lignite and coal, particularly if it is, or was) overlain by acidic volcanic rocks or is in a basin through which ground water drained from a granitic, arkosic, or acidic volcanic terrane; metamorphosed black shale; and conglomerate-bearing sequences deposited on a crystalline basement. More specifically, if abnormally radioactive igneous rocks and a few vein deposits have been discovered in a mountainous orogenic belt, placers and other vein deposits in favorable structural settings might be found, particularly in the vicinity of igneous rocks. In the less deformed erosional debris within and marginal to this belt, especially if the climate is arid, semiarid, or dry continental, one should look for deposits of the sandstone type, uraniferous lignite or coal, uraniferous petroleum residues, and perhaps placer deposits. As an example, deposits of all these types might be expected to occur in the Triassic and younger basins within and adjacent to the Bohemian massif and particularly in those adjacent to the Erzgebirge in the northern half of the massif. Similarly, if sandstone-type deposits are found in a basin, one might profitably look for vein deposits in the adjacent mountains, provided that acidic igneous rocks and favorable structures are present.

The same principles apply to ancient shield areas where veins, uraniferous rocks, and placers are most likely to be in the strongly deformed, metamorphosed and intruded portions and uraniferous conglomerate may occur in peripheral rocks that are less strongly deformed, metamorphosed and intruded. Though uraniferous coal and petroleum residues are not to be expected, small deposits of modern uraniferous peat might occur locally.

In any prospecting program the probable influence of climate, both at present and in the past should be carefully considered.

As a corollary to the province concept, the authors would not expect to find more than a sporadic exploitable deposit in relatively recent eugeosynclinal belts or basic volcanic chains such as the Coast Ranges of California and Oregon, much of the Caribbean area, Hawaii, the Philippine Islands, the Aleutian chain, and Kamchatka and the Kuril Islands. Similarly, broad areas covered by rather thick sequences of relatively recent undeformed basaltic flows are relatively unfavorable, even though they may be surrounded and underlain by favorable geologic settings. However, where eugeosynclinal rocks and especially basic igneous rocks have been involved in later orogeny and intruded by acidic igneous rocks, they may assume a relatively high degree of favorability, for many vein deposits seem to favor basic igneous host rocks (Lang, 1952, p. 20–21).

GENERAL CRITERIA FOR PROSPECTING

In conclusion, several criteria are listed for selecting areas deserving a high priority in the search for uranium.

Positive criteria:

1. The presence of epigenetic uranium deposits, particularly if those deposits are of more than one type or age.
2. The presence of acidic and alkalic igneous rocks, particularly small highly differentiated plutons of granitic and syenitic type.
3. The presence of mineralogically complex veins of base and precious metals.
4. The association of lignite or coal with acidic tuffs.

Negative criteria:

1. The presence of abundant basalt, gabbro, and sedimentary rocks derived from such rocks, and the lack of younger acidic igneous rocks.
2. The rocks of the area are thin accumulations of essentially undeformed platform type that are not cut by acidic intrusives. Uraniferous black shale or phosphorite may be found in such environments but important epigenetic deposits probably will not.
3. An extremely wet climate. Soluble uranium will tend to be flushed out of such areas.

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