

815
Un31p
RM6

UNITED STATES ATOMIC ENERGY COMMISSION

[Publications]

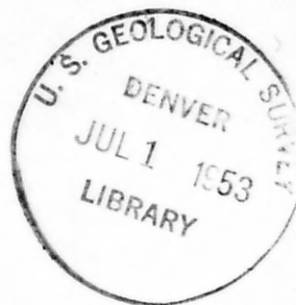
RMO-732

**GEOLOGY OF URANIUM DEPOSITS—
A CONDENSED VERSION**

**By
Donald L. Everhart**

**With Mineral Tables By
Muriel Mathez**

**May 1951
SI-63
Division of Raw Materials
Exploration Branch**



Technical Information Service, Oak Ridge, Tennessee

METALLURGY AND CERAMICS

Reproduced direct from copy
as submitted to this office.

CONTENTS

	<u>Page</u>
INTRODUCTION	1- 2
GENERAL FEATURES	3- 4
DEPOSITS IN IGNEOUS AND METAMORPHIC ROCKS	4
Hydrothermal Vein Deposits	4- 6
Shinkolobwe mine, Belgian Congo	6- 8
Vein deposits in the United States	8-10
Disseminated Deposits in Igneous Rocks	10-11
Pegmatites	11-12
DEPOSITS IN SEDIMENTARY ROCKS	13
Carnotite Deposits	13-14
Copper-uranium Deposits	14-16
Uranium-bearing Asphalt Deposits	16-17
Uranium-bearing Limestone Deposits	17-18
Uranium-bearing Phosphorites	18-20
Uranium-bearing Black Shales	20-22
Alluvial and Placer Deposits	22-23
Lacustrine-saline Deposits	23
USE OF FIELD INSTRUMENTS FOR RADIATION DETECTION . . .	24-26
SUGGESTED SAMPLING PROCEDURES AND THE EVALUATION OF URANIUM ORE BODIES	26-28

TABLE I - COMMON URANIUM MINERALS

GEOLOGY OF URANIUM DEPOSITS
- A Condensed Summary -
by
Donald L. Everhart

Mineral Tables
by
Muriel Mathez

INTRODUCTION

In an effort to stimulate the search for uranium deposits among professional geologists and mining engineers, the following pages present a brief summary of some of the pertinent facts and ideas concerning the geology of uranium deposits evolved by many individuals who have been actively engaged in uranium exploration. This work has been done by members of the U. S. Geological Survey, the U. S. Atomic Energy Commission, geological surveys of several other countries, mining companies, and several educational and research institutions.

The writer recommends that the following bibliography be consulted in conjunction with this paper: Selected Bibliography of Published References on Uranium Occurrences and Radioactive Ore Deposits, compiled by Margaret Cooper, Division of Raw Materials, U. S. Atomic Energy Commission, New York, N. Y., March 1951.

Invariable or infallible geologic guides to uranium ore have not been completely formulated, and the character of even the most common of the uranium minerals in many instances is not fully understood. Furthermore, any system of classification of uranium deposits

must be considered tentative, for varied uranium-bearing mineral assemblages continue to be found in igneous, sedimentary, and metamorphic rocks of nearly all ages. The art and science of exploring for uranium deposits are uniquely aided, however, by the fact that all concentrations of uranium exhibit abnormal radioactivity. Thus, in addition to standard geologic and physical techniques used in exploration, geologists and engineers have at their disposal an additional tool based upon radioactivity detection.

Incentives for mining uranium ore include not only an assured market, but guaranteed prices for a specified length of time. Further, there are negotiated prices that take into account special cost factors involved in developing new sources of uranium. The by-product value of uranium recovered during operations for other metals offers an additional incentive to the mining industry.

Concepts as to the nature and distribution of uranium ore deposits are being formulated as exploration and research activities progress, and new types of uranium deposits are disclosed. These pages contain a condensation of the current information on these subjects. Some is fact; other is interpretation based upon comparatively limited experience. As work progresses, ideas on many of these subjects will undoubtedly change, and this presentation is intended only as an interim summary.

GENERAL FEATURES

Perhaps the most striking feature of uranium ore deposits is the wide variety of geologic environments in which uranium mineral concentrations have been found, and the range of ore types that are being studied and developed. Uranium ore deposits are known to occur in igneous, sedimentary, and metamorphic rocks, and in many different types of rock within each of these classifications.

In igneous and metamorphic rocks, ranging from pre-Cambrian to late Tertiary in age, primary uranium-bearing deposits are distributed throughout at least four general major geologic features of the earth's crust: the Cordilleran belt of North and South America, the western marginal areas of the Canadian Shield, the areas of igneous intrusion in Europe, and the continental "backbone" area of central and southern Africa.

Uranium deposits in sedimentary rocks likewise have wide distribution throughout the world. For example, in the United States, concentrations of carnotite and copper-uranium mineral assemblages are distributed widely within sandstones and mudstones of the Colorado Plateau in adjoining portions of Colorado, Utah, Arizona, and New Mexico. The host rocks range from Permian to Cretaceous in age. Miocene and Pliocene phosphate-bearing marine formations, which contain appreciable amounts of uranium, occur throughout a broad area in central Florida, and uranium-bearing phosphate beds have also been studied throughout Permian formations of Idaho, Montana, and Wyoming.

Jurassic limestone of the Zuni Uplift region in New Mexico contains some recently discovered uranium deposits. Low-grade concentrations of uranium exist in several carbonaceous shale formations of Paleozoic age in the Central and Great Plains regions and in saline-lacustrine beds in California. Similar deposits in correlative sedimentary rocks have been described throughout the world.

The general geologic features of some of these major types of deposits, together with examples, are first discussed, followed by brief comments concerning the radioactivity characteristics, suggested sampling procedures, and means of evaluating the deposits. Table I, at the end of the discussion, presents current data on the common uranium minerals.

DEPOSITS IN IGNEOUS AND METAMORPHIC ROCKS

Uranium deposits within igneous and metamorphic rocks occur largely in hydrothermal veins, but disseminated bodies of less present commercial significance are also known, and scattered amounts of uranium are found in pegmatites throughout the world.

Hydrothermal Vein Deposits

The major hydrothermal uranium-bearing vein deposits of the world are typically mesothermal in character, although a few indicate temperatures of deposition that approach those of epithermal deposits. In most of them, pitchblende (b, in the mineral table - Table I) is the major uranium mineral, accompanied by various secondary alteration

products. Compilation of data and geologic appraisals of a number of the best-known pitchblende deposits of the world are currently in preparation (1), and emphasize the following general features.

The host rocks of the known primary uranium vein deposits include igneous, sedimentary and metamorphic types, of which the most favorable appear to be felsic intrusives and arenaceous metasediments. Unmetamorphosed sedimentary rocks are apparently relatively poor hosts. Within the veins themselves, associated minerals containing, in decreasing order of abundance, iron, copper, cobalt, lead, silver, nickel, and bismuth indicate favorable geologic environments for primary uranium minerals. Typical associated gangue minerals include silica in a variety of forms, several types of carbonates, fluorite, barite, and, in a few places, tourmaline and hydrocarbons. Of these, crystalline beta quartz, calcite, and dolomite are clearly the most common. In the sequence of deposition within the veins, the uranium oxides appear to occupy an intermediate to early position although there are notable exceptions. In several instances, pitchblende has evidently been deposited after the early high-temperature sulphides and before the later silver and lead minerals. In other places, uranium oxides were deposited before all of the associated sulphides, under conditions of relatively high temperature. In still others, pitchblende was obviously the latest addition to the vein even following carbonates. Structurally, pitchblende-bearing veins tend to form open-space fillings, though replacement of previously existing vein

1. Everhart, Donald L. and Wright, Robert J., Some geologic characteristics of primary uranium-bearing vein deposits: U. S. Atomic Energy Commission, New York, N. Y.

quartz has occurred in one notable instance; elsewhere, replacement has been relatively unimportant, and confined to a few types of siliceous host rock. The effect of the pitchblende-depositing solutions on the wall rock is complex and not fully understood. In many instances the ore-bearing solutions have produced a distinctive red hematitic alteration which, particularly in the Canadian Shield, is a valuable guide to ore. In other places, notably in the granitic host rocks of the Rocky Mountain areas of the United States, the wall rock has been altered in part to clays with high base-exchange properties, together with kaolinite, and, in addition, it has been affected locally by chloritization, sericitization, and silicification.

Shinkolobwe mine, Belgian Congo. The primary vein deposits in the Shinkolobwe mine of the Belgian Congo are by far the largest and richest known at present, and a brief description (2) of their geology may prove helpful in the search for other similar deposits.

The rocks of the area surrounding Shinkolobwe have been divided into three stratigraphic groups: the basement complex, the Katanga system of pre-Cambrian age, and the overlying Karroo system. Near the bottom of the Katanga system, a series of five formations, comprising the "Mine series," consists of: an upper or "hard" dolomite, dolomitic shale, cellular quartzite, thin-bedded quartzite, and talcose dolomite. A series of tight overturned folds, the axial planes of which

2. Merritt, P. L., Pitchblende - the primary source of uranium: Conference on radioactive ores, Michigan College of Mining and Technology, Houghton, Michigan, May 6, 1949, pp. 10-11.

dip to the north, and thrust faults of considerable displacement are characteristic structures. Thrust plates of the Mine series have been moved from the northeast to over-ride the overlying Kundelungu series, the upper rocks of the Katanga system.

Shinkolobwe mine explores a series of complex fault structures. One of the principal faults trends westward, transecting the strike of the Mine series at a low angle. Associated with this main structure are numerous irregular cross-faults with varying attitudes and strike lengths. The ore bodies in these cross-faults are localized where the faults intersect the thin-bedded quartzites, cellular quartzites and dolomitic shales of the Mine series, and the brecciated zones adjacent to the principal fault structures.

The veins, varying in width from a few inches to several feet, pinch and swell both vertically and horizontally and commonly cannot be traced for more than a few feet along the strike. They may contain pitchblende with little other filling, or may consist dominantly of cobalt or copper sulphides with or without associated pitchblende. Elsewhere, pitchblende, associated with cobalt minerals, occurs in a quartz-carbonate vein matrix. Open fissures and brecciated zones in the siliceous rock have favored pitchblende ore deposition. Cobalt mineralization, on the other hand, has not been confined to the brecciated zones and cross-faults, but has been disseminated through the massive dolomitic wall rocks. In addition to the principal uranium and cobalt minerals, the Shinkolobwe ores carry significant quantities of copper, molybdenum and iron sulphides, and gold, platinum, and palladium.

Oxidation of the ore bodies has extended several hundred feet in depth. In the near-surface deposits there are a host of complex hydrous oxides, phosphates, and silicates such as becquerelite (1), uranophane (x), gummite (y), and torbernite (aa) - (see Table I). This supergene torbernite contains more than half of the uranium in the oxidized zones of the ore body. A typically altered lens of ore has a central core of pitchblende surrounded by successive zones of the yellow, orange, and green secondary minerals. The green phosphates are generally disseminated extensively through the surrounding rocks of the Mine series.

Vein deposits in the United States. Uranium-bearing vein deposits of the United States, like most of those in other parts of the world, are typically mesothermal base-metal veins. The most favorable host rocks observed to date are either felsic rocks such as granite, quartz monzonite, or syenite, or siliceous metasediments such as quartzite, quartz-biotite schist, or quartz-rich slate. The characteristic uranium mineral in the veins is pitchblende, which occurs in extremely fine-grained mixtures with iron, copper, lead, and zinc sulfides, and hematite. The major associated minerals of the deposits include pyrite, chalcopryite, arsenopyrite, tetrahedrite, galena, sphalerite, argentite, and proustite, as well as native silver and hematite. The major gangue minerals are quartz, opal, chalcedony, siderite, calcite, fluorite, and barite.

The known pitchblende-bearing vein deposits of the United States constitute open-space filling of definite fractures or faults. Replacement of the other vein minerals and the host rock by pitchblende has occurred only on a very small scale (3). The relative age of the pitchblende with respect to the other minerals is variable. At some places, it was precipitated early in the mineralization sequence, while in others, it appears to have been late in the sequence. Because of the solubility of uranium oxide, it is probably reconstituted and reprecipitated at various stages in the overall mineralization process, including secondary action.

The solubility of pitchblende in even slightly acidic ground waters has generally led to the secondary redistribution of uranium in oxidized parts of the vein deposits adjacent to the surface, especially in arid or semi-arid regions (4). In these oxidized deposits, the uranium minerals are largely phosphates, sulfates, and hydrous silicates, and the grade is commonly lower than in the unoxidized veins. As a general rule, these oxidized parts of the deposits have the following four characteristics: (1) they are controlled by persistent tensional fractures of a type that could have been favorable for the upward passage of hydrothermal solutions from below; (2) the fractures are filled by secondary metallic minerals that may have been derived from sulfides or oxides of base metals, and gangue minerals that are typical of hydrothermal deposits; (3) the uranium minerals

3. Thurlow, Ernest E. and Wright, Robert J., Uraninite in the Coeur d'Alene district, Idaho. Econ. Geol. v. 45, 1950, pp. 401-402.

4. Everhart, Donald L., Some features of the secondary redistribution of uranium in oxidation zones: Paper presented at Geol. Soc. of Am. meetings, Washington, D. C., November 17, 1950.

include base metals in their lattices; and (4) the wall rock has been altered in part to clays with high base-exchange properties as well as kaolinite, and may have been affected by chloritization, sericitization, or silicification, or by all three processes.

Primary deposits assaying 0.2% or more U_3O_8 are currently mined commercially. The relatively limited tonnages of these deposits necessitate grades of this order. In semi-arid or arid climates, oxidized and impoverished vein outcrops may contain 0.1% U_3O_8 or less.

Disseminated Deposits in Igneous Rocks

Several volcanic flow rocks of the southwestern United States contain low-grade concentrations of uranium. Some of these deposits are distributed throughout broad shear zones covering sizeable areas, and others appear to be structurally controlled by local flexures and complimentary fractures in the flow rocks. In at least one shear zone in silicified rhyolite, pitchblende occurs within fragments of the country rock, which is brecciated and cemented by calcite, fluorite, galena, sphalerite, and chalcopryrite. In another deposit, secondary lead and copper minerals, including uranium-bearing pyromorphite, are distributed over a wide area in the fractures of a sheared zone in flow rock. Commonly, the uranium minerals disseminated through volcanic rocks at or near the surface include such secondary minerals as autunite (n), schroeckingerite (r), and uranophane (x) - (see Table I).

To date, none of these disseminated deposits in volcanic rocks has been a producer of ore. The overall grade of those investigated

averages less than 0.1% U_3O_8 , and the uranium is not distributed widely or uniformly enough to offset the relatively low grade.

Many granite masses contain uranium-bearing accessory minerals such as monazite (o), zircon, pyrochlore (i), allanite, thorite, and uraninite (a), and some of the more sodic types of granites carry more uranium-bearing accessories than the others. Albite-riebeckite types of granite are particularly radioactive and masses of this rock have been sampled in the White Mountains of New Hampshire, in Vermont, the San Francisco Mountains of Arizona, the Pikes Peak region, Colorado, and in Alaska and Nigeria. Even the most radioactive known granite bodies, however, contain less than 0.015% U_3O_8 and to date have nowhere been a productive source of ore.

Pegmatites

Uranium-bearing and rare-earth minerals, including columbates, tantalates, and titanites, are rather common accessories of many pegmatite deposits but in general these deposits are not capable of producing uranium on an appreciable scale. They are, however, sources of high-grade specimens, and pegmatite bodies containing appreciable tonnages of uranium minerals may yet be discovered. The primary uranium-bearing minerals in this type of deposits include uraninite and, in special cases, thucholite (d), as well as the

refractory columbo-tantalates such as euxenite (h), samarskite (g), pyrochlore (i), and fergusonite (f).

According to L. R. Page (5), potassium-rich pegmatites or zones in them have been found to be the most likely sources of uranium minerals, whereas sodium-rich or lithium-rich pegmatites or zones are somewhat less favorable.

The "grade" required in pegmatites for possible uranium production is not ordinarily expressed in the usual percentage U_3O_8 figure for the total rock. A few pegmatites have yielded uranium-bearing minerals as by-products of mica or feldspar mining. If several hundred pounds or tons of such minerals can be effectively separated, their recovery and sale, of course, becomes economic.

5. Page, Lincoln R., Uranium in pegmatites, Econ. Geol., vol. 45, 1950, pp. 12-34.

DEPOSITS IN SEDIMENTARY ROCKS

Uranium deposits in sandstone, siltstone, shale, and limestone formations appear to offer the most promise for producing large tonnages of ore in the United States. Currently, the carnotite-bearing sandstones and shales of the Colorado Plateau contribute the major proportion of our domestic production, and similar sandstone and shale formations in southern Utah and northern Arizona, which contain distinctive assemblages of copper and uranium minerals, promise to become significant producers in the next few years. At least one belt of recently discovered uranium-bearing limestone deposits in the Zuni Uplift area of New Mexico contains substantial reserves of ore which will also contribute to domestic production.

Carnotite Deposits

Concentrations of carnotites and related minerals in sandstone and shale have been found principally throughout the Colorado Plateau in the thick series of sedimentary rocks that underlies about 130,000 square miles of eastern Utah, northeastern Arizona, northwestern New Mexico, and Colorado west of the Rocky Mountains. Smaller carnotite deposits have been studied in the Mojave Desert area of southern California, in parts of the Mauch Chunk formation of Pennsylvania, and in rocks bordering the Front Range in Colorado.

In the Colorado Plateau area, carnotite deposits occur in the Coconino formation (Permian) and upwards through the stratigraphic column to include the Mesa Verde formation (Upper Cretaceous), but the important producing horizons have been in the Morrison and Entrada formations (Jurassic) and the Shinarump formation (Triassic). Most of the ore

deposits are irregular but roughly tabular in shape, with the greater dimensions in planes essentially parallel to the generally horizontal bedding of the enclosing sandstone and mudstone. Despite this general conformity to the bedding, the ore bodies tend in part to cut across the stratification, and in places they thicken to form concretion-like masses known as "rolls." The ore deposits commonly are associated with fossilized tree trunks, branches, or leaves, and some of the richest ores consist of logs partly replaced by uranium and vanadium minerals. All of the above features are generally associated with ancient stream channels, which seem to represent the dominant structural control of the ore bodies. There is yet considerable question as to whether the minerals were precipitated from ground water solutions after the sediments had accumulated but before deformation and fracturing of the rocks (6), or whether the major uranium-bearing solutions formed the deposits in post-Cretaceous time. In either event, the old stream channelways are considered the most important controlling structures.

The ore-forming minerals, which include mainly camotite, vanoxite ($2V_2O_4 \cdot V_2O_5 \cdot 8H_2O$), and hewettite ($CaO \cdot 3V_2O_5 \cdot H_2O$), are deposited as coatings on grains of sandstone or along the parting planes of shale, and most of the ore contains 0.2 to 0.4% U_3O_8 and 1.5% to 2% V_2O_5 .

Copper-uranium Deposits

Distinctive assemblages of copper and uranium minerals occur at many localities in conglomerate, sandstone, and shale formations of

6. Fischer, Richard P., Uranium-bearing sandstone deposits of the Colorado Plateau, Econ. Geol., vol. 45, 1950, pp. 1-11.

Triassic age in the western and southern parts of the Colorado Plateau. Most of these localities are in southern Utah and northern Arizona, in the Moenkopi, Shinarump, or Chinle formations of Triassic age. Copper-uranium mineralization appears to have occurred in a somewhat restricted stratigraphic horizon at the base of the Shinarump formation and in the upper few feet of the Moenkopi formation immediately beneath it. However, several notable copper-uranium deposits have been localized at several other stratigraphic horizons in the Triassic sedimentary rocks of southern Utah and northern Arizona. For example, in the White Canyon-Red Canyon district of San Juan County, Utah, a persistent sandstone or conglomerate, averaging 10 to 20 feet in thickness, near the middle of the Moenkopi strata, forms the locus for copper-uranium mineral concentrations. In the Silver Reef district of Washington County, the copper-uranium deposits appear to be confined to the Silver Reef sandstone member of the Chinle formation.

All of the host sandstones of the copper-uranium deposits are typically lenticular in character, thinning and thickening markedly along the strike of the bedding. This character is interpreted as indicating fluvial deposition in and adjacent to stream channels. As in the carnotite deposits, the mineral concentrations appear to be in or near the thickest and lowest parts of the sandstone or conglomerate beds - that is, along the ancient channelways. Characteristically the deposits are spotty and erratic in distribution. Although in general the uranium and copper minerals occur together, the visibly identifiable copper minerals are not a reliable guide to uranium ore, for copiously copper-stained beds may exhibit little or no radioactivity and beds with negligible copper content may contain appreciable amounts of uranium.

One of the characteristic features of the copper-uranium deposits is the mineralogic difference between the relatively unoxidized and the oxidized portions of the deposits. Although they have been studied and mined in only a few adits, the primary minerals include pitchblende, pyrite, chalcopyrite, covellite, bornite, galena, and gersdorffite. Chalcocite is also present in unoxidized zones, but may be secondary after the other copper sulfides. At the oxidized rim outcrops the primary minerals are typically altered to hydrous sulfates, phosphates, silicates, carbonates, and arsenates including johannite (p), torbernite, uranophane, schoepite (m) -becquerelite (l), and sippeite (z), with malachite, antlerite, chalcantite, brochantite, cyanotrichite, and erythrite (7). From the few deposits thus far studied, it appears that oxidized rim outcrops are depleted in uranium, and thus an improvement in grade may be expected with advancing development.

Currently, copper-uranium deposits that appear to contain several thousands of tons are considered potential ore producers if the oxidized rim outcrops assay more than 0.05% U_3O_8 . It is believed that unoxidized portions of such mineralized bodies may contain ore averaging several tenths of one percent U_3O_8 .

Uranium-bearing Asphalt Deposits

Uranium-bearing asphalt (8) or asphaltite occurs in lenses, globules, and irregular masses in certain sandstone beds of Triassic age in southern Utah. Structurally and lithologically, these deposits are

7. Mineral determinations are largely by J. W. Gruner and Lynn Gardiner, University of Minnesota.

8. Asphalt is defined here in the broad sense - as natural, or native, brown to black bitumen.

similar to the carnotite and copper-uranium deposits in the same formations. In many other asphalt deposits of the world, however, no economically significant amounts of uranium are present.

The uranium-bearing asphalt deposits in the San Rafael Swell area of Emery County, Utah, contain uranium in a variety of forms. In the Temple Mountain deposits on the east flank of the Swell, uranium- and vanadium-bearing asphalt, intimately associated with pyrite, partly in the form of black powdery corvusite and rauvite (c), cements the grains of the sandstone and forms replacement masses. In other parts of the Swell, uranium is present in relatively "pure" asphalt, although small amounts of copper minerals, including zeunerite (bb) are associated (9). The latter is an oxidation product of the uranium-bearing asphalt. Gypsum is almost universally associated with these deposits.

Uranium-bearing asphaltic sandstone deposits that contain at least an average of 0.2% U_3O_8 have been, and are currently, worked as economic producers of ore.

Uranium-bearing Limestone Deposits

Limestone formations containing commercial concentrations of uranium are relatively rare; however, certain limey phosphatic beds throughout the world, described in the following section, have been known for some time to contain appreciable quantities of uranium.

Uranium-bearing limestone deposits having commercial importance occur along the northeast flank of the Zuni Uplift in northeastern New Mexico. Uranium minerals here are concentrated in irregularly shaped

9. Mineral determinations by J. W. Gruner and Lynn Gardiner, University of Minnesota.

tabular zones, largely in the upper two or three feet of the Todilto formation of Jurassic age although uranium mineral concentrations extend downward into lower beds along joints and bedding planes. The upper beds of this formation, which varies from 2 to 20 feet in thickness, consist of massive, compact, coarsely crystalline limestone, and the formation as a whole generally caps benches underlain by the Entrada, Wingate, and Chinle formations of Jurassic and Triassic age.

Uranophane, carnotite, and tyuyamunite (t) are the most abundant uranium minerals; sklodowskite (w) and pitchblende occur in local concentrations. Associated minerals are fluorite, calcite, hematite, goethite, various manganese oxides, and carbonaceous matter (10). Pitchblende, hematite, and fluorite appear to form small replacement masses in the limestone, and the pitchblende occurs in "blebs," as much as 3 mm. in greatest dimension, intergrown with calcite. Haloes of amorphous secondary yellow uranium minerals in general - and carnotite and tyuyamunite in particular - appear to be confined to bedding planes, joints, and other smaller fractures in the rock, and it is these minerals that contain most of the uranium in the known deposits. The ore in these deposits, in which there is believed to be promise of considerable tonnage, averages about 0.2% U_3O_8 and 0.15% V_2O_5 .

Uranium-bearing Phosphorites

Uranium in significant quantities has been reported in phosphate deposits of Russia, Morocco, Algeria, Tunisia, and Egypt, in the Phosphoria

10. Mineral determinations by J. W. Gruner and Lynn Gardiner, University of Minnesota.

(Permian) formation of Idaho, Montana, and Wyoming, and in the Hawthorne (Miocene) and Bone Valley (Pliocene) formations of central Florida (11). Because of this association, the U. S. Geological Survey has been engaged for some time in investigating all known marine phosphate formations in the United States and an excellent summary of the salient conclusions derived from this work has been presented by McKelvey and Nelson (12). Some of their significant observations are repeated here.

All marine phosphate formations tested for radioactivity have been found to contain significant amounts of uranium. These uranium-bearing phosphates, which range in age from Paleozoic to Cenozoic, generally contain uranium in proportion to the phosphate content, although certain high-grade phosphate beds are relatively low in uranium and the most uraniferous beds known are not the most phosphatic. The phosphates are characteristically thin formations, and many are associated with unconformities.

The Phosphoria formation, which averages 200 to 500 feet in thickness, contains various amounts of intermixed phosphate, fine-grained clastic material, organic matter, carbonates, and chert, even the most "pure" phosphate beds being contaminated with these other materials. An inverse proportion appears to exist between uranium and carbonate, all samples assaying 0.01% U_3O_8 , or more, containing less than 2% CO_2 .

In Florida, according to Cathcart (13), three types of phosphate

11. McKelvey, V.E. and Nelson, J.M., Characteristics of marine uranium-bearing sedimentary rocks: Economic Geology, Vol. 45, No. 1, January-February 1950, p. 40.

12. McKelvey, V.E., and Nelson, J.M., op. cit., pp. 40-52.

13. Cathcart, James B., Uranium-bearing sedimentary rocks in the land pebble phosphate deposits of Florida: U. S. Geological Survey Trace Elements Investigations Report 79 (Confidential), January 1950, 16 pp.

deposits are found; the so-called land pebble, hardrock, and river pebble phosphates. Of these, only the "land pebble" type is marine in origin and is the only one known to contain significant amounts of uranium. Phosphate occurs in both the Hawthorne formation (lower middle Miocene) and the overlying Bone Valley formation (Pliocene) but it is the latter that includes most of the "land pebble" deposits. Uranium in the formation is restricted to the high-grade phosphate districts. Further, the thickest, high-grade, and most uraniferous phosphate deposits occur in depressions on the old erosional surface of the Hawthorne formation. Concentration of uranium is greatest in the upper or "leached" zone of the Bone Valley formation and much less in the underlying "matrix" phosphate, which is the principal source of commercial phosphate. Concentration of uranium in the "leached" zone was partly effected by removal of more soluble material following its apparently syngenetic deposition from marine waters.

Most of the uranium in known phosphate deposits appears to be in the minerals fluorapatite or collophane in which uranium probably replaces calcium in part. Uranium also undoubtedly is contained in some of the clay minerals of the phosphate deposits and is absorbed in some of the organic matter. Small amounts of minerals in the torbernite and autunite group have been identified in some of the phosphate deposits.

Uranium-bearing phosphates that are currently considered significant for possible production of uranium range between 0.01 and 0.03% U_3O_8 in grade.

Uranium-bearing Black Shales

Comparatively low concentrations of uranium in vast tonnages of carbonaceous and bituminous shales have been known in many parts of the

world for several decades. According to McKelvey and Nelson (14), uranium in black shale was first discovered in the alum shale, of Cambrian age, in Sweden in 1893. Since that time, uranium has been discovered at a progressively increasing rate in certain black shales in Russia, Estonia, Alaska, and throughout broad areas in the central part of continental United States. Many bituminous or carbonaceous rocks are not uraniferous, however, which suggests that special characteristics are required in rocks of this type if they are to offer favorable chances for discovery of appreciable uranium. The significant uranium-bearing marine shales are all black or very dark in color, have a high content of organic matter and sulfide, are low in carbonate, are relatively thin and thinly bedded, and, so far as known, are mostly pre-Mesozoic in age.

L. C. Conant, R. H. Stewart, and A. B. Keller (15) characterize the radioactive black shales of the United States as being comparatively uniform in thickness and composition, but locally containing abnormally radioactive lenses. The most common constituents are silica, organic matter or carbon, and clay minerals, with associated pyrite, marcasite, and phosphate. In the United States, the Chattanooga formation of upper Devonian-lower Mississippian age is a radioactive black shale which is distributed over wide areas in Tennessee, Kentucky, and adjacent states, but is only 5 to 100 feet thick throughout most of its extent. Its most uraniferous parts are in central Tennessee and southern Kentucky, where

14. McKelvey, V.E., and Nelson, J.M., op. cit., pp. 37-53.

15. Staff Report, Characteristics of radioactive carbonaceous and bituminous shales: U. S. Geological Survey Trace Elements Investigations Report 78 (Confidential), January 1950, 21 pp.

thousands of square miles of the uppermost part of the formation contain from 0.002 to 0.013% U_3O_8 and average 0.008% U_3O_8 . Formations correlative to the Chattanooga, extending throughout Indiana, Kentucky, Ohio, Michigan, and New York are less radioactive, but the uranium content of the roughly equivalent Woodford formation of Oklahoma and Kansas is comparable. Certain black shales of Pennsylvanian age in Alabama, Kansas, and Oklahoma also range from 0.003 to 0.013% in U_3O_8 content, but the average is somewhat less than that of the Chattanooga shale and they are not so widely exposed nor so mineable.

The mineralogy of the uraniferous black shales has not been completely solved as yet, and no definite uranium minerals are identifiable in most cases. Uranium occurs in the finer grained portions of the rock, and is soluble in acid; it may be incorporated into the crystal lattices of clay minerals and organic compounds. The exact structural types of clay minerals and organic compounds favorable to the adsorption of uranium ions are subjects of continuing research and, when fully determined, are expected to constitute valuable guides to uraniferous shale bodies.

The grade of even the most uraniferous shales described in the foregoing paragraphs is, of course, too low for economic recovery under present conditions. Ways and means of utilizing the available vast tonnages of shale are under constant consideration, however, and further exploration of such shales seems warranted. All thin black shale formations of Paleozoic, and probably pre-Cambrian age, representing periods of stable, slow sedimentation in shallow seas, are worthy of investigation if they afford large tonnages and may be mined at low costs.

Alluvial and Placer Deposits

Concentrations of uranium-bearing minerals in alluvial and placer

deposits are, in general, considered negligible sources of production. One notable exception to this generality must be pointed out, however, if one accepts an alluvial origin for the gold (and associated uranium) ores of the Witwatersrand in South Africa. Here, uraninite has been reported in many parts of the gold reefs, and Bain (16) has indicated that the grade of large tonnages of these ores is probably on the order of 0.01% U_3O_8 .

Elsewhere, however, attempts to recover uranium from minerals concentrated in alluvial and placer deposits have not, with few exceptions, proved successful. Most uraniferous minerals are not resistant and not amenable, therefore, to concentration by alluvial action. Those that are amenable--largely the "refractory" radioactive minerals originating in pegmatites and granitic rocks--are not very high in uranium content and concentrations of them are generally uneconomic.

Lacustrine -- saline Deposits

A few weak concentrations of secondary uranium minerals occur with saline minerals in the clays, silts, sands, and shaley limestones of former lake beds. Several such deposits have been described, for example, in the vicinity of Barstow, California. A similar origin has been postulated for schroeckingerite (r) deposits in the Lost Creek district, near Wamsutter, Sweetwater County, Wyoming. Current studies in this area by the U. S. Geological Survey, however, indicate that the uranium in the young sediments of the Wamsutter area may have migrated upward from below, along a major fault, and thus were not originally deposited by lacustrine action. In any case, uranium deposits of the lacustrine-saline type have not been ore producers and do not appear to offer any significant degree of promise at this time.

16. Bain, George W., Geology of the fissionable materials; Econ. Geol., vol. 45, no. 4, June-July 1950, p. 322.

USE OF FIELD INSTRUMENTS FOR RADIATION DETECTION

The simple techniques necessary for the operation of radiation detection instruments in the field are described in publications by the U. S. Government (17) and (18) and the Halross Instrument Corporation (19) and (20).

It is necessary, in addition, to consider carefully the specific application of radiometric instruments to evaluating the individual types of uranium deposits described in the foregoing paragraphs. The tendency of many prospectors is to place too much emphasis on the reaction of a radiation detecting instrument and to attempt quantitative interpretations of the recorded radioactivity. In general, these instruments are valuable only as qualitative indicators, and great care must be used to interpret the dial readings or impulse rates in the light of the physical environment.

In the examination of vein deposits, radiometric traverses are commonly required both over surface outcrops and in underground workings, either by Geiger-Mueller counters or by scintillation-type instruments.

-
17. Prospecting for uranium: U. S. Atomic Energy Commission and the U. S. Geological Survey, Washington, 1949, pp. 28-35.
 18. Use of the Geiger-Mueller counter for prospecting, U. S. Atomic Energy Commission, Raw Materials Operations, New York office, May 16, 1950.
 19. Operating Instructions - Model 939 Scintillometer, Halross Instruments Corp., Ltd., Winnipeg, Manitoba.
 20. Procedures of Geologic Surveys - Preliminary, Halross Instruments Corp., Ltd., Winnipeg, Manitoba.

The fact that veins generally have steep attitudes, of course, causes the anomalous areas, where intersected by nearly horizontal planes of erosion, to be very narrow (on the order of 2 or 3 feet) and linear in dimension. In addition, the spotty distribution of pitchblende creates a highly discontinuous anomaly pattern along the strike of a vein. Moreover, on the surface, a few feet of overburden mask the radioactivity. All of these factors tend to localize markedly the radioactivity detectable from uranium-bearing veins. Underground traverses with detection instruments away from the radioactive veins yield somewhat lower background readings than on the surface, but in drifts along the veins, the readings are generally higher and more uniform due to redistribution of the uranium by ground waters and the precipitation of secondary uranium minerals on the mine walls. As a general rule, when the probe of the instrument is held adjacent to pitchblende-bearing vein material, counts on the order of at least 30 times background are to be expected.

The use of radiation detecting instruments in examining and evaluating carnotite deposits is perhaps somewhat less important than in most other types, because of the distinctive yellow color of the ore. Here the visual identification of the uranium-bearing mineral is a relatively reliable guide although other yellowish minerals, such as jarosite, may be confused with it. Most carnotite deposits are in relatively flat-lying sandstone beds exposed on the rims of plateau cliffs. Although the ore bodies as a whole are erratic in size and dimension, the distribution of the carnotite within the mineralized beds is relatively uniform, and counts on the order of at least 20 times background are recorded consistently along the truncations of the ore beds when the probe

is held within an inch or two of the outcrop. The behavior of radiation detection instruments in the examination of uranium-bearing asphalt deposits is very similar to that observed at carnotite deposits, and typical ore beds 2 or 3 feet thick generally give counts of 5 to 20 times background.

The erratic distribution of uranium in the copper-uranium deposits and common departures from radioactive equilibrium create a special problem in evaluating this type of deposit in the field by the use of counters or scintillometers. Any quantitative interpretation must rely on chemical analyses of carefully collected channel samples and no conclusions as to the grade of a copper-uranium deposit can reliably be based on results obtained with a field radiation detecting instrument.

In the field examination of sedimentary formations such as phosphates, black shales, or lacustrine deposits, in which low-grade concentrations of uranium are relatively evenly distributed, counters and scintillometers are fairly reliable. Only the ordinary precautions of considering background counts and the geometry of the scanning operations need to be taken, and by standardizing the radiometric surveying procedures employed, even rough quantitative approximations can be achieved.

SUGGESTED SAMPLING PROCEDURES AND THE EVALUATION OF URANIUM ORE BODIES

The mineralogic and structural nature of the various types of uranium ore bodies described in the foregoing paragraphs has a definite bearing, of course, on the most reliable sampling procedures and other important factors in the proper evaluation of the deposits. Experience

to date has shown that certain general procedures should be strongly recommended in each of the various types of uranium deposits.

Uranium concentrations in primary vein deposits are so erratic and variable that, to obtain even an approximation of the grade of an ore body, careful channel sampling across mineable widths at least every three or four feet is essential. In complex vein systems, especially where the pitchblende is very fine-grained and intimately associated with sulfides, it is necessary in many properties to obtain bulk samples of several hundred pounds to get a true grade figure. The tonnages of ores must be calculated as increments in small blocks along the closely sampled segments of the veins. In general the ore bodies are relatively small and closely controlled by the structure of the veins, and their shape can be rather sharply defined. Thus, meaningful estimates of tonnage and grade are especially difficult to obtain in primary vein deposits without prior geologic mapping and close sampling.

Carnotite deposits, characterized by erratic distribution and irregular shape, offer special problems in the estimation of tonnage. Experience on the Colorado Plateau has shown that close-spaced drilling is commonly the only reliable method of obtaining the three-dimensional shape of ore bodies, and hence their tonnage. Grade figures are, in general, less erratic than in the vein-type and the copper-uranium deposits, and in many instances average grade figures, obtained by channel sampling, hold rather uniformly for large ore bodies. Special studies of the relationships between the ore bodies and the lithology of the sediments and structure of ancient channelways are most helpful in outlining carnotite

ore bodies. The problems of sampling and evaluation in uraniferous asphaltic sandstone bodies are generally similar to those in carnotite ore bodies.

It has been pointed out that the general geologic environment of the typical copper-uranium deposits is also similar to that of carnotite deposits. Their mineralogic character, however, leads to special problems in sampling and evaluation. In many of the deposits, oxidation and repeated solution and redistribution of uranium cause disequilibrium of radioactivity as well as highly erratic distribution. In addition, leaching action near the oxidized rim outcrops tends to indicate deceptively low grade for the ore body as a whole. Thus bulk sampling and chemical assays of mineralized rock, not only at the surface but also in relatively unoxidized portions of the ore bodies, are essential.

Erratic distribution of uranium is also characteristic in the phosphorite deposits, particularly in the "leached zone" of the Bone Valley formation in Florida. Hence, close channel sampling is also necessary in the evaluation of deposits of this type. In general, however, a satisfactory correlation between radiometric and chemical assays can be established and rapid radiometric assaying is adequate for the bulk of the samples.

In lacustrine deposits, the typical uranium minerals are perhaps more soluble, in general, than in any other type of deposit and hence their sampling and evaluation is proportionately difficult. The action of surface and ground waters may even alter the loci of uranium concentrations and the percentage of uranium content from year to year. This migration of "ore bodies" constitutes a significant factor in the evaluation of these deposits in general, and partly because of their unreliable behavior, they have not yet been considered economic sources of uranium.

[illegible]

BROWN MINERALS

[illegible]

YELLOW MINERALS

Name	Chemical Composition	Luster	Fluorescence	Hardness	Specific gravity	Fracture and Cleavage	Crystal System	Habit	Mode of Occurrence	Remarks
l) Becquerelite (also brownish yellow)	$2\text{UO}_3 \cdot 3\text{H}_2\text{O}$ (questionable)	Adamantine to resinous	None(?)	2-3	4.96-5.68	(001) perfect (101) distinct	Orthorhombic	Minute tabular crystals; polysynthetic twinning common.	An alteration product of uraninite, occurring with secondary uranium minerals.	A rare mineral.
m) Schoepite	$4\text{UO}_3 \cdot 9\text{H}_2\text{O}$ (H_2O variable)	Adamantine	Yellow-green(?)	2-3	4.83-4.96	(001) perfect	Orthorhombic	Tabular or short prismatic crystals commonly containing inclusions.	An alteration product of uraninite, occurring with secondary uranium minerals.	----
n) Autunite (lemon-yellow to apple-green)	Hydrated calcium uranium phosphate. Theoretical formula: $\text{CaO} \cdot 2\text{UO}_3 \cdot \text{P}_2\text{O}_5 \cdot 12\text{H}_2\text{O}$ (meta variety carries $8\text{H}_2\text{O}$).	Pearly, sub-adamantine	Always brilliant yellow or green on fresh surfaces.	2-3	3.05-3.19	(001) perfect	Orthorhombic (pseudotetragonal)	Basal tablets or micaceous masses with rectangular outline, foliated.	Associated with uraninite, guminite, uranophane, and uraniferous columbates; in oxidized zone of most uranium deposits.	A common uranium mineral always of secondary origin, isomorphous with uranospinites in which arsenic substitutes for phosphorus. The meta variety is more common.
o) Monazite (also brown)	$(\text{Ce}, \text{La}, \text{Nd}, \text{Pr})\text{PO}_4$ (up to 26% ThO_2 and 0.4% U_3O_8)	Resinous	None	5-5½	4.6-5.3	(001) perfect (100) distinct, conchoidal	Monoclinic	Flattened crystals; rounded grains.	Placers; an accessory constituent in felsic igneous rocks.	Not a commercial source of uranium.
p) Johannite (also green)	$(\text{Cu}, \text{Fe}, \text{Ni})_2\text{O}_3 \cdot \text{UO}_3 \cdot 3\text{SO}_3 \cdot 4\text{H}_2\text{O}$	Vitreous	None	2-3	3.3-3.9	(001) and (011) distinct	Triclinic	Minute lath-like crystals; polysynthetic twinning almost invariably present; in druses and reniform masses.	Occurs with secondary uranium minerals.	----
q) Trosgerite	$3\text{UO}_3 \cdot \text{As}_2\text{O}_5 \cdot 12\text{H}_2\text{O}$ (H_2O variable)	Pearly	Weak(?)	2-3	3.3 (variable)	Two cleavages at right angles.	Monoclinic(?) (Pseudotetragonal)	Thin tabular crystals resembling gypsum.	With secondary minerals including erythrite.	A rare mineral.
r) Schroeckingerite	Theoretical Formula: $3\text{CaO} \cdot \text{NaF} \cdot \text{UO}_3 \cdot 3\text{CO}_2 \cdot \text{SO}_3 \cdot 10\text{H}_2\text{O}$.	Pearly	Bright yellowish green	2-3	2.51	Perfect basal cleavage.	Orthorhombic	Small, rounded masses composed of aggregates of flaky crystals; pseudohexagonal micaceous plates.	Rounded masses distributed in gypsum-bearing sandy clay; as coatings in decomposed igneous rocks.	----
s) Carnotite	Theoretical Formula: $\text{K}_2\text{O} \cdot 2\text{UO}_3 \cdot \text{V}_2\text{O}_5 \cdot 1-3\text{H}_2\text{O}$	Usually earthy, crystals are pearly	None	2-3	4 (variable)	(001) perfect cleavage	Orthorhombic	Earthy, thin coatings, cryptocrystalline masses.	Cementing agent in sandstones, associated with fossil logs and bones in Colorado Plateau ores.	Color sometimes dulled or concealed by organic and iron staining; in such cases, pale greenish or brownish tinge.

[illegible]

ORANGE MINERALS

Name	Chemical Composition	Luster	Fluorescence	Hardness	Specific gravity	Fracture and Cleavage	Crystal System	Habit	Mode of Occurrence	Remarks
y) Gummite (also red and yellow)	$UO_3 \cdot nH_2O$; contains Pb, Ca, Ba, Si, P, Mn, Fe (up to about 70% U_3O_8 and 20% ThO_2)	Waxy, dull, greasy, occasionally vitreous	None	$2\frac{1}{2}$ -5	Variable	Conchoidal to uneven	?	Dense and massive, sometimes pseudomorphs.	An alteration product of uraninite and pitchblende.	Common. Gummite is sometimes considered a generic term for many alteration products of uraninite.
z) Zippeite	$2UO_3 \cdot SO_3 \cdot 2H_2O(?)$	Earthy, vitreous	Brilliant green	2-3	$3\frac{1}{2}$ Variable	(010) perfect	Monoclinic(?)	Earthy or powder, in minute lath-shaped crystals.	An alteration product of pitchblende and as a coating in asphaltic sandstones.	-----

Beta uranotil See Yellow Minerals

GREEN MINERALS

aa) Torbernite	$CuO \cdot 2UO_3 \cdot P_2O_5 \cdot 12H_2O$ (meta variety carries $8H_2O$)	Pearly, sub-adamantine.	None or very faint	$2-2\frac{1}{2}$	3.2-3.6	(001) perfect (100) distinct	Orthorhombic (pseudotetragonal)	Square tablets, basal plates, micaceous masses.	With other uranium minerals, especially those associated with copper minerals.	A common supergene mineral. Meta variety is more common.
bb) Zeuenerite	$CuO \cdot 2UO_3 \cdot As_2O_5 \cdot 12H_2O$ (meta variety carries $8H_2O$)	Pearly, vitreous	None or very faint	2-3	3.2-3.3	(001) perfect (100) good	Orthorhombic (pseudotetragonal)	Tabular (001) crystals resembling torbernite, square tablets, micaceous masses.	A secondary mineral with other uranium minerals, especially associated with arsenic minerals.	-----
Autunite	See Yellow Minerals									
Johannite	See Yellow Minerals									