Geology of Uranium-Bearing Veins in the Conterminous United States

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STEWART L. UDALL, *Secretary*

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Thomas B. Nolan, *Director*

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Introduction to the Geology of Uranium-Bearing Veins in the Conterminous United States

Including Sections on Geographic Distribution and Classification of Veins

By GEORGE W. WALKER *and* FRANK W. OSTERWALD

GEOLOGY OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

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INTRODUCTION TO THE GEOLOGY OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES, INCLUDING SECTIONS ON GEOGRAPHIC DISTRIBUTION AND CLASSIFICATION OF VEINS

By George W. Walker and Frank W. Osterwald

ABSTRACT

In the few years that have elapsed since uranium first became important in fields of atomic energy, a vast fund of geologic and related information has been collected by personnel of the U.S. Geological Survey; the U.S. Atomic Energy Commission or its predecessor organization, the Manhattan Engineer District; and, to a lesser extent, by staff members of other Federal and State agencies and by geologists in private industry. In this collection of geologic information are data of different kinds that bear directly on an understanding of the fundamental geology controlling the distribution of uranium in veins and that aid in understanding various hypotheses of origin for veins.

Veins, as defined herein, are masses of introduced minerals in and adjacent to fractures and fissures; the definition excludes any implications as to crystallization temperatures or to special mineral assemblages. Veins may contain uranium largely in the 4-valent state, entirely in the 6-valent state, or, most commonly, in both states. A descriptive and arbitrary classification based on mineral content of these veins is used in this report; 8 mineralogic classes of uranium-bearing veins are established, 7 of which are known to occur in the conterminous United States.

The pre-1940 history of uranium mining and geology is concerned largely with veins in widely separated parts of the world: included are deposits in Europe, South Africa, northern Canada, South Australia, and, to a limited extent, the United States. During and since the 1940's, many uranium-bearing veins were discovered in the conterminous United States; but, in general, these discoveries were completely overshadowed by the discovery and development of a number of very large nonvein deposits in New Mexico; in Big Indian Wash and White Canyon, Utah; and in the Gas Hills, Wyoming. Very large deposits of uranium in northern Saskatchewan, Canada; near Blind River, Canada; and in the Witwatersrand, South Africa, also were discovered and developed during this period.

Hundreds of uranium-bearing veins have been reported in the conterminous United States, in perhaps as many as 900 different localities. Most of the known uranium-bearing veins are in the western United States in such areas as the Front Range mineral belt of Colorado; the Boulder batholith area, Montana; the Sierra Ancha region, Arizona; and the Marysvale district, Utah. All the Western States, including Arizona, California, Colorado, Idaho, Montana, Nevada, New Mexico, Oregon, Utah, Washington, and Wyoming, contain veins that have yielded uranium ores. Production of uranium ores from veins in the eastern United States has been limited to deposits near Warwick, N.Y.

INTRODUCTION

PURPOSE AND SCOPE

The use of uranium as a source of atomic energy in the early 1940's started an intensive search for this metal in the conterminous United States that resulted in the accumulation of a tremendous amount of geological information about uranium-bearing veins. One objective of this report is to bring together into a single volume the more pertinent parts of this information, which is scattered throughout numerous reports, many of them unpublished and consequently not generally available. Some geologic data concerning foreign vein deposits are included partly for purposes of comparison with deposits in the United States but principally to establish a broader geologic base on which to classify uraniferous veins and to evaluate better the diverse geologic characteristics of the deposits and their structural and petrologic environments.

A second objective of this report is to critically review the voluminous data in both published and unpublished reports on the geology of uranium-bearing veins in the conterminous United States and to review the concepts and generalizations that have been based on these data. Particular emphasis is placed on critical reviews of kinds of host rocks, wallrock alteration, mineralogy, paragenesis, physical characteristics, supergene alteration, processes of deposition, and concepts of origin of uraniferous veins. This general review has led to several new generalizations, or variations on old generalizations, which are here presented and, insofar as available data permit, substantiated.

Among the different chapters composing this volume, there is little uniformity in the amount of data taken from reports prepared by other geologists in relation to that originating with the authors of this volume. Most descriptive information in these chapters was obtained from cited reports, but some brief field checking was done on a small number of deposits—perhaps about 6 to 8 percent of the deposits listed at the end of this chapter—by the authors of this volume. Some laboratory work was also done on ore and wallrock samples chiefly to establish the paragenetic relationship of minerals in ore specimens and the textural characteristics of the hypogene uranium minerals. Considerable office work and a little fieldwork were done on the structural controls and tectonic environments for deposits and districts, particularly in the Cordilleran foreland of western United States.

Reviews of available reports and compilation of data for this report were started in the late autumn of 1953 and continued, with many interruptions, until June 1957. In general, data from reports that became available after June 1957 were not included in this paper, but this cutoff date was not rigorously observed. The authors have tried to review all reports that have a direct bearing on the geology of the uraniferous veins in the United States, but some sources of information undoubtedly have been overlooked; others, though reviewed, have been intentionally omitted. Some reports are not referred to because (a) they are known to be inaccurate or incomplete, (b) different data within a given source report are grossly conflicting, or (c) other reports present the same data in greater detail. Most geologic reports reviewed resulted either directly or indirectly from the Federal Government's program on raw materials for atomic energy. The basic philosophy behind the program changed from one largely restricted to ore finding and prospecting to one directed toward fundamental studies of geologic distribution, uranium mineralogy and geochemistry, and geophysical principles related to uranium. This transition in the program from one of immediate economic, military, and political importance to one of scientific interest took place principally in the years 1953–55, during which time this report was planned and partly written.

This chapter deals principally with the classification and geographic distribution of uranium-bearing veins in the conterminous United States and includes some comments on the history of uranium geology and mining. The other chapters deal principally with pertinent geologic information on kinds of host rocks, wallrock alteration, mineralogy, physical characteristics, processes of deposition, and concepts of origin of uraniferous veins.

DEFINITIONS

In the preparation of this introductory chapter, many problems have been encountered, most of which are caused by the different usage of geologic terms by different geologists. As a result, several geologic terms are defined to aid in establishing the scope of the report and to determine which deposits should be included as uranium-bearing veins.

VEIN

Any classification of uranium-bearing veins is dependent basically upon segregating uraniferous "vein deposits" from other types of uranium deposits. To classify uranium-bearing veins and to establish their geographic and geologic distribution, a logical and useful, although arbitrary, definition of a vein is required. The lack of agreement among geologists about the distinguishing characteristics of a vein precludes unanimous endorsement of any classification of uranium-bearing veins, whether based on processes of deposition, mineral assemblage or metal ratios, shape of deposits, structural setting, kinds of host rocks, or on origin. Many uranium deposits have diverse geologic characteristics, because uranium is concentrated by a wide variety of processes in many different physical and chemical environments and because many deposits have been acted upon by several of these processes. Commonly, the resulting uranium deposits, as pointed out by McKelvey (1955, p. 4), "* * * grade into one another so subtly and completely that it is difficult to segregate them descriptively." A single deposit may show both structural and stratigraphic control; locally it may contain an assemblage of minerals that indicates deposition from thermal solutions, whereas in other parts of the deposit the mineral assemblage indicates a deposition from nonthermal solutions; it may have several varieties of favorable or mineralized host rock; and the ore and gangue minerals may show evidence of both replacement and open-space filling. These and other data indicate diverse origins for uranium deposits. Furthermore, for many deposits positive criteria are lacking as to mode of origin and to the processes that concentrated and deposited the metals. Consequently, any definition of a vein based on mode of origin is inherently burdened with the vagaries of unproved and, commonly, unwarranted speculation. The authors prefer a descriptive rather than genetic definition of a vein.

Lindgren (1933, p. 155–156), in describing the spatial relations of veins, defines veins as follows:

> Veins are tabular or sheetlike masses of minerals occupying or following a fracture or a set of fractures in the enclosing rock; they have been formed later than the country rock and

fractures, either by filling of the open spaces or by partial or complete replacement of the adjoining rock, or most commonly by both of these processes combined.

Lindgren's definition of a vein, with minor modifications, was selected for use in this report because (a) the definition is relatively simple, is subject to little, if any, misinterpretation, and essentially is based on well-established, observable geologic features; (b) it commonly assigns shape and general structural setting to a vein deposit or a part of a deposit and outlines the overall geometric distribution of the introduced minerals; and (c) it excludes most, if not all, factors related to mode of origin, crystallization temperatures of ore and gangue minerals, nature of ore solutions, and whether only certain mineral assemblages are characteristic of uranium-bearing veins. The exclusion from the definition of any concept of temperature is justified, particularly for uranium deposits, by the lack of definite data on temperature during crystallization and by geologic evidence indicating or suggesting a wide range of crystallization temperatures, even within a single deposit, from relatively high temperatures to those approaching the temperature of near-surface ground water.

The definition has some limitations that are principally related to the nature of the fractures or the sets of fractures and to the resultant shape of a deposit. Consequently, some supplemental information is necessary to establish more clearly the characteristics of a vein. Fractures or sets of fractures, as used in the definition, encompass most induced openings in rocks. The induced openings may be the result of compressive, tensile, or torsional stresses related to folding, faulting, and intrusion of igneous masses; they also may be related to volcanic pipes, collapse breccias, and solution caves or to near-surface postsedimentation slumping and release of stress. The tabular nature of veins, therefore, may be apparent only in detail in parts of a deposit, or it may encompass an entire major ore body. Furthermore, in some deposits, ore minerals are concentrated in lenses, pods, irregular masses, or in shoots along tabular structures. In addition, a few uraniferous vein deposits, principally those characterized by extensive alteration and replacement of the wallrocks, apparently are not tabular in shape. However, because most uranium-bearing veins are tabular either on a large or small scale, this qualifying term has been retained in the definition with the realization that it is not all inclusive.

Only those deposits in which the induced openings dominated in localizing the introduced minerals are herein defined as veins. Locally, replacement of wallrock constituents is prevalent; but, in general, it is confined to relatively thin zones adjacent to the induced openings. The definition includes those deposits or concentrations of uranium minerals that are localized in epigenetic fractures or cavities irrespective of the valence state of the uranium or the character of any associated metallic or nonmetallic minerals. Many other uranium deposits localized dominantly by favorable wallrocks or by original cavities and structures in these rocks may show vein affinities where induced cavities have been partly instrumental in localizing the introduced minerals. Some of these deposits, as for example several in the Todilto Limestone of Jurassic age, San Mateo Valley area, Grants district, New Mexico; several small deposits in the Wingate Sandstone at Temple Mountain, Utah; a few deposits in the Kayenta Formation and Wingate Sandstone in Richardson Basin, Utah; and others in Paleozoic and Mesozoic rocks of the Colorado Plateau, are characterized by epigenetic structures that have contributed to the localization of the deposit.

DEPOSIT

The term "deposit" is used herein to denote any abnormal concentration of uranium minerals; it has no connotation of size or potential for commercial exploitation of the uranium concentrations. As used in this definition, an abnormal concentration of uranium minerals is restricted, in general, to localities where uranium is more concentrated than that occurring in the enclosing wallrocks by a ratio of approximately 2 or more to 1.

ACKNOWLEDGMENTS

The compilation of data and preparation of this report by members of the U.S. Geological Survey were done on behalf of the Division of Raw Materials, U.S. Atomic Energy Commission. The report is based on both published and unpublished information collected principally by personnel of the Geological Survey; the Atomic Energy Commission or its predecessor organization, the Manhattan Engineer District; and to a lesser extent by staff members of other Federal or State agencies and by geologists in private industry. Each geologist who prepared a report on some property, district, or subject from which data was extracted for use in this report could, in a sense, be considered a coauthor of a part of this summary. Furthermore, some of the ideas expressed in this report have resulted from discussions with colleagues in the Geological Survey and with geologists of the Atomic Energy Commission. Beyond the acknowledgment implied by the references themselves, we wish to express special appreciation to G. J. Neuerberg of the

Geological Survey for stimulating discussions of many of the problems encountered in the preparation and planning of the report and to Wendell Walker, also of the Geological Survey, who aided in the preparation of the photographic illustrations.

HISTORY

Some of the principal milestones in the history of uranium discovery and mining, insofar as they pertain to uranium-bearing vein deposits mostly in the conterminous United States but also in other parts of the world, are briefly discussed below. The history of uranium vein deposits is not completely separable from the history of other kinds of uranium deposits and also of deposits of precious and base metals. For more complete coverage on the history of uranium (or radium) discovery, production, uses, mineralogy, and geology, the reader is referred to reports by Pratt (1901), Moore and Kithil (1913), Hess (1913, 1922, 1924, 1927, 1929, 1933, 1934a, b), Tyler (1930), Prost (1938), Kohl (1942, 1954), Palache, Berman, and Frondel (1944, 1951), Bain (1950), Meister (1954), Brüyn (1955), Kerr (1956), and Weeks (1956), and to the many references listed in these papers.

EARLY HISTORY

Most of the pre-1900 history of uranium mining centered in Europe, where most uranium ores were utilized either in the chemical industry or for pigmentation. The discovery of radium in 1898 (Curie and others, 1898) had little immediate effect on the mining of uranium ores, and not until the early to mid-1910's did radium extracted from these ores become commercially important in medical therapy (Hess, 1913, p. 1033–1034), in the manufacture of luminescent paint—one of the principal uses during World War I (Hess, 1919, p. 806)—and in other uses.

Mining of uranium minerals many centuries ago is suggested by a reference (Weeks, 1956, p. 264) to pale-green glass from a mosaic mural found near Naples that contained more than 1 percent of an oxide of uranium; authorities believe that the mosaic dates back to about A.D. 79. No information is available as to the source of the uranium in the glass nor is there any documentation that this is the first "knowledgeable" use of uranium minerals.

Some of the earliest documented references to the exploitation of metalliferous deposits for the "profitable" recovery of uranium pertain to veins in the border area between Czechoslovakia and Germany, particularly near St. Joachimsthal in Bohemia (the Czechoslovakian name for St. Joachimsthal is Jáchymov) and Johanngeorgenstadt and Schneeberg in Saxony. Deposits in this area, worked since the 14th or 15th centuries and well developed by the 16th century (Katzer, 1892, p. 416), have yielded considerable quantities of silver, tin, tungsten, cobalt, bismuth, lead, uranium, nickel, and copper. Small amounts of uranium ore were produced at Schneeberg (Königliche Bergakademie, 1827) and in the Johanngeorgenstadt and Schwarzenberg area during the 1820's (Königliche Bergakademie, 1829). Mines in both Saxony and Bohemia were being actively worked by the middle of the 19th century for uranium minerals (Kohl, 1942, p. 163; Katzer, 1892; Schneiderhöhn, 1938, p. 952) which went to chemical factories in the area that produced uraniferous pigments of different colors for use in the glass and porcelain industries (Fuchs and Launay, 1893, p. 180–182; Janda, 1902, p. 283; Schiffner, 1912). The principal uranium production in this region, in addition to that from St. Joachimsthal, came from deposits at Schneeberg, Johanngeorgenstadt, Freiberg, Annaberg, Marienberg, and Breitenbrunn-Schwarzenberg in Saxony; from deposits at Schmiedeberg in Silesia; and from deposits near Dürrmaul, Schlaggenwald, and Pribram in Bohemia. Production figures for years prior to World War II (Kraus, 1915, p. 99–112; Schneiderhöhn, 1938, p. 953; Kohl, 1942; Prost, 1938), all of which are admittedly incomplete and commonly represent products of different type and grade, indicate that the total amount of pitchblende or high-grade pitchblende concentrate produced from the deposits in Saxony and Bohemia can be estimated at hundreds of tons and may total as much as several thousand tons. Hess (1925, p. 579) indicates that between 1853 and 1913 the mines at St. Joachimsthal produced 1,659 short tons of pitchblende ores of unknown uranium content, and Kohl (1954, p. 203) indicates that about 76 grams of radium were produced between 1927 and 1936; the 76 grams of radium indicate that more than 700 tons of pitchblende concentrate containing about 50 percent U_3O_8 was produced during this period from an unknown tonnage of mined ore. Schneiderhöhn (1938, p. 953) states that about 500 tons (metric) of pitchblende concentrates was produced from 1854 to 1914, and 250 to 300 tons was produced in the period 1920 to about 1938; the concentrates presumably contained about 50 percent U_3O_8. Only very fragmentary data are available on production from mines in this region during and since World War II. Prior to about 1914, the bulk of the world's supply of radium came from the ores of St. Joachimsthal (Tyler, 1930, p. 33).

Interest in uranium minerals also had an early start in the ancient tin mines of Cornwall, England. Phillips (1816) had noted uranium minerals in mines of the region as early as 1805, and exploitation of these minerals had started at least by 1854, as shown by production figures contained in a report by Penrose (1915, p. 171). Principal mines in the Cornwall region that were worked for uranium minerals are the South Terras, the Saint Ives or Trenwith, and the St. Austell Consols; one of the richest pitchblende-bearing lodes —called the Radium lode—was first found in the South Terras mine in 1873 (Robertson and Dines, 1929, p. 147). Penrose (1915, p. 171) indicated that about 500 tons of ore was sold up to 1907 from the South Terras mine and that about 576 tons of uranium ores was produced from the St. Austell district in the period 1854–1906. Production figures reported by Hess (1913, p. 1026; 1927, p. 254) indicate that the region yielded more than a thousand tons of uranium ore in the following 16 years (1907–22, inclusive); no production is reported for the years 1918 and 1919. Davidson (1956, p. 205) reported that

* * * the South Terras property near St. Stephen, was once a mine of some importance, which before the discovery of Shinkolobwe ranked next to Jáchymov and Urgeirica as the third most productive source of uranium in the world. Its past output of uranium oxide, almost all obtained from one high-grade oreshoot, amounted to between 70 and 90 tons.

One of the earliest, if not the first, documented occurrence of pitchblende from veins on the North American continent was recorded by LeConte (1847) from material apparently collected near the mouth of the Montreal River on the east shore of Lake Superior in what is now the Province of Ontario. LeConte (1847) called the mineral coracite because he thought that although the mineral had much in common with pitchblende, it had a different lustre and specific gravity; later investigators, however, indicate that the mineral described by LeConte as "coracite" actually is pitchblende (Lang, 1952, p. 3). Recent prospecting in the area has uncovered a number of pitchblende-bearing veins, all of which contain only small amounts of uranium if compared with other recent and very large discoveries in other parts of Canada.

Within the conterminous United States, the first pitchblende of potential economic interest was discovered on the dump of the abandoned Wood mine, Gilpin County, Colo., in 1871 by Richard Pearce (1875; 1898, p. 156). According to Brüyn (1955, p. 22),

* * * Pearce arranged to have some 200 pounds of the mineral hand-sorted and sent him at Swansea; there he further screened it and sold the selected lot to Johnson and Matthey of London for the equivalent of about $200.

Presumably this waste product from the mining of gold-quartz veins constitutes the first uranium "ore" mined in the United States that was sold for its content of uranium and radioactive distintegration products. Within the ensuing few tens of years, pitchblende mineralization had been discovered in several nearby mines, namely the Kirk, German and Belcher, Calhoun, and Jo Reynolds mines; and by 1920 about 300 tons of high-grade pitchblende concentrates had been produced, with most of the production coming from the Kirk and Wood mines in the 10-year period, 1897–1906 (Moore and Kithil, 1913; Moore and Butler, 1952, p. 1; Harrison and Leonard, 1952, p. 1; King, Leonard, Moore, and Pierson, 1953, p. 2; Sims, Osterwald, and Tooker, 1955, p. 2). Uranium also was known to occur in the Leyden Coal mine, Jefferson County, Colo., as early as 1875 (Berthoud, 1875, p. 365), but no uranium ores were produced until the early 1950's. Another early reference to a vein deposit in sandstone in the conterminous United States is to the Rajah mine, known earlier as the Copper Prince (Brüyn, 1955, p. 31). Shoemaker (1956) stated that "The initial shipment from the mine, made in 1898, consisted of 10 tons of ore that averaged over 20 percent U_3O_8 and 15 percent V_2O_5." Presumably this is the same 10-ton shipment of carnotite ore referred to by Kimball (1904) as having been mined by him from the Roc Creek deposit and sold in Denver for $2,600. Several other vein-type deposits of uranium discovered prior to 1920 include the deposits at Richardson, Utah (Parsons, 1913, p. 944); the Silver Cliff mine, Wyoming (Lind and Davis, 1919), which yielded several carloads of ore containing more than 4 percent U_3O_8 in 1918 (Hess, 1921, p. 812); carnotite deposits in Routt County, Colo. (Gale, 1908); and deposits at San Acacia, N. Mex. (Lovering, 1956, p. 316). According to Parsons (1913, p. 944), an attempt to extract radium in this country apparently was first made about 1904 on carnotite ores from the deposits at Richardson.

Shortly after 1900, uranium-bearing veins were discovered at Radium Hill (Sprigg, 1954, p. 7–8) and Mount Painter (Broughton, 1926, p. 37), both in South Australia, and in Portugal (Segaud and Humery, 1913, p. 111; Hess, 1934b, p. 505). Production from the Australian deposits prior to World War II was not large, apparently amounting to less than a gram of radium (Sprigg, 1954, p. 8) extracted from an unknown tonnage of ore. Portuguese radium production started around 1909 and in pre-World War II years apparently reached one peak in the late 1910's and early 1920's and another in the mid-1930's. According to Hess (1927, p. 254), "The Portuguese production of ore is reported to have been, in 1919, 1,380 metric tons; 1920, 437 metric tons; 1921, 1,032 metric tons, all with a content of uranium oxide between 0.5 and 1.5 percent." Further, in 1924, 367 metric tons of uranium ore and 1 ton of concentrate were exported from Portugal (Hess, 1928, p. 617). Lund (1936, p. 506) reports more than 1,500 tons production of uranium ore in the period 1934–35, largely from the Urgeirica mine.

According to Seniger (1923, p. 335),

> The discovery of the first radium ore in the Katanga was made in 1913 in the course of some prospecting work on the Luiswishi copper mine [near Elizabethville, Belgian Congo]; a second and more important discovery took place in 1915 at Chimkolobwe [Chinkolobwe or Shinkolobwe] * * * (Kasolo) * * *.

Production of radium ores from Shinkolobwe began in late 1921 or 1922 (Prost, 1938, p. 742, 744–745), reached large proportions in 1924, and, until the discovery and development of the deposits at Great Bear Lake, Canada, in the early 1930's, constituted the world's major source of radium. Hess (1927, p. 245) reports,

> In 1923 the mining of uranium and vanadium ores was reduced to a very small industry in the United States, as the newly exploited uranium deposits in Katanga, Belgian Congo, came into large production.

In the spring of 1930, Gilbert Labine and E. C. St. Paul discovered pitchblende and native silver on the eastern shore of Great Bear Lake, Northwest Territories, Canada (Kidd, 1932, p. 145), at a cobalt occurrence originally discovered in 1900 by J. Macintosh Bell (see Lang, 1952, p. 3). The deposit, later to be known as the Eldorado mine, was first developed in 1931 when 20 tons of ore was shipped (Hess, 1933, p. 331). Prior to the discovery and development of the Eldorado mine, the world's radium market was largely controlled by the Belgian Congo through radium produced from Shinkolobwe ores; production from the Eldorado mine during the middle and late 1930's tended to break the Belgian monopoly (Lang, 1952, p. 3; Lund, 1936, p. 501). In 1939 an agreement was reached between Union Minière du Haute Katanga, Belgian Congo, and Eldorado Gold mines, Ltd., Canada, to share the world's radium market (Tyler, 1939, p. 755).

Until World War II, the commercial history of the uranium (or radium) industry was a series of monopolies based on production first (pre-1910's) from the deposits in Saxony and Bohemia—principally the mines at St. Joachimsthal, then from carnotite deposits in the conterminous United States (1910's to early 1920's), then from Shinkolobwe in the Belgian Congo (1923 to roughly 1934), and finally on production from both Shinkolobwe and the Eldorado mine, Northwest Territories, Canada. The great bulk of the uranium ores that created these monopolies was mined from vein-type uranium deposits, with the exception of most of the carnotite ores mined during the 1910's to 1920's in Utah and Colorado.

RECENT HISTORY

The recent history of uranium mining and geology is closely bound to research projects carried out in the late 1930's and early 1940's that ultimately led to controlled atomic fission and to the realization of a vast potential source of energy. The production of uranium ores for use in fields of atomic energy became essential in the early 1940's (Matthews, 1943, 1945; Nighman, 1946, 1947) almost exclusively for military purposes. Within a period of only a few years the demand for radioactive materials—largely uranium—increased rapidly, and, as a consequence, many prospecting and exploration programs were put into operation throughout the world. The results of these programs in countries other than the United States or in deposits other than veins in the conterminous United States have been described elsewhere, and many have been briefly reviewed in the "Proceedings of International Conference on Peaceful Uses of Atomic Energy, Geneva, 1955." Many of the mining districts of the world that prior to World War II were known to contain uranium were reexamined, and this resulted both in discoveries of new deposits and in extensions of old deposits. Furthermore, many new uranium districts were discovered in widely separated parts of the world, including districts in France, Italy, French Morocco, South Africa, Australia, South America, and Canada.

Within the conterminous United States, prospecting and exploration programs both by the Federal Government and by private industry were put into operation during the 1940's. Systematic radiometric and geologic examinations of large and small mining properties and districts during the period 1945–53 led to the discovery of additional uranium ore in many mines already known to contain uranium and to many hundreds of new deposits of uranium minerals. Most newly discovered deposits of uranium minerals in the conterminous United States were small, commonly containing only a few tons of uranium ore at best; many were so small or geographically so situated that they could not be worked profitably. On the other hand, many deposits were discovered that either yielded small to large tonnages of uranium ore or represented potential but unexploited sources of uranium. Of these new discoveries, most of the deposits that contained hundreds of thousands of tons of uranium ore, and locally even millions of tons of ore, are the kind of uranium deposit variously classified as sandstone-type, plateau-type, bedded-type, or carnotite-type. Examples include deposits in the Big Indian Wash and White Canyon districts, Utah; the Gas Hills area, Wyoming; and the Grants-Laguna area, New Mexico. A few veins that contain hundreds of thousands of tons of uranium ore were discovered, but most are very much smaller.

Some of the uranium-bearing veins in the western United States discovered during the middle to late 1940's included the deposits at Marysvale, Utah (Gruner, Fetzer, and Rapaport, 1951, p. 243; Brüyn, 1955, p. 113–115); deposits in the Coeur d'Alene district, Idaho (Thurlow and Wright, 1950, p. 395); the Garm-Lamoreaux mine, Idaho (Trites and Tooker, 1953); several uraniferous fluorite deposits in western Utah, including the Staats mine (Thurston and others, 1954, p. 5); deposits at Majuba Hill, Nevada (Trites and Thurston, 1958); the Schwartzwalder or Ralston Creek mine (Bird and Stafford, 1955), the Caribou mine (Moore, Cavender, and Kaiser, 1957), and the Copper King mine (Sims, Phair, and Moench, 1958), in Colorado; and several of the deposits in the Boulder batholith, Montana, including the Free Enterprise and W. Wilson mines (D. Y. Meschter, written communication, 1953). Discoveries in these areas stimulated additional prospecting and, as a result, many other deposits were found. Little, if any, uranium ore was produced from any of these properties or areas prior to 1950; however, within the next several years many thousands of tons of ore was mined from the veins at Marysvale and at the Schwartzwalder mine (Bird, 1956, p. 8), and smaller amounts of ore were mined from a number of other properties.

In 1950, uranium was discovered at the Red Bluff mine, Gila County, Ariz. (Kaiser, 1951, p. 1), in the Dripping Spring Quartzite of Precambrian age. Within a few years many additional deposits, some of which contained substantial tonnages of uranium ore, were found in the same formation in nearby areas.

As the search for uranium widened both geographically and geologically in the ensuing few years, uraniferous veins were discovered in areas that previously were not known to contain uranium; several of these deposits have yielded substantial tonnages of uranium ore. Included are the Early Day and Buckhorn mines in Nevada, found respectively in 1953 (Sharp and Hetland, 1954, p. 5) and 1954 (Hetland, 1955, p. 5); the Midnite and Daybreak mines in northeastern Washington, found respectively in 1954 and 1955 (Norman, 1957, p. 662); the Los Ochos mine in the Cochetopa district, Colorado, discovered in the summer of 1954 (Malan and Ranspot, 1959, p. 3); the White King and Lucky Lass mines of south-central Oregon (Matthews, 1955, p. 87); and deposits in the Pryor Mountains–Little Mountain area of Montana and Wyoming (Hauptman, 1956, p. 14).

Of the several tens of uranium-bearing veins known in the eastern United States, most were discovered from the late 1940's to mid-1950's. During this period, uranium was discovered at the Huron River deposit, Baraga County, Mich. (Vickers, 1953), at several localities in western North Carolina (Stow, 1955; Klemic, 1955), and in iron-ore deposits near Warwick, N.Y. (Engineering and Mining Journal, 1957). Of the vein-type uranium deposits known in the Eastern United States, only those near Warwick, N.Y., have yielded uranium ore.

The discovery between 1945 and 1956 of these uranium-bearing veins, some containing hundreds of thousands of tons of uranium ore, was completely overshadowed by the discovery and development of a number of multimillion-ton deposits in New Mexico (for example, Jackpile mine and deposits in the Ambrosia Lake area); in Big Indian Wash and White Canyon, Utah; in the Gas Hills, Wyo.; in northern Saskatchewan, Canada (for example, Ace, Fay, and Gunnar mines; Robinson, 1955); and in Precambrian quartzitic conglomerates near Blind River, Canada, and the Witwatersrand in South Africa.

GEOGRAPHIC DISTRIBUTION

Domestic vein deposits in which uranium minerals have been identified and from which samples have shown a uranium content of 0.01 percent or more can be numbered in the hundreds and perhaps total as many as 900 different localities. All of these are in the conterminous United States, and more than 95 percent are in, or to the west of, the Cordilleran foreland.[1] Most are notably concentrated in the Front Range mineral belt of Colorado; the Boulder batholith area, Montana; the Sierra Ancha region, Arizona; and the Marysvale district, Utah. Fewer are known in the Black Hawk and White Signal districts of southwest New Mexico; the Thomas Range and the Beaver area, Utah; the Kern River area, California; the Yellow Pine (Goodsprings) district, Nevada; the Wallapai district, Arizona; the Cochetopa district, Colorado; south-central Oregon; northeastern Washington; and northern Michigan. Other uranium-bearing veins are known in widely distributed localities in the western United States—in South Dakota (Curtiss, 1955), Montana (Jarrard, 1957), Wyoming, Colorado, Texas (Flawn and Anderson, 1955; Eargle, 1956), New Mexico (Anderson, 1955; Lovering, 1956), Arizona, Utah, Idaho (Cook, 1955, 1957), Nevada (Lovering,

[1] The Cordilleran foreland is the area east of the Cordilleran deformed belt (Osterwald and Dean, 1961).

1954), California (Walker, Lovering, and Stephens, 1956), and Washington (Huntting, 1957). A small number of widely distributed uranium-bearing veins also are known in the eastern United States in New York, New Jersey, eastern Tennessee, North Carolina, Vermont, Pennsylvania, and Georgia.

The distribution of known uranium-bearing veins is in part attributable to geologic conditions and in part to the intensity of prospecting in areas where deposits have already been found. Furthermore, some areas in the Western United States are more easily prospected because (a) bedrock is extensively exposed with relatively little soil and vegetation cover; (b) near-surface efflorescences of 6-valent uranium minerals are common which have led, locally, to the discovery of primary uranium ores beneath the outcrops; and (c) land laws are, in general, more favorable as related to the right of location and exploitation of mineral deposits.

The geographic distribution of uranium-bearing veins in the conterminous United States and the distribution of veins from which uranium ore has been produced are shown on plate 1. The deposits are listed alphabetically by States in the list of deposits (table 1) at the end of the chapter, and the numerical order within the different States is generally from north to south by counties. Where properties are densely clustered, as for example in the Front Range mineral belt, the Sierra Ancha region, and in parts of the Boulder batholith, a single symbol on the map (pl. 1) or a single number in the list may represent a group of deposits. Within the list, the mineralogic class of each deposit is designated where information is available. Furthermore, the deposits have been segregated into five production classes as based on production data that were available to the authors in the spring of 1957. The five classes are:

1. Veins that have yielded more than 1,000 tons of commercial uranium ore. Some of these, including the Midnite mine, Washington; the Buddy (or Sunnyside), Freedom, Prospector, and Bullion Monarch (Farmer John) mines at Marysvale, Utah; and the Schwartzwalder and Los Ochos mines, Colorado, have yielded several thousands or tens of thousands of tons of ore.
2. Veins that have yielded less than 1,000 tons of ore but more than 100 tons.
3. Veins that have yielded less than 100 tons of ore but from which some production of uranium is reported.
4. Veins from which uranium production has been reported but the amount is unknown.
5. Deposits that, as far as is known, have yielded no uranium ore. Although several of the deposits in this last class are potential sources of uranium, ore has not been shipped because the property is inaccessible, the ore is not readily amenable to standard metallurgical processes, the cost of mining or transportation is excessive, or for several other reasons.

CLASSIFICATION OF URANIUM-BEARING VEINS

Many different classifications of ore deposits have been proposed (Bateman, 1950, p. 355–365); some are based on empirical data, and others are based on theoretical deductions. Mode of origin, temperature and pressure relations, processes involved in deposition, mineral content, geometry, position of constituent minerals, and structural setting have been used to establish arbitrary classes of ore deposits. Many of these classifications are vulnerable from several critical aspects, particularly because of the lack of definite data on temperature and pressure at time of deposition and on the chemical composition, physical state, and origin of the ore solutions. Perhaps the most valid classification of ore deposits should be one based on the tectonic and petrologic environment of deposits, but here again critical data are lacking. As a result, a descriptive and arbitrary classification based on the mineral content of the deposits was selected for use in this report. The classification is based largely on the mineralogic characteristics of uranium deposits in the conterminous United States and, to a lesser extent, on the characteristics of deposits in other parts of the world. Data regarding foreign deposits are used partly for purposes of comparison and partly to establish better the validity of the classification; their use has resulted in the establishment of one class—davidite-bearing veins—that is not known to occur in the conterminous United States.

Uranium-bearing veins are tentatively divided on the basis of mineralogy into eight classes, most of which are overlapping and only a few of which have proved to be important commercial sources of uranium in the conterminous United States. These types are (1) fluorite-bearing veins; (2) base-metal sulfide veins; (3) veins dominantly of uranium minerals but which may contain minor amounts of other introduced metallic minerals; (4) magnetite or other iron oxide-bearing veins, excluding deposits in gossan derived from supergene alteration of base-metal sulfide deposits but including those uraniferous deposits characterized dominantly by magnetite, hematite, or limonite; (5) veins dominantly of thorium or rare earths minerals; (6) brannerite-bearing quartz or siliceous veins; (7) davidite-bearing veins; and (8) hydrocarbon-rich uranium-bearing veins.

FLUORITE-BEARING VEINS

Uranium deposits in fluorite-bearing veins are characterized by common or abundant fluorite gangue associated with uraninite, colloform pitchblende, or uranothorite and their alteration products, including several 6-valent uranium minerals,[2] principally uranyl phosphates, silicates, carbonates, and locally vanadates (Wilmarth and others, 1952). In addition to fluorite, the most common gangue is either quartz or cryptocrystalline silica minerals; and some deposits, most of which are foreign, contain some barite and calcite. Some of the deposits also contain small to moderate amounts of lead, zinc, copper, iron, or molybdenum sulfides; these are not necessarily listed in order of abundance. Several of the deposits are fissure veins, commonly with ore-grade uranium concentrations in shootlike structures; some are stockworks and breccia zones accompanying faults; and others are breccia "pipes." In the fissure veins, coarse crystals of fluorite, banded vein filling, vugs, and drusy textures are common.

Most of the deposits are probably the result of deposition from low- to moderate-temperature hydrothermal solutions; some of the minerals in the upper parts of the deposits may have been deposited directly by solfataric action or by nonthermal ground waters.

The deposits in the Marysvale district, Utah (Gruner and others, 1951; Taylor and others, 1951; Kerr and others, 1952; Walker and Osterwald, 1956a; Kerr and others, 1957), in this class, have been some of the chief sources of uranium from veins in the conterminous United States. Some of the deposits, as for example those in the Thomas Range (Staatz and Osterwald, 1959) and the Staats Flourspar mine (Wilmarth and others, 1952), Utah; in the Jamestown district, Colorado (Phair and Shimamoto, 1952); and several in New Mexico (Gillerman, 1952; Lovering, 1956), have been prospected and developed principally for fluorite but have yielded only small amounts of uranium ore. The grade of the ore in Marysvale deposits and in similar deposits elsewhere is typically a few tenths of a percent uranium and locally, for very small tonnages of ore, may be as much as 0.5 percent. Most of the uranium is in separate pitchblende masses, thin seams, or sooty powder, or in secondary 6-valent uranium minerals near the ground surface. Most deposits exploited principally for fluorite contain only a few hundredths of a percent uranium that occurs as finely divided pitchblende particles disseminated in the fluorite, possibly substituting for calcium in the calcium fluoride molecule, or locally, near the surface, as sparse crystals of 6-valent uranium minerals (Staatz and Osterwald, 1959). In the Thomas Range the uranium content varies independently of the fluorite content within individual deposits (Staatz and Osterwald, 1959), and a similar relation may exist elsewhere.

Foreign deposits in this class include several near Wölsendorf, Germany (Kohl and Haller, 1934; Everhart and Wright, 1953); Marienbad, Czechoslovakia; possibly some of the uraniferous veins of the Central Massif, France (Geffroy and Lenoble, 1953); and the Rexspar mine, British Columbia, Canada (Leaming, 1953).

BASE-METAL SULFIDE VEINS

Uranium deposits in base-metal sulfide veins are characterized dominantly by sulfides or sulfarsenides of base metals commonly with different amounts of precious metals either in a carbonate or siliceous gangue. The uranium minerals in these veins include uraninite or colloform pitchblende, coffinite, and many brightly colored alteration products, principally uranyl phosphates, silicates, sulfates, carbonates, and locally arsenates. The deposits generally are fissure fillings, although replacement of wallrocks is prevalent locally.

Although most classifications of uranium-bearing veins (Bastin, 1939; Everhart and Wright, 1953; McKelvey, 1955; Klepper and Wyant, 1957) have indicated a relatively clear cut and logical distinction between simple base-metal sulfide veins and those veins characterized by sulfides and sulfarsenides of cobalt and nickel, in this report they are considered variants of a single class and are discussed as base-metal sulfide veins. A classification somewhat similar to this was used by Geffroy and Sarcia (1954) for European vein deposits of uranium.

The base-metal sulfide veins and veins characterized by sulfides and sulfarsenides of cobalt and nickel are grouped together because (a) the structural setting and textural characteristics of vein filling are similar; (b) virtually all the veins are considered to be the result of mesothermal to lower epithermal deposition; (c) taken as a group, the similarity of cation and anion content of the sulfide-bearing veins as a whole is more impressive, to the authors, than the dissimilarities; (d) there is an almost continuous gradation in the content of cobalt, nickel, silver, and probably uranium, from simple base-metal sulfide veins to those previously classed as nickel-cobalt-native silver-pitchblende veins (Bastin, 1939); and (e) although a spatial relation between pitchblende and sulfides of cobalt, nickel, and silver is obvious in some deposits, locally this only denotes a favorable structural setting for deposition

[2] The term "6-valent uranium minerals" is used in this report to denote uranyl compounds.

and not a genetic tie between the metals. The dissimilarities in cation content and differences in the relative abundance of cations may depend largely on their relative availability and only to a minor extent on the processes involved in deposition.

DOMESTIC DEPOSITS

Many domestic uranium-bearing veins contain both 4-valent and 6-valent uranium minerals associated with, but generally in amounts subordinate to, sulfides of copper, lead, zinc, and iron. Commonly the gangue is quartz or chalcedony, though locally lesser amounts of calcite, siderite, ankerite, rhodochrosite, or barite may occur. Several of the deposits in this class are gold and silver bearing; some contain mercury, arsenic, and molybdenum minerals; and some are characterized by hematite, either in the veins or as stain on the adjacent wallrocks. A few deposits contain minor amounts of bismuth, and some contain sulfides or sulfarsenides of cobalt and nickel. Uraniferous gossans containing 6-valent uranium minerals produced by supergene alteration are known at several of the deposits that originally contained mostly pyrite, sphalerite, and galena, with minor amounts of silver, copper, gold, probably uraninite or colloform pitchblende, and trace amounts of vanadium. Examples are some of the properties in the Wallapai district, Arizona, and the Yellow Pine (Goodsprings) district, Nevada. Adsorbed uranium (Lovering, 1955), associated with hydrated iron oxides and lead, zinc, and copper carbonates and sulfates, is present in some of the gossans.

Most of the deposits are fissure veins or vein systems with uranium minerals commonly confined to shoots; locally pitchblende stringers or lenses and pods are erratically distributed along the fissure veins. In some of the uraniferous lead-zinc deposits of the western United States, the ore filled open fissures and replaced carbonate wallrock. In these deposits, most of the uranium is disseminated in the lead-zinc ore; although, locally, sparse small irregular masses of hard or sooty pitchblende may be erratically distributed in the ore.

Because the uranium in the base-metal sulfide deposits is locally concentrated and elsewhere is erratically distributed, the grade of the ore ranges widely. Small parts of veins or of ore shoots may contain several percent uranium, although the average in mined ores is typically a few tenths of 1 percent. In most deposits the tonnage of ore-grade material is small and may be only a few tons, but several properties in the United States contain several thousand tons of uranium ore.

Examples of uraniferous veins in this class are the Carroll, Cherokee, Copper King, Wood, and Calhoun mines in Colorado and the Comet and Gray Eagle mines in Montana; several deposits in the Yellow Pine (Goodsprings) district, Nevada, and the Wallapai district, Arizona; the Silver Cliff mine, Wyoming; and pitchblende deposits at Huron River, Mich., and in the Rustler group, Idaho. Other examples of veins that contain abnormal amounts of either cobalt or nickel, or both, in addition to sulfides of lead, zinc, and copper are the Caribou mine, Colorado; the Blackhawk mine, New Mexico; and perhaps several deposits in the Coeur d'Alene district, Idaho.

FOREIGN DEPOSITS

Foreign occurrences in this class have been the dominant source of uranium from vein-type deposits and to 1955 probably had yielded more uranium than all other sources combined; a few have yielded large amounts of silver and lesser amounts of other metals. This class includes the Shinkolobwe mine in the Belgian Congo (Thoreau and du Trieu de Terdonck, 1933; Everhart and Wright, 1953), which is probably the richest and largest known vein deposit of uranium; deposits in the Joachimsthal and Johanngeorgenstadt districts of Bohemia and Saxony; and the deposits at Great Bear Lake, Northwest Territories, Canada (Kidd and Haycock, 1935). Smaller deposits are known in the Cornwall district, England (Everhart and Wright, 1953); near Freiberg, Saxony; in the Carrizal Alto district, Chile (Everhart and Wright, 1953); Vilcabamba district, Peru (George, 1949); Rum Jungle district, Northern Territory, Australia (Fisher and Sullivan, 1954); and elsewhere.

Most of these deposits are mesothermal fissure veins and vein stock works. Crystalline uraninite, or more commonly massive or colloform ptichblende, is present as veins and veinlets ranging from a fraction of an inch to several feet in thickness and pods and irregular masses as much as several tons in weight. Pitchblende grains also are disseminated in sheared and unsheared wallrock; some of the disseminations are spatially related to the massive veins and pods, and some are not. Iron, in the form of pyrite, magnetite, or hematite, is ubiquitous and commonly abundant in most deposits. Other metallic constituents, some of which locally have been principal or coproducts of mining, are copper, lead, zinc, molybdenum, cobalt, nickel, silver, bismuth, and gold. Most are sulfides, arsenides, sulfarsenides, or locally sulfantimonides, although the native elements silver, bismuth, and some copper and gold have been identified. Calcite or dolomite gangue is most commonly associated with pitchblende or uraninite in these veins; but other carbonate minerals, quartz, chalcedony (or jasper), barite, and chlorite, are locally major vein constituents. A few deposits contain virtually no gangue minerals.

Near-surface supergene alteration has produced a host of hydrated uranyl oxides, sulfates, phosphates, arsenates, and silicates, most of which also contain copper, calcium, magnesium, barium, lead, or other cations. Ianthinite, a "supergene" uranium mineral that contains 4-valent uranium (George, 1949), has been identified in several of these deposits but may have formed by low-temperature hydrothermal alteration (Kohl and Haller, 1934).

VEINS DOMINANTLY OF URANIUM MINERALS

Veins consisting dominantly of uranium minerals may contain 4-valent or 6-valent uranium minerals, with or without small amounts of hydrated iron oxides or sulfide minerals of which pyrite and marcasite are most common. The uranium mineral may be associated with quartz, cryptocrystalline silica, or hyalite opal gangue, or there may be virtually no gangue minerals. Deposits of this class commonly contain 6-valent uranium minerals, principally autunite (or meta-autunite), torbernite (or metatorbernite), and uranophane; locally uranyl arsenates or vanadates, such as metazeunerite, heinrichite, novacekite, carnotite, or tyuyamunite are the dominant uranium minerals. In other deposits pitchblende is most abundant, occurring either in a hard dense form in veinlets or irregular masses or in a finely divided powdery form coating fractures and disseminated in altered wallrock.

Many deposits are characterized by 6-valent uranium minerals coating fractures and shears and may be the result of (a) solution of the uranium from the wallrocks by ground water and deposition wherever a change of chemical environment decreased the solubility of the uranium, (b) evaporation of uranium-bearing ground waters under suitable climatic conditions to form caliche-like concentrations, or (c) oxidation, essentially in place, of 4-valent uranium minerals originally introduced by thermal or nonthermal aqueous solutions. Several of these deposits have been explored only to shallow depths and may be the near-surface expression of uranium-bearing veins of some other class.

Large deposits of this class are represented by the Midnite mine in Washington, which is probably the largest uranium-bearing vein in the conterminous United States, and by the Los Ochos mine in Colorado. Both mines have comparatively large reserves of ore averaging a few tenths of 1 percent uranium. Most of the deposits in this class, however, are small and contain only a few tens or hundreds of tons of mineralized rock containing slightly less than 0.1 percent uranium.

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The W. Wilson and Free Enterprise mines in Montana, the White King mine in Oregon, and the Schwartzwalder mine in Colorado are included in this class, although they locally contain minor to moderate amounts of base-metal sulfide minerals, which suggests that they are transitional between veins in which uranium minerals are dominant and base-metal sulfide veins.

Some of the large vein deposits in the Goldfields region, Saskatchewan, are in this class, whereas other uranium deposits of the region apparently are characterized by common or abundant base-metal sulfide minerals (Lang, 1952, p. 71). Certain siliceous veins in Portugal that contain pitchblende and several 6-valent uranium minerals resemble veins dominated by uranium minerals, although some have yielded ores rich in galena, hematite, and fluorite (George, 1949). Other foreign deposits, probably of this class, include those at Tyuya Muyun, Ferghana, USSR (Pavlenko, 1933; Shimkin, 1949); deposits in the Cuneo-Lurisia district, Italy (Nininger, 1954); and a deposit at Bukhova, Bulgaria (Bain, 1950).

MAGNETITE OR OTHER IRON OXIDE-BEARING VEINS

Several deposits, including the Prince mine in New Mexico (Walker and Osterwald, 1956b), pitchblende deposits near Critchell, Colo., deposits near Peekskill, N.Y. (Walthier, 1955), deposits near Warwick, N.Y. (Engineering and Mining Journal, 1957), and Oxford, N.J., and possibly uraninite or pitchblende deposits in oxidized iron ore of the Iron River Iron-formation Member of the Michigamme Slate in northern Michigan, contain abundant magnetite or hematite or both, but commonly only minor amounts of base-metal sulfide minerals. Gangue minerals commonly are lacking, but minor amounts of recrystallized or altered minerals of the wallrocks occur in some deposits.

Locally, the uranium in these deposits is contemporaneous with and genetically related to the iron-oxide minerals, whereas in other deposits the uranium minerals were deposited in or near fractures or fissures that cut concentrations of magnetite or hematite.

The deposits probably have diverse origins but in general are related to (a) pyrometasomatic replacement of wallrocks by iron-rich minerals, (b) possible redistribution of "syngenetic" uranium during metamorphism of ferruginous sedimentary rocks, or (c) deposition directly from thermal solutions in a favorable, iron-rich environment. The latter possible origin is similar to that postulated for deposits near Schmiedeberg, Germany, by Berg (1936) and Meister (1926).

Tetravalent uranium is present in pitchblende stringers, veinlets, or small pods; in some deposits the uranium is in minute unidentified particles disseminated through the magnetite, possibly as ions substituting for zinc, copper, cadmium, or other ions in the spinel (magnetite) lattice. Near-surface oxidation and alteration of some of these deposits formed abundant hydrated iron oxides and, locally, 6-valent uranium minerals that commonly coat fractures or fill pore spaces.

Most of the deposits are small and contain only a few hundreds or, locally, thousands of tons of mineralized rock commonly averaging a few hundredths of 1 percent uranium. A few deposits, principally those characterized by veins or veinlets of pitchblende, may average a few tenths of 1 percent uranium; but, in general, they contain only a few tons of material of this grade.

VEINS DOMINANTLY OF THORIUM OR RARE-EARTHS MINERALS

Although most concentrations of thorium and rare-earths minerals contain only a few thousandths of 1 percent uranium, several in the United States contain a few hundredths and, locally, tenths of 1 percent uranium. In some, the uranium is combined, probably in solid solution, with thorium and rare earths of the cerium group in a variety of high-temperature, relatively refractory minerals including thorianite, monazite, and allanite. Geometrically, deposits of this type can be classed as veins because the introduced minerals commonly occur in fissures. These deposits are probably of high-temperature, hydrothermal origin in which most of the minerals were emplaced under near-pegmatitic conditions. In other deposits of this class, the uranium is in some unidentified form, possibly either absorbed or adsorbed by hematite, which is a common constituent of the thorium- and rare-earths-bearing veins. The uranium in some deposits of this type possibly was deposited contemporaneously with the hematite and other introduced minerals, but in others it may have been deposited much later in a favorable, iron-rich environment either by hydrothermal solutions or by circulating ground water.

Examples of deposits in this class are known in the Powderhorn district, Colorado (Roger Malan, oral communication, 1955; Wallace and Olson, 1956), San Bernardino County, Calif. (Walker, Lovering, and Stephens, 1956), Johnson County, Tenn., Lemhi County, Idaho (Moen, 1957), and several other widely distributed localities in the western United States. The tonnage of uranium-bearing rock at all the properties is probably small; and, as of 1957, none had yielded commercial ores of thorium, rare earths, or uranium; however, a few do contain several hundreds of tons of vein material with a thorium content of about 1.0 percent.

BRANNERITE-BEARING QUARTZ OR SILICEOUS VEINS

Brannerite, an oxide of titanium, uranium, and calcium with minor yttrium, thorium, and iron, was identified in quartz veins in Chaffee County, Colo. (Adams, 1953), Mono County, Calif. (Pabst, 1954), and in a few deposits elsewhere. Common to veins in the Chaffee County and Mono County areas are minor amounts of muscovite, pyrite, chalcopyrite, and molybdenite. The Colorado deposits contain, in addition, beryl and very small amounts of molybdite, rutile, and fluorite. The California veins contain several silicate minerals and minor magnetite, calcite, and bismuthinite. According to Adams, the veins in Colorado are transitional between pegmatites and hydrothermal veins, and Pabst (1954, p. 109) believes that the California deposits are mesothermal quartz veins "* * * related genetically to nearby pegmatite and aplite * * *."

The brannerite occurs only as a trace constituent in both areas, commonly as sparse euhedral crystals. Nevertheless, commercial deposits may be found in the United States, because potentially exploitable deposits with somewhat similar mineralogy have been reported in the Middle Vosges, France (Geffroy and Lenoble, 1953), and Bou Azzer, French Morocco (Jouravsky, 1952a; 1952b, p. 226–230). Brannerite, associated with molybdenite, chalcopyrite, and small crystals of uraninite, occurs in high-temperature veins in the Vosges (Branche, Chervet, and Guillemin, 1951). In the French Moroccan deposits brannerite occurs in quartz veins associated with molybdenite, chalcopyrite, and native gold. At Bou Azzer, nickel-cobalt-gold veins that cut the brannerite-bearing veins do not contain uranium.

A uranium deposit at Crockers Well, South Australia, may also be a representative of this class. According to King (1954), absite—a new mineral species resembling brannerite and consisting essentially of uranium and titanium, with some thorium and rare earths—is associated with biotite, rutile, apatite, and blue quartz in brecciated Archean rocks.

DAVIDITE-BEARING VEINS

Davidite, an iron-titanium oxide in which rare earths, uranium, thorium, and other cations substitute for iron or titanium, has been found in high-temperature hydrothermal veins at Radium Hill, near Olary, South Australia, and in the Tete district of Mozambique; no comparable deposits are known in the United States. The deposits at Radium Hill and Mozambique have yielded commercial uranium ore.

According to Parkin and Glasson (1954, p. 822), the davidite at Radium Hill "* * * occurs in intimate intergrowth with rutile, ilmenite, hematite, and some magnetite * * *" associated with biotite and quartz in a series of veins cutting Precambrian metasedimentary rocks that were intruded by both mafic and silicic rock types. The veins are probably late-stage replacements in shear and fracture zones and apparently are transitional between hydrothermal veins and pegmatites. Near-surface oxidation of the davidite produced fracture coatings consisting of carnotite, metatorbernite, and other 6-valent uranium minerals containing vanadium (Sprigg, 1954, p. 44). The deposits apparently are in part similar to base-metal sulfide veins, for they contain cobalt, nickel, copper, gold, silver, lead, and zinc (Sprigg, 1954, p. 22) in addition to uranium.

At Mavuzi in the Tete district of Mozambique, a black opaque mineral, considered to be a variety of davidite by Bannister and Horne (1950), occurs in sheared, scapolitized, and carbonatized pre-Karroo (Precambrian) norites and anorthosites (Davidson and Bennett, 1950). Most of the davidite, which is associated with rutile, sphene, magnetite, ilmenite, apatite, and molybdenite, not necessarily in order of abundance, is found in rock facies rich in scapolite and calcite or dolomite. The deposits also contain minor pyrite, pyrrhotite, chalcopyrite, hematite, and large amounts of vein quartz.

HYDROCARBON-RICH URANIUM-BEARING VEINS

Different uranium-bearing hydrocarbons, many of which have been called thucholite, are known from many localities in the conterminous United States and elsewhere; at only a few of these localities are the deposits classed as veins. In a few deposits, principally foreign ones, the uranium-bearing hydrocarbon apparently is the most abundant of the introduced materials, and for this reason a separate class has been established. None of these veins are important sources of uranium ore, however. Most of these veins, either foreign or domestic, are similar to base-metal sulfide deposits principally because much of the uraniferous hydrocarbon is closely associated with pitchblende, sulfides of iron, copper, lead, and zinc, and locally with minerals containing silver, cobalt, nickel, and molybdenum. Gangue minerals, including calcite, quartz, barite, and chlorite, also are common.

The uranium in these deposits is contained in pitchblende, coffinite, 6-valent uranium minerals, and possibly as organouranium complexes; some of the pitchblende is in minute particles disseminated in the hydrocarbon. The uranium content of the hydrocarbons is different in different places; locally, selected specimens contain several percent uranium (Davidson and Bowie, 1951; V. R. Wilmarth and R. C. Vickers, written communication, 1952), but the quantity of material of this grade is apparently small.

Best known among domestic deposits of this class are those near Placerville, San Miguel County, Colo., in which uranium-bearing hydrocarbons are associated with base-metal sulfide minerals and locally some pitchblende, molybdite, erythrite, and annabergite in a gangue of calcite, barite, and quartz (Wilmarth and Vickers, written communication, 1952). The deposits are along faults cutting sedimentary rocks, principally sandstone and conglomerate, of the Cutler and Dolores formations and, according to V. R. Wilmarth and R. C. Vickers (written communication, 1952), Kerr and others (1951, p. 25), and J. W. Gruner and Lynn Gardiner (written communication, 1950), are probably hydrothermal in origin.

Small amounts of uranium-bearing hydrocarbons are widespread in mesothermal veins in the Lake Athabasca area, Saskatchewan, Canada (Robinson, 1955, p. 69; Lang, 1952, p. 80, 91, 93, 96). Uraniferous bitumen, apparently in veins, also has been reported associated with chalcopyrite in the Laxey lead-zinc mine on the Isle of Man, Great Britain (Davidson and Bowie, 1951, p. 2), at the Moonta bornite mine near Adelaide, South Australia (Davidson and Bowie, 1951, p. 2), in Russia (Orlov, 1932), and elsewhere.

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*

[Mineralogic classes: 1, fluorite-bearing veins; 2, base-metal sulfide veins; 3, veins dominantly of uranium minerals, but which may contain minor amounts of other introduced metallic minerals; 4, magnetite or other iron oxide-bearing veins; 5, veins dominantly of thorium or rare-earths minerals; 6, brannerite-bearing quartz or siliceous veins; 7, davidite-bearing veins (not known to occur in the United States); 8, hydrocarbon-rich uranium bearing veins. Production classes: A, 1,000 tons or more; B, 100 to 1,000 tons; C, less than 100 tons; D, some reported production; amount unknown; all others, no ore shipped]

Number on pl. 1	Name	Mineralogic class	Production
	Arizona		
	Apache County		
1	Garnet Ridge (Bluestone) deposit	2?	C
	Coconino County		
2	Grand View mine	2?	
3	Orphan Lode (mine)	2	A
4	Boranca de Cobra	2	
5	Ridenour mine	3?	?
	Mohave County		
6	Hack Canyon claim	2	A
7	Copper Mountain claim	2	
	Copper House 1	2	
	Copper House Coalition	2	
8	Chapel claim	3	C
9	Corley, Lind, and Ellington mine.	2	
10	De la Fontaine	2	
11	Bobtail mine	2	
	Detroit group	2	
	Frontier group	2	
	Jim Kane mine	2	
	J. C. and Fort Lee claims	2	
	Prosperity claim	2	
12	Big Ledge prospect	2	
13	Democrat mine	2	
14	Uranium Basin claims	5	
15	White Owl group	5	
16	State mine	3	
17	Lucky Four property	3	
	Red Hills (Tate) prospect	1	
	Yavapai County		
18	Hillside mine	2	
	Kitten 1	3	
	Seven Stars	?	C
19	Cardinal	3	
20	Uranus group	1?	
	Mizpah	1?	
21	Abe Lincoln mine	2	
	Denver group	2?	
22	Ford claim	3	
23	Fairview group	5	
24	Willbank property	?	
	Black Donkey group	3	
25	Golden Duck group	3	
	Maricopa County		
26	Arrowhead group	3	
	Faith in You group	3	
27	Copper Kid group	3	
	Cottonwood claims	3	
28	Manley and Bickle groups	1	C
29	Lucky Find group	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Arizona—Continued		
	Gila County		
30	Trek claims	3	D
31	Blevens Canyon group	2	D
	Black Brush (adit) group	3	
	Definitely group	3	
	Donna Lee claims	3	
	Fairview group	3	
	Heigh Power group	2	
	Hope mine	2	A?
	Little Joe claims	3	
	Lucky Stop	2?	B
	Melinda-Lost Dos	?	B
	Rainbow deposit	3	
	Red Bluff claim (prospect, mine).	3	A
	Suckerite group	3?	
	Sue claims	3?	B
	Workman (deposit) claim	3?	B
32	Shepp 2 claim	3?	
33	Ash Creek property	?	
34	Tomato Juice deposit	3	
35	Bronx Copper 6	2	
	Red Hill and Castle Dome	2	
36	Copper City	2	
37	Black Hawk	2	
38	Lucky Boy group	3	
	Graham County		
39	Cactus 1	3	
40	Goldondrina claim	2	
	Pinal County		
41	Waterfall claims	3	
42	Honey Bee claims	2?	
	Shorty group	4?	
	Wooley 1	2	
43	Name Unknown	2	
44	Red Dog group	3?	
45	Mineral Butte group	2?	
	Yuma County		
46	Bonanza mine	2	
47	Rayvern group	3	
48	State lease	5	
	Topaz claims	5	
	Name unknown	5	
	Name unknown	3?	
49	Red Knob claims	3	
50	Wooley group	3	
51	McMillan prospect	3?	
	Pima County		
52	Linda Lee (prospect) claims	4	
53	Sure Fire claim 1	1?	
54	King mine	2?	
55	New Years Eve mine	2	
56	Diamond Head group	2	
	Escondida claims	2	
	Glen claims	3?	
	Leadville group	2?	
	Lena 1	2	
	San Juan 1 and 2	2	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Arizona—Continued		
	Pima County—Continued		
57	Black Dyke	2	
58	Papago Chief mine	2	
59	St. Joe prospect	3	
60	Iris and Natalia property	2	
	Santa Cruz County		
61	Grand View group	2	
	Little Doe	2	
	Lone Star 1	3	
62	Santa Clara claim	3	C
	Annie Laurie prospect	2	
63	"Spelbrink" claim	2	
64	Silver mine claim	3	
	White Oaks mine	2	C
65	Alto mine	3	
	Bowling Green group	2	
66	Lucky Spur group	2	
67	Duranium claim	2?	
	Cochise County		
68	Redfield claims	3	
69	Valley View	2	
70	Uranium Hill claims	1	
71	Elanna	3?	
72	First Chance	1?	
	"Howard" claim	3	
	Name unknown	1	
	Bisbee district		
73	Campbell-Briggs mine	2	
	Campbell-Denn mine	2	
	Coal mine	2	
	Irish Mag mine	2	
	Judea claim	2	
	Junction mine	2	
	Oregon ore body	2	
74	Walnut mine	2	
	California		
	Lassen County		
1	Lola G	3	
	Noma J	3	
2	Buckhorn group	3	(See Nevada)
3	Black Jack 1 and 2	3	
4	Madonna Mia	2	
	Plumas County		
5	Guidice mine	2	
	Perry Jones claims	2?	
	Name unknown	3	
	Nevada County		
6	Green Boy claims	1	
	Truckee Canyon group	2	
	Calaveras County		
7	Rathgeb mine	2	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	California—Continued		
	Tuolumne County		
8	Name unknown	3	
9	Juniper claim	3	
	Mono County		
10	Name unknown	6	
11	CB group	3	
12	Margaret Bryant claims	3	
13	San Antonio claim	3	
14	Claw group	?	
15	Wild Bill (Banner or Dog) group	2	
	San Benito County		
16	Pinnacles National Monument	3	
	Monterey County		
17	Arajo property	3	
	San Luis Obispo County		
18	Bethel 1	3	
19	Wakefield	3	
20	Hillbilly 10	3	
	Tulare County		
21	Tomlee	?	
22	Jay Bird 1	3	
23	Los Tres Burros 1	3?	
	Inyo County		
24	Bonanza mine	3	
25	Scintiscope	?	
26	Big Horn property	3?	
27	Thunderhead	3	
28	Golden Nugget claim	2?	
29	Linda Sue group	3	
	Ontario Minerals property	2?	
30	Spit Fire claims	2	
31	Big Horn group	2?	
	Kern County		
32	Chilson (Uranus) claim	3	D
	Summit Diggings	3	
33	Kervin	3	
	Lucky Seven	3	
34	Monitor group	3	
35	Buckeye group	3	
	Kergon mine	1?	C
	Little Sparkler	3	
	Lucky Sparkler	3	
	Miracle mine	3	C
	Monte Cristo	3	
36	Big 4 No. 1	2?	
37	Four Horsemen claims	3	
38	Surprise 1 claim	3	
	High Hat claim	3	
	Tres Amigo	3	
39	Gasko 5	3	
	Red Cap	3	
40	S and W group	1?	
41	Donovan claim	3	C?

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	California—Continued		
	Kern County—Continued		
41	Jumpin claim	3	
	Rosamond Uranium prospect	3	
	"School Section"	3	
	Stillwell property	3	
42	Silver Lady claims	2	
43	Nob Hill	3	C
	Los Angeles County		
44	Good property	3?	
	Turtle group	3	
45	Lookout Lode claim	2	
46	Rafferty property	3	
	San Bernardino County		
47	Harvard Hills	3	
48	Lucky Belle group	2	
49	Paymaster mine	2	
50	Jeep 2 claim	2	
51	Mountain Pass deposits	5	
52	Brooke Molybdenite	2?	
	Big Hunch claim	2?	
53	Red Devil claim	2	
54	Hoping 1 claim	1?	
55	Copper Mountain Uranium claims.	5	
56	Black Dog claim	5	
57	Thum Bum claim	3	C
58	Yerih group	2	
	Riverside County		
59	Ram group	2?	
	Name Unknown	3	
60	Bald Eagle group	2	
61	North East 1 claim	3	C?
	Imperial County		
62	Lady Katie group	3	C?
63	Brazero Negro group	3	
64	Lucky Star	3	
65	Black Hawk	2	
	Colorado		
	Larimer County		
1	Copper King (Black Hawk, Cherokee) mine.	2	B
2	Batterson property	?	
	Revis claim	2	
	Twenty Plus claim	3	
	Uranium Queen	?	
3	Crystal Mountain 1	?	
	Eureka group	3	
	Name unknown	?	
4	Name unknown	?	
	Jackson County		
5	Fred Brands ranch	?	
6	James Bird	?	
	Pedad claims (prospect)	1	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Colorado—Continued		
	Routt County		
7	Hahn's Peak	?	
8	Willow Creek claims	3	
9	Dead Horse claims	3	
10	Fair-U	3	
11	Mical	?	
	Moffat County		
12	Bob Cat group	3	
13	Claim 1	3	C?
	Leon	?	
	Margie (Marge)	3	D
	Sugar Loaf (Sugarloaf?) claim 1.	2	D
	Cedar Mining group	3	
	Name unknown	3	
14	September Morn claims	3?	
15	Skull Creek	3?	
	Grand County		
16	Beaver Creek	?	
	Lucky Jack	?	C
17	Phillips 1	?	
18	No names claims	3	
	Boulder County		
19	Argo mine	1	
20	Bell group	2	
	Black Cloud	2	
	Blue Jay mine	1	
	Brown Spar mine	1	
	Caribou mine	2	C
	Chancellor mine	1	
	Diamond group	3	
	Emmett mine	1	
	Gibson	?	
	Goldsmith Maid	2	
	Great Northern Silver mine	2	
	Lady Bug	?	
	Lehman Lode	1	
	Lucky Lode	?	
	Lulu B	?	D?
	Marc 1	?	
	Miller group	3	C
	Miranda A. Johnson Lode	3	
	Nations Treasure mine	1	
	No Sopi	?	
	Orion mine	1	
	Poorman mine	1	
	Rose Mary mine	?	
	Gilpin County		
21	Alps mine	2	
	Bezant	?	
	Bonanza mine	2	C
	Buckley mine	2	
	Bullion	2	
	Calhoun	2	C
	California mine	2	
	Carroll mine	2	C
	Cherokee mine	2	D
	Claire Marie mine	2	
	Diamond group	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Colorado—Continued		
	Gilpin County—Continued		
21	East Calhoun	2	C
	Elliott mine (Wealthy Lode)	2	
	Essex mine	?	
	Flack 3 mine	2	
	German (and Belcher) mine(s)	2	C
	Golden Anchor	?	
	Golden Chief mines	?	
	Iron mine	?	
	J. P. Whitney	?	
	Kirk (Richards?) mine	2	B
	Leavenworth	?	
	Mitchell	?	
	Perigo	?	
	Pewabik	?	
	Priscilla	?	
	Rara Avis	2	
	R.H.D. claim (McKay shaft)	2	
	Spread Eagle mine	2	
	Telegraph mine	2	
	Tippecanoe	?	
	Two Sisters (mine) claim	2	C
	Wood (Richards?) mine (vein)	2	B
	Wyandotte	2	
	Clear Creek County		
22	Albro	2	
	Almadin (Blazing Star) mine	2	
	American Sisters	?	
	Argo	2	
	Ariadine	3	
	Baltic Tunnel	2	
	Belle Creole	2	
	Belle of the West	2	
	Bellevue-Rochester mine	2	
	Big Chief	2	
	Bonus	?	
	Brazil	2	
	Crazy Girl	2	
	Diamond Joe	2	
	Diamond Mountain (Alpine) mine.	2	
	Dixie	2	
	Eclipse	2	
	Ella McKinney	3	
	Goldconda mine	2	
	Gold Bar mines	3	
	Golden Calf	2	
	Golden Chloride	3	
	Golden Glen	3	
	Gomer	2	
	Harrisburg	2	
	Jo Reynolds mine	2	C
	Keiper	?	
	Kitty Emmet	3	
	Lamartine tunnel	2	
	Little Johnnie	?	
	Lone Star	?	B
	Lone Tree	3	
	Martha E. (mine) claim	2	C
	Mary Foster Humbolt	3	
	Mary Tunnel	2	
	Miller	2	
	Muscovite	3	
	Name unknown	2	
	Name unknown	2	
	Old Settler shaft	2	
	Polar Star mine	2	
	Poorman	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Colorado—Continued		
	Clear Creek County—Cont.		
22	Robineau claims	3?	
	Spanish Bar	2	
	Stanley mines	2	
	Sunnyside Tunnel	2	
	Tolland County Tunnel	2	
	Urad mine	2	
	Jefferson County		
23	Bankers Lode	?	
	Ladwig lease	3?	A
	Name unknown	3?	
	Name unknown	3	
	Nigger Shaft (Hoffmeister property, Mena mine deposit).	3?	B
	North Star mine	3?	
	Schwartzwalder (Ralston Creek) mine.	3	A
	White prospect	2	
24	Leyden (coal mine	3	B
25	Appel lease	3	
	Ascension mine	3	B
	Buckman adit	2?	
	F.M.D. mine	2?	
	Gary mine	3	D
	Golden Gate Canyon claims	2	
	Grapevine property	4?	
	Halfmile gulch	8	
	Ladwig group	3?	
	Mann mine	3	D
	Morrison (Pallaoro, Four Corners) deposit.	3	B
	Union Pacific (deposit) prospect.	3	
	Vanadium Queen	3	
	Wright lease (Foothills uranium, Idledale).	3?	
	Yellow Queen (Nare)	3	
26	Bonzo 1	3	
	Billiken lode	3?	
	Name unknown	4?	
	Quayle prospect	?	
	Park County		
27	Redskin (mine) claim	2	
	Shamrock-Irish group	2?	
28	Shirley May mine	3?	B
29	Champaign fissure	3	
	Kentucky Bell adit	3?	
	London Extension mine	2	
	Orphan Boy	2?	
	South London mine	2	
	Lake County		
30	Climax mine	6	
31	Griffin vein zone	3	
	Josie May	2	
	President mine	2?	
	Turquoise Chief	2	
	Wilkesbarre mine	3?	
32	Name unknown	3?	
	St. Kevin mine	2	
	Eagle County		
33	Eagle claim	?	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Colorado—Continued		
	Pitkin County		
34	Smuggler mine	2	
	Gunnison County		
35	Matchless group	2	
36	Roberts prospect	5	
	Lady-in-Red prospect	5	
37	Silent Friend mine	2	
	Chaffee County		
38	Madonna mine	2	
39	Swiss Boy mine	2	
40	California mine	6	
41	Little Jimmie prospect	2	
42	Lucky John 2	5	
	Lucky Break placer	4	
	Saguache County		
43	Storey (La Rue?) claims	3	C
44	Los Ochos (Thornburg) mine	3	A
45	Anna claim	4	
46	Brinkerhoff	3	C
	Vulcan claims	3	C?
	Erie group	3	D
	Little Indian group	3	B?
47	Bonite 2	3	
48	Whale mine	2	
	Name unknown	2	
49	I. Kreiner property	3?	
	Fremont County		
50	Lightning 2	3	
51	A. Griffin ranch	2	
52	Mary L claim	3	C?
53	Colexco property	3	
	Teller County		
	Lady Stith	1	
	El Paso County		
55	Duffields property	1	
56	Mike Doyle (Lucky Ben lease).	3	C
	Custer County		
57	Watter's ranch	5	C
	Hinsdale County		
58	Rio Grande claims	3	
	Ouray County		
59	Pony Express mine	?	
60	Bear Creek falls	3?	
	Larson Property	2	
	Michael Breen	2?	
	Name unknown	2	
	National Bell	2	
	Southwest Metals	2	
	Yankee Girl mine	2	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Colorado—Continued		
	San Juan County		
61	Koehler Tunnel	2	
62	Surprise claim	3	
	San Miguel County		
63	Barbara Joe	8	
	Black King (prospect) group (Weatherly property).	8	
	New Discovery	8	
	Robinson property (White Spar).	8	
64	Bald Eagle mines	3	
	Early Morn	3?	B
	Morning Glory	3	
65	Spaniard 1	3	
	Montrose County		
66	Cashin (copper) mine	2	
67	Rajah (Copper Prince) mine	3	A?
	Huerfano County		
68	Name unknown	3	?
69	Stumbling Stud	1	
	La Plata County		
70	Tomahawk group	2	
	Georgia		
	Dekalb County		
1	Stone Mountain deposit	3	
	Idaho		
	Boundary County		
1	Golden Sceptre	5	
2	Name unknown	3?	
	Bonner County		
3	Hottentot group	3	
	Shoshone County		
4	Bunker Hill mine	2	
	Coeur d'Alene mine	2	
	Cresent mine	2	
	Galena mine	2	
	Page mine	2	
	Silver Bell mine	2	
	Sunshine mine	2	
	Latah County		
5	Muscovite mine	3	
	Lemhi County		
6	Surprise claims	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Idaho—Continued		
	Lemhi County—Continued		
6	Moon mine	3?	
7	Garm Lamoreaux (deposit) mine.	2	
8	Donna Lou 1	3	D?
	McConnell-Sargent claims	3?	D
	Name unknown	3	D?
9	Wonder Lode mine	5	
	Valley County		
10	Howdy Doody claim	2?	
	Custer County		
11	Little Bill	1?	D
12	Bell Cross claim	2	
13	Empire mine	2	
	Clark County		
14	First Discovery claim	3?	
	Elkhorn group	3	
	Blaine County		
15	Black Cinder	2?	
	Camas mine	2	
	Hardee (Golden Star)	2	
	Hattie group	2	
	Rustler group	2	?
	Camas County		
16	Five Point mine	2	
	Oneida County		
17	Curley Jack	2	
	Michigan		
	Baraga County		
1	Huron River deposit	2	
2	Graphite quarry	3	
	Iron County		
3	Sherwood mine	4?	
	Dickinson County		
4	Isham claims	4	
	Marquette County		
5	M and G property	?	
6	Francis mine	2	
7	Buck (and Cardiff) mine	2?	
	Montana		
	Lincoln County		
1	Oro property	2	
	Montana—Continued		
	Mineral County		
2	Waterhole 8	3	
3	Keith property	2	
	Powell County		
4	Lilly group	2	
	Sure Thing group	2	
	Lewis and Clarke County		
5	Bridgett-Braligan property	2	
	Name unknown	2	
6	Bunker Hill mine	2?	
	Jefferson County		
7	Hinman prospect	3	
	King Solomon Ridge group:		
	Black Magic	3	
	Blue Monday	3	
	Fortyniner	3	
	Liverpool mine	2	
	President group:		
	A. Lincoln	3	
	Harry S.	3	
	G. Washington	3	
	W. Wilson mine	3	B
8	Lone Eagle (mine, claim) deposit.	2	C
9	Josephine mine	2	
	Seven Consolidated Gold Mines, Inc.	3	
10	Atomizer claim	3	
	Redstone claim	3	
	Beaverton Ranch	3	
11	Comet mine	2	
	Gift mine	2	
	Gray Eagle mine	2	
	Hattie Ferguson	2	
	Sylvan mine	2	
12	Comstock claims	2	
	Free Enterprise mine	3	B
	May Day Four group	3	
	Nickelodeon claim	2	
	Silver Bell (Haynes?)	?	
	Uranium claim	2	
13	Jack	2	
14	Golden Sunlight group	3	
	Silver Bow County		
15	Mooney claim	2	
16	Carnotite claims	3?	
	Ravalli County		
17	Little Joe prospect	3	
	Beaverhead County		
18	Trapper 1 and 4 claims	5	
19	Iola	2	
	Madison County		
20	R. and M. claims	3?	
	Uranium claims	3	
21	Braunzell and Eby prospect	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Montana—Continued		
	Park County		
22	Ray and Al Rudd property	5?	
	Carbon County		
23	Weaver prospect	3?	
24	Royse property	3	
25	Windmill	3	
26	Drinkard	3	D
	George Guaye and Assoc	3	C
	Perc group	3	
	Pryland Company	3	C?
	Pryor Mining Co. property	3	D
	Teton Exploration Co. property.	3	
27	Buckhorn 1	3	
	Nebraska		
	Sheridan County		
1	Craig lease	3?	
	Nevada		
	Elko County		
1	Southam claims	5	
2	Garnet Tungsten mine	2	
3	Autunite group	3	
	Big Joe 1	?	C?
	Happy Joe	3	
	October group	3	
	Tag claims	3	
	Humboldt County		
4	Getchell mine	2	
5	Granite Point claims	3?	
	Moonlight (group) mine	1	B
6	Copper King group	2?	
	Morning Star group	2?	
	Wedding Ring group	2?	
7	Blue Jack	2	
	Pershing County		
8	Majuba Hill	2	
9	Stalin's Present	3?	
10	Long lease	2?	
11	Lucky Day group	3	
	Two Chuckers claim	3	
	Washoe County		
12	Lost Partner group	3	D?
13	Armstrong claim	3	D?
	Bing group	3	
	Lowary claims	3?	
14	Tick Canyon	3	
15	Black Hawk claims	3?	
16	Buckhorn (mine) claims	3	B
17	O'Blarney claims	3	
18	Good Luck claims	3?	
	Ormsby County		
19	8 Spot group	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Nevada—Continued		
	Churchill County		
20	Liverpool mine	2	
21	Chalk Mountain mine	2	
22	Lovelock and Nickel mines	2	
	Lander County		
23	Pinto-Hart claims	3	
24	Early Day (mine) claims	3	B
	Eldorado claims	3	
25	Low Boy claims	3	
	Douglas County		
26	Julietta	3	
	Lyon County		
27	Boerlin ranch	?	
	Far West Willys group	2	
	Northwest Willys group	2	
	West Willys group	2	
28	Silver Pick	?	
	Mineral County		
29	Wespac group (Carol R)	3	B
30	Cinderella	2	
	Lucky Horseshoe	3	
	Silver Bell group	3	
	Silver State claims	3	
	Esmeralda County		
31	Rich and Rare	3	
	Silver Queen group	3?	
32	Coaldale	3	
	Phillips and Wentlandt	3	
	Quinseck	3	
33	Jet claims	3	
34	Checkmate 1	3	
	Nye County		
35	Nyemin group	3	
36	Henebergh (Rainbow) tunnel (claims).	3	
	Green Top claim	2	
37	Nighthawk group	3	
38	Blue Bird 1	3	
39	Roberts claims	3	
	Currant claims	3	
40	Thor group	3	
41	First Strike	3	
42	Shoe-shoe mine	2	
43	Black Bart extension	3	
	National Bank group	3	
	Lincoln County		
44	Atlanta mine	2	
45	Blue Bird mine	3	B?
	Nevada Rath group	3	
46	Name unknown	3	
	Clark County		
47	Golden Glow claim	3	?
	Carnotite Lode claim	3	?
48	Big Horn claims	3?	
49	Name unknown	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Nevada—Continued		
	Clark County—Continued		
50	Name unknown	3	
51	Desert Valley prospect	2	
	Green Monster mine	2	C
52	Copper Flower Quartz mine	2	
	Singer mine	2	
	New Jersey		
	Passaic County		
1	Ringwood mine	4	
	Morris County		
2	Name unknown	2	
	Warren County		
3	Rock Products Co. quarry	3	
	Hunterdon County		
4	M. C. Mulligan and Sons quarry.	3	
5	Stockton deposit	3	
	New Mexico		
	Colfax County		
1	Blasted Pine claims	5?	
	Rio Arriba County		
2	Tusas Mountain prospect	3?	?
	Moran-Sawyer-McLind prospect.	3	
	Teggs East Slope 5	3	C
3	Anomaly property	?	
	San Juan County		
4	Tyler claim	3	?
	Valencia County		
5	Name unknown	1	
6	Woodrow "pipe" property (Woodrow mine).	3	D
	San Miguel County		
7	Name unknown	4	
	Sante Fe County		
8	La Bajada mine	2	D
	Hiser-Moore 1	3	
	Sandoval County		
9	Mimi 4	3	
	Minn 4	3	
	Bernalillo County		
10	White-Lovelace claims	3	
	New Mexico—Continued		
	Torrance County		
11	Thomas and Melbourn	?	
	Socorro County		
12	Sevilleta grant	3	
	Name unknown	2	
13	Jeeter-Wright-Paye mine	3	
	Charles group	3	
	San Acacia mine	2	
14	Holly Uranium Co. claims	3	D
	Lincoln County		
15	Prince mine	4	
16	Barlejon 2 claim	5	
17	Silvertone claim	4?	
	Sierra County		
18	Hanosh mines property	1	
	Pitchblende Strike (claims) prospect.	1	
	Terry prospect	1	
19	Empire group	2?	
	Plainview prospect	2?	
	Catron County		
20	Baby mine	1	
	Grant County		
21	Purple Rock mine	1	
22	Prince Albert 1 claim	3?	
23	Alhambra mine	2	
	Black Hawk mine	2	
24	Acme claim	3?	
	Apache Trail deposit	3?	
	Arrowhead claim	3	
	Blue Jay	3	
	California claim	3	
	Floyd Collins claim	3	
	Inez (7-X-V ranch) claim	3	B
	Merry Widow mine (claim)	2	
	Name unknown	3	
	Shamrock claim	3	
25	Langford	1	
26	Hines 1	1	
	Luna County		
27	Name unknown	1	
28	High Hope group	2	
	Hidalgo County		
29	Name unknown	3	
30	Boles prospect	3	
	Dona Ana County		
31	Unknown	1	
	Unknown	1	
	Eddy County		
32	Rocky Arroyo area	8	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineral-ogic class	Production
	New York		
	St. Lawrence County		
1	Name unknown	4	
	Dutchess County		
2	Clove mine	3?	
	Putnam County		
3	Phillips mine	4?	
	Orange County		
4	Name unknown	2	
5	Clove mine	4	
6	Ramapo Uranium Corp. property	4	D
	North Carolina		
	Avery County		
1	Harper Creek prospect	3	
	Lost Cove Creek deposit	3	
	Name unknown	2	
	Name unknown	3	
	Oklahoma		
	Caddo County		
1	Lester-Mills property	3	C
	Cement (Okla.) deposit		
	Oregon		
	Union County		
1	Name unknown	2	
	Crook County		
2	Sage Hollow	3?	
	Jackson County		
3	Board Mountain group	3	
	Canyon Creek group	3	
	Lake County		
4	White King mine	3?	A?
	Lucky Lass	3	B
	Marty K	3	
	Name unknown	3	
	Name unknown	3?	
	Name unknown	3?	
	Harney County		
5	Alex-Ladd property	3	
	Name unknown	3	
	Pike Creek Carnotite claim	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineral-ogic class	Production
	Pennsylvania		
	Northampton County		
1	Williams quarry	3	
	Berks County		
2	Rohrback prospect	4	
	South Dakota		
	Harding County		
1	C. Robbins lease	3	
2	Square Top Butte	3	
3	Buck Horn 4	3	
	Cedar Canyon deposit	3	?
	Lawrence County		
4	Annie Creek	3	
	Budzynski prospect	3	
	Dakota mine	2	
	Dark Horse claim	?	
	Gen. Grant	?	
	Green Point	?	
	Hays group	?	
	Margaret	?	
	Mikado claim	?	
	Mill Lode (?Montezuma claim).	3	C
	New Reliance mine	3	
	Revival	?	
	Ross Hanibal mine	?	
	Silver Spring	?	
	Stanley	?	C
	Twilight	?	
	Name unknown	3	
	Pennington County		
5	Dakota	?	D
	Grizzley Creek	?	
	Harney 2	?	
	Kool claim	3	C?
6	Name unknown	?	
	Custer County		
7	Elkhorn 1	3	
	Tennessee		
	Carter County		
1	Walnut Mountain deposit	5	
	Row Brand	2?	
	Name unknown	5	
	Texas		
	Hudspeth County		
1	Bonanza mine	2	
2	Rossman prospect	2	
	Name unknown	3?	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Texas—Continued		
	Presidio County		
3	Morgan prospect	3	
	Brewster County		
4	Big Bend Exploration Co	3	
5	Adobe Walls Mountain property.	1	
6	Stillwell Ranch property	3	
	San Saba County		
7	Egger property	3?	
	Burnet County		
8	Rainbow prospect	3?	
	Karnes County		
9	Minnie and W. R. Hoffman property.	3	
	Duval County		
10	Wiederkehr property	3	
11	Piedras Pintas salt dome	3	
	Palangana salt dome	3?	
	Utah		
	Daggett County		
1	Yellow Canary claims	3	
	Weber County		
2	Kathy Ann claim	3?	
	Salt Lake County		
3	North Bingham mine	3?	
	Tooele County		
4	Silver King (claims) prospect	2?	
	Juab County		
5	Erickson district	1	
6	Orin Porter Rockwell	2	
7	Autunite 8	1	
8	Bell Hill (property) mine	1	C
	Blowout property	1	
	Dell (claim) group	1	
	Eagle Rock claim	1	C
	Floride (Original Spor) mine	1	
	Fluorine Queen 4	1	
	Fluorite group	1	
	Harrisite property	1	
	Lost Sheep property	1	
	Lucky Louie pipe	1	
	Thursday property	1	
9	Bell group	1	
	Honeycomb group	1	
	Honeycomb Hills	1	
	Spider group	1	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Utah—Continued		
	Uintah County		
10	Jensen Draw prospect	3	
11	Blanca 1	3	
	Sevier County		
12	Tiger Eye 1	3	
13	Better Be	3	
	La Veta prospect	3	
14	Mt. Terrel group	3	
	Emery County		
15	Helm claims	8?	
16	Little Joe prospect	8	
17	Fumerole mine	8	D
	Lopez mine	8	D
	Name unknown	3	?
	Grand County		
18	Cobalt 1	2	
19	Parco 23	3	
20	Red Head group	3?	B
21	Atomic King	3	B?
22	You-All claims	2?	
	Wayne County		
23	Copper Queen	2	
24	Name unknown	2?	
	Piute County		
25	Marysvale district:		
	Benny K 1	3	?
	Buddy (Sunnyside) mine	1	A
	"Buddy Winze" vein		
	Bullion Monarch (Farmer John) mine.	1	A
	Dark Horse claim	3	
	Dreamer group	?	
	E. Slope Uranium claims	3	C
	Flat Tire	1?	C
	Freedom (group) 2 mine	1	A
	Glenny-Cutler	?	
	J. and L. Alunite mine	3?	
	North Star claims	3?	
	Papsy's Hope 1 and 2	3	
	Potts Fraction mine	1	A
	Prospector (group) mine	1	A
	Saturday claims	3?	
	Seegmiller mine	1	D
	Yellow Canary (deposit) Prospect.	3	
26	Great Western mine	2	
	Shamrock mine	2	
27	Deer trail	2	
28	Nucular Sniffer 1	3	
	Beaver County		
29	Beehive	3	?
	Little Sisters group	3	C
	Mystery group	1	C
	Sniffer group	1	
30	Canary group	3	D
	U-Beva	1	D

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineral-ogic class	Production
	Utah—Continued		
31	Old Hickory-Amelias Summit-Gothland mines.	4	
32	Horn-Silver-King David	2	
33	Surprise claims	3	
34	Kay claims	3?	
35	Staats Fluorspar mine	1	B?
	Eureka and Monarch claims	1	D
36	Commissary	?	
	Iron (Washington?) County		
37	Epsolon	3	B
	Garfield County		
38	Name unknown	1	
	Kane County		
39	Radiant claims	3?	C
	San Juan County		
40	Red Mesa Copper Pit	?	
	Vermont		
	Lamoille County		
1	Udall mine	2	
	Washington		
	Pend Oreille County		
1	Silver Dollar claims	3	
	Spokane County		
2	Curtin property	3	
	Ingram lease	3	
	Lehmbecker property (North Star Uranium).	3	D
	Name unknown	3	
	Sprague property	3	
	Van Magen property	3	
3	Daybreak mine (Dahl Ranch)	3	A
	Schaefer lease	3	
	Willard Toner property	3	
	Stevens County		
4	Big Smoke Uranium property	3	
	Deer Mountain deposit	3	
	Lowley lease	3	
	Midnite (Dawn, Midnight?) mine.	3	A
5	Harp property	3	
	Ferry County		
6	Box Canyon claim	?	
7	Fathers Day claims	3	
8	H. and R. claims	3	
	Lucky Leslie	3	
	Lucky Monday claims	3	

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineral-ogic class	Production
	Washington—Continued		
9	Porcupine 2 claim	3	
10	Albion 1 claim	3	
	Snohomish County		
11	Dewey claim	2	
	King County		
12	Quartz Creek mine	6	
	Western States Copper Corp. mine?	6	
	Chelan County		
13	Holden mine	2	
14	Keefer Bros. claims	2	
	Lincoln County		
15	Spokane Molybdenum mine	2	
	Wyoming		
	Big Horn County		
1	Horseshoe group	3	
	Saunders	3	C?
	Smits-Pouleson	3	
2	West Big Horn 1	3?	
	Western Big Horn group	3	
3	Fuesner mine	3	A?
	Name unknown	3	
4	Big Hill group	?	
	Crook County		
5	Bear Lodge manganese deposit(s).	5?	
	Black Rock	?	
	Climax group	5	
	Home Fire group	1	
	Inum group	5	
	Old Clur Lode	1	
	Sunrise Lode	5?	
6	Apex	3?	D
	Johnson County		
7	Ramsbottom prospect	5	
8	Name unknown	?	
	Sublette County		
9	Long Shot 1	?	?
	Fremont County		
10	Long Shot 4	3	
11	Whiskey Mountain	?	
12	De Pass mine	2	
	Discovery 1	3?	D
	Fuller 2	?	D
	Hesitation	3	C
	"Old Copper" mine	2	
	Short Cut 1	?	
13	John claim	3	D
14	Ring	3?	D
15	Hazel (mine) 3	3	D

TABLE 1.—*List of uranium-bearing vein deposits in the conterminous United States*—Continued

Number on pl. 1	Name	Mineralogic class	Production
	Wyoming—Continued		
	Converse County		
16	Trail Creek mine	2?	C
17	Lucky Ann 3 claim	3	C
	Mickey 1 claim	3	
18	Name unknown	3	
	Niobrara County		
19	Old Rocky claims	?	
20	Silver Cliff mine	2	B
21	Potten lease	3	
	Goshen County		
22	Copper Belt mines	2	
23	Old Chicago	?	
24	Green Hope	?	
	Name unknown	?	
	Name unknown	?	
	Albany County		
25	Diamond Bell	?	
	Maggie Murphy	?	
26	Albany 1	4?	C
	Carbon County		
27	Jim claim	3	
	Jem claim	?	
28	Bug claim	?	
29	Omega	?	
30	Becky Lynn	?	
	Doozle 3	?	
31	Hard Head	?	
32	Little Man mine	2?	C
33	Doane-Rambler mine	3	

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Age of Uranium-Bearing Veins in the Conterminous United States

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By George W. Walker

ABSTRACT

Isotopic age determinations as well as geological interpretations related to age of host rocks and confining structures indicate that the dominant age of uranium mineralization in veins in the conterminous United States is Late Cretaceous or Tertiary. Deposits of this age are widely distributed throughout the western United States and include virtually all the veins from which significant amounts of uranium ore have been produced or which contain large ore reserves. Other periods of uranium mineralization in veins in the conterminous United States are Precambrian, Paleozoic, and possibly Mesozoic in age.

Dominant periods of uranium mineralization in other parts of the world seem to be mainly Precambrian or Paleozoic in age.

INTRODUCTION

Uranium-bearing veins in the conterminous United States are dominantly Late Cretaceous or Tertiary in age, but some are Precambrian, Paleozoic, and possibly early Mesozoic; a few veins may even have formed during Quaternary time. Most age estimates are based on geologic interpretations related to age of host rocks and confining structures, and presumably some ages are based on analogies with periods of mineralization of other metals in the same districts or regions. Calculations based on isotope ratios in uranium minerals or other minerals that occur either in the veins themselves or in the enclosing rocks have been used to estimate the age of uranium mineralization in some deposits.

In reviewing the age of uranium-bearing veins, the geologic literature dealing with isotope age determinations made on materials from or related to veins in the United States has been carefully, but not exhaustively, searched.

The principles of isotopic age determinations have been presented and discussed in many papers (Nier, 1939; Stieff, Stern, and Milkey, 1953; Faul, 1954; Kulp, Broecker, and Eckelmann, 1953; Kulp, 1955; Stieff and Stern, 1956), and many ages have been calculated for a variety of materials from widely separated localities throughout the world (Nier, 1939; Collins, Lang, Robinson, and Farquhar, 1952; Collins, Farquhar, and Russell, 1954; Faul, 1954; Eckelmann and Kulp, 1957). Among these many age determinations are a few that are based on minerals collected from uranium-bearing veins in the United States, particularly from veins in the Front Range of Colorado. In a few places, age determinations were based on minerals from the host rocks of veins. Some isotopic age determinations as well as a few age determinations based on helium, lead-alpha, and unit-cell methods are presented in table 1 without comment as to their validity or precision. The large discrepancies between lead-uranium and lead-lead ages for pitchblende samples from geologically young deposits—as for example those in the Front Range of Colorado and the Boulder batholith, Montana, which are unquestionably of Late Cretaceous or Tertiary age—relate to such factors as mass spectrometer errors in establishing Pb^{207} abundances, uncertainties regarding isotopic composition of common lead, uncertainties regarding disintegration constants, and contamination by radiogenic lead (Stieff and Stern, 1956, p. 552–553).

In a few uranium-bearing veins, mineral relationships indicate several stages of pitchblende deposition (chap. D.). In general, this does not signify several different and distinct periods of mineralization but rather that the original hypogene uranium minerals were mobilized and redeposited, in some places several times. Consequently, the ages determined for pitchblende samples from these veins date only the stage of uranium deposition represented by the sample and not necessarily the age of first uranium mineralization in the deposit. As pointed out by Robinson (1955, p. 92), for deposits near Goldfields, Saskatchewan, Canada, isotopic age determinations for pitchblende tend to fall into distinct groups with the oldest group representative of the earliest introduction of primary pitchblende into the deposits and later age groups representative of mobilization and redeposition of the

TABLE 1.—*Age determinations on various materials collected from uranium-bearing veins and their host rocks in the conterminous United States*

Locality	Mineral	Method	Age (years X 10^6)	Reference and remarks
Arizona				
Bisbee, Cochise County	Uraninite	Pb^{206}/Pb^{207}	104±6	Bain, 1952.
Cole mine, Bisbee, Cochise County	do	Pb^{206}/U^{238} Pb^{207}/Pb^{206}	175± 1,200±	Stieff and Stern, written communication; preliminary calculations.
Black Brush (adit) group, Gila County	do	Unit cell	730	Granger, 1956, p. 208.
Red Bluff claim (prospect, mine), Gila County	do	Pb^{206}/U^{238} Pb^{207}/Pb^{206}	585 725	Granger and Raup, 1956, p. 204.
Workman (deposit) claim, Gila County	do	Pb^{206}/U^{238} Pb^{207}/Pb^{206}	830 1,100	Do.
California				
Kern River area, Kern County, Isabella granodiorite.	Zircon	Lead-alpha	85–96	MacKevett, 1960.
Pinto Mountains, Riverside (?) County	Uraninite	Lead-uranium	175	Stieff, L. R., written communication, 1958; preliminary calculation.
Colorado				
Wood mine, Gilpin County	Pitchblende	Pb^{206}/U^{238}	57	Nier, Thompson, and Murphey, 1941, p. 113.
Gilpin County	do	Pb^{206}/U^{238}	59	Do.
Wood mine, Gilpin County	do	Pb^{206}/U^{238}	60±5	Stieff and Stern, 1952, p. 108; Stieff, Stern, and Milkey, 1953, p. 13.
Iron mine, Gilpin County	do	Pb^{206}/U^{238}	70±5	
Gilpin County	do	Lead-uranium	50–60	Eckelmann and Kulp, 1954, p. 1247.
Wood(s) mine, Gilpin County	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	56±5 60±11 192±300	Kulp, 1955, p. 614; calculated from data in Nier, Thompson, and Murphey, 1941.
Gilpin County	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	58±5 64±10 293±350	Do.
Wood mine, Gilpin County	do	Pb^{206}/U^{238}	66±5	Kulp, 1955, p. 614; calculated from data in Stieff and Stern, 1952.
Do	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	35± 42±2 430±130	Eckelmann and Kulp, 1957, p. 1128.
Do	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	55±1 56±2 150±110	Eckelmann and Kulp, 1957, p. 1128; calculated from data in Nier, Thompson, and Murphey, 1941.
Gilpin County	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	59±1 61±1 170±100	Do.
Richards (Rickards; Wood or Kirk?) mine, Gilpin County.	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	56±1 62±6 320±230	Eckelmann and Kulp, 1957, p. 1128.
German mine, Gilpin County	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	51±1 54±2 315±100	Do.
Do	do	Pb^{206}/Pb^{210}	58±3	Kulp, Broecker, and Eckelmann, 1953, p. 21.
Richards (Wood or Kirk?) mine, Gilpin County	do	Pb^{206}/Pb^{210}	61±3	Do.
Copper King mine, Larimer County	do	Pb^{206}/U^{238}	68±7	Faul, 1954, p. 263; calculated from unpublished data collected by George Phair.
Do	do	Pb^{206}/U^{238}	55±6	Do.
Do	do	Lead-uranium	55–76	Sims, Phair, and Moench, 1958; Phair and Antweiler, 1954, p. 94.
Do	Magnetite	α-helium	700 and 740	Sims, Phair, and Moench, 1958.
Copper King mine	Pitchblende	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	55±2 56±2 170±100	Eckelmann and Kulp, 1957, p. 1128.
Do	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	71±4 75±5 280±200	Do.
Idaho				
Sunshine mine, Shoshone County	Pitchblende	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	710 ±10 750±10 850±50	Kerr and Kulp, 1952; Kulp, 1955, p. 615.
Do	Galena	Lead/lead Lead/lead	600± 1,100±	Cannon, 1956, p. 306–309.
Coeur d' Alene district	Pitchblende	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	620±1 770±17 1,240±77	Stieff and Stern, written communication; Sample GS/406.
Do	do	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	1,090±2 1,120±25 1,190±76	Stieff and Stern, written communication; Sample GS/407.
Michigan				
Upper Huronian Iron formation	Pitchblende concentrate	Pb^{206}/U^{238} Pb^{207}/U^{235} Pb^{207}/Pb^{206}	384±5 421±6 650±35	Kulp, Eckelmann, Owen, and Bate, 1953.

TABLE 1.—*Age determinations on various materials collected from uranium-bearing veins and their host rocks in the conterminous United States—Continued*

Locality	Mineral	Method	Age (years X 10^6)	Reference and remarks
Montana				
Boulder batholith, Jefferson County	Zircon in alaskite	Pb/α	61	Faul, 1954, p. 262.
	Monazite in alaskite	Pb/α	72	Do.
	Zircon in quartz monzonite	Pb/α	69	Do.
	do	Pb/α	69	Do.
	do	Pb/α	71	Do.
W. Wilson mine, Jefferson County	Pitchblende	Pb^{206}/U^{238}	95	Stieff and Stern, written communication; preliminary calculations. Sample (GS/256/53) poorly suited for age determinations.
		Pb^{207}/U^{235}	450	
		Pb^{207}/Pb^{206}	1,380	
Haynes property, Jefferson County	do	Pb^{206}/U^{238}	50	Stieff and Stern, written communication; sample (GS/257/53) contained some uranophane.
		Pb^{206}/U^{238}	55	
		Pb^{207}/Pb^{206}	135	
New Jersey				
Ringwood mine, Passaic County	Magnetite	Helium	410	Hurley and Goodman, 1943, p. 310.
Utah				
Bingham, Salt Lake County	Galena	Helium	51	Hurley and Goodman, 1943, p. 308.
Marysvale, Piute County	Pitchblende	Pb^{206}/U^{238}	9.8±1.2	Kulp, Eckelmann, Owen, and Bate, 1953, p. 18–19; Kerr and others 1957, p. 61.
Do	do	Pb^{206}/U^{238}	10.5±1.2	
Do	do	Pb^{207}/U^{235}	24±10	Kulp, Eckelmann, Owen, and Bate, 1953, p. 18.

uranium minerals. Thus, in considering the many different isotope ages of pitchblende from the Ace mine, Robinson (1955, p. 90) states,

> * * * that the chalcopyrite-rich pitchblende deposits of the ore zone east of the [Ace] shaft are distinctly younger than those of the zone west of the shaft.

ISOTOPIC AGES

Certain isotopic ages for pitchblende or uraninite from veins in the United States (table 1), particularly those based on Pb^{206}/U^{238} and Pb^{207}/U^{235} methods, tend to fall into two main groups that indicate a Precambrian period of uranium mineralization and a Late Cretaceous or early Tertiary period of mineralization. The Precambrian period of mineralization might be separated on the basis of both lead-uranium and lead-lead ages into two periods, including one about 1,100 million years ago and another about 700 million years ago. Age values of 600 to 800 million years have been determined for pitchblende from vein deposits in the Coeur d'Alene district, Idaho, and from deposits in the Dripping Spring Quartzite, Gila County, Ariz. These late Precambrian ages of uranium mineralization have been further substantiated by a few lead-lead ages and by unit cell measurements for a specimen of uraninite from Black Brush adit, Gila County, Ariz. (Granger, 1956, p. 208). One sample of pitchblende from the Coeur d'Alene district seems to have been deposited about 1,100 million years ago on the basis of both lead-uranium and lead-lead ratios (table 1). The lead-lead ratios in several other pitchblende specimens indicate mineralization about 1,100 to 1,200 million years ago, and this age is substantiated in part by lead-lead ages of galena from the Coeur d'Alene district.

A Late Cretaceous or early Tertiary period of uranium mineralization in veins is indicated by Pb^{206}/U^{238} and Pb^{207}/U^{235} ages that range from a little less than 50 million years to slightly more than 75 million years (table 1). Most of the ages within this range were determined for pitchblende collected from vein deposits in the Front Range of Colorado, including the Wood, German, Iron, and Copper King mines; two ages were for pitchblende from deposits in the Boulder batholith, Montana. As pointed out by Stieff, Stern, and Milkey (1953, p. 13), the ages of pitchblende from these vein deposits are strikingly similar to some of the ages determined for uranium mineralization in deposits on the Colorado Plateau. The 50- to 75-million-year ages have been duplicated by Pb^{206}/Pb^{210} ages (Kulp, Broecker, and Eckelmann, 1953) for pitchblende from the German mine and the Rickards (probably Wood or Kirk) mine, whereas age determinations based on Pb^{207} and Pb^{206} ratios are markedly different and are invariably older by 100 to 200 million years.

Several isotopic age determinations for primary uranium minerals from veins do not fit into a broad twofold grouping of a Precambrian and a Late Cretaceous or early Tertiary age. Bain (1952) published a lead-lead age for uraninite from Bisbee, Ariz., that indicates that uranium mineralization took place 104 ± 6 million years ago, or approximately during the middle part of the Cretaceous Period. However, preliminary calculations by Stieff and Stern (written communication, 1958) indicate an age of about 175 million years using Pb^{206}/U^{238} ratios and an age of 1,200 million years using Pb^{207}/Pb^{206} ratios in uraninite from the Cole mine. Geologic interpretations of the age of base-metal mineralization in the Bisbee district also are contradictory. Tenney (1932) considers the mineralization as of Tertiary age, whereas Trischka (1938) and S. R. Wallace (oral communication, 1956) think that the ores were pre-Cretaceous in age. A preliminary age of about 175 million years was also obtained for a specimen of uraninite from the Pinto Mountains in southeastern California (L. R. Stieff, written communication, 1958). An early Miocene to early Pliocene age—on the order of 10 to 25 million years—has been determined for pitchblende from veins at Marysvale, Utah, on the basis of lead-uranium age methods (Kerr and others, 1957, p. 61; Kulp, Eckelmann, Owen, and Bate, 1953, p. 18).

Table 1 also includes several age determinations made for (a) magnetite from uraniferous vein deposits (for example, the Copper King mine, Colorado, and the Ringwood mine, New Jersey), (b) galena from a deposit near Bingham, Utah (one of the deposits at Bingham is known to contain some uranium minerals), and (c) accessory minerals from rocks of the Boulder batholith and the Kern River area. None of the age determinations made for magnetite or galena has much direct meaning in terms of the age of uranium mineralization in the same deposit. The age determined for the magnetite in the Copper King mine is Precambrian, whereas lead-uranium ratios in pitchblende indicate that the uranium mineralization took place during early Tertiary time. In the Ringwood mine, New Jersey, the magnetite seems to be either Cambrian or Ordovician, but the uranium in the deposit may or may not be of the same age. Lead-alpha ages of zircon and monazite from alaskite and quartz monzonite from the Boulder batholith place a maximum limit of Late Cretaceous on the age of pitchblende mineralization in these rocks at the W. Wilson and Free Enterprise mines, Jefferson County, Mont. Similarly, lead-alpha age determinations on zircon from the granodiorite host rock in Kern Canyon, California, place a maximum limit at the beginning of the Late Cretaceous Epoch on the age of uranium mineralization in the Miracle and Kergon mines.

The isotopic ages dating primary pitchblende mineralization in veins in the conterminous United States are slightly to grossly different from the isotopic ages for pitchblende mineralization in other parts of the world. Robinson (1955, p. 82–90) has shown that isotopic ages for uranium mineralization in the Goldfields region, Saskatchewan, Canada, range from 190 to 1,850 million years and that several groupings of the many age determinations are possible. Some of these possible groups are (a) a group representing primary mineralization from 1,385 to 1,585 million years ago, or of middle or possibly early Precambrian age; (b) another, a period of mineralization dated about 900 million years ago, of late Precambrian age; (c) a group of ages ranging from 590 to 665 million years, of late Precambrian age; and (d) a group of ages ranging from 235 to 365 million years, suggesting a late period of mineralization during the Paleozoic Era. Isotopic ages of pitchblende from other uranium-bearing veins in the Canadian Shield generally indicate early to middle Precambrian deposition, as for example at the Eldorado mine, Northwest Territories, and several veins near Theano Point, Ontario, all with age determinations commonly on the order of 1,000 to 1,400 million years (Collins, Farquhar, and Russell, 1954; Faul, 1954). Age determinations of pitchblende from deposits at Schmiedeberg and St. Joachimsthal indicate uranium mineralization during late Paleozoic time (about 220 million years ago) or during the Variscan (or Hercynian) orogeny. A Precambrian age is indicated for uranium mineralization at Shinkolobwe (Faul, 1954, p. 266–267, p. 270–271). Age determinations based on Pb^{206}/U^{238} and Pb^{207}/U^{235} ratios in pitchblende from the Urgeirica and Lenteiros mines, Portugal, range from about 80 to 97 million years (L. R. Stieff and T. W. Stern, written communication, 1957) and indicate uranium mineralization of Cretaceous age. According to Collins, Farquhar, and Russell (1954), the uranium mineralization at Radium Hill, South Australia, is Precambrian in age (1,540 $\pm$ 100 million years), as based on Pb^{207}/Pb^{206} ratios in davidite.

GEOLOGIC AGES

Geologic interpretations of the ages of host rocks and confining structures of uranium-bearing veins tend to substantiate many of the isotopic age determinations listed in table 1 and lend support to the concept that uranium was first introduced into most veins in the United States during Late Cretaceous or Tertiary time (Kaiser and Page, 1952; Everhart, 1956, p. 102–103). By themselves, the ages of host rocks and confining structures have meaning only in establishing the maximum permissible geologic age of a deposit; however, a review of available data implies that although veins occur in rocks and structures of many different ages, uranium was introduced into most veins in the conterminous United States probably during Cenozoic time.

Within the United States, uraniferous veins have been found in nearly all ages of host rocks; some of the oldest are middle Precambrian (Vickers, 1956), or possibly early Precambrian, in age (Aldrich, Wetherill, and Davis, 1957; Gast and Long, 1957), and some of the youngest are of late Tertiary age (Kerr and others, 1957, p. 195, 197; Walker and Osterwald, 1956, p. 124–125; Sharp, 1956; Davis and Hetland, 1956; Wood, 1956; this chapter, table 1). Among the many hundreds of uranium-bearing veins for which the geologic ages of the host rocks are known, those in rocks of Precambrian age are most abundant; those in rocks of Cenozoic age slightly less abundant; those in rocks of Paleozoic and Mesozoic age, least abundant. (See fig. 1.) The distribution of veins according to ages of host rocks (fig. 1) means little in establishing the dominant age of mineralization for deposits in rocks of Precambrian, Paleozoic, and Mesozoic ages as well as for deposits in host rocks of unknown age. A large number of the vein deposits in host rocks of Precambrian age in the Front Range of Colorado are coextensive with alkali-rich Tertiary intrusive rocks (King, Moore, and Hinrichs, 1952; Phair, 1952; Sims and Tooker, 1956, p. 109) and fill structures of Tertiary age in the Precambrian rocks; some of these structures originated much earlier (Lovering and Goddard, 1950, p. 57–59; Osterwald, 1956, p. 331) but were repeatedly reopened during Tertiary time. These data on the geologic ages of associated rocks and structures, in combination with isotopic age determinations, suggest that primary pitchblende mineralization in veins in the Front Range of Colorado, totaling well over a hundred deposits, is probably of Tertiary age. As pointed out by Walker and Osterwald (1956, p. 124), the veins at and near Marysvale, Utah, are in faults and fractures that probably are genetically related to several large high-angle faults that bound the Sevier River Valley fault block. These high-angle faults probably are analogous to other high-angle faults in central Utah which are of Pliocene age (Eardley, 1949, p. 22–23). The White King mine, the Lucky Lass, and other properties near Lakeview, Oregon, are in faults and fracture zones that seem to be related genetically to the great high-angle faults exposed several miles north and northeast of the deposits along Abert and Winter Rims. These high-angle faults disrupt rocks of middle and possibly late Tertiary age, and, consequently, the uranium mineralization in the area is probably late Tertiary or possibly even of Quaternary age. Several uranium deposits near the Midnite mine, Stevens County, Wash., are in and adjacent to faults that cut tuffaceous sedimentary rocks of Oligocene age; presumably some and perhaps all of the uranium mineralization in the area postdates this faulting. MacKevett (1960) infers that some of the faults and fractures in which uranium occurs in the Kern River area, California, are early Pleistocene in age. The uranium deposits are thought to be of Quaternary age.

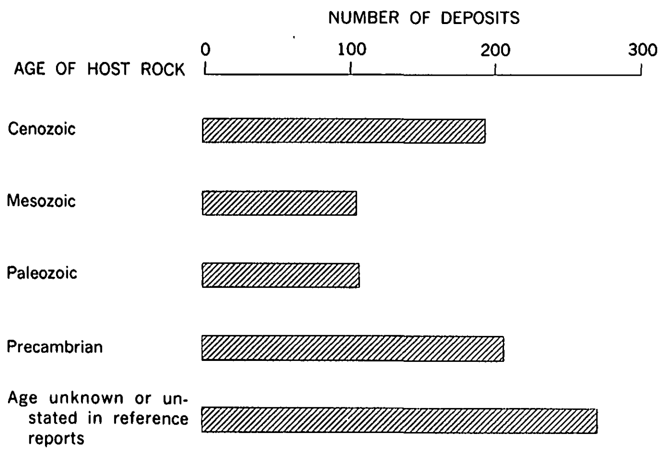

FIGURE 1.—Relative distribution of uranium-bearing veins in the conterminous United States, by ages of host rocks.

Among the several hundred veins for which geologic ages of host rocks are unknown or unstated in reference reports (see fig. 1), a large number are in geologic terranes dominated by rocks of Late Cretaceous and Tertiary age and characterized by extensive deformation during Tertiary time. Examples include parts of western Utah, many of the basins of Nevada, and parts of California, Oregon, and southern Arizona. Many of the uranium deposits in such terranes may be of Cenozoic or possibly Late Cretaceous age. Presumably some of the deposits in rocks of Paleozoic and Mesozoic age also are of Late Cretaceous or Tertiary age, particularly in the western United States.

Uranium mineralization in about 190 veins is of Cenozoic age, as established strictly on the basis of the age of the enclosing rock (fig. 1); in addition to these are several hundred other veins in rocks of Precambrian, Paleozoic, or Mesozoic age in which geologic interpretations or isotopic age calculations indicate a Late Cretaceous or Tertiary age for the uranium mineralization. Consequently, there is little doubt that the dominant period of uranium mineralization in veins in the western United States is of Late Cretaceous or Tertiary age, although in two areas, the Coeur d'Alene district of Idaho and the Sierra Ancha region of Arizona, uranium mineralization is of Precambrian age. Little, if any, data are available to establish the age of uranium mineralization in veins in the Appalachian orogenic belt. Most of the uranium-bearing veins in this region are in metamorphic rocks thought to be of Precambrian age; exceptions include the deposits at Stone Mountain in Georgia, which are in granitic rocks of Paleozoic age, and small deposits near Stockton, N.J., in sedimentary rock of Mesozoic age. In general, the uranium deposits in veins in these eastern regions are thought to be pre-Cretaceous in age and related to crustal disturbances of Precambrian, Paleozoic, or Late Triassic age.

SUMMARY

The dominant period of uranium mineralization in veins in the conterminous United States is of Late Cretaceous or Tertiary age; this age designation is demonstrated both by calculations based on isotopic ratios in pitchblende or other vein minerals and by geologic interpretations of the age of confining structures and of enclosing host rocks. This Late Cretaceous or Tertiary age agrees with the age of uranium mineralization established for sandstone-type deposits (Stieff, Stern, and Milkey, 1953; Eckelmann and Kulp, 1957, p. 1128–1129) exemplified by those on the Colorado Plateau and in the sedimentary basins of Wyoming. Other periods of uranium mineralization in veins in the United States are Precambrian, Paleozoic, and possibly Mesozoic in age.

The veins of Late Cretaceous or Tertiary age are widely distributed throughout the western United States and include many of the larger uraniferous vein deposits, as for example those at Marysvale, Utah, the Schwartzwalder (or Ralston Creek) mine, Colorado, and possibly the Los Ochos mine, Colorado, and the Midnite mine, Washington; the White King mine, Oregon, may even be of Quaternary age. Mineralization of Precambrian age is restricted largely to veins in the Coeur d'Alene district, Idaho, and the Sierra Ancha region of Arizona. Meager isotopic and geologic data suggest that uranium mineralization is of Paleozoic or early Mesozoic age in a few veins mostly in the eastern and southwestern United States.

Dominant periods of uranium mineralization in other parts of the world are of Precambrian, Paleozoic, or Mesozoic age. Precambrian mineralization has been established for Shinkolobwe and other uranium deposits in the shield area of South Africa; for deposits in the Canadian Shield, including the Eldorado mine, N. W. T., and the deposits near Goldfields, Saskatchewan; and for deposits in the shield areas of Australia. Uranium mineralization in deposits in Cornwall, England, and in the vicinity of St. Joachimsthal, or Jachymov, Czechoslovakia, is of Paleozoic age and is related to Variscan (Hercynian) orogeny; in France, Spain, and Portugal, uranium mineralization is partly, and perhaps largely, of Paleozoic age and related to Variscan (Hercynian) orogeny. Some of the deposits, however, may be much younger, possibly even of Cretaceous or early Tertiary age, as suggested by isotope ages for pitchblende from the Urgeirica and Lenteiros mines in Portugal.

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Host Rocks and Their Alterations as Related to Uranium-Bearing Veins in the Conterminous United States

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HOST ROCKS AND THEIR ALTERATIONS AS RELATED TO URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

By George W. Walker

ABSTRACT

Many different kinds and ages of igneous, metamorphic, and sedimentary rocks are the host for uranium-bearing veins in the conterminous United States. In mineralogic and chemical composition, these host rocks show a wide variation and include some composed dominantly of salic minerals and others composed dominantly of mafic minerals. Some of the host rocks are characterized by an abundance of graphitic carbon, by clay minerals, by calcium or magnesium carbonate minerals, by iron oxide minerals, or by phosphate minerals. Even though nearly all textural, chemical, and mineralogic types of rocks have been reported as the host for uraniferous vein deposits, the veins are most abundant in holocrystalline, commonly equigranular, igneous and metamorphic rocks characterized by a moderate to high silica content and by physical properties that are somewhat alike. Similarities in physical properties are related largely to the behavior of these rocks under stress. In general, they lack any important plastic-flow phenomena under near-surface conditions of pressure and temperature and are more apt to rupture under stress than other kinds of rocks.

Most of the host rocks of uranium-bearing veins have been modified, reconstituted, or mineralized either before, during, or after the introduction of the uranium. Consequently, the physical, chemical, and mineralogic character of the petrologic environment of uranium deposition is poorly known.

Many of the uranium-bearing veins in the conterminous United States are enclosed in alteration halos commonly consisting of three principal zones characterized by sericitized, argillized, and chloritized wallrocks. Hematite in uranium-bearing veins or hematitic alteration of adjoining wallrocks is not particularly common and, consequently, seems to have limited usefulness as a diagnostic feature of uranium mineralization.

INTRODUCTION

Uranium-bearing veins in the conterminous United States are in many different kinds of igneous, metamorphic, and sedimentary host rocks that range from Precambrian to late Tertiary in age. Most host rocks have been altered adjacent to uraniferous veins, but some veins are enclosed in fresh, unaltered rock. Where alteration effects are evident, several distinct zones of alteration are commonly present at a single deposit as successive sheaths around the veins and, locally, as zones approximately parallel to the ground-surface profile.

Both published and unpublished information regarding the character of host rocks and their alterations has been evaluated in order to (a) present descriptive data concerning the host rocks of uranium-bearing veins; (b) establish, if possible, whether certain kinds or groups of rocks are more favorable for the occurrence of uranium in veins than other kinds of rocks; (c) determine whether favorable host rocks, if they exist, have any mineralogic, chemical, or physical characteristics in common; and (d) ascertain the nature and any unique features of wallrock alteration accompanying the veins. No genetic relations between these host rocks and the veins that they contain are implied, although locally such relationships may exist.

The lithology, mineralogy, and chemistry of the host rocks of uraniferous veins and the wallrock alterations associated with these veins have been studied in detail in only a very few places. Most uraniferous veins have received little study; most identifications of enclosing rock and descriptions of wallrock alteration were based only on field observations. Consequently, these identifications have introduced several problems of interpretation. Some of the major problems concerning the host rocks are closely bound to the varied petrographic nomenclature and classification, particularly as related to igneous and metamorphic rocks, and to the paucity of adequate petrographic descriptions and chemical analyses and the resultant inaccuracies in naming rocks. Many of the inaccuracies are perhaps minor, as for example rocks with the physical, chemical, and mineralogic characteristics of a diorite that were hastily called granite or granitic rock, or monzonite, or quartz monzonite, or granodiorite on the basis of megascopic field examinations. Some "igneous" host rocks, particularly those derived or altered by metasomatic processes or those in which assimilation of invaded rock is prevalent, consist of a mineral assemblage and (or) chemical composition that is completely incompatible with the field names.

Because very little other than a superficial field name is known about the majority of these host rocks, somewhat greater emphasis has been placed in this report on data from districts or deposits in which the host rocks intimately related to uranium-bearing veins have received more petrographic study. Principal among these are deposits in the Boulder batholith, Montana; the Marysvale district, Utah; the Thomas Range, Utah; the Front Range of Colorado; and the Sierra Ancha region, Gila County, Ariz.

KINDS OF HOST ROCKS

A generalized classification of the host rocks of uranium-bearing veins seems most useful and is commensurate with available data. Consequently, the host rocks are subdivided into igneous, sedimentary, and metamorphic rocks. For purposes of generalization and comparison, the host rocks are further subdivided herein into seven arbitrary groups, which are: (a) felsic to intermediate plutonic and hypabyssal igneous rocks, including related rocks derived through metasomatic processes; (b) felsic to intermediate volcanic rocks; (c) intermediate to mafic plutonic, hypabyssal, and volcanic rocks; (d) clastic sedimentary rocks, excluding clastic limestone and dolomite; (e) carbonate rocks; (f) low-grade metamorphic rocks; and (g) intermediate- to high-grade metamorphic rocks.

IGNEOUS HOST ROCKS

FELSIC TO INTERMEDIATE PLUTONIC AND HYPABYSSAL IGNEOUS ROCKS

The felsic to intermediate plutonic and hypabyssal igneous host rocks compose a group of intrusive crystalline rocks that range from granite through diorite, or their alkali-rich equivalents, in composition. The group probably includes some crystalline rocks derived wholly or in part from metasomatism or modified by deuteric solutions and some rocks, presumably largely of magmatic origin, that contain greater or lesser amounts of assimilated material from the invaded rocks.

Included in this group are the host rocks designated by the authors of reviewed reports as granite, microgranite or aplite, granodiorite, quartz monzonite or monzonite, syenite, quartz diorite, diorite, alaskite, pegmatite, and felsite, and those rocks identified only as "granitic." Although the rocks within this group are diverse in mineral composition and chemistry, they show some uniformity in physical characteristics in that they are holocrystalline and that most are massive and competent in the sense that under near surface conditions they lack major plastic flowage characteristics; they exhibit many textural variants and may be either coarse or fine grained.

Most of these host rocks are thought to be of Late Jurassic, Cretaceous, or early Tertiary age; some are of Precambrian age; and a few, as for example the quartz monzonite host at Marysvale, Utah, are thought to be of middle Tertiary age (Kerr and others, 1957, p. 5).

Most available chemical analyses of both fresh and altered host rocks of this group are presented in table 1. Although the analyses indicate considerable variation in chemical composition, modal analyses of these rocks as compared to modal analyses of felsic to intermediate igneous host rocks from other areas indicate that considerably greater variation in chemical composition must be expected.

A few of the variations, even within a single district, can be demonstrated by available data for host rocks at Marysvale, Utah. At Marysvale, uranium minerals are localized principally in a rock identified as quartz monzonite by Callaghan (1939), but they are also known to occur in microgranite as well as other kinds of rock. Several modal analyses of quartz monzonite and one of microgranite are compared below:

Modal analyses of quartz monzonite and microgranite

	1	2	3	4
Quartz	6	3.8	6.0	29.7
K-feldspar	29	48.8	44.5	59.2
Plagioclase	33	29.7	24.6	5.7
Biotite—partly as chlorite	14	2.7	4.8	.7
Augite	11			
Pigeonite		12.7	16.2	
Magnetite	7			
Opaques		1.2	3.0	
Apatite		.8		
Accessory minerals			.2	
Calcite			.2	
Pyrite				2.9
Fluorite				2.0
Totals	100	99.7	99.5	100.2

1. Quartz monzonite from Marysvale area; chemical analysis of specimen given in table 1, column 1. (Callaghan, 1939, table 1)
2. "Quartz monzonite" from Sunnyside mine, Marysvale, Utah. (Analysis by G. W. Walker)
3. "Quartz monzonite" from wall of Freedom 2 vein, Marysvale, Utah. (Analysis by G. W. Walker)
4. Microgranite from Yellow Canary deposit, Marysvale, Utah, (Analysis by G. W. Walker)

These few modal analyses indicate not only that the quartz monzonite host rock is inhomogeneous, at least as related to the relative abundance of the constituent minerals, but also that the mineral composition, and undoubtedly the chemical composition, of the quartz monzonite and the microgranite are very different. Furthermore, both modal and chemical analyses indicate that the rocks from Marysvale identified as quartz monzonite are unusual and have little in common with the quartz monzonite of the Boulder batholith and probably with other host rocks identified as quartz monzonite in other parts of the western

TABLE 1.—*Chemical analyses of felsic to intermediate plutonic and hypabyssal intrusive host rocks of uranium-bearing veins*

[Includes complete and partial rock analyses]

	Marysvale, Utah		Boulder batholith, Montana							Colorado Front Range		
	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	57.96	57.81	68.01	65.30	66.05	64.44	69.13	59.86	76.85	54.25	55.66	57.63
Al_2O_3	15.71	16.10	15.52	15.06	14.80	14.37	15.15	22.30	13.50	20.27	19.89	20.47
Fe_2O_3	3.38	3.33	.29	8.85	1.52	9.21	.20	1.74	.69	4.26	2.57	1.13
FeO	4.11	3.34	2.95	.18	2.71	(9.21, total iron, spans Fe_2O_3 and FeO rows)	1.74	.14	.10	3.87	3.10	2.83
MgO	3.16	3.21	1.42	.07	1.58	.46	1.94	.87	.89	1.43	1.24	1.09
CaO	5.11	4.81	2.69	.07	2.68	.03	2.74	1.21	.09	3.70	3.34	1.65
Na_2O	3.48	3.66	3.10	.18	2.57	.07	2.83	2.24	.58	3.42	3.31	.82
K_2O	4.08	4.66	3.24	3.16	5.00	3.61	4.49	3.80	2.66	5.55	6.18	10.26
H_2O+	1.26	.74	.72	5.21	.83	1.75	.81	7.10	3.84	------	------	------
H_2O-	.11	.11	.22	.60	.28	.04	.18	2.00	.53	------	------	------
TiO_2	1.05	1.15	.48	.47	.52	.40	.48	.64	.68	------	------	------
P_2O_5	------	.42	.10	.23	.13	.00	.08	.10	.04	------	------	------
MnO	.11	.11	.04	.02	.30	.03	------	------	------	------	------	------
CO_2	Trace	.02	.02	.01	.74	.02	.35	.12	.31	------	------	------
BaO	------	.09	.01	.04	.04	.01	------	------	------	------	------	------
S	.07	------	.99	.02	n.d.	7.65	.32	Trace	.02	------	------	------
Cr_2O_3	.02	------	------	------	------	------	------	------	------	------	------	------
V_2O_5	------	.01	------	------	------	------	------	------	------	------	------	------
FeS_2	------	.02	------	------	------	------	------	------	------	------	------	------
F	------	.15	------	------	------	------	------	------	------	------	------	------
Cl	------	.05	------	------	------	------	------	------	------	------	------	------
SrO	------	.07	------	------	------	------	------	------	------	------	------	------
	99.61	99.86	99.80	99.47	99.75	102.09	100.44	102.12	100.78	96.75	95.29	95.88
Less O	------	------	.25	.01	------	------	------	------	------	------	------	------
Total	99.61	99.86	99.55	99.46	99.75	102.09	100.44	102.12	100.78	96.75	95.29	95.88

1. Quartz monzonite from east side of Marysvale Canyon at mouth of Deer Creek. Analyst: R. E. Stevens (from Callaghan, 1939, table 1, No. 5).
2. Quartz monzonite from north end of Monzonite Hill. Analyst: E. H. Oslund (from Kerr and others, 1953, table 8, No. F, p. 86).
3. Quartz monzonite from G. Washington claim, Jefferson County, Mont. Lab. No. B256. Analyst: Jean Theobald (Sam Rosenblum, written communication, 1956).
4. Argillized quartz monzonite from G. Washington claim, Jefferson County, Mont. Lab. No. B250. Analysts: L. N. Tarrant and Jean Theobold (Sam Rosenblum written communication, 1956).
5. Quartz monzonite from Bunker Hill mine, Lewis and Clark County, Mont. Lab. No. B249. Analysts: L. N. Tarrant and L. D. Trumbull (Sam Rosenblum, written communication, 1956).
6. Altered quartz monzonite from Bunker Hill mine, Lewis and Clark County, Mont. Lab. No. B246. Owing to the presence of acid soluble sulfide, the ratio of FeO to Fe_2O_3 is not reliable. Total iron is shown as Fe_2O_3; oxygen correction and total are therefore omitted. Analysts: L. N. Tarrant and L. D. Trumbull (Sam Rosenblum, written communication, 1956).
7. Quartz monzonite from W. Wilson mine, Jefferson County, Mont. Sample 2615 (from H. D. Wright, B. H. Bieler, and W. P. Shulhof, written communication, 1953; Ledoux and Co., analyst).
8. Moderately altered quartz monzonite from W. Wilson mine, Jefferson County, Mont. Sample 1880 (from H. D. Wright, B. H. Bieler, and W. P. Shulhof, written communication, 1953; Ledoux and Co., analyst).
9. Altered quartz monzonite from W. Wilson mine, Jefferson County, Mont. Sample 1876 (from H. D. Wright, B. H. Bieler, and W. P. Shulhof, written communication, 1953; Ledoux and Co., analyst).
10. Essentially fresh syenite from Caribou mine, Boulder County, Colo. (from Wright, 1954, table 1, Zone 4, West Section. Analysis obtained through Dr. C. J. Rodden, New Brunswick Laboratory, Atomic Energy Commission).
11. Essentially fresh syenite from Caribou mine, Boulder County, Colo. (from Wright, 1954, table 1, Zone 4, Middle Section. Analysis obtained through Dr. C. J. Rodden, New Brunswick Laboratory, Atomic Energy Commission).
12. Altered syenite from Caribou mine, Boulder County, Colo. (from Wright, 1954, table 1, Zone 1, Middle Section. Analysis obtained through Dr. C. J. Rodden, New Brunswick Laboratory, Atomic Energy Commission).

United States. According to Meschter (written communication, 1953),

> A typical specimen * * * [of the quartz monzonite host rock at the W. Wilson mine, Jefferson County, Mont.] * * * has the following approximate modal composition: Plagioclase, 50 percent; orthoclase, 25 percent; quartz, 15 percent; biotite, 5 percent; and hornblende, 2 to 3 percent. The accessory minerals are magnetite, apatite, sphene and zircon.

Greater variations in the mineralogic and chemical composition of rocks within and among districts or deposits could be demonstrated if modal or chemical analyses or both were available for host rocks identified as porphyritic quartz monzonite at the Midnite mine, Washington (P. L. Weis, written communication, 1956); quartz monzonite, grandiorite, and alaskite in deposits in the Boulder batholith, Montana (Roberts and Gude, 1953; Becraft, 1956, p. 119); granodiorite and quartz diorite in Kern Canyon, California (MacKevett, 1960); greisen at the Redskin mine, Park County, Colo.; quartz monzonite at the Early Day claims, Nevada (Sharp and Hetland, 1954); granite pegmatite and bostonite porphyry in the Front Range of Colorado (Sims and Tooker, 1956, p. 108); and for other igneous host rocks from deposits in other parts of the country.

FELSIC TO INTERMEDIATE VOLCANIC ROCKS

The host rocks within the group defined as "felsic to intermediate volcanic rocks" range in composition from rhyolite through andesite and include both alkalic and calc-alkalic varieties. These rocks occur as plugs and related near-surface concordant and discordant intrusives, flows, flow breccias, and welded tuffs. These rocks are composed dominantly of glass or silica and silicate minerals, in various proportions, and contain many kinds of varietal and accessory minerals. The flows, flow breccias, and intrusives are composed dominantly of crystals or of volcanic glass, which may be either altered or unaltered. The welded tuffs consist of different proportions of crystals or crystal fragments, glass or products of devitrification, and rock fragments that may be similar to, or very different in composition from, the matrix.

Dominant among the petrographic names, as applied by the authors of reviewed reports and thus placed in this group, are rhyolite, dacite, latite, and andesite; some host rocks have been termed simply "acid volcanic rock" in available reports. Although specific mineralogic data are lacking, it seems reasonable to infer that several mineralogic varieties of these rocks are represented. Many of these rocks, as named by the authors of reviewed reports, are flows; some of the rocks called flows are, in fact, welded tuffs composed of different proportions of crystal and lithic fragments and glass, as established both by thin-section study and by reexamination of field relations in the course of the present study.

For the known uranium-bearing veins, virtually all the host rocks in this group are of Tertiary age, although a few may be of late Mesozoic age.

Where unaltered or only slightly altered, these rocks are, in general, hard and brittle, and some are massive.

The three chemical analyses (columns 11, 12, 13, table 2) do not indicate the range in chemical composition of the host rocks in this group, but they are the only available analyses of host rocks that are closely related in space to uranium-bearing veins. These three analyses are used herein only for purposes of comparison with the chemical composition of the other groups of host rocks; they represent some of the

TABLE 2.—*Chemical analyses of several kinds of host rocks of uranium-bearing veins*

[Includes complete, partial, and rapid rock analyses]

	Colorado Front Range										Thomas Range, Utah			Michigan		Sierra Ancha region, Ariz.		
	1	2	3[1]	4[1]	5[1]	6[1]	7[1]	8	9	10	11	12	13	14	15	16[1]	17[1]	18[1]
SiO_2	71.76	68.61	76.3	75.5	52.4	51.4	49.7	54.86	51.70	32.87	77.24	76.54	74.67	77.20	18.60	59.4	56.9	61.5
Al_2O_3	14.37	14.10	12.2	12.1	8.2	9.4	10.5	14.65	18.06	9.10	10.81	12.16	12.26	6.17	19.10	14.7	14.4	17.7
Fe_2O_3	1.13	2.33	.9	2.3	11.7	10.9	4.9	4.66	12.36	.45	1.66	.92	.71	5.16	10.77	3.7	3.0	1.6
FeO	1.80	1.72	2.0	.68	13.9	15.0	16.8	7.99	.16	10.57	.27	.37	.27			.35	5.8	.54
MgO	.58	.64	.48	.44	2.8	3.8	2.0	3.40	1.15	5.60	.33	.14	.11	.75	2.22	1.0	.31	.04
CaO	2.05	2.51	1.7	.12	5.4	3.0	2.3	6.67	2.41	12.03	1.48	.78	.61	.08	.35	1.8	.53	.82
Na_2O	4.95	3.60	3.7	.11	.10	.09	.09	3.28	2.46	.21	2.59	3.50	3.31	----	----	.18	.55	.92
K_2O	2.02	1.15	1.1	4.6	.49	1.8	.31	.79	3.30	7.13	4.12	4.97	5.05	----	----	12.4	11.6	14.1
H_2O+	.33	1.22	.83	1.6	.74	.87	1.4	1.35	3.74	.23	.37	.11	2.24	----	----	.77	.72	.72
H_2O-	.03	1.71						.30	1.93	.15	.49	.05	.13	----	----			
TiO_2	.27	.54	.22	.16	.32	.52	.38	1.41	1.72	.81	.20	.09	.14	----	----	.86	.72	1.0
P_2O_5	.04	.11	.06	.06	.70	.59	.52	.31	.25	.36	.06	.02	.01	----	----	.11	.10	.12
MnO	.06	.14	.02	.01	3.5	3.2	3.5	.22	.28	.29	.02	.05	.05	----	----	.02	.03	.00
CO_2	.54	1.49	.20	$<.05$	.25	.13	8.0	.05	.17	20.58	.13	.16	.01	----	----	2.5	.56	.05
S	----	----	----	2.0	1.2	.94	1.2	.02	.01	----	----	----	----	2.65	5.45	2.7	3.7	1.1
Cl	----	----	----	----	----	----	----	----	----	----	.01	----	.10	----	----	----	----	----
F	----	----	----	.61	----	----	----	----	----	----	.04	.32	.26	----	----	----	----	----
C	----	----	----	----	----	----	----	----	----	----	----	----	----	6.96	29.11	----	----	----
	99.93	99.87	99.7	100.3	101.7	101.6	101.6	99.96	99.70	100.38	99.82	100.18	99.93	----	----	100.5	98.9	100.2
Less O	----	----	----	----	----	----	----	.01	----	----	.02	.13	.13	----	----	----	----	----
Total	99.93	99.87	----	----	----	----	----	99.95	99.70	100.38	99.80	100.05	99.80	----	----	----	----	----

[1] Analyses made by rapid method.

1. Biotite-quartz-plagioclase gneiss from Essex mine, Gilpin County, Colo. Lab. No. A13. Analyst: L. N. Tarrant (from E. W. Tooker, written communication, 1956).
2. Altered biotite-quartz-plagioclase gneiss from Essex mine, Gilpin County, Colo. Lab. No. A10. Analyst: L. N. Tarrant (from E. W. Tooker, written communication, 1956).
3. Least altered quartz monzonite gneiss from East Calhoun mine, Gilpin County, Colo. Lab. No. 147561. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from E. W. Tooker, written communication, 1956).
4. Most altered quartz monzonite gneiss from East Calhoun mine, Gilpin County, Colo. Lab. No. 147564. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from E. W. Tooker, written communication, 1956).
5. Garnet-quartz rock from Fall River area, Clear Creek County, Colo. Lab. No. 140577. Analysts: H. F. Phillips, P. L. D. Elmore, P. W. Scott, K. E. White (from C. C. Hawley, and F. B. Moore, written communication).
6. Garnet-quartz rock from Fall River area, Clear Creek County, Colo. Lab. No. 140578. Analysts: H. F. Phillips, P. L. D. Elmore, P. W. Scott, K. E. White (from C. C. Hawley, and F. B. Moore, written communication).
7. "Altered" garnet-quartz rock from Fall River area, Clear Creek County, Colo. Lab. No. 140573. Analysts: H. F. Phillips, P. L. D. Elmore, P. W. Scott, K. E. White (from C. C. Hawley and F. B. Moore, written communication).
8. Hornblende gneiss from Union Pacific prospect, Jefferson County, Colo. Lab. No. 54–219CD. Analyst: L. M. Kehl (from Adams and Stugard, 1956a).
9. Altered hornblende gneiss from Union Pacific prospect, Jefferson County, Colo. Lab. No. 54–220CD. Analyst: L. M. Kehl (from Adams and Stugard, 1956a).
10. Breccia reef material from Union Pacific prospect, Jefferson County, Colo. Lab. No. 54–222CD. Analyst: L. M. Kehl (from Adams and Stugard, 1956a).
11. Porphyritic rhyolite from the Thomas Range, Juab County, Utah. Lab. No. B393. Analyst: E. Thomasi (from M. H. Staatz, written communication).
12. Rhyolite flow from the Thomas Range, Juab County, Utah. Lab. No. 52-2008CD. Analyst: L. M. Kehl (from M. H. Staatz, written communication).
13. Glassy base of rhyolite flow from Thomas Range, Juab County, Utah. Lab. No. B237. Analyst: E. Tomasi (from M. H. Staatz, written communication).
14. Black slate from the Sherwood mine, Iron County, Mich. (from L. P. Barrett, 1953, p. 11).
15. Black slate from the Sherwood mine, Iron County, Mich. (from L. P. Barrett, 1953, p. 11).
16. Siltstone from Dripping Spring Quartzite, Gila County, Ariz. Lab. No. 145747. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from H. C. Granger, and R. B. Raup, Jr., written communication).
17. Hornfels from Dripping Spring Quartzite, Gila County, Ariz. Lab. No. 145748. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from H. C. Granger, and R. B. Raup, Jr., written communication).
18. Recrystallized hornfels from Dripping Spring Quartzite, Gila County, Ariz. Lab. No. 145749. Analysts: P. L. D. Elmore, K. E. White, S. D. Botts (from H. C. Granger and R. B. Raup, Jr., written communication).

most silicic host rocks for which analytical data are available. Significant differences in the chemical composition of host rocks within this group could assuredly be established if analyses were available for those host rocks identified as rhyolite porphyry at the Staats Fluorspar mine, Utah (Thurston, Staatz, Cox, and others, 1954, p. 18), as altered and silicified rhyolitic and latitic tuffs and flows at the Moonlight mine, Nevada (Taylor and Powers, 1955, p. 8), as partly glassy to devitrified and altered rhyolitic dikes in the Bullion Monarch (Farmer John) mine, Marysvale district, Utah (Taylor and others, 1951), as andesite at the Pitchblende Strike prospect, New Mexico (Everhart, 1956), as rhyolite porphyry at the White Oaks mine, Arizona (R. B. Raup, Jr., written communication, 1953), and as rhyolite, quartz porphyry, and rhyolite breccias at Majuba Hill, Nevada (Trites and Thurston, 1958).

INTERMEDIATE TO MAFIC PLUTONIC, HYPABYSSAL, AND VOLCANIC ROCKS

Both primary and secondary uranium minerals have been found in veins enclosed in a group of rocks defined herein as "intermediate to mafic plutonic, hypabyssal, and volcanic rocks." Host rocks of this group have been identified principally as sills and dikes of diabase or locally of lamprophyre; as sills, dikes, and flows of basalt; and, in a few places, as "intrusive" masses of hornblende-rich rock that apparently are altered, in part, to minerals of the serpentine group. These rocks are the host for uranium-bearing veins in about 30 different places or deposits within the United States; and a very much larger number of uranium-bearing veins, though enclosed in other kinds of rock, are closely related in space to mafic igneous rocks both within the United States and elsewhere. Examples of uraniferous vein deposits in rocks of this group are known in the White Signal district, New Mexico (Granger and Bauer, 1956, p. 334, 343, 345), at the Escondida claims and the Linda Lee prospect, Pima County, Ariz., and at the Two Chuckers claims, Nevada (C. L. Twitchell, written communication, 1955).

Detailed data bearing on the mineralogic or chemical composition of these rocks are lacking in places where the rocks represent the host for concentrations of uranium minerals in veins. However, judging from the petrographic names that have been applied to them, these host rocks probably are composed almost exclusively of calcic plagioclase and ferromagnesian minerals; locally, some contain noteworthy amounts of simple oxides of iron and titanium. Most host rocks of this group have been identified as of either Precambrian or Tertiary age.

SEDIMENTARY HOST ROCKS

CLASTIC SEDIMENTARY ROCKS

This group of host rocks includes all varieties of both marine and nonmarine clastic sedimentary rocks; it excludes all carbonate sedimentary rocks. Because detailed data are lacking in regard to the differences in texture and in mineralogic and chemical composition among host rocks of this group, no further subdivision of clastic sedimentary rocks is possible.

Data in available literature indicate that most uraniferous veins in clastic sedimentary rocks are either in quartzitic or feldspathic sandstone or in tuffaceous rocks which, in some places, are composed largely or exclusively of pyroclastic debris. A smaller number of uranium-bearing veins have been found in rocks described as conglomerate, shale, siltstone, and coal.

The field names that have been applied to rocks of this group are indicative of considerable inhomogeneity. Some of the rocks are phosphatic, or carbonaceous, or calcareous, whereas others are characterized by an abundance of silica, iron oxides, or alumina; not uncommonly the phosphate, carbonate (largely as calcite), and silica occur as cement. Most, if not all, rocks of this group contain some of either nonexpandable-lattice (such as kaolinite) or expandable-lattice (such as montmorillonite, beidellite, and nontronite) clay minerals. The expandable-lattice clay minerals, commonly derived by devitrification of vitric ash, are particularly prevalent in the tuffs and tuffaceous sedimentary rocks; in places, these rocks also are phosphatic. Organic carbon is characteristic of most of these rocks, occurring in some in only trace amounts and in a few host rocks as a major constituent. Rocks of this group are inhomogeneous in texture, in degree and kind of cementation, and in competence.

Some of the different lithologies and ages of host rocks of this group are exemplified by the Los Ochos mine, Colorado, in sandstone of the Morrison Formation of Jurassic age (Derzay, 1956); by the Pallaoro (or Morrison) deposit, Colorado, in the Dakota Sandstone of Cretaceous age; by veins in siltstone of the Deadwood Formation of Cambrian age in South Dakota (Vickers, 1953); the Ridenour mine, Arizona (Miller, 1954), in the top sandy member of the Supai Formation of Permian age; by the Orphan mine, Arizona, in the Coconino Sandstone (Permian) and possibly Supai Formation (Permian); by veins cutting a sheared and partly silicified coal bed in the Laramie Formation (Upper Cretaceous) at the Leyden Coal mine, Colorado (F. A. McKeown and A. J. Gude, 3d, written communication, 1951); by several deposits in fault gouge and brecciated sandstone and arkose of the Rico (Pennsylvanian and Permian?), Cutler (Permian), and Chinle (Triassic) formations in the Moab-Inter-river area, Utah (E. N. Hinrichs, written communication, 1954); and by numerous uraniferous vein deposits enclosed in tuffaceous sedimentary rocks of Tertiary age in south-central and southeastern Oregon, western Nevada, southeastern California, and central Wyoming.

CARBONATE ROCKS

Sedimentary rocks composed dominantly of either calcium or magnesium carbonate minerals or both host uranium-bearing veins in several widely distributed deposits in the western United States. Most of the deposits are fissure fillings, although replacement, probably by uranium minerals and certainly by closely associated base-metal sulfide minerals and by uraniferous fluorite, is locally prevalent. Most of these host rocks have been described in reports simply as limestone or dolomite, although several textural, chemical, and mineralogic varieties are represented. Some are clastic carbonate rocks, as for example clastic dolomite in the Thomas Range (Staatz and Osterwald, 1959), whereas others are chemical precipitates.

Some of these host rocks are nearly pure calcite or dolomite, and some contain greater or lesser amounts of silica commonly in the form of chert; others are argillaceous or arenaceous carbonate rocks. In some places these host rocks have been modified by diagenetic processes to form silicified or dolomitized limestone.

In general, data in available reports are not specific as to the kind or detailed characteristics of the carbonate host rocks; nor, as far as known to the author, are any chemical analyses or any detailed petrographic descriptions available except for dolomitic host rocks of Silurian age in the Thomas Range, Utah. According to Staatz and Osterwald (1959), the uranium-bearing fluorite pipes and veins of the Thomas Range district are enclosed largely in clastic dolomite locally characterized by minor to moderate amounts of chert as blebs and discontinuous layers along the bedding. In general, the lime content is about 30 percent, and the magnesia content is about 20 percent.

Several well-known uraniferous vein deposits enclosed in rocks of this group are the Green Monster mine, Clark County, Nev., in which kasolite and dumontite are concentrated in the oxidized parts of a lead-zinc ore body in brecciated rocks of the Bullion Dolomite Member of the Monte Cristo Limestone of Carboniferous age; deposits at Bisbee, Ariz., in which uraninite is present in sulfide ores enclosed in carbonate rocks of Paleozoic age (Bain, 1952); the Smuggler mine, Pitkin County, Colo., in which uranium minerals are associated with base-metal sulfide minerals in a breccia of dolomite and shale (Boyd and Bromley, 1953, p. 17); and the Blue Bird mine, Lincoln County, Nev., where uranium minerals are concentrated in a breccia of silicified limestone and quartzite (B. J. Sharp and B. L. Myerson, written communication, 1956). Other deposits are known in cherty parts of the Madison Limestone (Mississippian) in Carbon County, Mont., and Big Horn County, Wyo., in silicified limestone of the Kaibab Limestone (Permian) adjacent to the Hurricane fault in Washington County, Utah, in the Furnace Limestone of Vaughan, 1922 (Paleozoic), in San Bernardino County, Calif. (Walker, Lovering, and Stephens, 1956, p. 23), and in other Paleozoic limestone or dolomite strata elsewhere.

METAMORPHIC HOST ROCKS

LOW-GRADE METAMORPHIC ROCKS

The group "low-grade metamorphic rocks" includes those host rocks transitional in character between obviously metamorphosed on one hand and obviously unmetamorphosed on the other. In general, host rocks placed in this group, regardless of the rock names used by various authors, are probably correlative in grade of metamorphism with Turner's (1948) "greenschist" facies on the basis either of the broad geologic environment of their occurrence or of further reexamination in the course of the present study. This group serves to set apart from the igneous and sedimentary rock groups those host rocks slightly to moderately recrystallized.

Arbitrarily, host rocks of Precambrian age to which sedimentary rock names such as siltstone, shale, and quartzite are applied by various authors are placed herein. This is done on the basis that most, if not all, Precambrian rocks are at least slightly recrystallized. Again arbitrarily, host rocks are included herein that are not necessarily in a recognized metamorphic terrain but which are described as quartzite, slate, phyllite, argillite, hornfels, and those identified only as metasedimentary and metavolcanic rocks. The mineralogic and chemical composition of host rocks placed in this group is diverse; many are highly siliceous, whereas others contain large to moderate amounts of clay minerals, carbonate minerals, graphite, iron sulfide or hydrated iron oxides, lime silicate minerals, or other constituents. In general, host rocks in this group are highly indurated and are hard and brittle.

Partial or "complete" chemical analyses of a few host rocks of this group are included in table 2 (columns 16, 17, 18) principally for comparative purposes with other kinds of host rocks. The analyses of the three samples of host rock from the Dripping Spring Quartzite in the Sierra Ancha region, Gila County, Ariz., are, according to H. C. Granger (oral communication, 1956), representative of the formation in those places where it contains concentrations of uranium minerals. Available analytical data indicate that these are the most potassic host rocks of uranium-bearing veins. Only a few analyses are available for host rocks characterized by a relatively high carbon content. The two analyses presented in table 2 (columns 14, 15), both of which contain carbon, are indicative, though probably not representative, of the composition of black-slate host rocks of late Huronian age in northern Michigan; locally, these rocks are highly ferruginous near concentrations of uranium minerals.

Several of the different kinds of host rocks for uraniferous veins of this group, in addition to those for which analyses are available, are exemplified by the quartzitic and phyllitic members of the Belt Series in the Coeur d'Alene district, Idaho (Kerr and Robinson, 1953), and at the Garm Lamoreaux deposits, Lemhi County, Idaho (Trites and Tooker, 1953, p. 167; F. C. Armstrong and P. L. Weis, written communication, 1954), the metasedimentary rocks—including quartzite, phyllite, silicified limestone, and hornfels—of Paleozoic age in the Reese River mining district, Lander County, Nev. (Sharp and Hetland, 1954), and the highly siliceous Red Creek Quartzite of Precambrian age at the Yellow Canary claims, Daggett County, Utah (Wilmarth, 1953).

INTERMEDIATE- AND HIGH-GRADE METAMORPHIC ROCKS

Metamorphic rocks, including amphibolite, skarn, and many mineralogic varieties of schist and gneiss, host a large number of uranium-bearing veins principally in the Front Range and adjoining areas of Colorado and in more widely distributed areas in Arizona, California, Nevada, New Mexico, New York, North Carolina, Washington, and Wyoming. These completely recrystallized host rocks are the products both of dynamic and thermal metamorphism and, locally, of metasomatic processes. Virtually all the rocks have been designated as of Precambrian age, though some probably are metamorphosed Paleozoic or younger rocks.

The mineralogy of several of the host rocks identified as schist is not given in the reports that describe them. Because such mineralogic data are lacking, all rocks, designated as schist by the various authors, arbitrarily have been included in this group. Some of these rocks may be the products of low-grade metamorphism and, consequently, would be correlative in grade of metamorphism with Niggli's (*in* Grubenmann and Niggli, 1924) "epizone" or Turner's (1948) "greenschist" or "epidote-amphibolite" facies.

Although available data permit the establishment of some qualitative differences in host rocks of this group, data on quantitative chemical and mineralogic differences are scarce or lacking. Virtually all the diversities in mineralogic and chemical composition exemplified by the host rocks heretofore described, by groups, also are known in this group. In addition, several host rocks in this group, particularly skarn, are enriched in certain elements or contain large to moderate amounts of minerals that are present in much smaller amounts in other host-rock groups. A few of the minerals that apparently are most abundant in host rocks of this group are chlorite, biotite, muscovite or sericite, several varieties of amphibole, molybdenite in molybdenite-graphite schist, tourmaline, lime silicate minerals of different compositions, and metamorphic aluminum silicate minerals. These rocks are holocrystalline, exhibit many textural variants and, in general, are foliated, banded, or massive.

Several chemical analyses of these host rocks are presented in table 2, columns 1 to 10; all these analyses are of samples collected from uraniferous vein deposits in the Front Range of Colorado. Considerable variation in the content of basic oxides and acid radicals is indicated by these few analyses, even within this limited geographic area, and greater variations are predictable on the basis of the petrographic names that have been applied to high-grade metamorphic host rocks both in the Front Range and elsewhere.

Uraniferous veins are reported in garnet-quartz rock in the Fall River area, Clear Creek County, Colo. (Hawley and Moore, 1955); in a carbonate-potassium feldspar breccia reef cutting hornblende gneiss at the Union Pacific prospect, Jefferson County, Colo. (Adams and Stugard, 1956a, 1956b); in altered biotite-quartz-plagioclase gneiss and amphibolite in deposits on Nigger Hill, Gilpin County, Colo. (Sims, Osterwald, and Tooker, 1955, p. 5); in lime silicate rock, tourmaline gneiss, and other metamorphic rock types in deposits near Ralston Creek, Jefferson County, Colo.; in quartz-garnet-hornblende-magnetite gneiss (locally magnetite rich) in deposits near Critchell, Colo.; in skarn at the Copper King mine, Colorado

(Sims, Phair, and Moench, 1958); in molybdenite-graphite schist at the Little Man mine, Carbon County, Wyo. (J. W. Adams, oral communication, 1956); in quartz diorite gneiss in the Black Hawk district, New Mexico (Gillerman and Whitebread, 1956); in schist and gneiss in Avery County, N. C.; and in many other kinds of metamorphic host rocks elsewhere.

SOME ASPECTS OF THE PETROLOGIC ENVIRONMENT OF URANIUM-BEARING VEINS

The foregoing summary descriptions of the host rocks of uranium-bearing veins provide some data on the character of the petrologic environment in which uraniferous veins have been found in the conterminous United States. These data demonstrate some of the quantitative and more largely qualitative differences in the mineralogic and chemical composition of the host rocks. The mineralogic and chemical composition of these rocks is extremely diverse, and, even within a single district, many different kinds of rock constitute the host for concentrations of uranium minerals in veins. The physical characteristics of the host rocks also are diverse, particularly as regards their texture, structure or lack of structure, and their competence or lack of competence under stress. Further, the data establish that uranium-bearing veins are in rocks of nearly all geologic ages but are most common in rocks of Precambrian, late Mesozoic, and Tertiary ages.

Although these data establish that the petrologic environment of uranium-bearing veins is extremely diverse in terms of the physical, chemical, and mineralogic character of the host rocks as we now see them, the nature of the petrologic environment at the time of uranium deposition is very obscure. The physical, chemical, and mineralogic character of many of these rocks has been changed either before, contemporaneous with, or after uranium deposition, and not uncommonly these changes are localized or best exemplified in or adjacent to the shear zones containing the veins. Many of these host rocks have been subjected to metasomatism, deuteric alterations, or metamorphism either before, contemporaneous with, or after the introduction of uranium, and many have been altered by either ore solutions or other solutions. Cataclasis has affected the rocks in some deposits to form pseudotachylyte, mylonite, fault gouge, or breccia, any one of which may be critical in establishing the physical characteristics of the environment of uraniferous veins. Furthermore, the petrologic environment of uranium deposition may be characterized in part or entirely, in some deposits, by the nature of metallic or nonmetallic minerals that have been deposited in the vein prior to the introduction of uranium. Thus, although data now available indicate considerable diversity in the petrologic environment of uranium-bearing veins in the United States, the physical, chemical, and mineralogic character of the environment at time of uranium deposition is poorly known.

FREQUENCY DISTRIBUTION OF VEINS BY HOST ROCKS

A critical review was made of the frequency distribution of uraniferous veins in host rocks, using the specific rock names quoted in reports and several different groupings of these rocks, to determine which specific kinds or groups of rocks provide the more favorable environments for uranium-bearing veins and, further, to determine whether these more favorable rocks have particular physical and chemical characteristics in common. This review indicated that the descriptions of host rocks were sufficient only to indicate in a generalized manner the true nature of host rocks and that any comparisons between a large number of the veins in the conterminous United States and their host rocks could only be based on the general characteristics of these rocks. The arbitrary classification of host rocks into the seven groups heretofore described is adequate to segregate the loosely used rock names into geologically meaningful groups and at present is considered the most useful classification in revealing any relationships between veins and host rocks. Further, the classification does permit relatively easy determination of the group in which to place a host rock, regardless of whether that rock has been percisely identified or, as in most places, has been given a general name such as "granitic."

The frequency distribution of 705 deposits that are estimated to represent about 80 percent of the known uraniferous veins in the United States is shown in table 3, by 6 mineralogic classes of uraniferous veins and by the 7 host-rock groups. Inspection of the frequency distribution by host-rock type and by mineralogic class immediately indicates that (a) the host rocks for about one-third of the deposits are felsic to intermediate plutonic or hypabyssal intrusive rocks, (b) the host rocks for one-half of the deposits are igneous rocks, and (c) about one-half of the deposits are in the mineralogic class "veins, dominantly of uranium minerals" (chap. A, p. 11), and these deposits are well represented in all the different host-rock groups. However, the percentage figures as shown on table 3, must be evaluated, and the favorability or nonfavorability of groups of host rocks must be judged with considerable caution. The percentage figures are influenced to different but quantitatively unknown degrees by (a) the relative abundance of outcrops of a

TABLE 3.—*Approximate frequency distribution, in percent, of 705 uranium-bearing veins in the conterminous United States, by mineralogic class, according to host-rock type*

Rock group	Mineralogic class of uraniferous veins						
	Uranium minerals with fluorite gangue abundant or common	Uranium minerals subordinate to base-metal sulfide minerals	Uranium minerals dominant	Magnetite or other iron oxide minerals dominant	Thorium or rare earths minerals dominant	Uraniferous hydrocarbons dominant	Totals by rock group
1. Felsic to intermediate plutonic or hypabyssal intrusive rocks, including alkalic and calcic-alkalic varieties	4.3	10.8	13.3	0.7	1.3	--------	30.4
2. Felsic to intermediate volcanic rocks, including alkalic and calcic-alkalic near surface intrusive, extrusive, and pyroclastic varieties	1.8	2.6	8.9	--------	[1] .1	--------	13.4
3. Intermediate to mafic plutonic, hypabyssal, near surface intrusive and extrusive rocks	--------	1.3	2.0	[1] .1	--------	--------	3.4
4. Clastic sedimentary rocks	.4	2.3	9.1	--------	.3	1.0	13.1
5. Carbonate rocks	2.1	3.5	4.1	.3	--------	.4	10.4
6. Slightly recrystallized sedimentary and igneous rocks, including principally metasedimentary and metavolcanic varieties	.3	3.1	4.8	.3	.4	--------	8.9
7. Low-grade and high-grade metamorphic rocks, including principally silicic to subsilicic varieties of gneiss and schist	.7	10.9	6.1	1.1	1.3	.1	20.2
Total	9.6	34.5	48.3	2.5	3.4	1.5	99.8

[1] One deposit.

particular kind of rock within mining districts or geographically limited areas that have been intensely prospected—particularly the Front Range mineral belt, Thomas Range, Boulder batholith area, White Signal district, Marysvale district, and Sierra Ancha region—in contrast to those districts that have been examined in less detail, (b) the interpretation necessary in classifying some of the different host rocks according to the seven groups, and (c) the difficulty in establishing what constitutes a single uraniferous vein deposit, particularly in those mines or prospects characterized by several veins or ore shoots enclosed in different kinds of host rock. Furthermore, the frequency distribution of uraniferous veins in the seven different groups of host rock may be dependent, in part or entirely, on the relative abundance of a particular host rock within selected parts of the earth's crust or to its outcrop distribution. No valid figures are readily available to solve this problem.

The percentage figures representing totals by rock group (table 3) may conceivably reflect the relative abundance of the different kinds of rocks that crop out in (a) those districts characterized by many known uranium-bearing veins, (b) those parts of the western United States that have been more intensely prospected than others, (c) the Western United States, or (d) those parts of the United States that have been systematically prospected. If these percentage figures are correlative—or nearly so—with the outcrop distribution in any of these four categories, the relations between uraniferous veins and the enclosing host rocks could be fortuitous; and, as a result, the percentage figures would not indicate favorability of one host-rock group in relation to other groups.

The foregoing review of the kinds of rocks that constitute the host for uranium-bearing vein deposits in the conterminous United States has shown that such veins are in rocks of nearly all textural, chemical, and mineralogic types and that they are most abundant in holocrystalline, igneous, and metamorphic rocks characterized by a moderate to high silica content. These rocks have diverse chemical compositions but similar physical characteristics in regard to deformation under stress.

WALLROCK ALTERATION

Although few detailed and comprehensive studies have been made of the wallrock alteration adjoining uranium-bearing veins, the results of these few studies, in combination with voluminous field data, indicate that such alteration is analogous in nearly all ways to the alteration haloes that enclose other kinds of vein deposits. Because of these similarities, the results of recent studies and summaries on the character of wallrock alterations and the processes involved in their formation by Lovering and others (1949), Lovering (1950), Sales and Meyers (1948), Kerr (1955), Schwartz (1955), White (1955), and others, have a direct bearing on the wallrock alteration associated with uranium-bearing vein deposits. This section of the report will adhere, in so far as is practical, to these similarities and will discuss any apparent or real quantitative or qualitative difference.

Most alteration halos are mineralogically zoned as a result of decreasing alteration intensities from the vein outward with boundaries between different zones being either sharp or gradational. For purposes of generalization in this report, three principal zones are delineated—namely, a sericitic zone closest to the vein, an argillic zone, and a chloritic zone furthest from the vein (fig. 2). In some veins none of these zones has been recognized, and presumably in these places the rocks are unaltered.

PHYSICAL ASPECTS OF ALTERATION

Some uranium-bearing veins are enclosed in unaltered rocks, but most exhibit some megascopic evidence of wallrock modification or reconstitution adjacent to the vein. In most places the mineralogic and chemical alteration of the wallrock is manifest by readily observable physical changes in color, texture, and competence. Bleaching and softening of the rocks is most common, largely as a result of the transformation of original silicate minerals into a more or less porous incoherent fine-grained mass of light-colored alteration products of which the most abundant are sericite and minerals of the kaolinite or montmorillonite groups. Some veins show wallrock alteration as envelopes that are faintly to intensely stained red, yellow, or brown, largely by iron oxide minerals, or grayish green or green, in part through the development of secondary silicate minerals containing ferrous iron; some alteration envelopes are hard, resistant silicified zones that are of different shades of gray, green, red, yellow, brown, or white. Though some alteration sheaths are rather uniform in their appearance, many show considerable heterogeneity of coloring material, alteration textures, porosity, and competence. The heterogeneous character of these alteration halos has resulted largely from (a) differences in the composition and relative stability of host rocks, (b) probable local differences in chemistry of altering solutions, and (c) differences resulting from several periods and kinds of alteration. Many alteration halos contain different zones representing different types and intensities of alteration; locally, this zonation is megascopically distinct.

In some deposits the alteration zones are closely related in space to concentrations of uranium and associated minerals, but elsewhere alteration is much more widely distributed than the ore and gangue minerals. Locally, the alterations form a sheath of rather uniform thickness adjacent to veins or fractures, particularly where the host rocks are physically and mineralogically uniform. Where the host rocks are diverse or where fracturing is intense and widespread, the alteration halos are commonly quite irregular in shape. The alteration halos—or the different zones within a halo—range from a fraction of an inch to several tens of feet in thickness.

MINERALOGIC ASPECTS OF ALTERATION

The alterations most frequently referred to in the literature as associated with uranium-bearing veins are those in which the wallrocks have been silicified, argillized, sericitized, chloritized, pyritized, or hematitized; most common reference is made to argillic alteration. Less common reference is made to several other alterations including albitization or feldspathization, tourmalinization, dolomitization, propylitization, and carbonatization. An accurate analysis of the geologic significance of these less common alterations is complicated by (a) the lack of data on spatial and paragenetic relations of several of these alterations to uranium and associated minerals, even though they are known to occur in the same deposit, and (b) the presence of many of the minerals characterizing these alterations—particularly secondary feldspars, chlorite, epidote, and zoisite derived through propylitization,

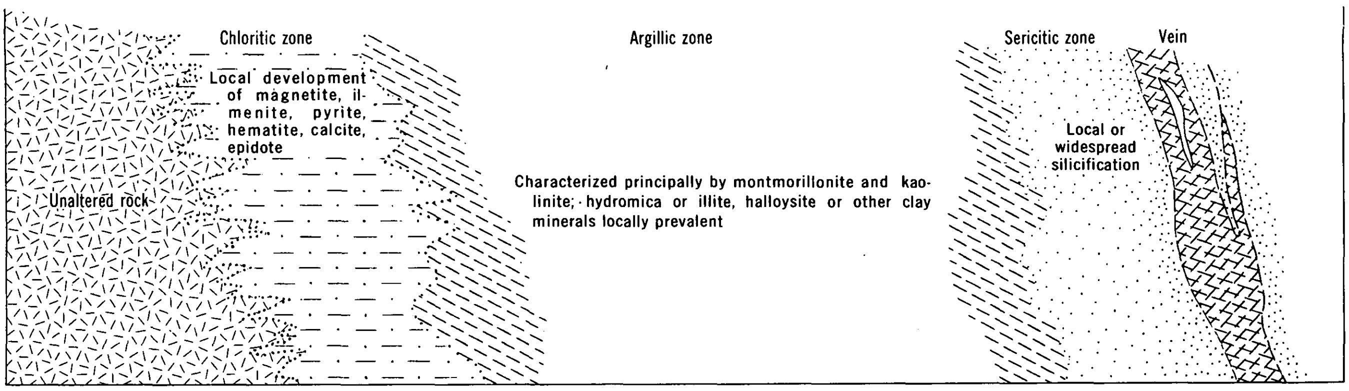

FIGURE 2.—Composite sketch diagram showing general mineralogic features of wallrock alteration zones adjoining uranium-bearing veins.

and secondary carbonate minerals—as constituents of alteration halos that are dominated by sericitized, argillized, or chloritized rocks. The assemblage of alteration minerals that has been reported includes not only all those specifically characterizing the different alteration zones but also several other minerals derived wholly or in part from constituent minerals of the host rocks. Included are magnetite, ilmenite, hydrated iron oxides, hydromica or illite, alunite, opal, chalcedony, and biotite.

In those places where wallrock alterations associated with uranium-bearing veins have been studied in detail, the alterations have been shown to exhibit similarities in mineralogy and in the distribution of alteration products. Wright (1954, p. 146), in reporting on the alteration halo at the Caribou mine, Boulder County, Colo., states,

> The major features of the pattern—relative stability of the primary mineral groups in zones of different alteration intensity, the alteration minerals developed, sequence of formation of the alteration products, and progressive chemical changes with increasing intensity of alteration—conform rather closely to a general pattern that has emerged from hydrothermal alteration studies in many districts * * *.

His statement applies with equal cogency to alteration halos accompanying many uranium-bearing veins.

The major mineralogic features of the wallrock alteration pattern, as shown diagramatically in figure 2, can be generalized into three principal zones characterized most commonly by the presence or dominance of sericite, by different clay minerals, and by chlorite in the altered host rock. This generalized alteration pattern is based largely on the results of studies at the Caribou mine (Wright, 1954; Moore, Cavender, and Kaiser, 1957), of base-metal sulfide veins that locally contain uranium in the Central City–Idaho Springs area, Gilpin and Clear Creek Counties, Colo. (Tooker, 1955; Sims and Tooker, 1955; Tooker, 1956; Sims, Osterwald, and Tooker, 1955, p. 15–16; Kerr and others, 1951), of uraniferous veins in the Boulder batholith, Montana (D. Y. Meschter, written communication, 1953; Wright and Bieler, 1953; Wright and others, 1954; Roberts and Gude, 1953, p. 148–149; Becraft, 1956, p. 120; Sam Rosenblum, written communication, 1956), and at Marysvale, Utah (Taylor and others, 1951; Kerr and others, 1952, 1953; Kerr, 1956; Kerr and others, 1957). Many other alteration halos associated with uraniferous veins, though described in considerably less detail, apparently also conform to a part or all of this alteration pattern. The halos in some deposits exhibit zones of sericitized, argillized, and chloritized rock, whereas in other deposits one or another of these zones of alteration is absent in the halo.

The sericitic zone, which is closest to the vein, is characterized principally by sericite and fine-grained quartz but may contain considerable kaolinite and pyrite and, locally, some disseminated base-metal sulfide minerals. Characteristically, the quartz-sericite ratio increases veinward, and, locally, an innermost siliceous part of the sericite zone is gradational into the adjacent vein. Consequently, detailed descriptions of several alteration halos have delineated a siliceous subzone immediately adjacent to the veins. Furthermore, Rosenblum (written communication, 1956) reports concentrations of tourmalinized rock in the silicified part of the sericite zone adjacent to veins in the Boulder batholith; Trites and Thurston (1958) report tourmalinized rock associated with sericitized and silicified rhyolite porphyry at Majuba Hill, Nev.; and Wright (1954, p. 138) reports abnormal amounts of calcite in the sericite zone at the Caribou mine.

The argillic or intermediate zone is characterized principally by minerals of the montmorillonite or kaolinite groups although other clay minerals or hydromica (illite?) are locally prevalent; most commonly the kaolinite-montmorillonite ratio increases toward the vein, but some minor reversals in this pattern have been noted. Several detailed descriptions of alteration halos indicate a subdivision of the argillic zone into montmorillonite-rich and kaolinite-rich zones or subzones.

The chlorite, or outermost, zone of alteration is characterized principally by chlorite, derived largely from ferromagnesian minerals in the host rock, and by the incipient alteration of plagioclase to montmorillonite, kaolinite, and sericite. Several other alteration products are common and locally may be more abundant than chlorite; dominant among these are magnetite, ilmenite, biotite, epidote, calcite, and either hematite or pyrite.

All the alterations described by various authors differ in minor details from the composite and idealized alteration pattern—composed of chloritic, argillic, and sericitic alteration zones—shown in figure 2. These minor differences are (a) the absence of one or more of the three alteration zones in some deposits, (b) the distinction by several geologists of additional alteration zones (or subzones) in a few deposits, or (c) variations from one deposit to another in the presence or relative abundance of certain alteration minerals within comparable zones. Many of these differences are the result of original compositional differences in the enclosing rocks, whereas other differences are more largely attributable to alteration intensities and to the physical and chemical characteristics of the altering solutions.

Characteristically, the chloritic zone of alteration is lacking or only weakly developed around deposits enclosed in host rocks with only minor amounts of ferromagnesian minerals, as for example at Majuba Hill in rhyolite porphyry (Trites and Thurston, 1958), at the Moonlight mine, Nevada, in acid volcanic rocks (Taylor and Powers, 1955), at uranium deposits in siltstone and hornfels of the Dripping Spring Quartzite in Gila County, Ariz. (Granger and Raup, 1959), in the Colorado Front Range at several deposits enclosed in felsic crystalline rocks (P. K. Sims, oral communication, 1956), and probably at the Los Ochos mine, Colorado, in the Morrison formation (Derzay, 1956). Because a typical chloritic zone is lacking, these deposits are characterized principally by argillized, sericitized, and commonly silicified rocks. The alterations accompanying many uraniferous veins in felsic igneous rocks and in some feldspathic sedimentary and metasedimentary rocks have been identified in the field as argillic or kaolinitic; presumably, most have formed at lower alteration intensities than alteration halos characterized by sericitic zones.

Where the host rocks contain greater amounts of ferromagnesian minerals or, locally, where altering or ore solutions introduced iron and possibly other ions, the chloritic zone is commonly developed. Within the chloritic zone of alteration, several different iron minerals are commonly present, including several iron silicate minerals as well as magnetite, pyrite, and hematite. Because hematite—or hematitic alteration—has received considerable attention by uranium geologists throughout the world and because this alteration may be more commonly associated with uranium-bearing veins than with other veins, the hematite alteration will be discussed further.

HEMATITE ALTERATION

Hematite in and adjacent to uranium-bearing veins in many different parts of the world has led to the generally accepted concept that hematitic alteration is perhaps a widely applicable and diagnostic feature of uranium mineralization in veins. This general concept has been cited by Everhart and Wright (1953, p. 94), who state, "One of the most persistent features of pitchblende deposits is accompanying hematitic alteration of vein matter and wallrock." Nininger (1954, p. 27–28), in describing the morphology and occurrence of pitchblende, has given further recognition to this concept as follows:

> The presence of hematite (a red iron oxide mineral) extending from the pitchblende a few inches to a few feet into the wall rock is the most characteristic feature [of alteration]. The formation of hematite has occurred in all of the major pitchblende vein deposits and in many of the deposits of minor importance.

Although the spatial association of uranium minerals and hematite in many uraniferous vein deposits throughout the world cannot be denied, it is by no means universal; and, within the conterminous United States, Everhart (1956, table 2) has demonstrated that this association is not particularly common. Consequently, the pertinent data bearing on this concept are reviewed.

No clear-cut distinction is made in the following pages between hematite in the vein, which may constitute either a hypogene vein mineral, a product of supergene alteration, or a product of radiation-induced oxidation (Adams, Gude, and Beroni, 1953, p. 16; Lovering, 1955, p. 192), and hematite in the wallrocks, which presumably is derived wholly or in part as a product of hydrothermal alteration; because, for many deposits, data are lacking to make such a distinction.

Red, hematitic alteration or iron-stained chert or jasper in association with concentrations of uranium minerals in veins has been noted in most deposits in the Goldfields region of Saskatchewan, Canada (Lang, 1952; Robinson, 1955), at the Eldorado mine, Northwest Territories, Canada (Lang, 1952, p. 53; Murphy, 1946), in several deposits in the Montreal River district, Ontario (Lang, 1952; Wright, 1951), at both St. Joachimsthal and Johanngeorgenstadt in central Europe (Everhart and Wright, 1953), in deposits in Cornwall, Great Britain (Davidson, 1956, p. 205), in some but not all vein deposits in Portugal (Cavaca, 1956, p. 184) and in France (Geffroy and Sarcia, 1954), at the President Perón deposit, Argentina (Belluco, 1956, p. 87), and at Radium Hill (Sprigg, 1954; Whittle, 1954a,b, p. 139), Mount Painter (Stillwell and Edwards, 1954, p. 95), and Rum Jungle (Fisher and Sullivan, 1954) in Australia. Other uraniferous vein deposits of lesser importance characterized by hematitic alteration could be listed. Within the conterminous United States, hematite is a common associate of uranium minerals in and adjacent to several vein deposits; although, at most deposits, the pervasive stain or coloration of wallrocks characteristic of several of the foreign vein deposits is absent. Hematite—or iron-stained jasper—has been noted in greater or lesser quantities at the Sunshine mine, Idaho (Kerr and Robinson, 1953, p. 506–507), at Marysvale, Utah (Taylor, and others, 1951; Kerr, 1956, p. 634; Walker and Osterwald, 1956b, p. 125), at the Red Bluff mine, Arizona (Everhart, 1956), the Caribou mine, Colorado (Wright, 1954, p. 136), the Union Pacific prospect and the Buckman adit, Colorado (Adams and Stugard, 1956a), at the Prince mine, New Mexico (Walker and Osterwald, 1956a), at Bisbee, Ariz. (Bain, 1952, p. 308–309), at the Silver King claims, Utah (Hillier, 1956), and in several other vein deposits elsewhere.

The presence of hematite in these deposits, irrespective of any stated or inferred genetic or environmental relationship, has led to the general concept heretofore mentioned.

In contrast to those uraniferous vein deposits characterized by the presence of hematite, there are a larger number of deposits which, according to available data, probably contain little or no hematite. Neither Thoreau and du Trieu de Terdonck (1933) nor Derriks and Vaes (1956) mention the presence of hematite at Shinkolobwe, one of the largest known uraniferous vein deposits in the world, although Derriks and Vaes (1956, fig. 6) do delineate several units of rose and lilac breccia; the identity of the coloring material is not given, Hematite seems to be lacking in the vein deposits at Tyuya Muyun, Turkistan, in some of the deposits of Portugal and France, in a few of the deposits in the Goldfields region, Saskatchewan, Canada, and in the Mary Kathleen uranium deposit, Australia (Matheson and Searl, 1956). The deposits in the vicinity of Spokane, Wash., and Kern Canyon, Calif., many of the deposits in acid volcanic rocks in Oregon, Nevada, and California, those in the Boulder batholith, Montana, deposits in the Cochetopa district, Colorado, the lower parts of the vein deposits at Marysvale, Utah, and most of the deposits in the Front Range of Colorado and the Dripping Spring Quartzite, Arizona, which collectively represent a very large part of all the known uraniferous vein deposits in the conterminous United States, do not contain abnormal amounts of hypogene hematite either in the vein or as hematitic alteration of the adjoining wallrocks.

Although there is little doubt that hematite and uranium occur together in a large number of veins throughout the world, the geologic significance of this association is not well documented. Hematite, which forms by either hypogene or supergene processes, is a ubiquitous and locally abundant mineral in the earth's crust irrespective of the presence or absence of uranium minerals. Consequently, it is difficult to establish (a) what is an "abnormal" amount of hematite, particularly in consideration of the trace amounts of hematite necessary to give the characteristic red coloration, either in a uraniferous vein deposit or elsewhere; (b) what is the ratio of hypogene hematite to supergene hematite in those uraniferous vein deposits characterized by this association; (c) what percentage of the hematite in these deposits results from radiation-induced oxidation of ferrous iron (chap. D); (d) what, if any, genetic association exists between uranium and hematite; (e) in what percentage of different places is this association fortuitous, and, conversely, in what places does this association represent a favorable iron-rich environment for the precipitation of uranium minerals; and (f) what percentage of nonuraniferous ore deposits contain hematite. None of these questions can be answered with complete satisfaction, and some data bearing on the problem are conflicting. It is interesting to note, however, that magnetite and hematite are abundant in many pyrometasomatic deposits (Knopf, 1933, p. 538) and are major constituents of many hydrothermal deposits (McLaughlin, 1933, p. 558) that are not known to contain uranium.

It is generally accepted that some, and perhaps most, of the hematite in and adjacent to uraniferous vein deposits is hypogene and is closely related to, though not necessarily contemporaneous with, uranium deposition. A mechanism whereby primary uranium minerals can be deposited simultaneously with the formation of hematite is based on ferrous iron, presumably in the wallrocks, acting as a reducing agent for uranyl ions carried in solution. Gruner (1952, p. 16) has coprecipitated pitchblende and hematite under controlled conditions in the laboratory, and McKelvey, Everhart, and Garrels (1956, p. 43–44) have postulated that the "widespread" association of iron oxides with pitchblende in veins can be explained by the following reaction:

$$3H_2O+2Fe^{+2}+(U^{+6}O_2)^{+2} \rightarrow Fe_2O_3+U^{+4}O_2+6H^{+1}.$$

In some deposits the spatial association and the apparent simultaneous deposition of uranium and hematite would seem to bear out the efficacy of this oxidation-reduction reaction; in other deposits the hematite appears to have formed either prior to or after pitchblende deposition through oxidation of iron-bearing minerals of the wallrocks. Whittle (1954a, p. 66) and Webb and Whittle (1954, p. 121) have presented evidence indicating that the uranium was introduced after the formation of hematite and, locally, replaces it in several of the Australian deposits. Conybeare and Campbell (1951, p. 76, 78–79) have indicated that pitchblende in deposits north of Goldfields also was introduced after hematite mineralization. A brief description by K. R. Dawson (*in* Lang, 1952, p. 27) of the red alteration in the Goldfields district includes the following:

> The width of the altered zone does not appear to bear any consistent relationship to occurrences of pitchblende. In the Martin Lake workings, the alteration was effective for the same uniform width along barren fractures as along radioactive veins. At the Ace, it bears a closer relationship to the St. Louis fault than to the occurrence of pitchblende, as though the alteration preceded the pitchblende mineralization. The veins in that mine occur in shatter zones within the zones of strong red alteration, unaccompanied by any additional alteration. I do not believe a general rule regarding the width of the alteration relative to the occurrence of pitchblende will be found to apply to the camp as a whole. It is also noteworthy that there are numerous zones of "red alteration" in the area around Goldfields, which are megascopically identical with those carrying pitchblende but which are barren.

A closer relation between hematite and uranium for deposits in the Goldfields region has been indicated by Robinson (1955, p. 58), who stated that hematite "* * * is the most common and intimate metallic associate of pitchblende * * * and * * * almost invariably forms a thin coating on all available surfaces of masses of pitchblende."

As a result of detailed paragenetic studies of the ores from the Eldorado mine, Canada, Kidd and Haycock (1935) have found that hematite was formed later than the pitchblende and earlier than several carbonate gangue minerals and many of the base-metal sulfide minerals. This paragenetic relationship between hematite and pitchblende tends to substantiate an impression held by the author that hematite is not coextensive, in detail, with pitchblende. The author's impression is based both on personal observation of the Eldorado mine in 1954 and, more largely, on discussions with Mr. L. T. Jory, then Chief Geologist at Eldorado. Furthermore, according to Jory (oral communication), argillic alteration is the most dominant alteration on all veins and seems to be closely associated with uranium mineralization.

Hematite, in the President Perón deposit, Argentina, apparently was derived as a result of supergene alteration of magnetite, pyrite, or other iron-bearing minerals. According to Belluco (1956, p. 87), "* * * The hematite, as a product of alteration, partly colors the oxidized zone of the veins red * * *."

Adams and Stugard (1956a), in studying the Union Pacific prospect, hypothesized that ferrous iron released by alteration of hornblende in the wallrocks is partly oxidized to hematite and that uranium is simultaneously reduced and deposited as pitchblende in the vein; in the nearby Buckman adit, hematite replaces quartz and sulfides and veins the pitchblende. Both hypogene crystalline hematite and supergene hematite are present in the Prince deposit, New Mexico; some evidence indicates contemporaneous precipitation of uranium and the hypogene hematite (Walker and Osterwald, 1956a). At Marysvale, a thin alteration zone marked by trace amounts of hematite around some ore bodies—and incidentally peripheral to zones of fracturing—occurs principally in the hypogene(?) zone, but at places it persists in the zone of supergene alteration. The distribution of other kinds of alteration at Marysvale, upon which the hematite zone seems to be impressed, suggests that most of the alteration may be related to near-surface oxidation of pyrite (Walker and Osterwald, 1956b, p. 125). If so, the hematite at Marysvale mostly likely is also supergene, although Laverty and Gross (1956, fig. 37*F*) indicate that some hematite is paragenetically closely related to many of the hypogene minerals of the deposit. Hematite, both in the vein and as intense wallrock staining, is prevalent in several of the deposits in the United States characterized principally by thorium and rare earths minerals and lesser amounts of uranium. According to J. W. Adams (oral communication, 1956), some, and perhaps most, of the hematite in these deposits has resulted from the near-surface oxidation of pyrite.

The general concept that hematite in veins or hematitic alteration of adjoining wallrocks is a widely applicable and diagnostic feature of uranium mineralization in veins is neither proved nor disproved by a critical review of the pertinent data. Like other kinds of alteration, hematitic alteration or iron-stained chert or jasper locally serve as useful guides to permeable structures that may or may not be mineralized with uranium.

SUMMARY

Although many of the published and unpublished data regarding the host rocks of uranium-bearing veins in the conterminous United States are of questionable accuracy, these data, in combination with some precise data, field and office review, and selected thin-section study, do permit several broad generalizations regarding the petrologic environment of uraniferous veins.

In general, the host-rock environment of uranium-bearing veins in the United States is diverse; the age and the mineralogic and chemical composition of the rocks in which such veins are known to occur are especially diverse. In physical characteristics, the host rocks also are dissimilar; however, three-quarters of the known uranium-bearing veins are enclosed in igneous and metamorphic rocks that lack any important plastic-flow phenomena under near-surface conditions of pressure and temperature and that are more apt to rupture under stress than other kinds of rock. The considerable differences in mineralogic and chemical composition of the host rocks, as we now see them, indicate that the environment of uranium deposition probably was equally diverse; however, because many of the host rocks have been modified, reconstituted, or mineralized either before, during, or after the introduction of the uranium, the true nature of the depositional environment is poorly known.

In general, uranium-bearing veins are enclosed in alteration halos that show no significant differences from alteration halos that enclose other kinds of vein deposits.

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Mineralogy, Internal Structural and Textural Characteristics, and Paragenesis of Uranium-Bearing Veins in the Conterminous United States

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GEOLOGY OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

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MINERALOGY, INTERNAL STRUCTURAL AND TEXTURAL CHARACTERISTICS, AND PARAGENESIS OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

By George W. Walker and John W. Adams

ABSTRACT

Of the many known minerals that contain uranium as either an essential or nonessential constituent, 55 species have been reported from uraniferous veins in the conterminous United States. Among these are a few simple oxides or silicates of uranium, a few multiple oxides of uranium in combination with other elements, and a large number of brightly colored uranyl vanadates, phosphates, arsenates, silicates, carbonates, and hydroxides. The minerals that contain nonessential, extrinsic or vicarious uranium include fluorite, opal, rutile, pyromorphite, thorite, magnetite, and possibly hematite, and probably several of the rare-earths minerals.

The nonuraniferous minerals associated with uranium-bearing veins are those commonly found in metalliferous deposits, and no particular species appears to be distinctive. Dominant among the metallic minerals of uranium-bearing veins are pyrite or marcasite, galena, chalcopyrite, sphalerite, jordisite or molybdenite, arsenopyrite, argentite, stibnite, magnetite, hematite, and many of their oxidation products. The common nonmetallic minerals are fluorite, quartz, chalcedony, opal, barite, adularia, chlorite, and several varieties of calcium, magnesium, or iron carbonate minerals. In some deposits, radiation damage to some gangue minerals has created distinctive characteristics including changes in internal crystallinity, thermoluminescent properties, and coloration. The coloration changes are the most evident expression of radiation damage and are best demonstrated by dark purple to black fluorite, by smoky quartz, and possibly by a reddish-brown coloration in some deposits that may be attributable to radiation-induced oxidation of ferrous iron.

Uranium-bearing veins in the conterminous United States, in general, are similar in internal structural and textural characteristics to those epithermal and mesothermal vein deposits in which the introduced minerals fill open epigenetic pore spaces or cavities. Cataclastic textures are common, whereas replacement textures, specifically between uranium and nonuranium minerals, have been reported in only a few places. Texturally, primary uranous oxide in virtually all veins is the colloform or sooty variety of uraninite herein called pitchblende. Idiomorphic crystals of uraninite in vein deposits are known to occur only at Bisbee, Ariz., the Little Man mine, Wyoming, and in several deposits in the Dripping Spring Quartzite, Sierra Ancha region, Arizona. Idiomorphic brannerite and uranothorite have been reported in a few other veins.

Many metals are associated with uranium in vein deposits, but only a few metals—notably molybdenum, manganese, beryllium, tungsten, vanadium, niobium, yttrium, and zirconium—seem to show a positive and geologically significant correlation to uranium in some deposits, districts, or areas. The other metals associated with uranium, such as lead, zinc, copper, silver, and possibly cobalt, seem to be associated with uranium only in the sense of occurring within the same favorable geologic environment. The vein deposits in the conterminous United States that have yielded the largest tonnages of uranium ore in general contain less than economic quantities of metals other than uranium; these vein deposits include the Schwartzwalder and Los Ochos mines, Colorado, Marysvale deposits, Utah, Daybreak and Midnite mines, Washington, Early Day mine, Nevada, deposits in the Dripping Spring Quartzite, Arizona, and several other deposits in volcanic or tuffaceous rocks in the western United States.

Primary pitchblende is one of the earliest metallic minerals to form during any single stage of vein formation in most veins in the United States. However, the early pitchblende may be subject to partial solution and reprecipitation during later mineralization stages. This younger pitchblende may be represented by a hard highly lustrous colloform variety or by the sooty variety and can be expected to show apparently anomalous paragenetic relations.

INTRODUCTION

The study of the many uranium deposits discovered in the conterminous United States in recent years has contributed much data on the mineralogy of uranium-bearing veins and on the geographic distribution and abundance of the uranium-bearing minerals. Somewhat less data have resulted from these studies regarding the paragenetic relations of these minerals and the detailed textural or structural characteristics of the veins that contain them. Most uranium minerals in veins in the conterminous United States were originally identified and their occurrences described as a result of studies of a small number of deposits in districts of wide geographic distribution (Frondel, 1957), including principally Joachimsthal, Bohemia; Wölsendorf, Bavaria; deposits near Schneeburg, Saxony; Shinkolobwe, Belgian Congo; and Great Bear Lake, Canada. Many minerals that were identified in these and other deposits were thought to be very rare mineral species as late as 1949 (George, 1949); our knowledge of the occurrence and abundance of these minerals has increased enormously since then, and species once considered rare have been found to be sufficiently abundant to constitute ore in some places. In addition, several newly discovered species of uranium minerals, including principally andersonite, swartzite, bayleyite, umohoite, and coffinite, that occur in veins and other deposits have been described.

The purpose of this paper is to summarize and review some of the recent mineralogic information relevant to uranium-bearing veins in the United States as well as to describe some of the reported mineralogic associations and the modes of occurrence of the uranium minerals in veins.

For convenience, uranium-bearing veins are subdivided into eight mineralogic classes (chap. A, p. 8–13), most of which are intergradational, and only a few of which are commercially important sources of uranium in the United States. The classification is based largely on the mineralogic characteristics of more than 400 vein deposits in the conterminous United States and, to a lesser extent, on the characteristics of deposits in other parts of the world.[1] One mineralogic class of deposits—davidite-bearing veins—is not known to occur in the conterminous United States. The eight mineralogic classes of uranium-bearing veins are:

1. Fluorite-bearing veins
2. Base-metal sulfide veins
3. Veins dominantly of uranium minerals but containing minor amounts of other introduced metallic minerals
4. Magnetite or other iron oxide-bearing veins, excluding deposits in gossan derived from supergene alteration of base-metal sulfide deposits but including those uraniferous deposits characterized dominantly by magnetite, hematite, or limonite
5. Veins dominantly of thorium or rare-earths minerals
6. Brannerite-bearing quartz or siliceous veins
7. Davidite-bearing veins
8. Hydrocarbon-rich uranium-bearing veins.

URANIUM-BEARING MINERALS OF VEINS

Of the many known minerals that contain uranium as either an essential or nonessential constituent, 55 species have been reported from uraniferous veins in the conterminous United States (table 1). The uranium minerals containing 4-valent uranium are few in number and include uraninite or its colloform variety, pitchblende, ianthinite (or epianthinite), coffinite, uranothorite, and brannerite. All the known occurrences of these 4-valent uranium minerals indicate that, with the exception of ianthinite, possibly some coffinite, and some sooty pitchblende, deposition took place in a primary reducing environment. In addition, uranium-bearing hydrocarbons, present in several deposits, probably contain mostly 4-valent uranium. All the uraninite or pitchblende found in nature contains some 6-valent uranium that has been derived through oxidation of 4-valent uranium. Uranothorite, brannerite, and possibly ianthinite and coffinite also contain some 6-valent uranium as a result of either oxidation or metamictization.

A large number of uranium minerals characterized by 6-valent uranium have been found in the oxidized parts of veins; included are uranyl arsenates, carbonates, phosphates, silicates, sulfates, vanadates, and molybdates (table 1). Of these minerals, uranophane, autunite or meta-autunite, torbernite or metatorbernite, uranocircite or metauranocircite, carnotite, tyuyamunite, and kasolite have been reported in the largest number of deposits and presumably are the most abundant of the 6-valent uranium minerals in veins. In addition, reference has been made to "gummite" in a large number of deposits and to johannite or zippeite in several veins, the latter two minerals occurring as encrustations on mine walls. In many vein deposits these minerals have resulted from oxidation of primary 4-valent uranium minerals and are therefore rightly labelled "secondary" uranium minerals. In many other deposits, however, evidence indicates that the 6-valent uranium minerals were deposited in vein structures, under oxidizing conditions, directly from circulating ground waters or other solutions containing uranium of unknown origin; consequently, they are the primary uranium minerals of these deposits.

In some uranium-bearing veins, at least part of the uranium is a nonessential, extrinsic or vicarious constituent of a variety of minerals including fluorite, opal, rutile, pyromorphite, thorite, magnetite and possibly hematite, base-metal sulfide minerals, and probably several of the rare-earths minerals, as for example, allanite and monazite. Arbitrarily, the base-metal sulfide minerals are omitted from table 1 because they contain insignificant amounts of uranium, which is generally less than 10 parts per million (Wright and Shulhof, 1957a). In some minerals containing uranium as a nonessential constituent, the uranium is probably present as microscopic or, more commonly, submicroscopic inclusions of unidentifiable uranium minerals. In other minerals, the exact mode of occurrence of the uranium is unknown but probably follows

[1] Descriptions of the eight mineralogic classes of uranium-bearing veins and several examples of both foreign and domestic deposits of the different classes of veins are contained in chapter A.

TABLE 1.—*Minerals that contain uranium either as an essential or a nonessential constituent identified from veins in the conterminous United States*

Uranium minerals	Frequency of occurrence in vein deposits or districts [1]	Selected localities [2]	References or remarks
Arsenates:			
Heinrichite	Rare	White King property, Lake County, Oreg	Gross and others, 1958.
Metaheinrichite	do	do	Do.
Metazeunerite	Uncommon	Majuba Hill, Pershing County, Nev	Trites and Thurston, 1958, p. 202.
Novacekite?	Rare	White King property, Lake County, Oreg	Matthews, 1955.
Troegerite?	do	Bald Mountain district, Lawrence County, S. Dak	George, 1949, p. 158.
Uranospinite	do	Deposits in Washoe County, Nev	Laboratory report, U.S. Geol. Survey.
Walpurgite	do	Miracle mine, Kern County, Calif	W. A. Bowes, written communication, 1957.
Carbonates:			
Andersonite	do	Hillside mine, Yavapai County, Ariz	Axelrod and others, 1951.
Bayleyite	do	do	Do.
Leibigite	do	Midnite mine, Stevens County, Wash., and Silver Cliff mine, Niobrara County, Wyo.	Weis, 1955, p. 224; George, 1949, p. 179.
Rutherfordine	do	W. Wilson mine, Jefferson County, Mont	Roberts and Gude, 1953, p. 78.
Schroeckingerite	Uncommon	Marysvale, Piute County, Utah	Taylor and others, 1951.
Swartzite	Rare	Hillside mine, Yavapai County, Ariz	Axelrod and others, 1951.
Voglite	do	W. Wilson mine, Jefferson County, Mont	Roberts and Gude, 1953, p. 78.
Molybdate:			
Umohoite	do	Marysvale, Piute County, Utah	Kerr and others, 1953.
Titanate:			
Brannerite	Uncommon	Chaffee County, Colo., and Mono County, Calif.	Adams, 1953; Pabst, 1954.
Oxides-hydroxides:			
Becquerelite	Rare	Billikin lode, Jefferson County, Colo	Laboratory report, U.S. Geol. Survey.
Ianthinite and possibly epianthinite.	do	Marshall Pass area, Saguache County, Colo	E. J. Young, oral communication, 1956.
Schoepite	do	Abe Lincoln mine, Yavapai County, Ariz	Raup, 1954, p. 181.
Pitchblende and uraninite	Common	Marysvale, Utah and Central City district, Colorado	Everhart, 1956; Sims and Tooker, 1956.
"Gummite"	Common?	W. Wilson mine, Jefferson County, Mont.; Buckhorn claims, Washoe County, Nev., and Lassen County, Calif.	Becraft, 1956; Hetland, 1955.
Phosphates:			
Autunite	Common	White Signal and San Acacia districts, New Mexico	Lovering, 1956.
Bassetite	Rare	Deposits in Dripping Spring Quartzite, Gila County, Ariz.	Granger, 1955, p. 134.
Dumontite	do	Green Monster mine, Clark County, Nev	Albritton and others, 1954, p. 87-88.
Meta-autunite	Common	Daybreak mine, Spokane County, Wash	Weis, 1955, p. 225.
Metatorbernite	do	Eureka Gulch area, Gilpin County, Colo	Sims, Osterwald, and Tooker, 1955.
Metauranocircite	Uncommon	Deposits in Dripping Spring Quartzite, Gila County, Ariz.	Granger, 1955, p. 134.
Phosphuranulite	do	Marysvale, Piute County, Utah	Kerr and others, 1954, p. 44.
Sabugalite	Rare	Tusas Mountains, Rio Arriba County, N. Mex	Everhart, 1956.
Saléeite?	do	White King property, Lake County, Oreg	Schafer, 1955.
Torbernite	Common	Moonlight mine, Humboldt County, Nev	Taylor and Powers, 1955.
Silicates:			
Beta uranophane	Uncommon	Deposits in the Boulder batholith, Montana	Wright, Bieler, and others, 1954.
Coffinite	Uncommon ?	Leyden (Jefferson County) and Copper King (Larimer County) mines, Colorado.	Stieff, Stern, and Sherwood, 1956.
Kasolite	Common	East Walker River area, Lyon County, Nev	Staatz and Bauer, 1953.
Sklodowskite	Rare	Honeycomb Hills, Juab County, Utah	Wilmarth and others, 1952, p. 15.
Soddyite	do	do	Do.
Uranophane	Common	Silver Cliff mine, Niobrara County, Wyo	Wilmarth and Johnson, 1954.
Uranothorite	Uncommon	Jamestown district, Boulder County, Colo	Phair and Shimamoto, 1952.
Sulfates:			
Johannite	do	Gilpin County, Colo	Palache, Berman, and Frondel, 1944; 1951, v. 2, p. 607.
Uranopilite	Rare	Marysvale, Piute County, Utah	Gruner, Gardiner, and Smith, 1954, p. 31.
Zippeite	Uncommon	Garm-Lamoreaux mine, Lemhi County, Idaho	F. C. Armstrong and P. L. Weis, written communication, 1954.
Vanadates:			
Carnotite	do	Thomas Range, Juab County, Utah, and Kern Canyon, Kern County, Calif.	Staatz and Osterwald, 1956, 1959; Everhart, 1956.
Metatyuyamunite	do	Huron River deposit, Baraga County, Mich	Vickers, 1956.
Tyuyamunite	do	Deposits in Pryor Mountains, Carbon County, Mont	Laboratory report, U.S. Geol. Survey.
Rauvite	Rare	Marysvale area, Piute County, Utah	Walker and Osterwald, 1956a, p. 127.
Sengierite	do	Bisbee, Cochise County, Ariz	Hutton, 1957.
Uranium-bearing minerals and hydrocarbons:			
Fluorite	Common	Thomas Range, Juab County, Utah	Staatz and Osterwald, 1956, p. 133-134.
		Hanosh Mines property, Sierra County, N. Mex	H. D. Wolfe, written communication, 1953.
		Pedad prospect, Jackson County, Colo	E. C. Winterhalter, written communication, 1953.
Hydrated iron oxides	do		Lovering, 1955.
Hydrozincite	Rare	Goodsprings district, Clark County, Nev	Barton, 1956.
Chrysocolla	do	do	Do.
Hyalite opal	Common	Marysvale, Piute County, Utah	Kerr and others, 1952.
Pyromorphite	Rare	"Spelbrink" claim and Golondrina claim, Arizona	Wright, R. J., 1950.
Rutile	do	New Years Eve mine, Pima County, Ariz	Laboratory report, U.S. Geol. Survey.
Allanite and/or monazite ?	?	Black Dog claim, San Bernardino County, Calif	Walker, Lovering, and Stephens, 1956, p. 24.
Magnetite (or hematite) ?	Rare	Prince mine, Lincoln County, N. Mex	Walker and Osterwald, 1956b.
Thorite ?		Roberts prospect, Gunnison County, Colo	R. C. Malan, oral communication, 1956.
Uranium-bearing hydrocarbons	Uncommon	Golden Gate Canyon area, Jefferson County, Colo	Sheridan, 1955, p. 216.

[1] Actual frequency of occurrence is complicated by data that are not adequate for distinguishing between certain 6-valent uranium minerals and their beta and meta varieties.

[2] Other localities for many of these minerals are referred to in "Bibliography and index of literature on uranium and thorium and radioactive occurrences in the United States," by Margaret Cooper (1953a, b; 1954; 1955).

one or a combination of the different modes postulated by Neuerburg (1956, p. 55); these are

> * * * [a] uranium disposed in the structure of * * * minerals by diadochy and in structural defects in crystals, [b] uranium held in cation-exchange positions, [c] uranium in unknown form absorbed on surfaces of crystals, [d] uranium dissolved in fluid inclusions within * * * minerals, and [e] uranium dissolved in intergranular fluids * * *.

Although little evidence is available to document any one of these modes of occurrence, as applied to veins, several modes have been proposed for uraniferous fluorite deposits (Staatz and Osterwald, 1956; Wilmarth and others, 1952), uraniferous base-metal sulfide deposits (Wright and Shulhof, 1957a), and uranium-bearing magnetite-hematite deposits (Walker and Osterwald, 1956b).

In several oxidized veins, some or all the uranium is present presumably as adsorbed uranyl ions in "limonite" or "limonitic" gossans (Lovering, 1955), in hydrozincite and chrysocolla (Barton, 1956), and probably in other oxidation products.

The uranium minerals listed in table 1 are reported from vein deposits in the conterminous United States and have been identified with accuracy, principally by X-ray techniques, chemical analysis, and, for many of the minerals, by both methods. Although several other 6-valent uranium minerals could be listed, identification of a few of these is open to considerable question. For 1 or 2 other minerals, the identifications are as yet incomplete; the latter minerals may represent new species. For data on the physical and chemical properties of the minerals listed in table 1 and for the synonyms that have been applied to many of these minerals, the reader is referred to "A Glossary of Uranium- and Thorium-Bearing Minerals" (Frondel and Fleischer, 1955), "Dana's System of Mineralogy" (Palache, Berman, and Frondel, 1944, 1951), and to "Mineralogy of Uranium and Thorium Bearing Minerals" (George, 1949).

Within recent years there has been a tendency among geologists in the United States to abandon the term "pitchblende" for the colloform variety of uraninite; in this report both the terms "uraninite" and "pitchblende" are used. The term "pitchblende" is used herein for the massive, colloform or sooty variety of uraninite in much the same sense as that described in "Dana's System of Mineralogy" (Palache, Berman, and Frondel, 1944, p. 614) and in Geffroy and Sarcia's "Contribution á l'étude des pechblendes françaises" (1954, p. 4, 145); several distinctive features of pitchblende and uraninite have been described and reviewed briefly by Rogers (1947). Pitchblende is a massive, colloform or sooty variety of uranous oxide in which macroscopic or microscopic evidence of idiomorphism is lacking. In a very few vein deposits within the conterminous United States, the uranous oxide occurs as microscopic idiomorphic crystals or fragments of crystals; for these occurrences, the term "uraninite" is applied. A similar but more precise distinction is made by Croft (1954, p. 53) for the terms "uraninite" and "pitchblende":

> The term uraninite is reserved for the naturally occurring UO_2 having megascopic crystal size and often showing crystal form; while the term pitchblende is applied to material composed of crystallites on the order of 10^{-3} cm or less in size. A laue-type X-ray diffraction diagram made with characteristic radiation may be used to distinguish between these two types. The uraninite produces individual spots characteristic of a single crystal, while pitchblende produces debye-scherrer rings characteristic of the microcrystalline aggregate. There does not appear to be any gradation between the macro crystals and the microcrystalline aggregates.

Katz and Rabinowitch (1951, p. 75, 76) make a further distinction between uraninite and pitchblende on the basis of the presence of significant amounts of thorium and rare earths in uraninite and their virtual absence in pitchblende. No such chemical distinction is made by the authors of this paper because analytical data are lacking on the elemental content of pitchblende from most of the veins in which it has been reported. Arbitrarily, we have retained the terminology of the papers referred to in this report, although we are aware that, in several places, uranous oxide minerals exhibiting colloform textures and a lack of idiomorphism have been labelled "uraninite."

Most pitchblende in veins in the conterminous United States occurs as megascopic or microscopic gray to black colloform submetallic to pitchlike or dull masses. An olive-green or light-brown slightly translucent colloform pitchblende has been identified from the North Star mine, Colorado (figs. 3, 4), and brown slightly translucent pitchblende spherulites have been noted in the Nigger shaft deposit, Colorado (Adams, Gude, and Beroni, 1953, p. 12, 16). Presumably such pitchblende is comparable, or nearly so, to an ill-defined material called hydropitchblende ($UO_2 \cdot kUO_3 \cdot nH_2O$; $k = 2.3–5$; $n = 3.9–9$) by Getseva (1956). In some deposits, pitchblende occurs as gray to black minute sootlike particles in restricted and spotty disseminations or impregnations in altered or unaltered host rocks (figs. 5, 6) adjacent to faults or fracture zones; in some deposits it coats and veins hard unaltered pitchblende (King, Moore, and Hinrichs, 1952; Moore, Cavender, and Kaiser, 1957; Stugard, Wyant, and Gude, 1952). Presumably most, if not all, of this pitchblende is secondary and commonly was deposited close to masses of hard unaltered pitchblende in transi-

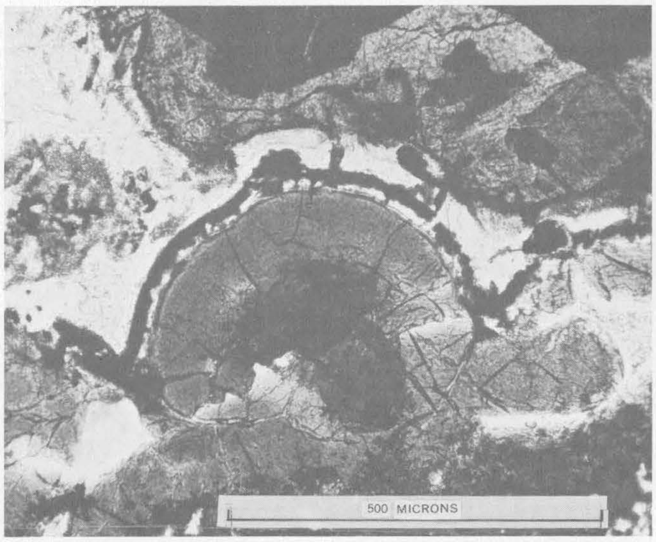

FIGURE 3.—Photomicrograph of hemisphere of altered slightly translucent olive-green pitchblende in matrix of mixed secondary copper and uranium minerals (white) and hydrated iron-oxide minerals (gray and black) from North Star mine, Jefferson County, Colo. Transmitted light.

tional zones where the environment was neither strongly oxidizing nor strongly reducing. According to L. R. Page (oral communication, 1956), the pitchblende is comparable to the "regenerated" pitchblende of Russian and some other European geologists.

No well-established correlation between different species of 4- and 6-valent uranium minerals and the eight mineralogic classes of veins can be demonstrated, with available data, beyond (a) the obvious mineralogic correlations resulting from the arbitrary classification of uraniferous vein deposits—that is, brannerite-bearing veins—and (b) several expectable

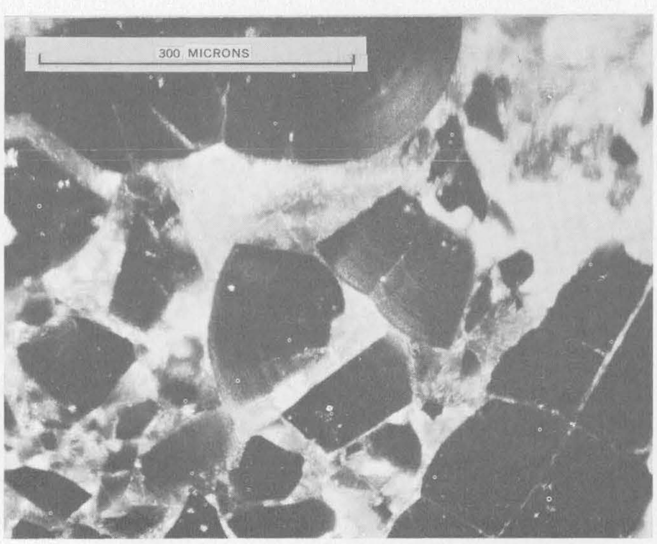

FIGURE 4.—Photomicrograph of brecciated colloform pitchblende, showing concentric banding, with interstitial secondary copper and uranium minerals from North Star mine, Jefferson County, Colo. Polarized, reflected light.

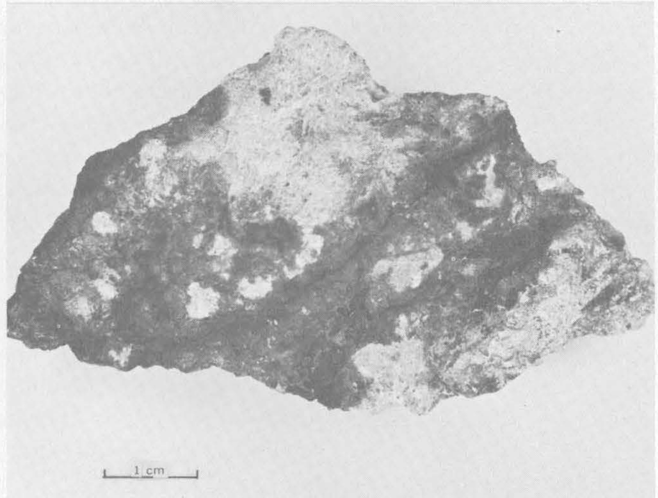

FIGURE 5.—Diffuse veinlets and impregnations of sooty pitchblende in altered fine-grained sedimentary rock from Los Ochos mine, Saguache County, Colo.

mineral associations resulting largely from the character of the original mineral assemblage of the deposit. Pitchblende has been reported in fluorite-bearing veins, in veins in which uranium minerals are subordinate to base-metal sulfide minerals, in veins in which uranium minerals are the dominant metallic mineral, in magnetite or other iron oxide-bearing veins, and in veins containing uraniferous hydrocarbons. The pitchblende in the several mineralogic classes of deposits appears to be identical in all essential characteristics and differs from deposit to deposit principally in the degree of oxidation or hydration. Coffinite and uranothorite have been reported in so few veins that no correlation is warranted.

In those places where uranium-bearing veins have been subjected to supergene alteration, the hypogene mineral assemblage—or the elements contained therein—tends to govern the assemblage of 6-valent uranium minerals. For example, kasolite is characteristic of uraniferous base-metal veins containing galena or alteration products of galena, and torbernite is most

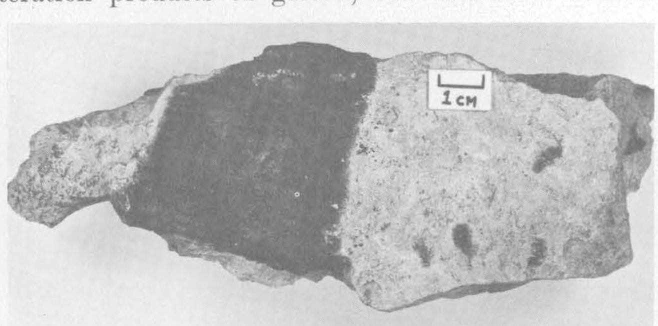

FIGURE 6.—Irregular impregnations of sooty pitchblende (black), commonly with fine-grained jordisite and marcasite or pyrite, in altered fine-grained sedimentary rock from Los Ochos mine, Saguache County, Colo.

common in deposits containing hypogene or supergene copper minerals. Uranium as adsorbed uranyl ions has been reported principally from deposits containing abundant hydrated iron oxides and (or) oxidized copper, lead, and zinc minerals; this mode of occurrence is most prevalent in the oxidized parts of uraniferous base-metal sulfide deposits.

GANGUE MINERALS OF URANIUM-BEARING VEINS

The gangue minerals associated with uranium-bearing veins are those commonly found in metalliferous vein deposits, and they demonstrate no tendency toward abundance or rarity of any particular species that could be considered distinctive; distinctive characteristics are present in some gangue minerals as a result of radiation damage. Quartz in its many varieties is perhaps the most widely distributed gangue mineral and has been reported as common to abundant in all eight mineralogic classes of veins. Considered as a group, the carbonate minerals—calcite, siderite, ankerite, dolomite, and rhodochrosite—are almost as common. Barite, adularia, chlorite, opal, alunite, and the clay minerals have been noted in many localities. One mineralogic class of veins is characterized by common or abundant fluorite that may or may not be uraniferous. Topaz and beryl are reported as gangue minerals only from brannerite-bearing veins.

Certain gangue-mineral assemblages tend to characterize some mineralogic classes of uranium-bearing veins (chap. A). A review of available data, which is most abundant for uraniferous base-metal sulfide deposits, suggests that the following assemblages—with the minerals listed in order of decreasing frequency of occurrence, an arrangement not necessarily coincident with their relative abundance—most commonly occur in the various classes shown.

Class 1. Fluorite-bearing veins.
Quartz, carbonate minerals, clays, chalcedony, opal, adularia.

Class 2. Base-metal sulfide veins.
Quartz, carbonate minerals, barite, chalcedony, chlorite, fluorite, microcrystalline quartz, adularia.

Class 3. Veins dominantly of uranium minerals.
Quartz, carbonate minerals, barite, chalcedony, opal, adularia.

Class 4. Magnetite or other iron oxide-bearing veins.
Quartz.

Class 5. Veins dominantly of thorium or rare earths minerals.
Quartz, barite, carbonate minerals.

Class 6. Brannerite-bearing quartz or siliceous veins.
Quartz, micas, tourmaline, fluorite, topaz, beryl, orthoclase, carbonate minerals.

Class 7. Davidite-bearing veins (not represented in United States).
Quartz, biotite, ilmenite, rutile, sphene, carbonate minerals.

Class 8. Hydrocarbon-rich uranium-bearing veins.
Carbonate minerals, barite, quartz, adularia.

The dissimilarities in gangue-mineral assemblages result not only from the arbitrary classification of deposits, as in the establishment of one class based on the presence of significant amounts of fluorite, but also from differences related to contrasting crystallization temperatures between different groups of deposits. For example, brannerite-bearing veins are largely a high-temperature mineral assemblage closely related to that in pegmatites and, as such, commonly contain a suite of minerals that would not be compatible with an epithermal base-metal sulfide deposit.

In their study of 13 uranium-bearing vein deposits of the world, Everhart and Wright (1953, p. 91) note a correlation between the gangue minerals and the host rocks of the deposits to the extent that deposits in metamorphic rocks generally have carbonate minerals as gangue whereas deposits in intrusive rocks have a dominantly siliceous gangue. The conclusions of Everhart and Wright (1953) in regard to this correlation tend to be verified by the review of published data and a study of many thin sections and polished sections by the authors.

EFFECTS OF RADIATION ON GANGUE MINERALS

The effects of radiation damage are perhaps the most distinctive features of gangue minerals in uranium-bearing veins. The gangue minerals in these deposits are subjected to a greater-than-normal radiation intensity from (a) adjacent uranium minerals, (b) radioactive elements that have migrated from adjacent uranium minerals, or (c) radioactive elements that may be incorporated in the structures of the gangue minerals themselves. The effects produced by radiation, particularly by alpha particles, are complex and may involve both physical and chemical changes in crystalline substances, such as reduction or loss of internal crystallinity, marked changes in thermoluminescent properties, and changes in coloration.

Changes in coloration are the most evident expression of radiation damage in gangue minerals, and these changes have been recognized for many years through the study of pleochroic halos in micas. In veins, these coloration changes are best demonstrated by fluorite, as a dark-purple to black variety rather than a light-purple to clear light-colored variety characterizes the mineral in radioactive environments. The darker coloration may be quite uniformly distributed through the fluorite, or it may be present only as irregular clots and patches. Where discrete grains of radioactive minerals are included in fluorite, darker colored halos of widths nearly equivalent to the penetration ranges of the alpha particles emitted by the inclusion may be produced (fig. 7). As the maximum effective range of alpha particles in fluorite is measured in tens of microns, the coloration effects produced by a few scattered inclusions is negligible and cannot explain the pervasive darkening of large fluorite masses. Such darkening is more probably the result of radioactive centers within the fluorite itself, a condition that is met in the substitution of uranium in the fluorite structure (Goldschmidt, 1954, p. 229) or, as postulated by George Phair (written communication, 1958) for the deep-purple fluorite at the Blue Jay mine, Colorado, by movement of radon along abundant and closely spaced cracks in the fluorite. In naturally occurring uraniferous fluorite, it has been noted (Wilmarth and others, 1952, p. 15) that, except for the white and brown earthy fluorite from the Thomas Range, Utah, a dark purple to black color is characteristic. The uraniferous fluorite from the Thomas Range may originally have been colored and later bleached; the bleaching of colored fluorite by prolonged and intense irradiation has been reported by Przibram (1956, p. 193).

Halos produced by radiation from both uranium and thorium disintegration products are present in fluorite from Jamestown, Colo. Because the thorium-derived halos surrounding included uranothorite crystals in this fluorite are larger than halos surrounding pitchblende grains owing to the greater energy of radiation from the thorium series, it is possible to distinguish uranothorite from pitchblende by the size of the halos (Phair and Shimamoto, 1952, p. 664). A uranium-derived halo in fluorite is shown in figure 7.

The darkening of quartz to a smoky color has been attributed to radiation damage resulting from higher concentrations of radium and uranium than those ordinarily found in quartz (Holden, 1925, p. 240). More recently, Farrington Daniels and D. F. Saunders (written communication, 1951) have suggested that cosmic-ray particles may produce some darkening. Their suggestion was based on a correlation between the color of Alpine quartz and the altitude of the vein from which it was obtained (Holden, 1925, p. 210).

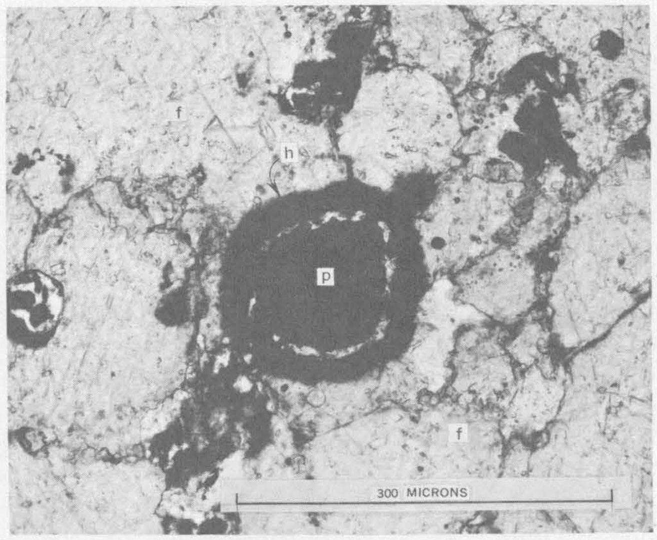

FIGURE 7.—Photomicrograph showing radiation halo (h) around pitchblende grain (p) in fluorite (f), Jamestown district, Colorado. Halo is dark purple in nearly colorless fluorite. Transmitted light.

Holden's observations may need verification by the more precise analytical techniques now available, and the influence of cosmic rays must be reconciled not only with the depth of cover and its shielding effect but with the common occurrence of both smoky and colorless quartz in the same deposit. Nevertheless, a relation between radiation and the darkening of quartz is indicated not only by the facility with which quartz can be artificially "smoked" (Frondel, 1945) but also by the common association of dark quartz with radioactive minerals in pegmatites (Page, 1950, p. 34).

The association of smoky quartz with uranium minerals in veins is not well demonstrated, perhaps because the distinction between colorless and smoky quartz might not be as obvious in fine-grained vein material as in coarse-grained pegmatite. Some inherent differences in the quartz itself may be involved, as Frondel (1945, p. 435) has observed that colorless quartz shows a wide variation in the degree of color response to artificial radiation, a variation that could not be correlated with the kind or amount of foreign elements present. These observations suggest that zonal distribution of color in natural smoky quartz may then be due to layers of "susceptible" or "unsusceptible" quartz or to layers containing different amounts of radioactive elements.

The effects of radiation on quartz and other gangue minerals are not necessarily limited to material that may have radioactive elements incorporated in its structure or that is in direct contact with radioactive minerals, for migration of daughter-product elements as well as of uranium itself may produce new radiation centers at some distance from the original source. Such a process is described by Yagoda (1946, p. 465–468) to explain iridescent halos in quartz from the pitchblende deposit at Great Bear Lake, Canada; the halos in this instance are ascribed to radiation from radium that has been leached from pitchblende and redeposited in fractured quartz as colloidal aggregates.

Radiation damage without appreciable coloration effects is shown (fig. 8) in quartz surrounding uraninite from the Little Man deposit, Wyoming. A halo of less translucent quartz has developed around the uraninite crystals, the width of the halo being comparable to the alpha-particle range in quartz.

Smoky quartz has been reported from the uranium-bearing vein at the Moonlight mine, Nevada (Taylor and Powers, 1955, p. 12), and the Midnite mine, Washington (Weis, 1956, p. 223); it also has been noted by the authors in specimens from Marysvale, Utah, and the Los Ochos and Schwartzwalder mines in Colorado. Probably the association of smoky quartz with uranium in veins is more common than is indicated by available literature.

Reddish-brown coloration has been noted in the gangue minerals of radioactive deposits, particularly in foreign uranium-bearing veins, and it has been considered a useful prospecting guide for both veins (Lang, 1952, p. 35; Everhart and Wright, 1953, p. 93) and pegmatites (Ellsworth, 1932, p. 63; Page, 1950, p. 34) This coloration is generally attributed to hematite, as at the Sunshine mine, Idaho, where ferric oxide is disseminated through finely crystalline or colloidal silica and forms a jasperlike material (Kerr and Robinson, 1953, p. 506–507); similar brown or reddish-brown jasper has been reported from veins in Portugal (Cavaca, 1956, p. 183).

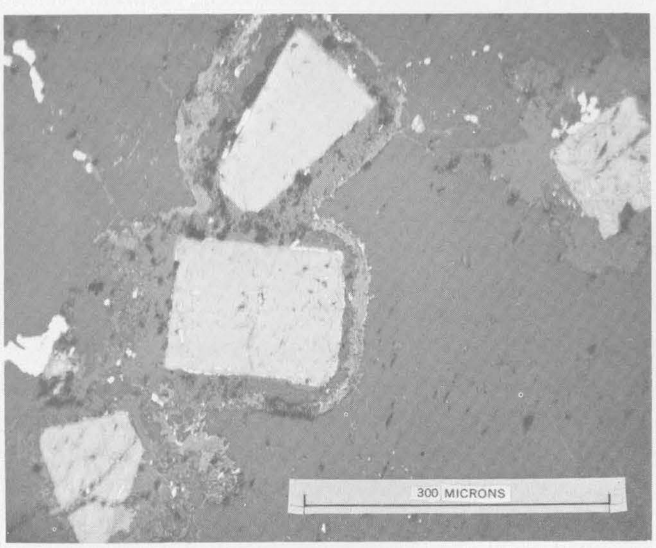

FIGURE 8.—Photomicrograph of idiomorphic cubic crystals and crystal fragments of uraninite (white) in quartz (gray) exhibiting halos probably resulting from radiation damage. Specimen from the Little Man mine, Carbon County, Wyo. Reflected light.

Some of the hematite causing the reddish-brown coloration is undoubtedly a hypogene vein mineral that formed either contemporaneously with early pitchblende or later in the mineral sequence. In other places the reddish-brown coloration more probably results from hydrated ferric oxides, notably goethite (Lovering, 1955, p. 187), formed by supergene processes from iron-bearing wallrock and vein minerals. It is possible, however, that the association of reddish-brown coloration in gangue minerals of uranium-bearing veins is more complex than a straightforward deposition of, or chemical alteration to, ferric oxides; the radiation may effect the development of the reddish-brown coloration. For example, experimental work with irradiated solutions (Amphlett, 1952; Harwick, 1952) is cited by Lovering (1955, p. 192) as indicating that the oxidation of ferrous to ferric iron might be facilitated by radiation under natural conditions. An increase in the rate of oxidation of ferrous to ferric iron should also increase the amount of ferric iron and thus inhibit the migration of iron under neutral to alkaline conditions through and out of a vein system; under acid conditions and in the presence of SO_4^{-2} ions, highly soluble ferric sulfate forms and ferric iron is removed. If radiation does cause an increased rate of oxidation of iron, such a process would be most effective near radiation sources, so that abnormal concentrations of ferric oxides and a corresponding reddish-brown coloration should show close spatial association with abnormal concentrations of radioactive elements.

Analogous to the darkening of quartz, the ferruginous staining of minerals in radioactive environments cited in the descriptions of many deposits is more obvious in pegmatites than in veins, largely because more grains are of megascopic size. Heinrich (1948, p. 68) notes that pods of monazite and euxenite in the Yard pegmatite in Colorado are surrounded by aureoles of pink to dark-red feldspar; he also notes that euxenite masses are the centers of conspicuous radial cracks. In a paper on uranium-bearing pegmatites in Canada, Ford (1955, p. 201) describes reaction rims of "limonite" in feldspar around both uraninite and monazite as well as the presence of "limonite" in fractures adjacent to the radioactive minerals. The feldspar adjacent to the uraninite appeared to be unaltered except for the red stain. Another example of ferruginous staining is reported by Rowe (1952, p. 16) from the Richardson deposit, Ontario, in which red hematite dust occurs along calcite grain boundaries around some uraninite crystals.

Radiation-induced oxidation of ferrous to ferric iron was proposed (Adams and others, 1953, p. 16) to explain reddish-brown bands in ankerite from the Nigger shaft deposit, Colorado. The bands are along ankerite-pitchblende interfaces (fig. 9) and are of a width (about 21 microns) that is close to the calculated alpha-particle range (22 microns) in ankerite. A radiochemical origin for these bands is supported by analogy to the origin of biotite halos as given by Yagoda (1949, p. 86):

In the passage of an alpha particle through a solid, the ionization maxima near the end of the trajectory produce an enhanced localized chemical action on the crystal lattice. In biotite mica the ferrous iron is oxidized to the trivalent state, and an intensified brownish color appears near the range termination.

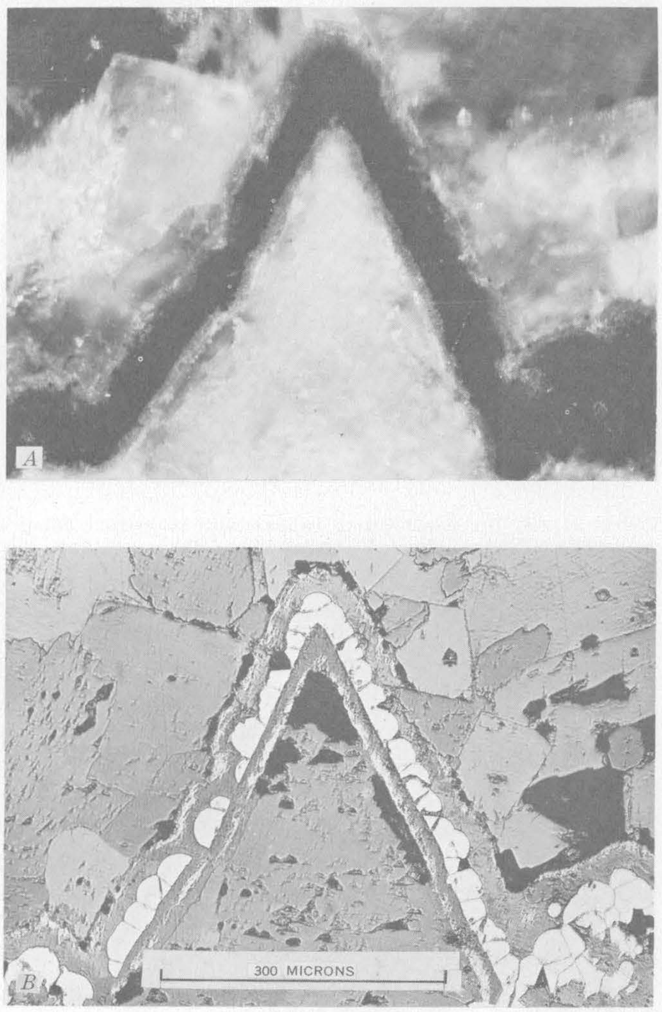

FIGURE 9.—Photomicrograph of radiation-damage bands between pitchblende and ankerite. Nigger shaft, Colorado. *A*, pitchblende (black); ankerite (white and gray); transmitted light. *B*, same field as *A*; reflected light.

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INTERNAL STRUCTURES AND TEXTURES OF VEINS

The internal structural and textural characteristics of many uranium-bearing veins in the United States are similar to those in epithermal and mesothermal vein deposits in which the introduced ore and gangue minerals fill open pore spaces or cavities. Some of these pore spaces formed as original openings in the rocks at time of formation, and some as solution cavities, but most have resulted from structural deformation. Both macroscopic and microscopic cataclastic textures are common in uraniferous vein deposits; replacement textures, specifically between uranium and nonuranium minerals, have been reported in only a few places.

In most deposits where the morphology of the primary uranium minerals has been ascertained, colloform or colloformlike textures dominate almost to the exclusion of other textures. In only a few veins do the primary uranium minerals exhibit crystal form; included are veins characterized by idiomorphic uraninite, uranothorite, or brannerite. In deposits where the uranium is present as either (a) a vicarious constituent of rare earths- or thorium-bearing minerals or other minerals or (b) minute particles of unidentified uranium minerals dispersed in other minerals, the morphologic form of the host persists.

INTERNAL STRUCTURAL CHARACTERISTICS

In general, uranium-bearing veins are tabular in shape and occupy fractures or sets of fractures. As used herein, the terms "fracture" or "sets of fractures" encompass most induced openings in rocks resulting from compressive, tensional, and torsional stresses. Some induced openings that contain uranium and associated minerals in veins are related to volcanic pipes, collapse breccias, and solution caves or to openings resulting from near surface postsedimentation slumping and release of stress. The tabular nature of veins may be apparent only in detail in parts of a deposit, or it may encompass an entire major ore body. In some deposits, ore minerals are concentrated in lenses, pods, irregular masses, or in shoots along tabular structures; the tabularity of these deposits may be apparent only in terms of the structures that localize the deposit. Other deposits, localized in part by fractures, are not tabular and principally comprise those associated with (a) wallrocks that are extensively altered and replaced, (b) porous gossan zones that are intensely leached, and (c) host rocks characterized by abundant and widespread syngenetic pore spaces of either sedimentary or magmatic origin. Most uranium-bearing vein deposits can be identified as one or a combination of the following: reticulated veins, stringer leads, ladder veins, stockworks, breccia veins, lenses, or pods, as defined by Emmons (1940, p. 150–153), or as pipelike deposits as defined by Lindgren (1933, p. 159).

The primary uranium minerals in these deposits are commonly associated with both gangue and other metallic minerals or with hydrocarbons and occur in the interstices of breccia (figs. 10, 11), as breccia fragments (fig. 12), and as macroscopic or microscopic well-defined veinlets either in fractured wallrocks (figs. 13, 14, 15) or in fractured preuranium vein fillings (figs. 16, 17). Other vein deposits contain pitchblende as microscopic veinlets along cleavage planes in micaceous minerals (fig. 18), as microscopic films between mineral grains or between mineral grains and hydrocarbons (fig. 19), and as diffuse veinlets (figs. 5, 20) or spotty, irregular, impregnations (fig. 6) adjacent to fracture zones. In still other veins, uranium occurs as disseminations of fine-grained equigranular or spheroidal masses of pitchblende or subhedral or euhedral crystals of uraninite in gouge, porous wallrock, or vein filling. In addition, some pitchblende in vein deposits has been found as fillings in elongate flow vesicles in rhyolite at Marysvale, Utah (Taylor and others, 1951, p. 12), and disseminated, locally with coffinite(?), in porous sandstone adjacent to arcuate fracture zones at the Orphan mine, Arizona. Uraniferous rutile is disseminated in molybdenite in quartz veins at the New Years Eve mine, Arizona; uraniferous hydrocarbons (fig. 21) containing disseminated small spheres or grains (commonly less than 5 microns in diameter) of pitchblende are present in several veins.

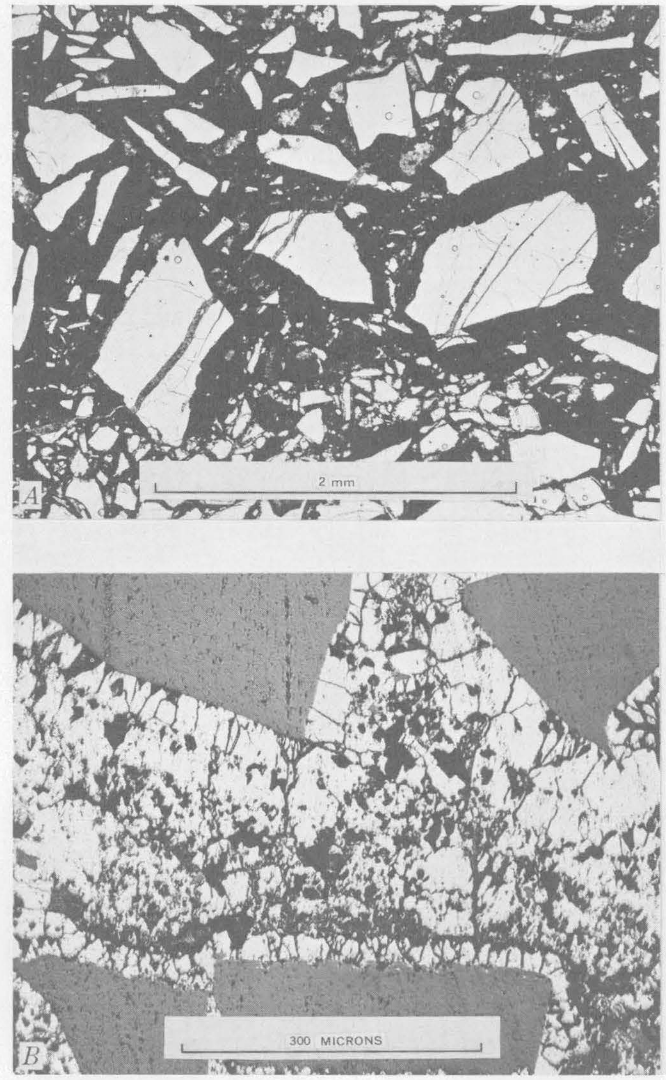

FIGURE 11.—*A*, Brecciated quartz (white) with interstitial filling of pitchblende (black) from Buckman adit, Jefferson County, Colo. Transmitted light. *B*, Photomicrograph of piece of same specimen as *A*. Quartz fragments (gray) and interstitial pitchblende (white). Black spots mostly are holes in polished surface. Reflected light.

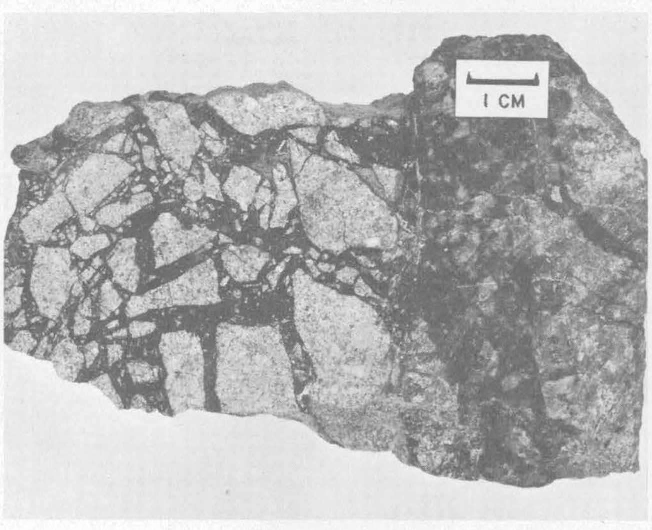

FIGURE 10.—Breccia ore from Marysvale, Utah. Dark vein filling composed dominantly of a mixture of fine-grained purple fluorite, pyrite, and pitchblende.

Most of the pitchblende in several deposits in the Colorado Front Range is in the form of irregular small pods, lenses, veinlets, and irregular masses (Bastin and Hill, 1917; Sims, Osterwald, and Tooker, 1955; Sims and Tooker, 1956, p. 108; King and others, 1953, p. 3; King, Moore, and Hinrichs, 1952). At the Caribou mine, Colorado, pitchblende is in the form of numerous small veinlets cutting gersdorffite, as coatings on chalcedony and quartz (Wright, 1954, p. 159) and, more commonly, as soft pitchblende coating fractures, vugs, and masses of hard pitchblende (Moore, Cavender, and Kaiser, 1957). Pitchblende occurs as sparse nodules, veinlets, and disseminated grains mostly in quartz or chalcedonic veins in deposits in the Boulder batholith, Montana (Becraft, 1956, p. 120–121), as

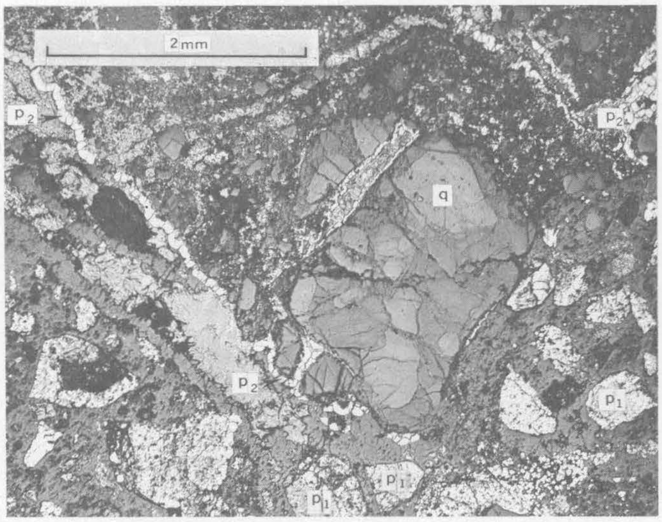

FIGURE 12.—Photomicrograph of brecciated early-stage pitchblende (p_1) and late-stage colloform pitchblende (p_2) veinlets and spherulites in gangue composed dominantly of quartz (q) and unidentified rock minerals. Float specimen of vein material from Marshall Pass area, Saguache County, Colo. Reflected light.

clusters of uraninite (pitchblende) veinlets, as segmented and fractured veinlets, and as fine disseminations of uraninite (pitchblende) in massive pyrite at the Sunshine mine, Idaho (Kerr and Robinson, 1953). Pitchblende is in small lenticular and irregular-shaped masses along relict bedding planes in hornfels and in veinlets and irregular-shaped masses transverse to the bedding in several deposits in the Dripping Spring Quartzite, Arizona (Granger and Raup, 1962). Furthermore, uraniferous fluorite occurs in veins, breccia zones, pipes, or tabular to irregular replacement bodies. Dustlike particles of powdery or sooty pitch-

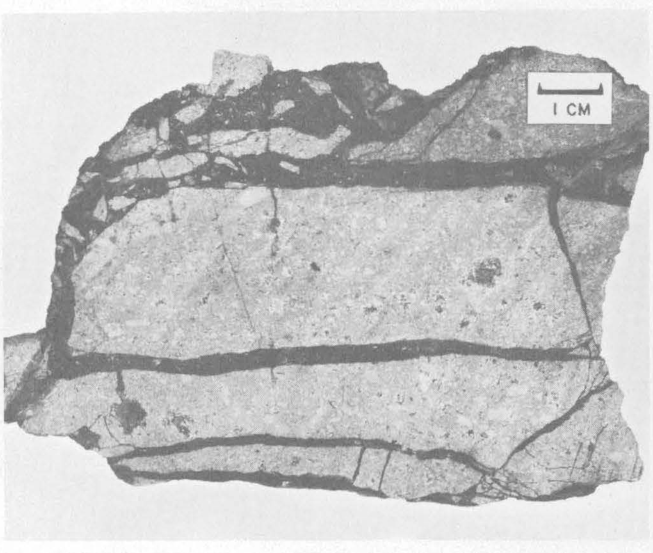

FIGURE 13.—Veinlets (black) from stockwork of veinlets, Freedom 2 mine, Marysvale, Utah. Veinlets composed of alternate bands of purple crystalline fluorite and purplish-black bands of fine-grained, mixed fluorite, pyrite, and pitchblende.

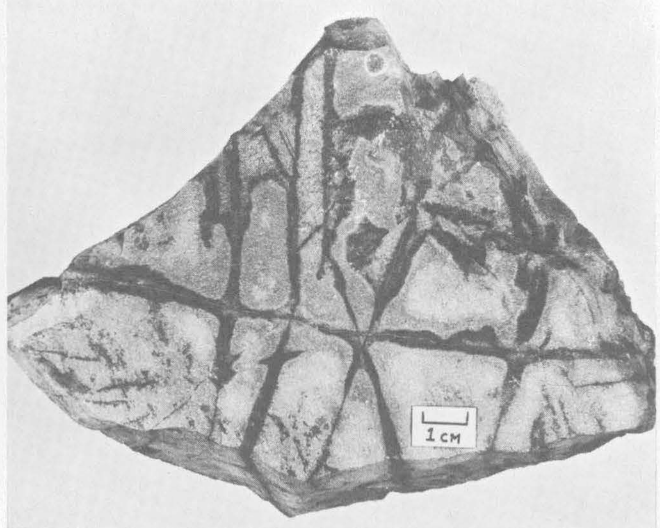

FIGURE 14.—Mineralized joints in specimen of Dripping Spring Quartzite, Red Bluff mine, Gila County, Ariz. Dark seams are highly radioactive and contain pyrite or marcasite, possibly pitchblende, 6-valent uranium minerals, or radio-colloids, and probably other introduced minerals.

blende, probably largely derived through the alteration of hard massive pitchblende of an earlier stage, coat vug minerals, surfaces of fractures or other openings in rocks, and, not uncommonly, rock fragments on mine dumps.

The 6-valent uranium minerals in veins commonly are distributed in much the same structural pattern as the 4-valent uranium minerals, occurring principally as fillings in original or induced openings either in the wallrocks, in gouge or brecciated rock, in boxworks or porous gossans, or in the vein structure. Pseudomorphous replacement and veining of primary ura-

FIGURE 15.—Photomicrograph of veinlets of pitchblende from deposit near Critchell, Jefferson County, Colo. Reflected light; partly crossed nicols.

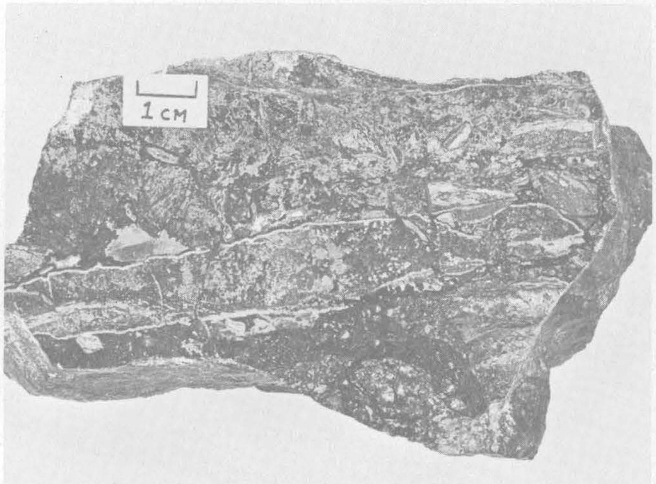

FIGURE 16.—Pitchblende veining brecciated base-metal ore from Copper King mine, Larimer County, Colo.

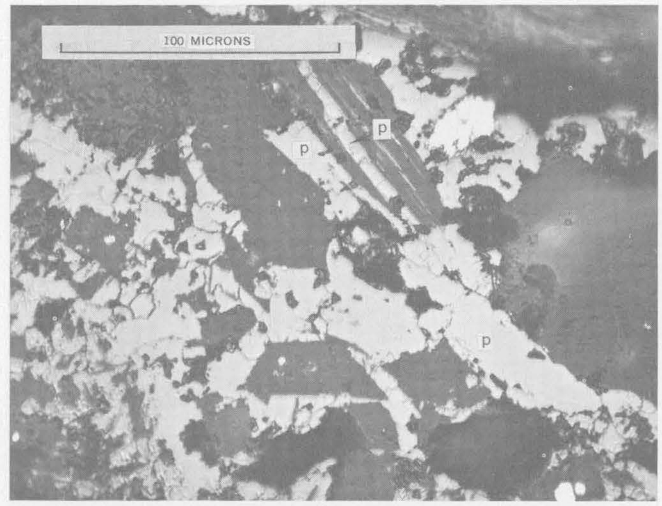

FIGURE 18.—Photomicrograph of pitchblende veinlets (p) along cleavage planes in micaceous mineral from Schwartzwalder mine, Jefferson County, Colo. Reflected light.

nium minerals by many of the 6-valent minerals are common, and in several places—as, for example, the Buckman adit and the Schwartzwalder mine—uranophane replaces siliceous constituents of the wallrocks or the veins; at the Two Sisters mine, Gilpin County, Colo., metatorbernite apparently replaces biotite (Sims, Osterwald, and Tooker, 1955, p. 17–18). Locally, the 6-valent uranium minerals occur in microscopic veinlets between laminae in micaceous minerals. Fracture coatings, or veinlets, or cavity coatings or fillings are the most common mode of occurrence of the uranyl arsenate, carbonate, phosphate, silicate, sulfate, and vanadate minerals; these minerals are earthy, finely crystalline, or coarsely crystalline (fig. 22). Aggregates of crystals, rosettes (fig. 23), or spherulites (fig. 24) occur in many places; crustified banding of 6-valent uranium minerals with calcite, chalcedony, and hyalite opal is present in many deposits.

Although many complex combinations of structural characteristics may be present in uranium-bearing veins in general, the uranium minerals in most vein deposits in the conterminous United States occur as (a) coatings on mineral or rock fragments in and adjacent to shear zones, (b) pore space fillings principally in brecciated rock, or (c) a combination of both.

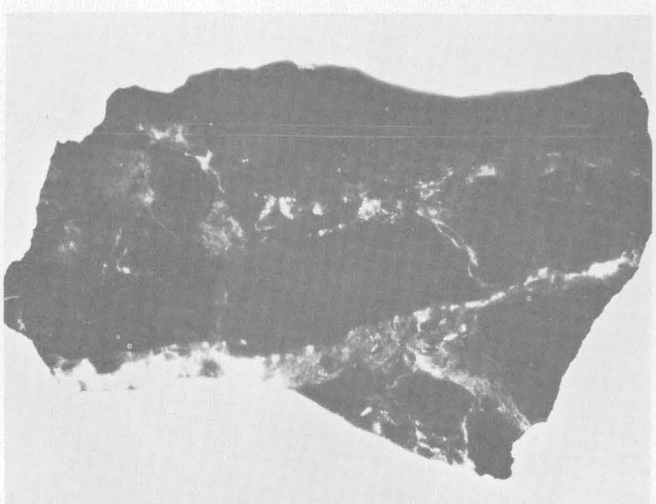

FIGURE 17.—Autoradiograph of specimen shown in figure 16 delineating pitchblende veinlets (white and gray areas).

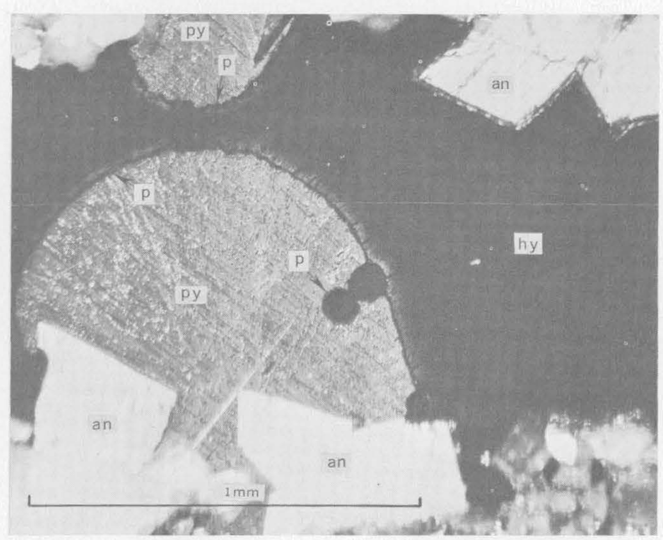

FIGURE 19.—Photomicrograph of pitchblende (p) as isolated spheroids and as microscopic films between pyrite (py) and unidentified hydrocarbon (hy) from Halfmile gulch, Jefferson County, Colo. Alteration halo in hydrocarbon adjacent to pitchblende. Rhombic crystals are ankerite (an). Reflected light; crossed nicols.

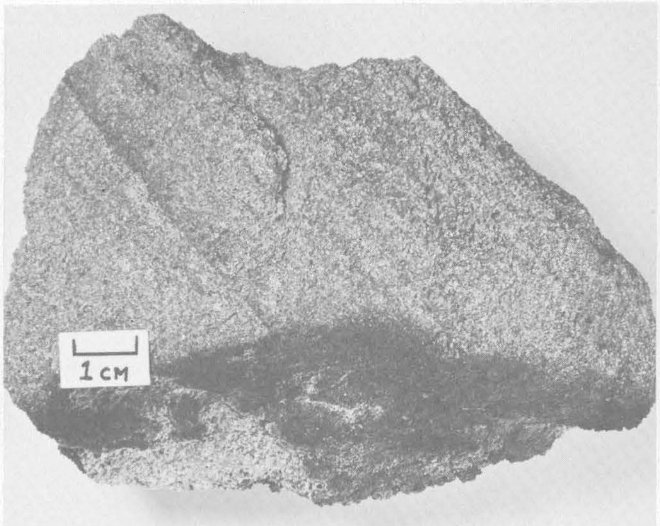

FIGURE 20.—Diffuse veinlet of sooty pitchblende (black) cutting sandstone from John claim, Gas Hills district, Fremont County, Wyo.

TEXTURAL CHARACTERISTICS

Studies of the textural characteristics of primary uranium minerals in veins in the conterminous United States indicate that although several different textures are represented, one group of textures is almost universally present and in many deposits dominates over all other textures. The textures within this group, herein collectively termed "colloform textures," are generally referred to by Bastin (1950), Edwards (1954), Lindgren (1933), Kidd and Haycock (1935), Ramdohr (1955), Ristic (1956), and others as denoting colloidal deposition, particularly when applied to "simple" uranous oxide minerals. We wish to retain the textural terms that have been applied to "colloidal" deposits because in most, if not all, essential features, they describe exactly the textures resulting from the coagulation of a hydrosol.

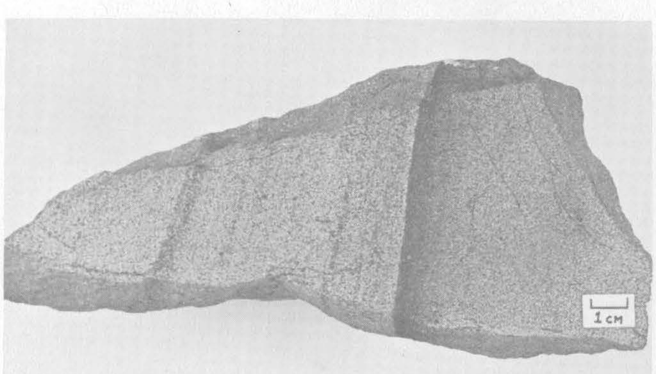

FIGURE 21.—Veinlets and disseminations of uraniferous hydrocarbon (black) in sandstone from deposit near Morrison, Colo. Veinlets cut sandstone bedding (not shown) at approximately 90°.

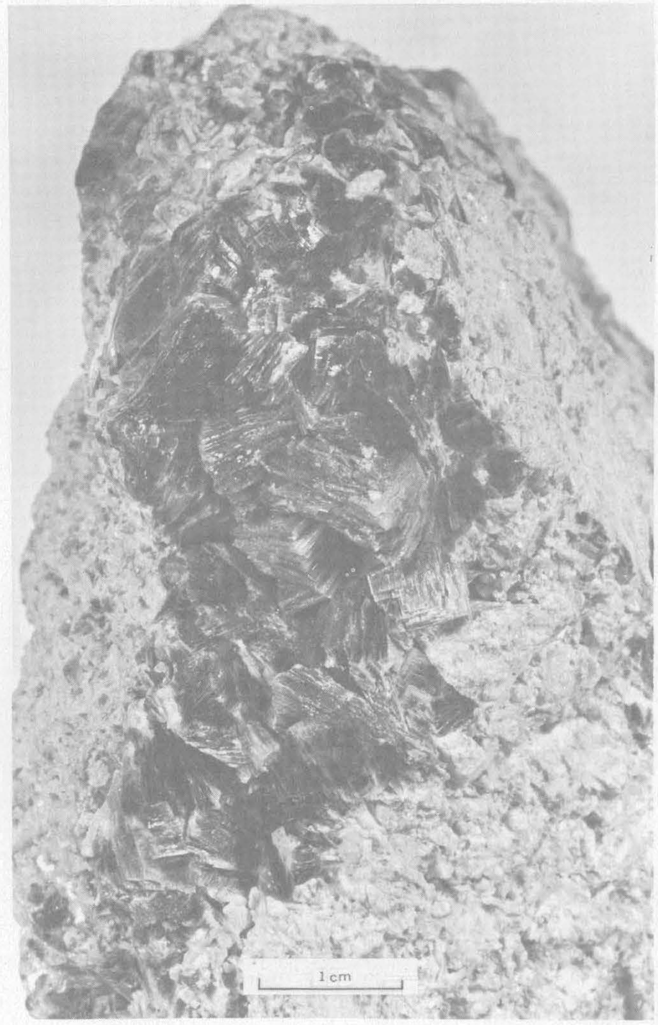

FIGURE 22.—Coarsely crystalline aggregates of meta-autunite from Daybreak mine, Spokane County, Wash.

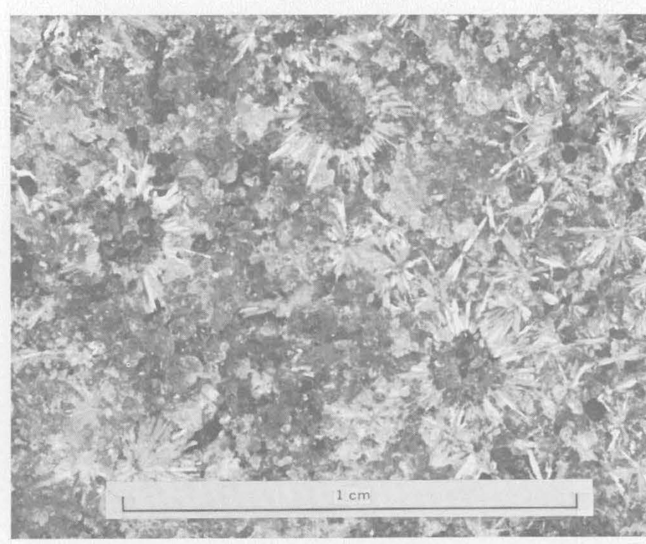

FIGURE 23.—Rosettes of uranophane crystals on fracture in sandstone from Silver Cliff mine, Niobrara County, Wyo.

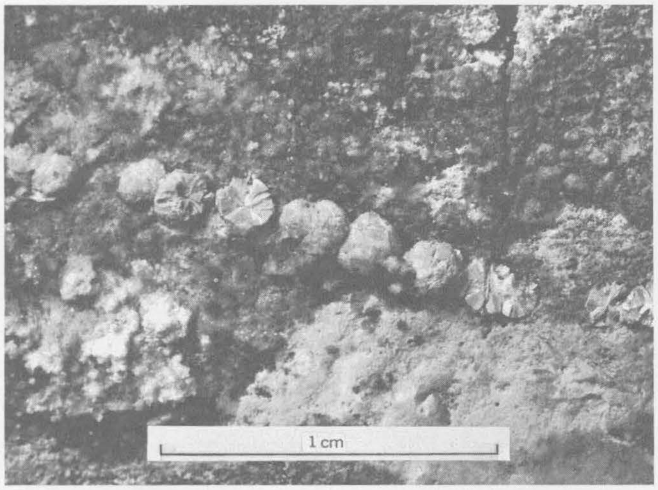

FIGURE 24.—Spherulites of tyuyamunite on joint surface from Fuesner mine, Big Horn County, Wyo.

The colloform textures of the primary uranous oxide minerals in veins in the conterminous United States are comparable in all essential characteristics to the "colloidal" textures of pitchblende in many of the uranium deposits in other countries. Furthermore, many of these same colloform textures are known to occur in pitchblende-bearing ore bodies in sandstone-type deposits of the Colorado Plateau, as, for example, at the La Sal mine, Utah (fig. 25), and the Mi Vida mine, Utah (Laverty and Gross, 1956, pl. 2*D*). Many of these colloform textures have been beautifully illustrated for pitchblende from veins in France (Geffroy and Sarcia, 1954; Carrat, 1955), from the Eldorado mine, Canada (Kidd and Haycock, 1935), and from deposits in the Goldfields region, Canada (Robinson, 1955). The colloform textures of pitchblende from several veins in central Europe—including those near St. Joachimsthal, Schmiedeberg, Schneeberg, and Wittichen (Schwarzwald)—and from veins at Azegour, French Morocco, have been illustrated by Ramdohr (1955); nearly identical textures have been found in pitchblende from several veins in the conterminous United States. Among uranium-bearing veins, idiomorphic crystals of uraninite apparently are common only at Shinkolobwe (Derriks and Vaes, 1956, p. 106, figs. 18, 80) and in gold-bearing metallic veins of British Columbia, Canada (Stevenson, 1951). Uraninite crystals are extremely rare in veins in the conterminous United States and, according to published literature, apparently are uncommon in vein deposits elsewhere.

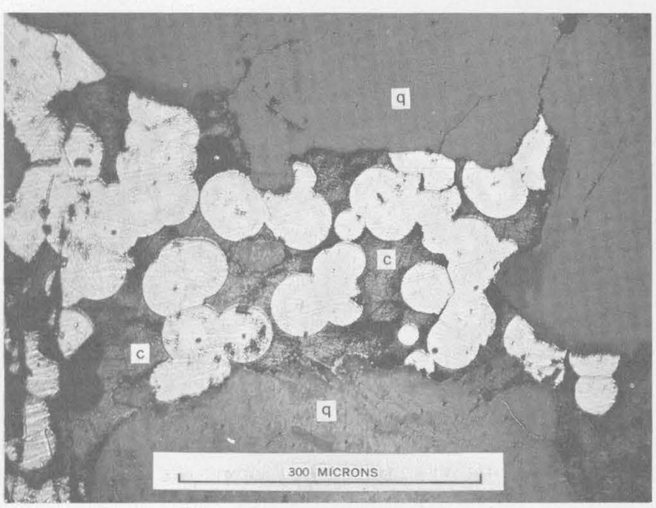

FIGURE 25.—Photomicrograph of pitchblende (white) spherulites exhibiting interference surfaces between individual spheroids and calcite (c) interstitial to quartz grains (q), from specimen of high-grade uranium ore, La Sal mine, San Juan County, Utah. Reflected light.

As may be seen from the photographs (figs. 26, 27) and photomicrographs (figs. 3, 4, 28, 29, 30, 31) of uranium ore samples from several veins, the collo-

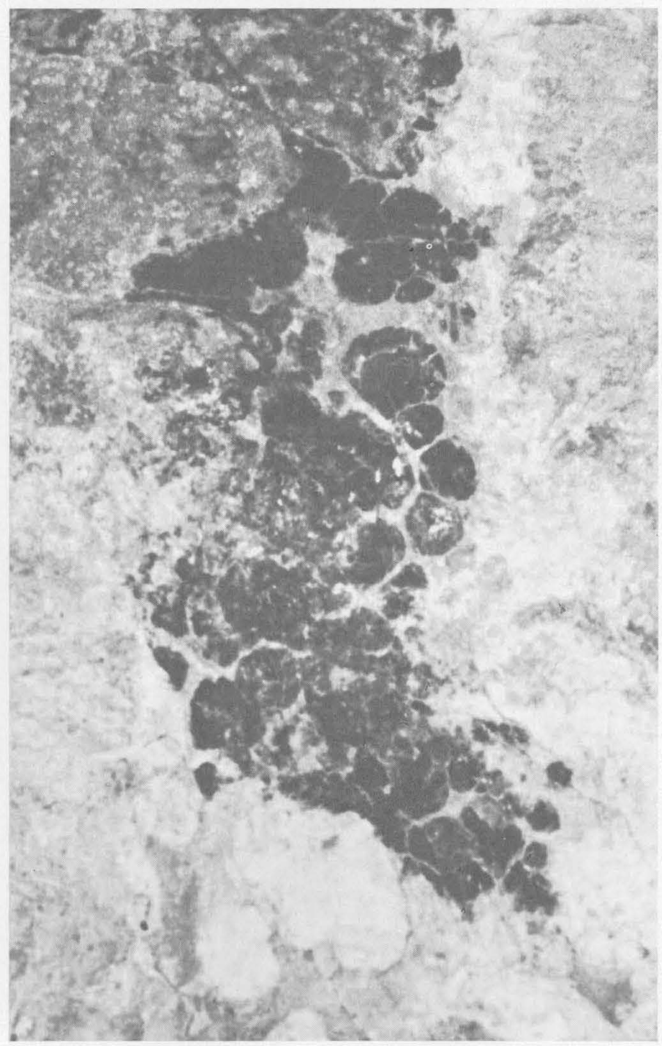

FIGURE 26.—Rounded pellets of pitchblende (black) with intervening seams of 6-valent uranium minerals (white) from W. Wilson mine, Jefferson County, Mont.

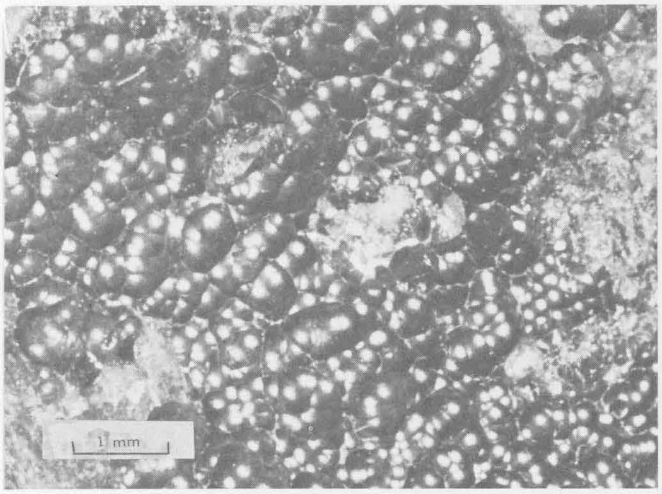

FIGURE 27.—Rounded, colloform pitchblende coating fractures from the Nigger shaft, Jefferson County, Colo.

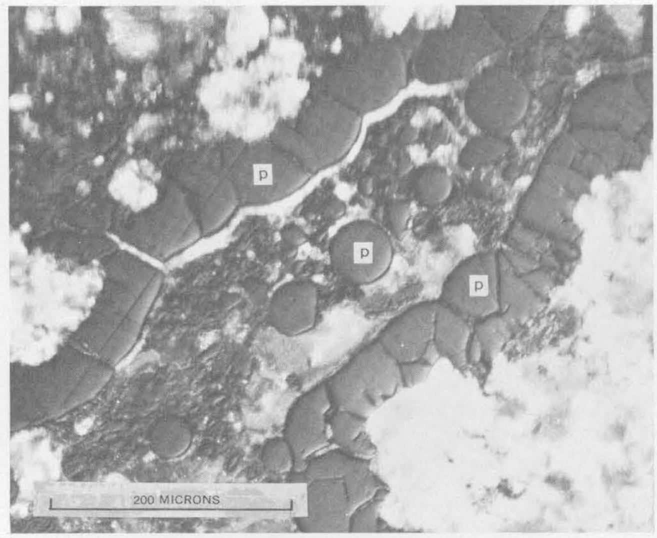

FIGURE 29.—Photomicrograph of spherulites and veinlets of pitchblende (p) from float specimen of vein material, Marshall Pass area, Saguache County, Colo. Reflected light, crossed nicols.

form textures are characterized principally by rounded or spheroidal pitchblende grains or aggregates of grains of both macroscopic and microscopic dimensions (a few microns as a minimum). The macroscopic rounded or spheroidal pitchblende masses, commonly referred to as botryoidal, nodular, mammillary, or colloform forms, are known to occur in the W. Wilson mine, Montana (fig. 26), in float specimens of vein pitchblende from the Marshall Pass area, Colorado, in the Nigger shaft or Mena mine, Colorado (fig. 27), and in deposits in the Central City district, Colorado (P. K. Sims, oral communication, 1956). Pitchblende showing microscopic colloform textures is more prevalent and has been reported in these and many other deposits.

Several of the colloform textures reported and illustrated by Kidd and Haycock (1935) for ore from the Eldorado mine, Canada, are represented in specimens from many veins in the conterminous United States. These textures include cellular or ringlike forms (fig. 30), spherulitic forms (fig. 32), and seams or veinlets exhibiting rounded surfaces. Not uncommonly, the seams or thin veinlets appear to be composed of many individual hemispheres (figs. 33, 34) or spheroids that have coalesced into chainlike forms. Interference surfaces (Bastin, 1950, p. 31–32) between individual commonly pie-shaped masses of pitchblende have been noted from many deposits; some of the more easily recognized interference surfaces are shown

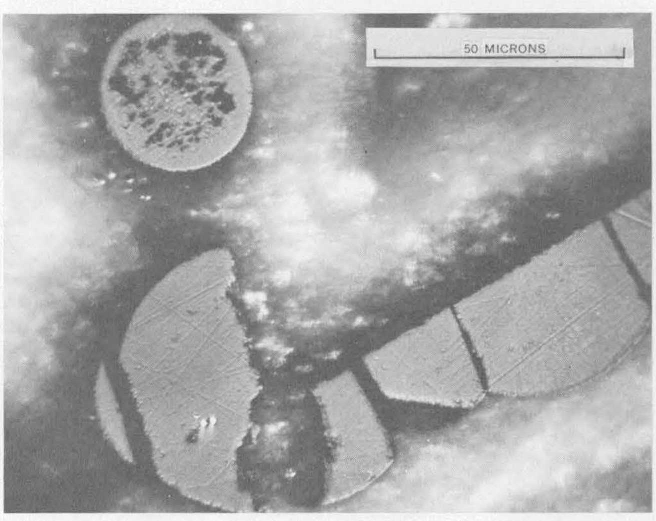

FIGURE 28.—Photomicrograph of spongy spherulite and veinlet of pitchblende in gangue of ankerite from Nigger shaft, Jefferson County, Colo. Black areas probably radiation-induced iron oxides. Reflected light.

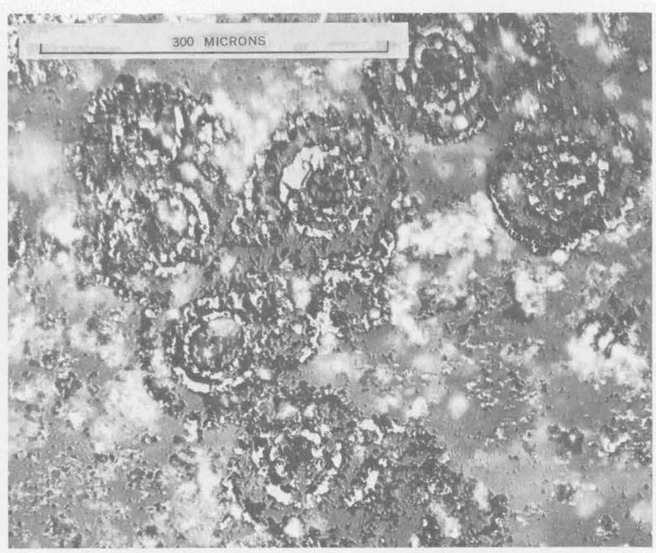

FIGURE 30.—Photomicrograph showing ringlike forms of pitchblende. Reflected light.

FIGURE 31.—Photomicrograph of pitchblende (white) spherulites and aggregates of rounded pitchblende masses from Marysvale, Utah. Reflected light.

in figures 25, 29, and 33. Locally, pseudoframboidal textures that resemble the form of a head of cauliflower are present. Concentric banding in pitchblende (fig. 4) and radial, concentric, and netlike shrinkage (or syneresis) cracks, as illustrated by photomicrographs of specimens from the Caribou mine (Wright, 1954, figs. 6, 7, 13, 23) and from deposits in the Central City district (Bastin, 1914; Sims, 1956, fig. 4), are almost universally present. No concentric banding or shrinkage cracks have been observed, however, in those deposits characterized by pitchblende spherulites or pellets (Bastin, 1950, p. 30) less than 10 or 15 microns in diameter, and the structures are uncommon in spherulites less than 50 microns in diameter.

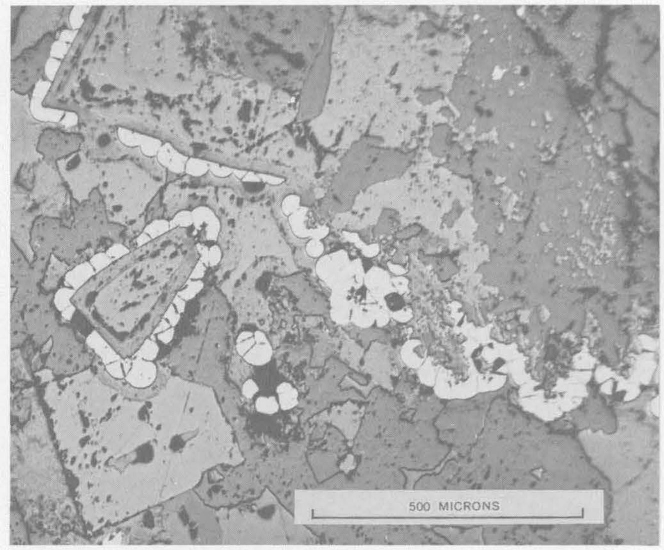

FIGURE 33.—Photomicrograph of veinlets and grain coatings composed of hemispheres and spheres of pitchblende (white) principally on crystals of ankerite from Nigger shaft, Jefferson County, Colo. Reflected light.

The morphology of some primary uranium minerals in several veins, particularly in the Boulder batholith, Montana, and in the Sierra Ancha region, Arizona, has been described as microscopic nearly equidimensional grains commonly occurring as restricted disseminations in vein filling or, locally, in host rock. Brief study of several polished sections from a few of these deposits indicates that some grains, which are commonly about 10 microns in diameter, are pitchblende spherulites, but whether most equidimensional grains tend toward spheroidal or colloform shapes or toward microscopic idiomorphic shapes has not been

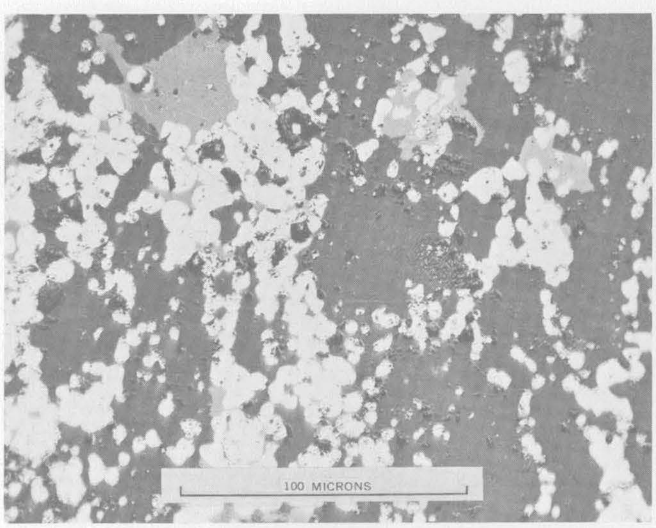

FIGURE 32.—Photomicrograph of pitchblende (white) spherulites and aggregates of spherulites in chalcopyrite (gray) and siliceous gangue (dark gray) from Hope mine, Gila County, Ariz. Reflected light.

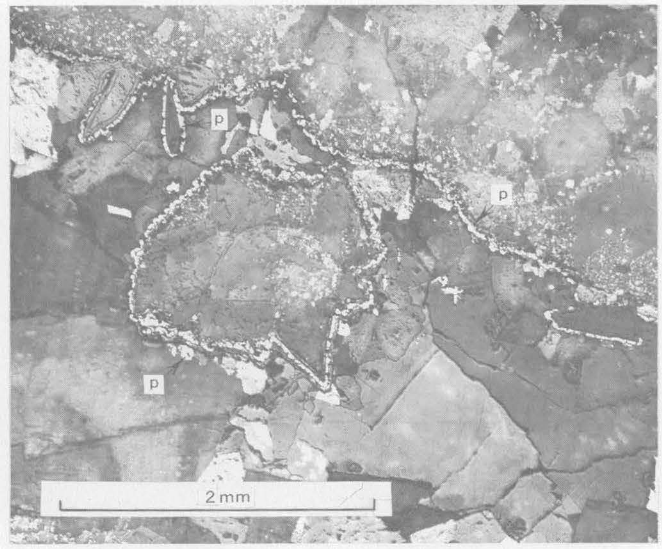

FIGURE 34.—Photomicrograph of veinlets and coatings composed of hemispheres of pitchblende from Nigger shaft, Jefferson County, Colo. Reflected light; partly crossed nicols.

established. A stage of uranium mineralization later than the equidimensional grains has been recognized in several deposits in the Sierra Ancha region and is characterized, in part, by euhedral uraninite cubes of microscopic dimensions—about 10 microns on a side (H. C. Granger, oral communication, 1958).

In a number of deposits, the colloform pitchblende is fractured and broken, forming either macrobreccias or microbreccias (fig. 4). Commonly, the breccia fragments of pitchblende are cemented by later colloform pitchblende or by other vein minerals; in several deposits, the breccia fragments, though not recemented, have a nearly continuous peripheral band or coat of colloform pitchblende.

Idiomorphic crystals of primary uranium minerals in veins are rare, but crystals of uraninite have been reported at Bisbee, Ariz., the Little Man mine, Wyoming, and in a few deposits in the Sierra Ancha region, Arizona; idiomorphic brannerite and uranothorite have been reported in a few other deposits. At Bisbee, Ariz., according to Bain (1952, p. 308), "* * * The principal uraninite occurs in micron-sized cubes along slip planes in the rocks of the Copper Queen block * * *." According to S. R. Wallace (oral communication, 1955), however, some euhedral crystals of uraninite, averaging about 50 microns in diameter, are generally hexagonal to nearly circular in outline, suggesting a dodecahedral rather than a cubic form; colloform pitchblende of a later stage of mineralization also is present. Cubes of uraninite as much as 1 mm on a side and fragments of cubes have been identified from the Little Man mine, Wyoming (fig. 8). One stage of uranium mineralization in several deposits in the Sierra Ancha region, Arizona, is represented partly by idiomorphic cubes of uraninite and more largely by minute irregular to equidimensional grains and aggregates of grains. Both the cubes and grains of this stage of mineralization are dull gray in reflected light in contrast to an early, more highly reflective variety of uraninite or pitchblende that occurs as equidimensional or spheroidal grains (fig. 32) rather than as cubes; some cubes are in microscopic fractures in the highly reflective grains. What may be idiomorphic crystals of uraninite from a vein deposit in the Marshall Pass area, Colorado, have been described by King (1957). In a specimen from this locality, pyrite and uraninite(?) occur as thin alternate layers parallel to the crystal faces of a pyrite nucleus forming a two-phase single crystal (fig. 35) to which King has applied the term "polycrystal." Positive identification of the uraninite could not be made because the size of the individual crystals (less than 30 microns) precluded separation of the two phases; the tentative identification was based on alpha-track studies and appearance in polished section. Sparse prismatic crystals of brannerite have been reported from siliceous veins in Chaffee County, Colo. (Adams, 1953), and Mono County, Calif. (Pabst, 1954), associated with quartz and hübnerite in the molybdenite deposits at Climax, Colo. (Vanderwilt and King, 1955, p. 48), and dispersed in a breccia zone mineralized with chalcopyrite and pyrite in King County, Wash. Uranothorite euhedra have been reported by Phair and Shimamoto (1952) from fluorite breccias in the Blue Jay mine, Jamestown, Colo.; colloform pitchblende coats pyrite in the same deposit.

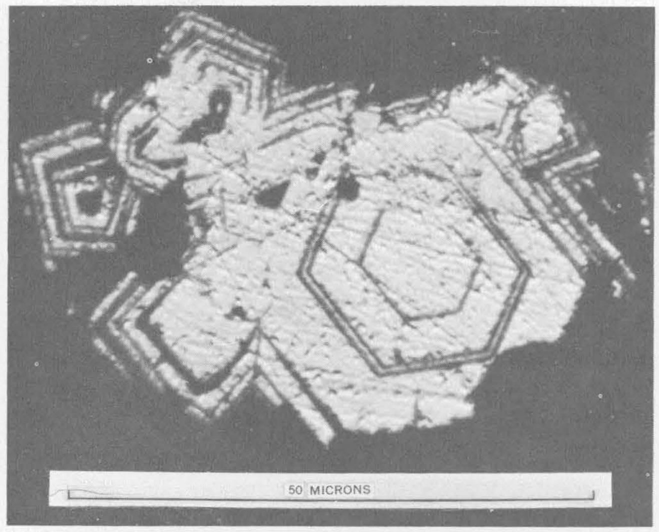

FIGURE 35.—Photomicrograph of alternate layers of pyrite (white) and uraninite(?) (gray) forming two-phase crystals from float boulder, Marshall Pass area, Saguache County, Colo. Reflected light. Photograph courtesy of A. G. King.

The idiomorphic form of uraninite is more commonly noted in pegmatites (Palache, Berman, and Frondel, 1944, p. 613), where initial temperatures presumably were higher than those of most veins. Some correlation may, therefore, exist between environmental temperatures and the growth of uraninite as idiomorphic crystals or as colloform masses of pitchblende.

Available data on replacement textures, pertaining specifically to uranium minerals in veins, demonstrate the following relations: (a) limited replacement of uraninite or pitchblende by gangue minerals or nonuraniferous ore minerals in a few veins; (b) replacement of siliceous gangue minerals and pyrite by pitchblende in two veins; (c) replacement of pitchblende by sphalerite, argentite, and proustite in one vein and by galena in another vein; and (d) replacement of ore, gangue, and host-rock minerals by 6-valent uranium minerals in several veins. Textures that have been used as evidence for replacement are varied and include principally guided penetration textures and, less commonly, embayment and pseudomorphic textures in which part of the primary fabric of the host is retained; in several places the textural data are inadequate to conclusively demonstrate replacement. Some replacement relations and textures pertaining to pitchblende have been described and illustrated by Wright (1954) for the veins at the Caribou mine, Colorado, and by Wright and others (1954) for the Lone Eagle deposit, Montana. In the Caribou mine, pitchblende replaces pyrite (Wright, 1954, figs. 16, 17) and is itself replaced by sphalerite (Wright, 1954, figs. 19, 21) and, less commonly, by proustite and argentite. Wright's evidence for replacement apparently is based largely on the presence of caries (embayments alternating with cusps; see Bastin and others, 1931, p. 602) in pyrite filled with pitchblende, caries in pitchblende filled with proustite, and sphalerite occurring along select concentric bands of colloform-textured pitchblende. Wright and others (1954, p. 67), in describing the textural relations of vein minerals in the Lone Eagle deposit, Montana, state,

> Pitchblende is found extensively as a fracture filling and replacement material in pyrite, but there is evidence in some cases that the pitchblende replaced chalcedony and sphalerite which filled fractures in pyrite. Replacement of the pyrite by pitchblende was quite extensive, and structures resembling pseudomorphs show remnant cores of pyrite.

Metatorbernite at the Two Sisters mine and the McKay shaft workings, Gilpin County, Colo., appears to replace minerals of the host rocks, principally biotite or its alteration products (Sims, Osterwald, and Tooker, 1955, p. 17–18), and uranophane replaces quartz and partly altered muscovite in quartz-tourmaline gneiss at the Schwartzwalder mine, Jefferson County, Colo.; in several places, uranophane replaces vein quartz. Six-valent uranium minerals replace primary uranous oxide minerals in an essentially pseudomorphous form in specimens from the Marshall Pass area, Colorado, and in several deposits where aggregates of 6-valent uranium minerals have replaced pitchblende spherulites.

METAL ASSOCIATIONS

Geologic studies of uranium-bearing veins and analyses of many hundreds of samples demonstrate that many metallic minerals and metallic elements are spatially related to uranium in vein deposits. The metals most commonly referred to as being concentrated in uraniferous veins include principally those that are among the more abundant constituents of the earth's crust (Fleischer, 1953), notably iron, lead, copper, nickel, zinc, vanadium, and zirconium. Several metallic elements that are not so abundant in the earth's crust—including molybdenum, cobalt, silver, arsenic, yttrium, and niobium—also have been reported in unusually large amounts in some uranium-bearing veins in the United States. The assemblage of minerals and metals associated with uranium in veins varies considerably among deposits and rarely, if ever, is the average total mineral or metal composition of a single vein known. Consequently, it is difficult to demonstrate characteristic and geologically significant metal associations for any large number of uranium-bearing veins. The problems of determining the abundance, distribution, and possible geochemical affinities of metals within uraniferous vein deposits are many. Most of these problems are concerned with (a) the inhomogeneity in distribution of the metallic minerals within veins and, consequently, the sampling difficulties attendant upon this kind of distribution; (b) the largely unpredictable distribution of many nonessential elements within common vein minerals; and (c) the complex paragenetic relations of vein minerals, particularly in multiple vein systems. Furthermore, many veins have been subjected to one or more periods of weathering; by intuitive reasoning, it can be assumed that some differential migration of metals has taken place, disturbing the metal associations characteristic of the hypogene mineral assemblage.

Fragmentary and sparse analytical data have been used by some geologists to demonstrate or suggest positive correlations between uranium and other elements, particularly with nickel, cobalt, silver, and bismuth. Commonly, little consideration is given to whether these few data are representative of a deposit (or group of deposits) and, further, whether the apparent positive correlations are fortuitous spatial associations or, conversely, have geologic and geochemical significance in terms of source of metals and methods of transport and deposition.

In places where metals occur together but no functional or genetic relation is demonstrable (or none has been demonstrated), the term "association" is applied herein. Such associations can occur, for example, where a mineralized Precambrian or Paleozoic fracture is reopened in late Tertiary time and remineralized with metals completely unrelated in geochemistry —except as a possible environmental aid to deposition—in genesis, or in time, to the earlier metals. Conversely, where metals have been deposited in a fracture as a result of a single and essentially continuous stage of mineralization, a genetic or functional relation among some of the introduced metals probably exists; in these places a correlation as well as an association among some of the metals would exist. Acceptable negative or positive correlations between metals can be demonstrated mathematically for some deposits in which metals are associated, but a functional or genetic relation must be indicated or suggested for the term "correlation" to be used in this report.

Selected analytical data on metal associations in uraniferous veins are presented in table 2; these data were selected because of the completeness of sample descriptions in terms of (a) precise geographic location, (b) the environment from which the sample was taken, or (c) the type of material collected. The data in table 2 are compiled largely from spectrographic analyses of mineral specimens, selected and channel samples of uranium "ore," and several mill-head pulps. These data permit few comparisons of metal assemblages from one deposit or district to another because (a) few, if any, of the samples are representative of the deposit from which they were taken; (b) essentially no data are available regarding the background level of metal content in the host rocks, except for a few deposits; (c) the analyses differ in type, completeness, and accuracy; and (d) some samples represent a mineral specimen of high-grade pitchblende, and others represent several tens or hundreds of tons of marketable uranium ore. Nevertheless, some of the included data indicating or suggesting the presence of abnormal amounts of metals, in conjunction with studies of the paragenetic relations of vein minerals, suggest a positive correlation of some metals to uranium not only in terms of parallel distribution or concentration but also in time of deposition. Most metal associations are probably fortuitous, however, denoting only a common locus of deposition.

Abnormally large amounts of the more abundant metallic elements of the earth's crust—specifically, iron, lead, zinc, nickel, and copper (Fleischer, 1953)—and of several less common elements—including silver, arsenic, cobalt, and molybdenum—are present in many of the uranium deposits or districts listed in table 2. However, paragenentic studies of the common minerals in uranium-bearing veins indicate that the deposition of minerals containing lead, zinc, copper, silver, arsenic, and cobalt is rarely, if ever, contemporaneous with the deposition of uranium minerals and, in many deposits, is separated in the paragenetic sequence commonly by one or more periods of brecciation. Furthermore, descriptions of mineral distribution within many deposits suggest that the distribution of uranium may be independent of the distribution of lead, copper, zinc, silver, arsenic, and cobalt; consequently, the common occurrence of these elements with uranium perhaps is best interpreted as a spatial association rather than as a correlation that implies a functional relation. Examples of deposits in which paragenetic data suggest that the uranium was introduced independently of the bulk of the base-metal sulfide minerals include deposits in the Central City district and the Copper King mine in Colorado, and in the Sunshine mine in Idaho; these are discussed in the following section on paragenesis. The association of iron and uranium in most veins also is thought to be a fortuitous spatial relation. However, in several veins part of the iron, principally in the form of pyrite but locally as magnetite or primary crystalline hematite, seems to show a pattern of distribution nearly identical with that of uranium, apparently is contemporaneous with uranium deposition, and consequently is thought to correlate with uranium. Molybdenum and, to a lesser extent, nickel show not only a coextensive distribution with uranium in some veins but also are coincident to uranium in time of deposition. Moreover, selected pitchblende specimens from some deposits or districts (table 2) contain unusual amounts of molybdenum. The association of molybdenum and uranium in a large number of widely distributed deposits and their intimate association in pitchblende from a few deposits would tend to suggest a positive correlation.

As may be seen in table 2, a variety of other elements occurs less commonly with uranium than do iron, copper, molybdenum, lead, zinc, and possibly silver, arsenic, nickel, and cobalt. The assemblage of these metals tends to vary from deposit to deposit. Most of these metal relations cannot be explained or interpreted, but in a few places correlations of uranium with manganese, beryllium, tungsten, niobium, yttrium, or zirconium are suggested. These tentative correlations are based on evidence indicating a coextensive distribution of elements within the veins and are further supported by paragenetic studies suggesting a coincident time of deposition. In a few deposits or districts, several of these metals occur together and, in such places, show a multiple correlation with uranium. Elsewhere, only one metal may be present or only one of the metals may appear to correlate with uranium, suggesting that some correlations are dependent partly on the availability and abundance of the metals. According to Sims (1955, p. 201),

> The pitchblende at Central City contains unusual quantities of Zr and Y and at places contains high Mo and W. The pitchblende at the Jo Reynolds mine, in the Lawson district, contains a similar trace-element suite. The pitchblende from Fall River, however, contains a notably different suite of trace elements; it is high in Mn and Ni and low in Zr and W.

Within the Central City district, a similar correlation between uranium and zirconium has been noted in quartz bostonites (Phair, 1952, p. 32–33); many uranium deposits of the district are closely related in space to bodies of the quartz bostonite (Alsdorf, 1916; Phair, 1952). Concentrations of yttrium appear to be associated with concentrations of uranium in deposits in Kern Canyon, Calif., the Almadin mine, Colorado, and the Wonder Lode mine, Idaho. Niobium, yttrium, and zirconium are concentrated in the Schwartzwalder mine, Union Pacific prospect, Nigger shaft, Buckman adit, Ascension mine, and Ladwig lease, all of which occur within a few mlies of each other in Jefferson County, Colo. Analyses of pitchblende from Marshall Pass, Colo., and a pitchblende concentrate from veins in Avery County, N.C., suggest an association of niobium, yttrium, and zirconium to uranium. A spectrographic analysis of hard unaltered pitchblende from the Copper King mine, Larimer County, Colo., indicates about 20 times as much zirconium and 10 to 15 times as much yttrium as that reported by Fleischer (1953) for the average abundance of these elements in the earth's crust; whether this constitutes a significant concentration and ensuing correlation of these elements with uranium is indeterminable. Both uranium and beryllium are concentrated in the fluorspar deposits of the Thomas Range, Utah, and presumably were introduced during the same period of mineralization (F. W. Osterwald, oral communication, 1956); this is one of the few districts where a positive correlation between uranium and beryllium is suggested. Minor amounts of uranium, in the form of brannerite, are associated with beryl and molybdenite in a quartz vein at the California mine, Colorado (Adams, 1953).

Studies of the metal assemblage in deposits in the Dripping Spring Quartzite by Granger and Raup (1958) have shown that a correlation exists among the elements uranium, lead, copper, nickel, cobalt, ytterbium, and beryllium. In addition, cesium, dysprosium, erbium, neodymium, praseodymium, and lanthanum

TABLE 2.—*Metals associated*

Mine, prospect, or district [1]	Mineralogic class of deposits [2]	Metals [3]																	
		Fe	Mn	Ag	As	Au	Be	Bi	Cd	Ce	Co	Cr	Cu	Dy	Er	Eu	Gd	Hf	La
Marysvale district, Utah	1	x		x		x					x?	x?	x						
Marysvale, Utah. (Select pitchblende sample).	1				x?														
Do	1																		
Thomas Range, Utah	1						x												
Central City district, Colorado (Select pitchblende samples).	2																		
Jo Reynolds mine, Colorado. (Select pitchblende sample).	2																		
Fall River district, Colorado. (Select pitchblende samples).	2		x																
Caribou mine, Colorado	2	x		x							x		x?						
Almadin mine, Colorado	2	x		x	x								x	x	x				
Copper King mine, Colorado	2	x		x							x		x						
Copper King mine, Colorado. (Select pitchblende sample).	2		x?																
South London mine, Colorado	2		x	x		x					x		x						
Bisbee, Arizona	2	x	x										x						
Hillside mine, Arizona	2	x		x	x	x							x						
Annie Laurie prospect, Arizona	2	x											x						
La Bajada mine, New Mexico	2	x			x					x	x	x?	x						x
Silver Cliff mine, Wyoming	2			x									x						
Silver Cliff mine, Wyoming. (Surface, limonitic samples).	2		x		x								x						
Nigger (Mena) Shaft, Colorado	2? [4]	x?		x	x			x					x						
Nigger (Mena) Shaft, Colorado (Select pitchblende sample).	2? [4]							x											
Union Pacific deposit, Colorado	2? [4]	x?		x?	x			x					x						
Boulder batholith, Montana	2 and 3	x	x	x	x						x		x						
Huron River deposit, Michigan	2? [4]	x	x?	x?					x	x		x?	x						x
Merry Widow claim, New Mexico	2 [4]	x				x		x					x						
Deposits in Dripping Spring Quartzite, Arizona.	3, locally 2	x		x?			x?				x		x						
Schwartzwalder mine, Colorado	3	x		x															
Schwartzwalder mine, Colorado (Select pitchblende sample).	3							x											

See footnotes at end of table.

correlate with uranium in some deposits, and molybdenum shows a positive correlation at the Tomato Juice and Rainbow deposits but a negative correlation at the Hope mine and in one of the Lucky Stop veins.

Positive correlations of uranium to molybdenum, nickel, manganese, beryllium, tungsten, niobium, yttrium, or zirconium are suggested for some uranium deposits; conversely, most deposits characterized by unusually high concentrations of molybdenum, nickel, manganese, beryllium, and tungsten—largely those deposits containing economic quantities of these metals —apparently fail to show an analogous correlation with minor concentrations of uranium. Veins characterized by unusually high concentrations of niobium, yttrium, and zirconium are rare, although an occurrence of these metals with uranium is demonstrated in a vein on Walnut Mountain, Carter County, Tenn.; a correlation of these metals with uranium perhaps is better demonstrated by their occurrence in pegmatite minerals.

A study of the occurrence of uranium and vanadium in hydrothermal veins as well as other kinds of uranium deposits has been made by Fischer (1955). He states,

> vanadium apparently does not tend to concentrate in the normal hypogene environment, and specifically it does not appear to concentrate in most hypogene veins containing uranium ore.

Several exceptions to these generalizations also have been noted by Fischer (written communication, 1955), including the Schwartzwalder mine, Jefferson County, Colo., and the Miracle mine, Kern County, Calif.—in which the relationship between uranium and vanadium is unexplained—and some titanium-bearing veins—that is, deposits containing davidite and parts of the pitchblende-bearing Ace mine, Saskatchewan, Canada (Robinson, 1955).

In many other deposits that fall within the definition of vein as used in this report (chap. A, p. 2–3), vanadium also accompanies uranium, as demonstrated by the presence of uranyl vanadates in several deposits.

with uranium in vein deposits

Metals [3]—Continued														Remarks	Reference
Mo	Nb	Ni	Pb	Sb	Sn	Th	Tl	V	W	Y	Yb	Zn	Zr		
x		x?	x									x?			Kerr, Hamilton, and others, 1953.
x			x							x				Spectrographic analysis of select pitchblende sample.	Laboratory report, U.S. Geol. Survey.
x			x?					x						Same as above; also contains Sr.	Do.
															F. W., Osterwald, oral communication, 1956.
x									x	x			x	Spectrographic analyses of select pitchblende samples from 10 different localities.	Sims, 1955.
x									x	x			x	One spectrographic analysis.	Do.
		x												do	Do.
		x	x									x		Trace elements not given.	Wright, 1954, p. 168.
		x	x	x						x		x		Spectrographic analyses of high-grade uranium samples.	Laboratory report, U.S. Geol. Survey.
x	x	x										x		Spectrographic analyses of uranium-bearing samples and of host rocks.	Sims, Phair, and Moench, 1958.
x			x?							x		x?	x	Spectrographic analysis of select pitchblende sample; also contains Sr.	Laboratory report, U.S. Geol. Survey.
			x					x		x		x		Spectrographic analysis of select sulfide vein material containing pitchblende.	Pierson and Singewald, 1953.
			x									x		Tentative correlations. Trace elements not studied.	S. R. Wallace, written communication, 1955.
			x									x		Based on mine production and mineralogic composition of vein.	Axelrod and others, 1951.
			x									x		Based on mineralogic composition of vein	Wright, 1951.
x		x					x?						x	Spectrographic analysis of uranium ore sample.	Laboratory report, U.S. Geol. Survey.
														Analytical data suggest a spatial association only.	Wilmarth and Johnson, 1954.
x												x		Spectrographic analyses of oxidized surface.	Lovering and Beroni, 1959.
x			x	x				x?							Adams and others, 1953; Laboratory Report, U.S. Geol. Survey
	x		x							x			x	Spectrographic analyses of pitchblende concentrate.	D. M. Sheridan, written communication, 1957.
x			x	x						x		x	x	Spectrographic analysis of pitchblende-bearing ore.	Adams and Stugard, 1956.
x		x	x		x										Wright and others, 1954.
x?			x			x				x		x	x?	Spectrographic analysis of impure specimen of pitchblende.	R. C. Vickers, written communication, 1955.
														Based on mineralogic composition of vein.	Granger and Bauer, 1952.
x		x	x											Spectrographic analyses of many specimens.	Granger, 1955, p. 134, and written communication, 1956.
x		x		x				x?					x	Spectrographic analyses of 28 samples of host rocks and vein material.	D. M. Sheridan, written communication, 1957.
			x							x			x	Spectrographic analysis of pitchblende concentrate.	Do.

TABLE 2.—*Metals associated with*

Mine, prospect, or district [1]	Mineralogic class of deposits [2]	Metals [3]																	
		Fe	Mn	Ag	As	Au	Be	Bi	Cd	Ce	Co	Cr	Cu	Dy	Er	Eu	Gd	Hf	La
Ladwig lease, Colorado (Select pitchblende sample).	3							x											
Ascension mine, Colorado (Select pitchblende sample).	3																		
Buckman adit, Colorado (Select pitchblende sample).	3																		
Deposits near Golden Gate Canyon, Colorado. (Surface, limonitic samples).	3			x?	x			x?					x						
Wright lease, Colorado	3	x			x								x						
Marshall Pass area, Colorado (Select pitchblende sample).	3	x?			x														
Los Ochos mine, Colorado	3	x?			x				x		x		x						
Deposits in Kern Canyon, California	3	x	x		x								x?			x			
Yellow Canary claims, Utah	3	x?									x?		x						
Midnite mine, Washington	3	x?																	
White King mine, Oregon	3	x			x						x								
Little Man mine, Wyoming	3	x																	
Autunite occurrence, South Dakota	3									x	x								x
Harper Creek prospect, North Carolina. (Select pitchblende sample).	3	x?																	
Prince mine, New Mexico	4	x	x							x									x
Linda Lee prospect, Arizona	4	x											x?						
Wonder Lode, Idaho	5	x?	x										x						
Black Dog claim, California	5	x?								x						x			x
Roberts prospect, Colorado	5	x																	
Deposit on Walnut Mountain, Tennessee.	5	x								x					x		x	x	x
California mine, Colorado	6						x												
Climax mine, Colorado	6																		
Weatherly (Black King prospect) property, Colorado.	8	x?									x?	x							

[1] Where applicable, also includes information on unusual types of samples.
[2] Mineralogic classes of veins: 1. Fluorite-bearing veins; 2. base-metal sulfide veins in which uranium minerals are subordinate; 3. veins dominantly of uranium minerals; 4. magnetite or other iron oxide-bearing veins; 5. veins dominantly thorium or rare-earths minerals; 6. brannerite-bearing quartz or siliceous veins; 8. hydrocarbon-rich ura-

The authors consider the deposits at Tyuya Muyun, Russia, to be veins, as does Pavlenko (1933), and also some, if not all, the geologically similar deposits in the Pryor Mountains of Montana; deposits in both areas are characterized by uranyl vanadate minerals. Shoemaker (1956a, p. 183) reports uranyl and cupric vanadates as well as copper carbonates in the Navajo Sandstone at the Garnet Ridge diatreme, Arizona; the copper and vanadium minerals are disseminated in sandstone and coat fracture surfaces adjacent to a fault zone that contains a discontinuous dike of mica-serpentine tuff. Further, either uranyl vanadate minerals or what appear to be abnormally high amounts of vanadium have been reported in vein deposits in the Thomas Range, Utah, in the Ridenour mine, Arizona (Miller, 1954), in the Yellow Canary deposit, Daggett County, Utah, in the Weatherly (Black King prospect) property and Rajah mine (Shoemaker, 1956b), Colorado, in a vein deposit in Huerfano County, Colo. (Moore and Kithil, 1913), in the Nigger shaft deposit, Colorado, and elsewhere. The occurrence of uranium and vanadium in some veins and not in others is unexplained but may result largely from differences in the petrologic environment of the veins rather than from differences in the processes involved in their formation. The effect of petrologic environment is suggested by the prevalence of abnormally high concentrations of uranium and vanadium in vein deposits enclosed in limestone and dolomite, as for example at Tyuya Muyun, Russia, the Pryor Mountains, Mont. and the Thomas Range, Utah.

The positive correlation of certain metals—notably molybdenum, manganese, beryllium, tungsten, vanadium, niobium, yttrium, and zirconium—to uranium in veins seems to be reasonably well established within some deposits, districts, or restricted geographic areas, but none of these metals can be shown to correlate with uranium in all or even a large percentage of vein deposits. In addition to the metals that when present appear to correlate intimately with uranium, many other metals such as lead, zinc, copper, silver, and cobalt are associated with uranium in many deposits only in the sense of occurring within the same favorable structure. Some uranium in veins locally occurs in economic and large deposits of other metals, principally copper, lead, zinc, and silver, as for example at *uranium in vein deposits*—Continued

Mo	Nb	Ni	Pb	Sb	Sn	Th	Tl	V	W	Y	Yb	Zn	Zr	Remarks	Reference
	x		x							x			x	Spectrographic analysis of pitchblende concentrate.	D. M. Sheridan, written communication, 1957.
	x		x							x			x	do	Do.
	x		x							x			x	do	Do.
x			x	x						x?	x?			Spectrographic analyses of oxidized surface samples.	Lovering and Beroni, 1959.
x			x					x?						Spectrographic analysis of ore-grade uranium sample.	
	x									x		x?	x	Spectrographic analyses of "gummite" and pitchblende.	Laboratory report, U.S. Geol. Survey.
x	x	x	x		x		x					x		Spectrographic analyses of mill-head plups and several different host rocks.	Do.
x								x		x				High V in Miracle mine	MacKevett, 1956, p. 228; W. A. Bowes, written communication, 1957.
			x?					x						Spectrographic analyses of ore-grade uranium samples.	Wilmarth, 1953, p. 6.
x														Spectrographic analyses of soil samples across ore body.	Weis, 1955, p. 224.
			x		x	x						x			Matthews, 1955.
x														Based on mineralogic composition of vein.	
x	x				x										Vickers, 1953, p. 2.
			x					x?		x			x	Spectrographic analysis of high-grade pitchblende sample.	Laboratory report, U.S. Geol. Survey.
														Spectrographic analyses of continuous chip samples.	Walker and Osterwald, 1956b.
														Based on mineralogic composition of vein.	
						x				x		x		In general, only very small amounts of uranium present.	Laboratory report, U.S. Geol. Survey.
						x								Based on mineralogic composition of vein and analysis for U and Th.	Walker, Lovering, and Stephens, 1956, p. 24.
						x								do	R. C. Malan, oral communication, 1956.
	x					x				x	x		x	Spectrographic analysis of composite vein material; also contains Dy, Ho, Lu, Nd, Sm, Tm.	Laboratory report, U.S. Geol. Survey.
x														Based on mineralogic composition of vein.	Adams, 1953.
x									x					do	Vanderwilt and King, 1955.
x		x?	x					x						Spectrographic analyses of hydrocarbon and of host rocks.	V. R. Wilmarth and R. C. Vickers, written communication, 1952.

nium-bearing veins.
[3] Metals reported in more than normal amounts.
[4] Data on relative abundance of minerals not adequate to definitely establish mineralogic class.

Bisbee, Ariz., in many deposits in the Front Range of Colorado, in several deposits in the Coeur d'Alene district, Idaho, and in the Goodsprings district, Nevada; in many other deposits the ores are characterized by small quantities of both uranium and other metals, principally lead and zinc, or copper, or locally silver. Most vein deposits, however, that have yielded hundreds or thousands of tons of uranium ore in general contain less than economic quantities of metals other than uranium; these deposits include the Schwartzwalder and Los Ochos mines, Colorado, Marysvale deposits, Utah, Daybreak and Midnite mines, Washington, Early Day mine, Nevada, deposits in the Dripping Spring Quartzite, Arizona, and several other deposits in volcanic or tuffaceous rocks in the western United States.

PARAGENESIS OF URANIUM-BEARING VEINS

Detailed paragenetic studies have been made of relatively few uranium-bearing veins in the conterminous United States. The lack of such detailed studies resulted largely from the time limitations on the scientific investigations of individual deposits, as the national interest required that the efforts of most geologists concerned with uranium be directed toward the search for, and exploration of, new deposits. Such studies as have been made differ widely in scope and involve mineral relations that permit only partial paragenetic interpretation. Some investigations considered both ore and gangue minerals; but, for the most part, only fragmentary data are available, and much work needs to be done on this phase of the geology of uranium deposits.

The few detailed paragenetic studies of uranium-bearing veins have emphasized the relations among the primary hypogene minerals of the veins and, consequently, deal largely with the position of uraninite or pitchblende in the depositional sequence; in a few deposits the position of coffinite is considered. For those minerals characterized by 6-valent uranium, most of which are thought to be products of supergene alteration, the position within the depositional sequence generally is not considered. Some data on the formation and distribution of the 6-valent uranium minerals is presented in Chapter E.

TABLE 3.—*Paragenetic position of pitchblende in single-stage veins*

Deposit	Class [1]	Age of mineralization	Position of pitchblende in mineral sequence	Remarks	Reference
Marysvale, Utah	1	Tertiary	Intermediate	District composite, see fig. 40	Laverty and Gross, 1956.
Jamestown, Colo. (Blue Jay mine)	1	do	Early and intermediate	Uranothorite and some pitchblende are early.	George Phair and Kiyoko Onoda, written communication, 1950.
Buck mine, Michigan	2	Ordovician (?)	Intermediate	Pyrite earlier	R. C. Vickers, written communication, 1956.
Francis mine, Michigan	2	do	do	do	Do.
Union Pacific prospect, Colorado	2? [2]	Tertiary	Early	See fig. 37	Adams and Stugard, 1956.
Nigger shaft, Colorado	2? [2]	do	do	Ankerite earlier	Adams, Gude, and Beroni, 1953.
Deposits in Sierra Ancha region, Arizona.	3 and 2	Pre-Devonian	do	District composite	Granger and Raup, 1959.
Schwartzwalder mine, Colorado	3	Tertiary	do	See fig. 38	F. W. Kuehnel, written communication, 1956.
Los Ochos mine, Colorado	3	do	Late	Marcasite earlier; pitchblende probably regenerated.	Derzay, 1956.
W. Wilson mine, Montana	3	do	Intermediate	Pyrite earlier; galena and sphalerite contemporary with pitchblende.	
G. Washington mine, Montana	3	do	do	Pyrite earlier, no other sulfides	Wright and others, 1954.
Sherwood mine, Michigan	2? [2]	Ordovician (?)	do	Pyrite earlier	R. C. Vickers, written communication, 1956.
Placerville, Colorado	8	Post-Triassic	do [3]	Pitchblende precedes most sulfides; pyrite contemporaneous or earlier.	V. R. Wilmarth and R. C. Vickers, written communication, 1952.

[1] Mineralogic classes of veins: 1. Fluorite-bearing veins; 2. base-metal sulfide veins in which uranium minerals are subordinate; 3. veins dominantly of uranium minerals; 8. hydrocarbon rich uranium-bearing veins.
[2] Data on relative abundance of minerals not adequate to definitely establish mineralogic class.
[3] Represents paragenetic position of uraniferous hydrocarbon and included pitchblende.

The usefulness of paragenetic study goes beyond the interpretation of the sequence of mineral deposition, as it affords an insight into the chemical environment in which the deposition of the various minerals took place. Without knowledge of the sequence of deposition of the vein minerals, quite erroneous emphasis may be placed on mineralogical and elemental associations; this can be especially true for deposits that have resulted from more than one period of ore deposition.

DETAILED PARAGENETIC STUDIES

A summary of the paragenetic data concerning 24 uranium-bearing veins in the conterminous United States is given in tables 3 and 4. For many of these deposits, information regarding the sequence of mineral crystallization is incomplete, but 13 of the deposits have been studied in sufficient detail for discussion in the following pages. Of these 13 deposits, base-metal sulfide veins (class 2), in which uranium minerals are subordinate, predominate, but examples of fluorite-

TABLE 4.—*Paragenetic position of pitchblende in veins in which multiple stages of mineralization are recognized*

Deposit	Class [1]	Age of mineralization	Position of uranium stage in vein sequence	Position of pitchblende in uranium stage	Remarks	References
Central City, Colo. (composite)	2	Tertiary	Early	Early	Associated with quartz and pyrite	Sims 1956.
Almadin, Colo	2	do	do	do	Pitchblende and nickel minerals in early pyritic stage; base-metal stage later.	P. K. Sims, oral communication, 1956.
Caribou, Colo	2	do	Late	do	Preceded by gersdorffite; base-metal minerals later.	Wright, 1954.
Copper King, Colo	2	do	do	Intermediate	Early stage probably Precambrian; Siderite and iron sulfides precede pitchblende.	Sims, Phair, and Moench, 1958.
Lone Eagle, Mont	2	do	do	Early	With chalcedony, minor pyrite. (See also comments, p. 81 text.)	Wright and others, 1954.
Mooney claim, Montana.	2	Tertiary(?)	do	Indeterminate	Pitchblende(?) thought to be associated with black cherty quartz introduced into brecciated quartz-base-metal sulfide vein. Stibnite appears to replace black cherty quartz.	Moen, 1954.
Bisbee, Ariz	2	Cretaceous	Early	do	Crystallized uraninite associated with quartz and hematite.	Bain, 1952.
De la Fontaine, Ariz	2	Late Mesozoic	Late	do	Uranium deposition thought to follow brecciation of base-metal vein. H. D. Wright and W. P. Shulhof, (written communication, 1956) think pitchblende is late mineral of prebreccia suite.	Hart and Hetland, 1953.
Huron River, Mich	2	Ordovician(?)	do	Intermediate	See fig. 39. Pyrite earlier	R. C. Vickers, written communication, 1956.
Sunshine, Idaho	2	Precambrian(?)	Early	Early	Associated with quartz, pyrite, arsenopyrite(?).	Kerr and Robinson, 1953.
Halfmile gulch, Colo	8	Tertiary(?)	Late	Indeterminate	Asphaltite, pitchblende, and base-metal sulfide minerals later than an early-stage brecciated pyrite.	

[1] Mineralogic classes of veins—entire assemblage of multiple-stage veins used as a basis for classification: 2. Base-metal sulfide veins in which uranium minerals are subordinate; 8. Hydrocarbon-rich uranium-bearing veins.

bearing veins (class 1) and hydrocarbon-rich uranium-bearing veins (class 8) as well as veins dominantly of uranium minerals (class 3) are included.

CARIBOU MINE, COLORADO

A detailed paragenetic study of the ore assemblage from the Radium vein of the Caribou mine in Boulder County, Colo., indicates that mineralization took place during two stages separated by a period of brecciation (Wright, 1954); the sequence of mineral deposition is as follows:

Stage A

1. Quartz with calcite and siderite
2. Pyrite?
3. Chalcopyrite
4. Sphalerite
5. Galena

Stage B

1. Gersdorffite and chalcedony
2. Uraninite[2] and chalcedony (with minor pyrite)
3. Sphalerite and chalcopyrite (with minor pyrite and uraninite)
4. Pyrite
5. Argentite with chalcopyrite
6. Proustite (followed by very minor uraninite)
7. Native silver

Replacement of uraninite (pitchblende) by sphalerite, proustite, and argentite was noted in polished sections, and some pitchblende deposited late in stage B is thought to represent redeposition of earlier formed material (Wright, 1954, p. 161).

Moore, Cavender, and Kaiser (1957, p. 537) indicate that most pitchblende at the Caribou mine is soft and sooty and occurs as coatings on hard unaltered pitchblende, as fracture coatings, and as coatings on colloform quartz and fine oolitic pyrite in vugs. The distribution and occurrence of the sooty pitchblende suggests to them a second, late and probably low-temperature stage of deposition probably related to supergene processes.

COPPER KING MINE, COLORADO

Pitchblende and some coffinite occur in a sulfide-magnetite ore body at the Copper King mine in Larimer County, Colo. The ore body is in metamorphic rocks enclosed in granite and consists largely of an early high-temperature assemblage of magnetite and sulfide minerals that has replaced amphibole skarn and associated rocks. The minerals of the skarn ore probably formed during late Precambrian time (Phair and Sims, 1954).

[2] Note: Wright's usage of uraninite is retained in this table; although, by the usage adopted in this paper, the mineral is the pitchblende variety.

Magnetite was the first ore mineral to be deposited, followed in order by pyrrhotite, pyrite, sphalerite, and chalcopyrite. A little quartz was introduced after the deposition of magnetite (Sims and others, 1958).

During or after a period of brecciation of the skarn ore and the enclosing rocks, a second period of mineralization began with the introduction of siderite, pyrite, marcasite, and minor quartz. Some sphalerite and chalcopyrite also may have formed at this time. Fracturing of these minerals was followed by a third period of deposition during which pitchblende and fine-grained siderite veined the earlier minerals and filled openings between them (figs. 16, 17). Siderite is both earlier and later than pitchblende, and some pyrite was deposited as rims on pitchblende. Much later, resinous sphalerite, some siderite, and fine-grained quartz were formed, probably by supergene solutions. Also late in the sequence, pitchblende was deposited as thin coatings and colloform layers in vugs in the vein and in boxwork structures in pyrite (Sims and others, 1958). Coffinite is intimately intergrown with both the early and the late pitchblende.

Age determinations support the concept of two widely spaced periods of mineralization at the Copper King mine. Two specimens of magnetite from the skarn ore gave ages of 700 to 740 million years (Precambrian) when tested by the alpha-helium method (Sims and others, 1958), whereas lead-uranium determinations made on pitchblende from the deposit indicate an early Tertiary age (Phair and Sims, 1954).

CENTRAL CITY DISTRICT, COLORADO

The sequence of mineral deposition and the paragenetic position of pitchblende within this sequence in the Central City district, Colorado, is complicated by the presence of several stages of mineralization, all of Laramide age. Within the district, two distinct vein types have been recognized for many years (Bastin and Hill, 1917; Lovering and Goddard, 1950); both show a spatial distribution that is probably the result of hypogene zoning. The pattern is essentially one of an inner zone about 2 miles in diameter (Sims and Tooker, 1956, p. 106–107) in which quartz-pyrite veins are dominant and a peripheral zone in which galena-sphalerite veins are dominate. Composite veins have formed where quartz-pyrite-filled structures were reopened and minerals of the galena-sphalerite type assemblage introduced. Pitchblende occurs locally in the district, as in the composite-type lode at the Wood and East Calhoun mines (Moore and Butler, 1952; Drake, 1957). Recent detailed studies (Sims, 1956) indicate that the uranium minerals are unrelated to the

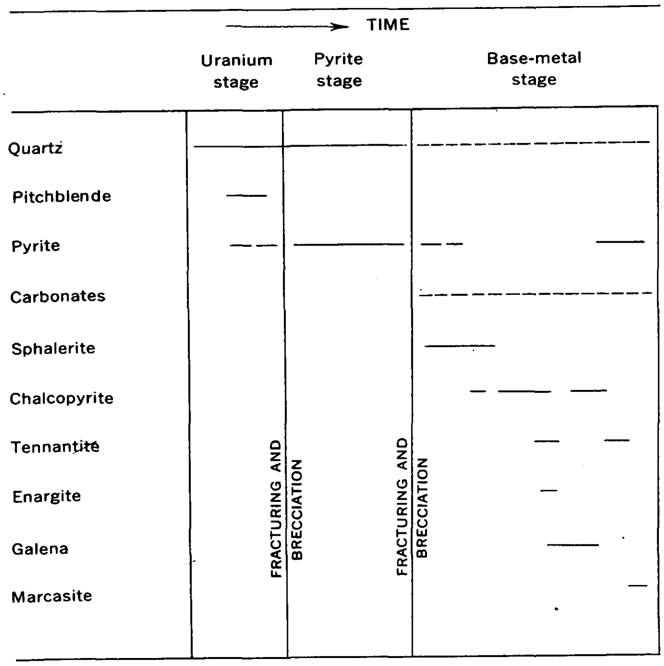

FIGURE 36.—Generalized sequence of deposition of principal vein-forming minerals, Central City district, Colorado (after Sims, 1956).

hypogene zonal pattern and that pitchblende deposition is distinct from and earlier than either of the major vein fillings. The vein filling of the pitchblende stage is thought to have its source in shallow bodies of quartz bostonite magma rather than in the deeper magmas from which the somewhat later ores were derived (Sims, 1956, p. 746; Phair, 1952). The general paragenetic sequences of the Central City veins, as established by Sims (1956), is given in figure 36.

SUNSHINE MINE, IDAHO

An extremely complex sequence of events is postulated by Kerr and Robinson (1953) for the pitchblende-bearing silver ores of the Sunshine mine, Idaho. Their conclusions may be summarized as follows:

1. Regional deformation of sedimentary rocks of the Belt Series
2. Early emplacement of uraninite-pyrite-quartz accompanied by local penetration of the wallrocks by arsenopyrite and pyrite
3. Intermineralization deformation with faulting and segmentation of uraninite veins
4. Main tetrahedrite-siderite epoch (major silver veins formed; some solution and reprecipitation of uraninite)
5. Post-silver deformation
6. Quartz-galena stage, barren or low-grade siderite veins; quartz-galena veins, white quartz veins
7. Post-mineral deformation

The early position of pitchblende in the Sunshine ore suite, as determined by Kerr and Robinson, is in agreement with the conclusions of J. W. Adams and R. U. King (written communication, 1950) but at variance with those of Thurlow and Wright (1950), who consider pitchblende to be posttetrahedrite and, hence, late in the mineral sequence.

Evidence supporting an early period of uranium deposition is afforded by chemical and lead-isotope analyses that suggest a Precambrian age for pitchblende from the Sunshine mine (Kerr and Kulp, 1952). The lead-silver mineralization of the Coeur d'Alene district is considered to be of late Mesozoic (Ross, 1933), early Tertiary (Anderson, 1951) or possibly Precambrian age (Cannon, 1956). If the dating of the pitchblende and the Mesozoic or early Tertiary age of lead-silver mineralization are correct, then uranium and lead-silver mineralization took place at widely separated intervals. On the other hand, if the Precambrian age for the lead-silver mineralization is correct, then uranium and lead-silver mineralization may be separated only by a depositional break in a single metallogenic period. It is obvious that the paragenetic position of pitchblende in relation to the lead-silver stage is critical in establishing the age of the main period of mineralization in the Coeur d'Alene district.

JEFFERSON COUNTY, COLO.

In Jefferson County, Colo., pitchblende has been found in shear zones of Laramide age cutting Precambrian metamorphic rocks (Adams, Gude, and Beroni, 1953). Paragenetic studies of two of these deposits (figs. 37, 38), the Union Pacific prospect (Adams and Stugard, 1956, p. 200–202, fig. 49) and the Schwartzwalder (Ralston Creek) mine (F. W. Kuehnel, written communication, 1956), indicate that pitchblende was deposited prior to the introduction of most of the sulfides. In both these deposits, pitchblende deposition is separated from deposition of most sulfide minerals by a period of fracturing; however, mineralization is thought to have been essentially continuous.

BOULDER BATHOLITH, MONTANA

Uranium-bearing veins of Tertiary age occur in quartz monzonite and related rocks of the Boulder batholith, Montana (Thurlow and Reyner, 1952; Roberts and Gude, 1953; Wright and others, 1954; Becraft, 1956; Wright and Shulhof, 1957b). These deposits include some silver-lead veins but are chiefly the so-called "siliceous reef" type that are chalcedonic vein zones in which metallic minerals are sparse. A tentative paragenetic sequence by Wright and others (1954)

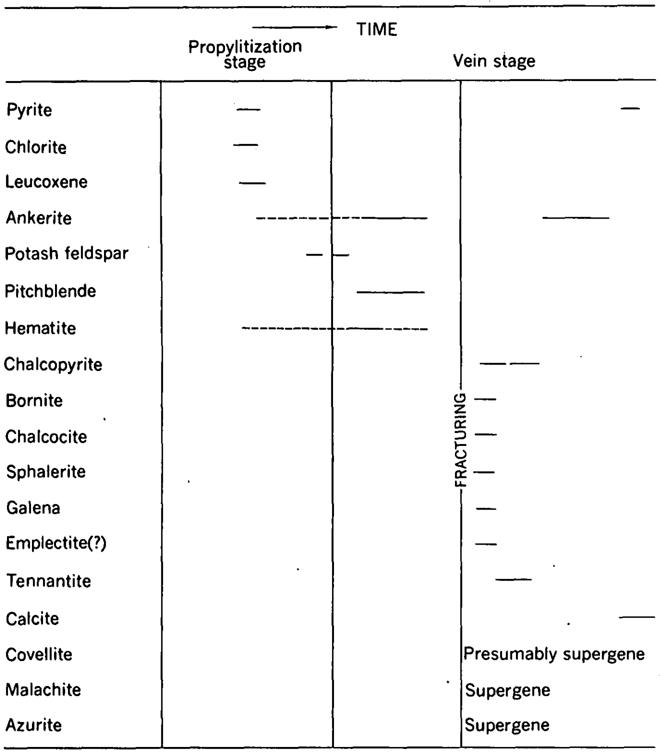

FIGURE 37.—Paragenetic sequence of minerals at the Union Pacific prospect, Jefferson County, Colo. (from Adams and Stugard, 1956).

for the chalcedony vein at the W. Wilson mine indicates that pitchblende formed late in the vein sequence. Studies of the paragenetic sequence by D. Y. Meschter (written communication, 1953) have established that pitchblende is essentially contemporaneous with pyrite and chalcopyrite in the deposit and that it is probably intermediate in the sequence if both metallic minerals and nonmetallic gangue minerals are considered. Repeated brecciation of the vein was accompanied by the introduction of microcrystalline quartz of various colors, a black to dark gray variety being associated with the pitchblende. Pitchblende is also associated with dark-colored quartz in the silver-lead veins, which appear to have reopened during the period of uranium mineralization (Becraft, 1956, p. 121).

The uranium-bearing deposit at the Lone Eagle mine is probably a mixed type vein showing characteristics of both the chalcedonic and the silver-lead veins (Becraft, 1956, p. 121). The paragenesis of this deposit as given by Wright and others (1954, p. 5) is as follows:

1. Microcrystalline quartz
2. Well-formed pyrite
3. Sphalerite, with chalcopyrite, galena, and fine-grained pyrite
4. Pitchblende and cryptocrystalline chalcedony
5. Sphalerite and galena with cryptocrystalline chalcedony
6. Argentite(?)

Extensive replacement of pyrite by pitchblende and pitchblende engulfed and veined by sphalerite have been reported in ores from the deposit (Wright and others, 1954, p. 67).

For the Lone Eagle mine, Wright and Shulhof (1957b) present a slightly revised paragenetic sequence of vein minerals in which a variety of galena and minor sphalerite and pyrite are apparently contemporaneous with pitchblende deposition. The galena associated with the pitchblende differs in microscopic appearance from an early-stage galena and conceivably may be of radiogenic origin, although Wright and Shulhof (1957b) do not so specify.

NORTHERN MICHIGAN

The paragenetic sequence of pitchblende-bearing ores from four deposits in northern Michigan has been established by Vickers (written communication, 1956). These ores occur in middle Precambrian (upper Huronian) rocks, but uranium deposition is thought to have taken place during Ordovician time (Kulp and

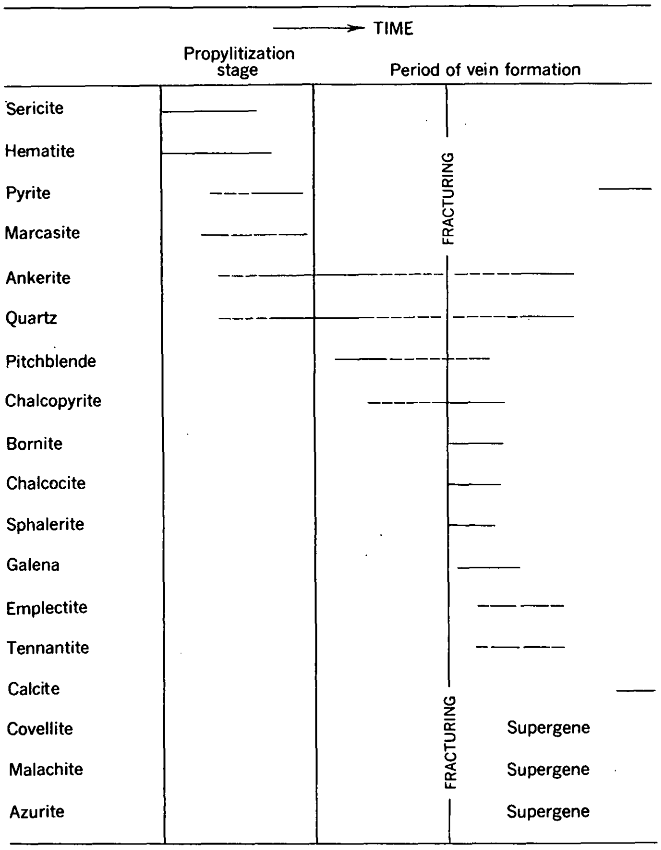

FIGURE 38.—Paragenetic sequence of minerals at the Schwartzwalder (Ralston Creek) mine, Jefferson County, Colo. (after F. W. Kuehnel, written communication, 1956).

others, 1953). The most detailed paragenesis is that given for the Huron River deposit (fig. 39), where Vickers (R. C. Vickers, written communication, 1956) recognizes two stages of mineralization separated by a period of fracturing. In the initial stage, only quartz and minor hematite were deposited; following fracturing, pyrite, pitchblende, base-metal sulfide minerals, and calcite were introduced. Pyrite, the earliest metallic mineral of the second stage, was followed by pitchblende and a suite of apparently penecontemporaneous sulfide minerals; deposition of calcite was continuous throughout the stage. Pitchblende from this deposit commonly encloses small grains and idiomorphic crystals of galena and may be cut by veinlets of chalcopyrite, galena, and calcite.

The three other deposits—Sherwood, Buck, and Francis mines—show only the pitchblende-sulfide mineral stage (fig. 39), with deposition orders analogous to that given for the second stage of the Huron River deposit.

SIERRA ANCHA REGION, ARIZONA

Pitchblende and sulfide minerals occur in the Dripping Spring Quartzite of Precambrian age in Gila County, Ariz. Rocks of this formation have locally been metamorphosed to hornfels adjacent to diabase bodies, and the ore deposits are best developed in the hornfels (Granger and Raup, 1959). These deposits have been dated radiochemically as of Precambrian age (see chap. B) and are believed to be genetically related to the diabase bodies.

Polished-section studies suggest that pitchblende formed before any of the sulfide minerals (Granger and Raup, 1959), of which pyrrhotite and molybdenite were the earliest. Chalcopyrite is later than pyrrhotite, which it locally replaces, and an alteration of pyrrhotite to marcasite was noted. Galena and sphalerite are present, but their relation to other sulfides is obscure. Gangue associated with the pitchblende is largely a green claylike material.

The minerals in ore from this district are extremely fine grained, and the various constituents are commonly dispersed, making relations difficult to establish. For these reasons, the paragenesis, as stated, is quite tentative and is subject to revision upon further study (H. C. Granger, oral communication, 1956).

BISBEE, ARIZ.

The occurrence and paragenetic relations of crystallized uraninite in Bisbee ores are described by Bain (1952). The uraninite crystals, which are cubes a few microns in size, are associated with minute flakes of hematite and crystals of quartz in limestone. Bain

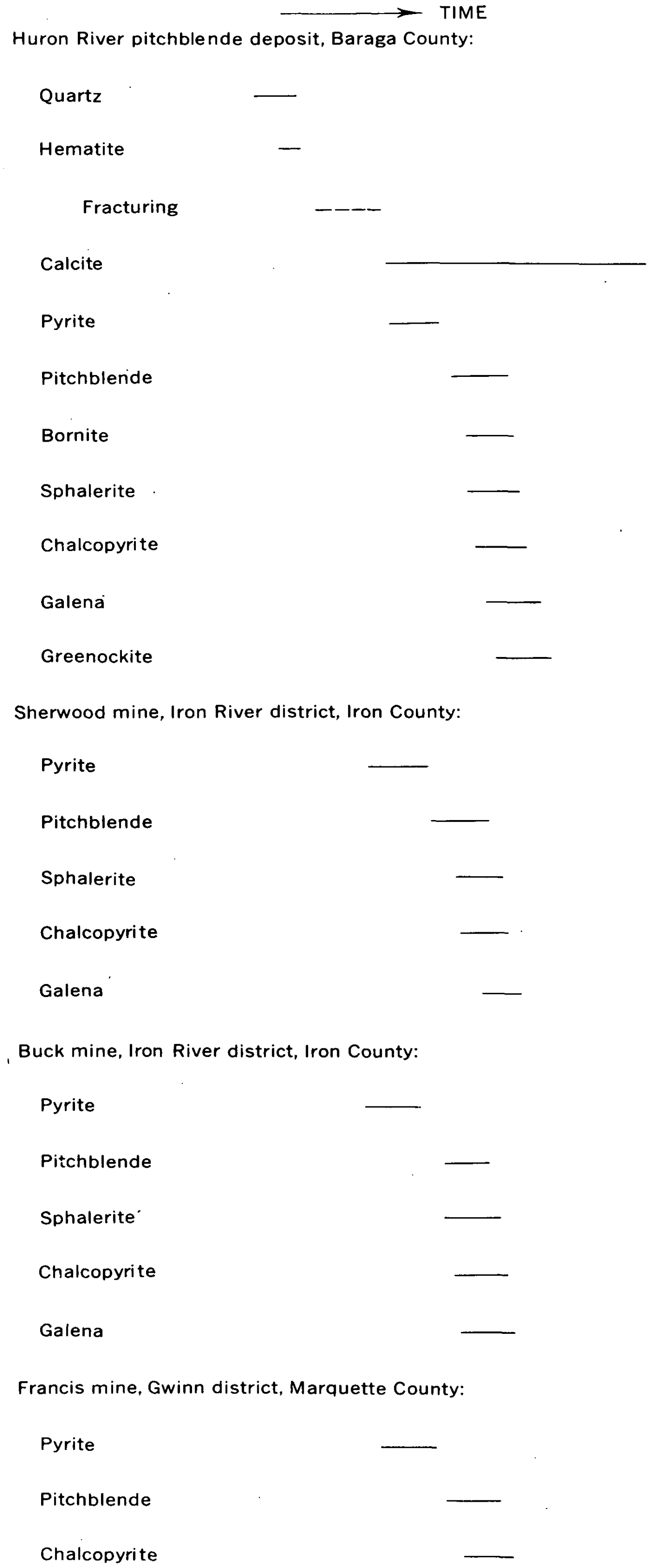

FIGURE 39.—Paragenetic sequence of the minerals at the four pitchblende occurrences in northern Michigan (after R. C. Vickers, written communication, 1956).

(1952, p. 308) describes the mineral sequence as follows:

Uraninite is almost the earliest mineral in the sequence at Bisbee and the copper minerals represent the closing phases of mineralization with some gold quartz veins representing possibly a later cycle. The intermediate stages show a pyritic phase, a galena-sphalerite phase, and a quartz-carbonate phase.

The theory that euhedral uraninite is early in the paragenetic sequence has been substantiated by S. R. Wallace (oral communication, 1956), although he also has established later stages of colloform and sooty pitchblende mineralization.

MARYSVALE DISTRICT, UTAH

Many features of the geology and mineralogy of the late Tertiary pitchblende-bearing fluorite veins of the Marysvale, Utah, district have been studied in considerable detail (Gruner and others, 1951; Kerr and others, 1952; Gruner and others, 1954; Walker and Osterwald, 1956a; Kerr and others, 1957); however, there is very little information available on the paragenesis of the ores.

The veins are of complex and varying mineralogy but consist primarily of quartz or chalcedony, fluorite, pyrite, and adularia. From a composite paragenetic sequence of Marysvale ores (fig. 40) given by Laverty and Gross (1956), it would seem that pitchblende deposition began at an intermediate stage of vein formation following a period of general brecciation. The so-called sooty pitchblende found largely in the oxidized parts of the veins probably results from the reworking of early hard pitchblende (Stugard, Wyant, and Gude, 1952).

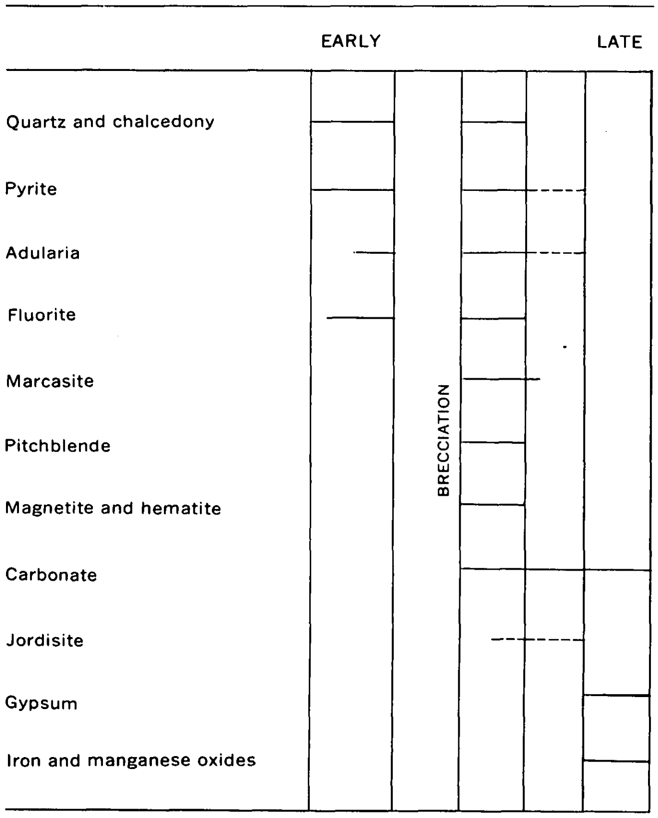

FIGURE 40.—Paragenetic sequence of the minerals at Marysvale, Utah. After Laverty and Gross (1956).

JAMESTOWN, COLO.

Fluorite deposits of Tertiary age at Jamestown, Colo. (Goddard, 1946) contain pitchblende that is largely concentrated in an assemblage of fine-grained minerals cementing coarse fluorite breccia. According to Goddard (1946), deposition of fluorite, quartz, pyrite, galena, and other sulfide minerals took place at about the same time. Owing to a change in the composition of the mineralizing fluids, part of the fluorite was dissolved, causing the collapse and brecciation of the ore bodies. The brecciated material was later veined and cemented by a second generation of fluorite together with some chalcedony, quartz, ankerite, hematite, clays, and finely disseminated sulfide minerals. Both uranothorite and uraninite (pitchblende?) are present in the early stage fluorite at the Blue Jay mine (Phair and Shimamoto, 1952), but most of the uraninite is found in the fine-grained cementing material. Some uraninite of the second stage may have been derived from uranium leached from uranothorite (George Phair, written communication, 1956) or uraninite during the period of fluorite solution. Colloform uraninite coating pyrite is reported as inclusions in fluorite by Phair and Kiyoku Onoda (written communication, 1950), but no detailed paragenesis is available.

In districts other than Jamestown, fluorite-bearing veins in which only 6-valent uranium minerals have been found are not uncommon (Wilmarth and others, 1952; Vickers, 1953; Lovering, 1956); fluorite veins are also known where these 6-valent minerals are accompanied by sooty pitchblende. Such deposits have offered little data as to the initial paragenetic position of the uranium except to suggest that the 6-valent uranium minerals and perhaps some sooty pitchblende were derived from uraniferous fluorite.

PLACERVILLE, COLO.

In the vicinity of Placerville, Colo., two hydrocarbon-bearing veins have been studied in some detail by V. R. Wilmarth and R. C. Vickers (written communication, 1952). These veins cut sedimentary rocks of late Paleozoic and early Mesozoic age and contain both uraniferous and nonuraniferous hydrocarbons (pyrobitumens), base-metal sulfides, calcite, barite, and quartz. Some hydrocarbons occur with calcite and pyrite in the rocks adjoining the veins. At the Robinson property (V. R. Wilmarth and R. C. Vickers, written communication, 1952) the following relations are shown:

1. Deposition of calcite and barite in the fault zone
2. Deposition of the uraniferous hydrocarbons and most of the pyrite
3. Fracturing
4. Main period of sulfide deposition
5. Deposition of calcite

Locally, euhedral quartz crystals were deposited prior to the early calcite-barite stage and show replacement by these minerals. Similar mineral relations were found at the nearby Weatherly (Black King) property.

Uraninite has been identified by X-ray powder pattern in a highly uraniferous hydrocarbon sample from the Weatherly property (V. R. Wilmarth and R. C. Vickers, written communication, 1952), and minute specks believed to be uraninite were noted in similar material by Kerr and others (1951). V. R. Wilmarth and C. C. Hawley (written communication, 1954) suggest that the uranium in the hydrocarbon in these deposits occurs both as discrete mineral grains of uraninite and coffinite and as metallo-organic compounds.

The direct precipitation of the uranium as a metallo-organic complex is favored by Wilmarth and Vickers (written communication, 1952) for the Placerville deposits, although replacement of uraninite by hydrocarbon compounds has been noted at other localities (Ellsworth, 1928; Spence, 1930; Davidson and Bowie, 1951; Liebenberg, 1955; Hausen, 1956).

HALFMILE GULCH, COLORADO

Hydrocarbon is abundant in a pitchblende-bearing base-metal vein in Precambrian metamorphic rocks of Halfmile gulch, Jefferson County, Colo. Most of the reddish-brown translucent asphaltic material partly or completely fills vein cavities in which marcasite, pyrite, and pitchblende are interstitial to crystals of pink ankerite. Some pitchblende occurs as spheroidal grains in colloform pyrite (fig. 19). Halos of almost opaque hydrocarbon have developed around grains of metallic minerals, and textures suggesting the replacement of these minerals, especially marcasite, by hydrocarbon are common. The complete paragenesis of the deposit has not been established, but observed relations indicate an early pyrite stage followed by brecciation and introduction of adularia, ankerite, pitchblende, marcasite, and second-generation pyrite. The asphaltite is probably later than all other vein minerals.

REVIEW OF PARAGENETIC DATA

The problem of chief concern in the paragenetic studies of uranium veins is the relation of the time of deposition of the primary uranium minerals to that of the associated ore and gangue minerals. With the exception of the crystallized uraninite at Bisbee, Ariz., and the Little Man mine, Wyoming, uraniferous hydrocarbon at Placerville, and uranothorite at Jamestown, the primary mineral in all the deposits under consideration is colloform pitchblende.

A summary of the detailed and partial paragenetic data available to the writers is shown in tables 3 and 4. Where the source material does not actually state whether the pitchblende occurs early, intermediate, or late in the mineral sequence, it has been necessary to interpret the data for incorporation in the tables.

In several deposits, at least two stages of mineralization have been recognized. Thus, at the Caribou mine (Wright, 1954), pitchblende is early in a suite of minerals that cement breccia fragments of an earlier quartz-carbonate-sulfide vein. It can be argued that the two stages recognized at the Caribou deposit should be considered either as separate entities or as a single, but interrupted, period of mineralization. An example in which the individual stages have been demonstrated to be widely separated is the Copper King deposit in Colorado (Sims, Phair, and Moench, 1958), where a Precambrian sulfide ore body is cut by pitchblende-bearing veins of Tertiary age. In such multiple-stage deposits it is obviously necessary to consider both the paragenetic position of pitchblende in relation to the other minerals of the same ore stage and also the relation of that stage to earlier or later stages.

Table 3 shows the paragenetic position of pitchblende in veins in which no appreciable evidence for multiple-stage mineralization has been presented. This again is a matter of interpretation, for although periods of disturbance resulting in fracturing (Union Pacific prospect) or intense brecciation (Blue Jay mine) probably took place during the formation of some deposits, ore deposition is assumed to have been essentially continuous.

Uranium-bearing vein deposits considered to be of multiple-stage origin are listed in table 4.

PARAGENETIC POSITION OF PITCHBLENDE

The data shown on tables 3 and 4 indicate that pitchblende in the deposits which have been studied is commonly early or intermediate in a depositional sequence that includes all the minerals of a particular vein stage.

Where only the gangue minerals are considered, the pitchblende is preceded or accompanied by quartz, chalcedony, carbonate minerals, or fluorite. Adularia has been noted as a prepitchblende mineral in some deposits.

Except for the pitchblende itself, there seems to be nothing unique in the mineral assemblage of uranium-bearing veins. The paragenetic sequence of the minerals, exclusive of pitchblende, is for the most part that of nonuraniferous veins in which the minerals tend to follow a depositional order proposed by Lindgren (1926, p. 88) and tabulated in a somewhat abbreviated form by McKinstry (1948, p. 150).

Whether or not pitchblende has a preferred position in the mineral sequence is much debated. It is almost always considered to be early (Ramdohr, 1955, p. 791) or variable (Geffroy and Sarcia, 1954, p. 12; Everhart and Wright, 1951; McKelvey, Everhart, and Garrels, 1955).

Paragenetic studies of deposits in the conterminous United States suggest a sequence of deposition in which pitchblende is an early ore mineral. Pitchblende may be preceded by some gangue or by iron sulfides or oxides (rarely, nickel-cobalt sulfosalts), but its deposition commonly starts before that of most associated metallic minerals and the bulk of the gangue in any single stage of mineralization.

The close association of pitchblende and pyrite in the veins studied is too recurrent to be fortuitous, and although pyrite may be somewhat earlier or later than the pitchblende, their positions in a depositional sequence may be considered to be mutually interchangeable. So far as initial deposition is concerned, pitchblende belongs among the early minerals of Lindgren's series (McKinstry, 1948, p. 150) and may be expected to form at about the same time as specularite, pyrite, arsenopyrite, and nickel-cobalt arsenides. The association of pitchblende with these minerals may represent only a common depositional tendency in a suitable structural environment and, as such, does not necessarily imply any intimate geochemical relation. That some relation does exist between iron minerals and pitchblende has been suggested on the basis of oxidation-reduction reactions (Gruner, 1952; McKelvey and others, 1955, p. 471; Adams and Stugard, 1956).

Although primary pitchblende is one of the earliest metallic minerals to form during any single stage of vein formation, it may be subject to partial solution and reprecipitation during later stages. Such "regenerated" pitchblende may be represented by a hard colloform variety (fig. 12) or by the sooty variety such as is found at the Copper King, Los Ochos (table 3), and Caribou mines (table 4) as well as elsewhere, and it can be expected to show apparently anomalous paragenetic relations.

In tables 3 and 4, which summarize the paragenetic position of pitchblende, most deposits belong to the mineralogic class of uranium-bearing veins in which base-metal sulfide minerals are dominant (class 2). Other deposits or districts listed include 2 representing fluorite-bearing veins (class 1); 4 in class 3, which are veins dominantly uranium minerals; 2 in class 8, characterized by hydrocarbon-rich uranium-bearing veins; and 4 in which either the mineralogic class has not been clearly established or deposits within a district belong to two different classes. The paragenetic position of pitchblende is almost invariably early or intermediate with respect to the mineral assemblage of any single stage of mineralization among these different classes of deposits.

AGE OF THE DEPOSITS AND THE PARAGENETIC POSITION OF PITCHBLENDE

From a review of the geology of pitchblende veins throughout the world, Everhart and Wright (1951, p. 66) note a partial correlation between the age of a deposit and the paragenetic position of pitchblende.

> On the whole, pitchblende occupies a variable paragenetic position; in some deposits it is one of the earliest minerals to form and in others it is one of the latest. It is noted that in the pre-Cambrian deposits studied pitchblende is early in the mineral sequence, in late Paleozoic-early Mesozoic deposits it is variable in position, in late Mesozoic-early Tertiary deposits it is commonly late in sequence.

This suggested correlation was restated in a more recent publication by McKelvey, Everhart, and Garrels (1955, p. 487).

Available data regarding uranium-bearing vein deposits in the United States offer little support for establishing any correlation between the age of a deposit and the paragenetic position of pitchblende. The ages of the veins shown in tables 3 and 4 are based on geologic or radiochemical dating, or both; the paragenetic positions of pitchblende shown in these tables are taken from the references quoted. However, the geologic significance that can be placed on the number of deposits falling into any particular grouping by age (tables 3 and 4) is severely limited by the scarcity and unbalanced distribution of adequate paragenetic data. Review of pertinent data does suggest that pitchblende tends to be early rather than late in paragenetic position and that there is little, if any, correlation of the paragenetic position of pitchblende with the geologic age of the deposit.

SUMMARY

More than 50 uranium-bearing minerals have been identified from veins in the conterminous United States. Of these, 43 species contain uranium as an intrinsic constituent. Except for several refractory minerals that contain uranium as an intrinsic constituent—notably brannerite and uranothorite—these minerals also have been identified from other types of uranium deposits on the Colorado Plateau and elsewhere (Weeks and Thompson, 1954; Gruner, Gardiner, and Smith, 1954; Gruner and Smith, 1955). However, certain 6-valent uranium minerals, particularly uranyl phosphates and silicates, are probably more characteristic of veins than of other kinds of uranium deposits. Several minerals, such as rutile and pyromorphite, which contain unusual amounts of extrinsic uranium, have been identified only from veins and are not known to occur in other types of uranium deposits.

The gangue minerals of uranium-bearing veins are those commonly found in metalliferous veins and demonstrate no distinctive tendency toward abundance or rarity of any particular species. Changes in coloration as a result of radiation damage are distinctive characteristics of gangue minerals in some uranium-bearing veins.

Many elements, including base and precious metals as well as many of the rare earths, are associated with uranium in vein deposits. Positive correlation of some of these metals—notably molybdenum, manganese, beryllium, tungsten, vanadium, niobium, yttrium, and zirconium—with uranium in vein deposits seems to be reasonably well established within some deposits, districts, or restricted geographic areas, but none of these metals can be shown to associate with uranium in all vein deposits.

No well-established correlation between different species of 4-valent and 6-valent uranium minerals and the eight mineralogic classes of vein deposits can be demonstrated beyond the obvious mineralogic correlations resulting from the arbitrary classification of uraniferous vein deposits and beyond several expectable mineral associations resulting largely from original differences in anion and cation content from one class of deposit to another. Furthermore, the internal structures and textures of veins are not specifically related to any one mineralogic class of veins. The texture of the primary uranous oxide mineral, pitchblende, in virtually all vein deposits is colloform, and idiomorphic crystals of uraninite are known to occur only in a few vein deposits. In general, pitchblende or uraninite is early or intermediate in a depositional sequence that includes all the minerals of a particular vein stage irrespective of the mineralogic class of the deposit or its geologic age.

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Supergene Alteration of Uranium-Bearing Veins in the Conterminous United States

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SUPERGENE ALTERATION OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

By George W. Walker

ABSTRACT

Nearly all uranium-bearing veins in the conterminous United States have been altered by supergene processes. The extent and effects of the chemical reactions that are a part of supergene alteration differ markedly, depending on the original hypogene assemblage of minerals in the veins, the mineralogic and physical characteristics of the enclosing wallrocks, the position of the deposit in relation to the ground surface (or presumably to the water table), and on the chemical and physical character and volume of altering solutions.

The assemblage of 6-valent uranium minerals that form as a result of supergene alteration of veins is similar to the assemblage in sandstone-type deposits of the Colorado Plateau and the northeastern part of the Cordilleran Foreland. Commonly these 6-valent alteration products are zonally distributed either around individual masses of pitchblende or, more commonly, outward from vein structures that contain masses of pitchblende.

In some deposits, the transformation of primary uranium minerals into secondary ones has occurred essentially in place; whereas in many other deposits, the transformation is characterized by solution and redistribution of the uranium and commonly results in enriched or impoverished zones.

INTRODUCTION

Virtually all uranium-bearing veins in the conterminous United States show some evidence of supergene alteration, but the degree and products of alteration vary markedly from deposit to deposit. The hypogene uranium minerals within these deposits, many of the associated nonuraniferous vein minerals, and, locally, some wallrock minerals have been altered at or near the ground surface into minerals that tend to be more stable in an oxygenated environment. In some deposits, the transformation of primary minerals into secondary ones has occurred for the most part in place; in many other deposits, some of the elements have been redistributed to form enriched or impoverished zones. Where the altering meteoric waters were moderately to strongly acid, particularly in some deposits containing abundant sulfide minerals, considerable leaching and removal of materials has resulted. Thus, three patterns of distribution—or redistribution—for uranium in the oxidized parts of veins can be demonstrated, namely enriched zones, impoverished zones, and unchanged zones in which alteration has occurred essentially in place.

Several studies of the chemistry of uranium and associated elements, under conditions of supergene alteration, have been made by Phair and Levine (1953), Weeks (1956), McKelvey, Everhart, and Garrels (1955), Lovering (1955), Barton (1956), and particularly by Garrels (1953, 1954, 1955), Garrels and Christ (1959), and Garrels and Pommer (1959). Most of these studies pertain to uranium deposits other than veins, but the chemical processes outlined, the physicochemical conditions of alteration, the relation of alteration zones to the water table (or, more correctly, to changes in the redox potential), and the resultant oxidation products are very similar to those of uranium-bearing veins in the conterminous United States. Although few qualitative differences exist between the oxidation of uraniferous veins and other kinds of uranium deposits, some quantitative differences such as the presence, abundance, or frequency of occurrence of certain minerals have been noted and are largely attributable to dissimilarities in the original assemblage of hypogene minerals in the deposits, to dissimilarities in the ions that may be available from the wallrocks, and probably to differences in permeability. Some uranium-bearing veins are characterized by abundant metallic sulfides, and the supergene alteration of these deposits, particularly under wet climatic conditions, commonly results in leached outcrops in which 6-valent uranium minerals are sparse or lacking. Furthermore, some evidence suggests that enrichment of uranium by supergene processes may be more prevalent in veins than in other kinds of uranium deposits.

PROCESSES OF SUPERGENE ALTERATION

The process of supergene alteration, including secondary enrichment, encompasses not only the oxidation and reconstitution of the original hypogene assemblage of minerals in uranium-bearing veins but also, in a few places, the subsequent reduction of some of the oxidation products. The process is similar to that described by Emmons (1917), Bateman (1950), and Anderson (1955) for copper deposits and differs principally in the character and, more largely, quantity of materials involved. Hydration, evaporation, saturation, and chemical interaction between solutions and vein filling or wallrocks are dominant aspects of the supergene alteration of uranium-bearing veins. In this report, the discussion of supergene alteration will be restricted largely to the effects upon uranium within vein deposits and only incidentally to the effects on associated elements.

Uranium in vein deposits is in both the 4- and 6-valent states. The 4-valent state is represented principally by uraninite or, much more commonly, by the colloform, sooty, or massive variety, pitchblende; in a few veins, the 4-valent state is represented by coffinite, uranothorite, brannerite, and several other minerals in which uranium is present either as an extrinsic or vicarious constituent (chap. D, p. 56–58). Partial and complete analyses of pitchblende from several vein deposits demonstrate that both 4- and 6-valent uranium is invariably present, most commonly with 4-valent uranium predominant (Palache, Berman, and Frondel, 1944, p. 612–613; Brooker and Nuffield, 1952). Uraniferous fluorite, which is common in several vein deposits, presumably contains principally 4-valent uranium. Six-valent uranium is present in veins principally as uranyl phosphates, silicates, vanadates, sulfates, arsenates, or carbonates, and, less commonly, as uranyl molybdates or hydroxide hydrates; adsorbed uranyl ions are prevalent in the oxidized parts of some veins (Lovering, 1955; Barton, 1956), although their abundance in most deposits is essentially unknown. In most veins, the 6-valent uranium minerals and adsorbed uranyl ions had their origin in the near-surface oxidation of pitchblende, coffinite, or, in a few places, uraniferous fluorite, according to the alteration and oxidation pattern described by Garrels and Christ (1959). Many veins, however, contain uranium only in the 6-valent state and lack evidence other than presence of uranyl compounds to indicate that 4-valent uranium minerals were ever present in the deposits. Conceivably, some or all these deposits resulted from the direct precipitation of uranyl compounds under near-surface oxidizing conditions and are not the result of the alteration, essentially in place, of 4-valent uranium minerals; such deposits presumably are genetically like those described as caliche-type by Bell (1956, p. 385).

Inasmuch as Garrels and Christ (1959) describe in some detail the behavior of uranium under oxidizing conditions, only a brief summary of their work will be presented here, largely in diagrammatic form (fig. 41). The processes and sequence of oxidation, as described by Garrels and Christ (1959), are based on the premise that uraninite and coffinite are the progenitors of all the 6-valent uranium minerals in deposits on the Colorado Plateau; a similar premise applies to most uranium-bearing vein deposits, for the only quantitatively important 4-valent uranium minerals reported from veins are pitchblende and, less commonly, coffinite, and uraniferous fluorite.

Figure 41, which is reproduced with slight modification from Garrels and Christ's figure 1, demonstrates the general features of the chemical reactions and the products that result from the oxidation of 4-valent uranium minerals in vein deposits. The sequence and pattern of alteration from hard massive pitchblende high in UO_2 through amorphous UO_3 to uranyl ions in solution and thence to a variety of chemically diversified uranyl compounds or to adsorbed uranyl ions are in all essential characteristics identical with those described by Garrels and Christ (1959) for deposits on the Colorado Plateau. The 4-valent uranium of coffinite and uraniferous fluorite is altered in an oxidizing environment to form uranyl ions in solution; these uranyl ions react in the same way as do those derived from pitchblende.

The uranyl ions in solution may (a) react with available anions and cations to form soluble or insoluble uranyl compounds, (b) be adsorbed on hydrated iron oxides or other colloidal materials (Rankama and Sahama, 1950), or (c) be carried away by migrating ground or surface waters either as uranyl ions or as soluble uranyl carbonate or sulfate complexes. According to Garrels and Christ (1959), "Uranyl ion may form complex carbonate or sulfate ions with resulting soluble compounds, but only in the absence of quinquevalent vanadium, arsenic, or phosphorous." The uranyl carbonate minerals—including schroeckingerite, andersonite, bayleyite, and swartzite, and the uranyl sulfate minerals johannite, uranopilite, and zippeite—apparently form only by the evaporation of ground water and, consequently, are most abundant in arid to semiarid regions. In those places where 5-valent vanadium, arsenic, or phosphorous are available, uranyl ions in solution may react to form slightly soluble uranyl vanadates, phosphates, or arsenates, the particular mineral species formed depending in part

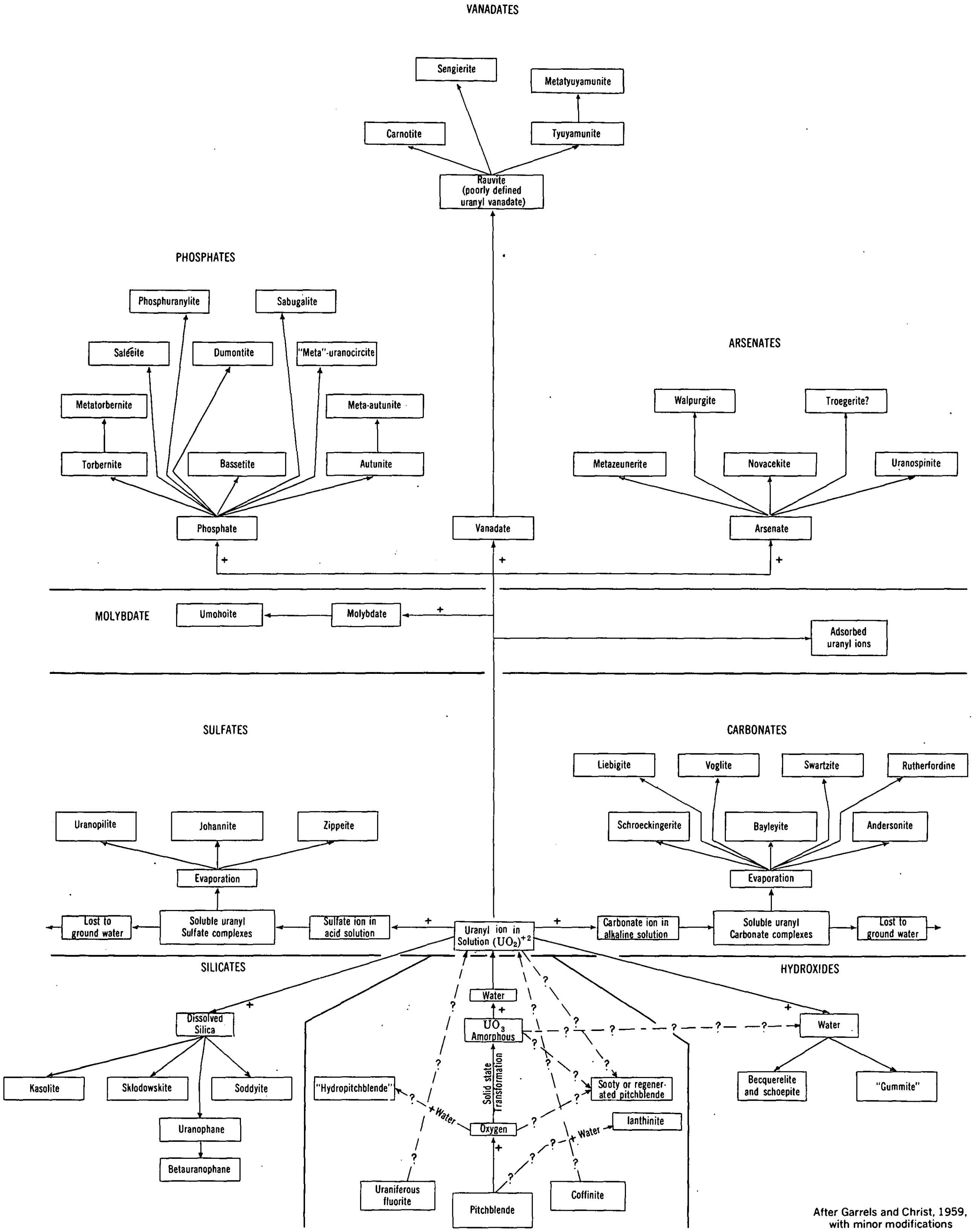

Figure 41.—Reactions and products related to supergene alteration of uranium-bearing veins.

on the presence and abundance of other cations, principally K^{+1}, Ca^{+2}, Pb^{+2}, and Mg^{+2}.

In the presence of reactive silica, uranyl ions in solution may react to form hydrous uranyl silicates, including uranophane, kasolite, and sklodowskite; however, according to Garrels and Christ (1959), "Little is known of the environment in which they form, or even concerning their stability after crystallization."

Umohoite, a hydrous uranyl molybdate (Kerr, Brophy, Dahl, and others, 1957, p. 66), has been reported from veins at Marysvale, Utah (Kerr, Hamilton, Brophy, and others, 1953, p. 45–51). Coleman and Appleman (1957) consider that the uranium or the molybdenum, or both, in umohoite are in an oxidation state lower than 6-valent, as based on studies of a uranium molybdate from the Lucky Mc mine, Wyoming; this umohoite occurs with partly oxidized uranium ore. The processes involved in the formation of umohoite are incompletely understood; it may be a hypogene vein mineral, as postulated by Kerr and others (1953), or it may be either a product of late-stage hydrothermal alteration or supergene alteration as suggested by Walker and Osterwald (1956, p. 127). Umohoite is hydrous and may contain principally 6-valent uranium; consequently, it seems to be more closely allied to the 6-valent uranium minerals that are derived through alteration in an oxidizing environment, and its distribution at Marysvale tends to support such a relationship. On the premise that some or all the umohoite may result from the interaction of uranyl and molybdate ions under conditions of supergene alteration, it has been shown on figure 41.

A few of the minerals containing 6-valent uranium, specifically becquerelite, "gummite," and schoepite, seem to be deposited directly from uranyl ions in solution (Garrels and Christ, 1959). In several veins, however, these uranyl hydroxide hydrate minerals, either separately or collectively, occur as pseudomorphous replacements of hypogene pitchblende in which both the external and internal colloform textures of the hypogene pitchblende are largely retained. In these places, it seems likely that the transformation of hard colloform pitchblende to becquerelite, "gummite," or schoepite by supergene processes occurs essentially in place and not as a result of precipitation from uranyl ions in solution; some uranium presumably is given up to solution as a result of the reaction.

Ianthinite, presumably a UO_2 hydrate, has been reported in association with pitchblende from the Marshall Pass area, Colorado (E. J. Young, oral communication, 1956); it is included as a product of supergene alteration, although there is considerable doubt as to its exact mode of formation. The ianthinite at Marshall Pass occurs as lavender idiomorphic crystals that coat the walls of cavities or vugs in hard colloform pitchblende. The distribution of the ianthinite indicates that it is derived through alteration of the pitchblende possibly by supergene processes or, as postulated by Kohl and Haller (1934) for ianthinite at Wölsendorf, by low-temperature hydrothermal alteration.

Hydration of pitchblende, with only partial oxidation, seems to be part of the supergene alteration of the uranium-bearing veins at the North Star mine and the Nigger Shaft deposit, Jefferson County, Colo. (Adams, Gude, and Beroni, 1953, p. 16). The hydrated pitchblende in both deposits is closely associated with a supergene suite of copper, iron, and uranium minerals and texturally is similar to hard unaltered colloform pitchblende that is present at depth. The hydrated pitchblende is brown or olive green in color, slightly translucent, and may be closely allied to the hydropitchblende ($UO_2 \cdot kUO_3 \cdot nH_2O$; $k = 2.3–5$; $n = 3.9–9$) of Getseva (1956). The formation of hydrated pitchblende containing greater amounts of UO_3 than UO_2 perhaps can be considered a side and intermediate product in the transformation of pitchblende rich in UO_2 to amorphous UO_3 (fig. 41).

In many veins, the mode of occurrence and the physical characteristics of sooty or regenerated pitchblende (chap. D) as well as its distribution in regard to hard massive pitchblende and to the zone of oxidation suggest that some, and perhaps all, of this material is derived through the process of supergene alteration; some may result from alterations related to hydrothermal or solfataric action. According to currently accepted concepts of uranium transport (Phair, 1952; Miller and Kerr, 1954; McKelvey, Everhart, and Garrels, 1955; Gruner, Gardiner, and Smith, 1953; Gruner, 1956), the derivation of "supergene" sooty or regenerated pitchblende perhaps can best be explained by (a) initial oxidation of 4-valent uranium minerals and formation of uranyl ions in solution, (b) migration of these solutions to zones of decreased oxidation potential, and (c) precipitation of uranium in the reduced, 4-valent state. Such a process is comparable to that proposed for the formation of sooty chalcocite (Anderson, 1955).

The extent and the effects of the different chemical reactions that are a part of supergene alteration (fig. 41) differ markedly from deposit to deposit, depending on the original hypogene assemblage of minerals in the veins, the mineralogic and physical characteristics of the enclosing wallrocks, the position of the deposit in regard to the ground surface (or presumably to the water table), and the chemical and physical character and volume of altering solutions. In arid to semiarid regions, supergene alteration of uranium-bearing vein deposits commonly results in abundant 6-valent uranium minerals at or near the ground surface that are attributable, in part, to the strongly oxidizing character of an arid environment (Mason, 1949, p. 67) but perhaps more largely to only slight removal by solution of alteration products. In wet regions, the uranium commonly is depleted or removed from near-surface extensions of uranium-bearing veins, and 6-valent uranium minerals are sparse or lacking; intensely leached outcrops are particularly prevalent in veins characterized by metallic sulfide minerals.

GEOLOGIC EXPRESSION OF SUPERGENE ALTERATION OF URANIUM-BEARING VEINS

The geologic expression of supergene alteration of uranium-bearing veins includes not only the presence of oxidized and hydrated uranium minerals or adsorbed uranyl ions but also, in some deposits, the presence of a zoned distribution of these minerals and (or) zones of uranium enrichment or depletion in different parts of vein systems, depending on local environmental conditions.

SOME MINERALOGIC ASPECTS OF SUPERGENE ALTERATION

Supergene alteration and the formation of 6-valent uranium minerals are quantitatively important in 3 of the 7 mineralogic classes of uranium-bearing veins known to occur in the conterminous United States (chap. A), namely (a) fluorite-bearing veins, (b) base-metal sulfide veins, and (c) veins dominantly of uranium minerals. Certain rather ill-defined assemblages of the more common uranyl minerals tend to characterize these three different classes of veins; these assemblages in part reflect the metal composition of vein filling and probably the presence of certain ions in the adjoining wallrocks. Many exceptions can be noted to the general characteristics of these assemblages. The 6-valent uranium minerals within the different assemblages are listed below in the approximate order of their decreasing frequency, an arrangement that is not necessarily coincident with their relative abundance in any one deposit or district.

Flourite-bearing veins:

Autunite and (or) meta-autunite, uranophane, torbernite or metatorbernite, carnotite, schroeckingerite, johannite.

Base-metal sulfide veins:

Torbernite or metatorbernite, autunite, kasolite, "gummite," zeunerite or metazeunerite, johannite, zippeite.

Veins dominantly of uranium minerals:

Autunite and meta-autunite, uranophane, carnotite, tyuyamunite or metatyuyamunite, torbernite or metatorbernite, "gummite," uranocircite or metauranocircite.

Several 6-valent uranium minerals, including troegerite?, voglite, dumontite, and kasolite have been reported only from veins; but of these minerals, only kasolite is quantitatively important. Kasolite has been identified from the oxidized parts of a number of vein deposits characterized by abundant hypogene or supergene lead minerals, and in one deposit—the Green Monster mine, Clark County, Nev.—it was the dominant uranium mineral of a few tons of uranium ore.

Data on the occurrence of 6-valent uranium minerals in veins suggest that uranyl phosphates and silicates are more characteristic of vein deposits than are uranyl vanadates and arsenates. Both uranyl phosphates and silicates commonly occur together in the same deposit, but in the vein deposits characterized by uranyl vanadates—such as the deposits near Cement, Okla., several in the Madison limestone in Carbon County, Mont. and Big Horn County, Wyo., and the Ridenour mine, Arizona (Miller, 1954)—phosphates, silicates, and arsenates of uranium commonly are present in only minor amounts. Carnotite is the dominant 6-valent uranium mineral in some parts of the Miracle mine, California (W. A. Bowes, written communication, 1957); whereas in other parts of the mine, autunite is most abundant.

Many other uranyl minerals have been reported from uranium-bearing veins (chap. D); but, because so few occurrences for each mineral species have been reported, no valid correlation with mineralogic class of vein is possible. In addition, no clear-cut correlation between sooty pitchblende and mineralogic class of deposit can be demonstrated; sooty pitchblende has been reported in fluorite-bearing veins, base-metal sulfide veins, and veins dominantly of uranium minerals. Sooty pitchblende has been reported most commonly from base-metal sulfide veins, and this apparent correlation may have geologic significance in that the metal sulfides may create an environment suitable for the reduction of uranyl ions in solution. On the other hand, this apparent correlation can be explained equally well by the fact that uraniferous base-metal sulfide veins have yielded more than their proportionate share of detailed data on the mineralogy of uranium-bearing veins.

The assemblage of uranyl minerals that form in veins (fig. 41; and chap. D, table 1) as a result of supergene alteration closely resembles the assemblage in sandstone-type deposits (Weeks and Thompson, 1954; Gruner, Gardiner, and Smith, 1954) as exemplified by deposits both on the Colorado Plateau and in the northeastern part of the Cordilleran Foreland. Some minor differences are real and result from differences in the original assemblage of hypogene minerals in the deposits and, consequently, the cations and anions that are available for reaction with UO_2^{+2} ions in solution. Other apparent differences probably result only from lack of data regarding the complete assemblage of uranium minerals in one or the other kinds of deposits. Whether geologically significant differences exist in the frequency of occurrence or abundance of secondary iron, copper, lead, or zinc minerals in veins as contrasted with other kinds of uranium deposits is difficult, if not impossible, to establish with available data. Obviously, secondary iron, copper, lead, and zinc minerals are common and locally abundant in the oxidized part of uraniferous base-metal sulfide veins; but in other kinds of veins, they are no more prevalent than they are in sandstone-type deposits.

ZONED DISTRIBUTION OF ALTERATION PRODUCTS

Supergene alteration of 4-valent uranium minerals in veins tends to create a zoned distribution of the uraniferous alteration products according to the stabilities and solubilities of these products. The general pattern of this zoning, considered either in relation to an individual mass of pitchblende or, more largely, to the ground surface and vein structure that contains masses of pitchblende, is shown diagrammatically on figures 42 and 43 and is described, in part, by Stugard, Wyant, and Gude (1952, figs. 14, 17).

As shown on figures 42 and 43, the hydrated oxides and hydroxides of uranium, either separately or together, constitute an innermost zone that forms closest to the unaltered pitchblende. Not uncommonly, the pitchblende appears to have been pseudomorphously replaced by "gummite," becquerelite, or schoepite; and rarely are the hydrated oxides or hydroxides found more than a few inches from pitchblende or what was pitchblende prior to supergene alteration.

An intermediate zone of alteration products is characterized by uranyl silicates, phosphates, vanadates, molybdates, or arsenates; the mineral species that form are dependent largely on the availability and abundance of the different anions. In the veins characterized by uranyl vanadates, the intermediate zone commonly contains only carnotite or tyuyamunite, and other uranyl minerals are lacking or are present in only very small amounts. Primary 4-valent uranium minerals have been reported in only a few of the veins containing uranyl vanadates; consequently, little information is available as to the spatial disposition of these alteration products in regard to the primary uranium minerals. However, oxidation in place with little or no migration of the uranium seems to characterize the deposits that contain uranyl vanadates (Garrels and Christ, 1959). The uranyl molybdate, umohoite, is known to occur only in one group of vein deposits (Marysvale, Utah), and there it is concentrated either deep in, or just below, the zone of supergene alteration. Its precise spatial relation to unaltered pitchblende is unknown, although it occurs closely associated with finely divided sooty pitchblende and presumably not far removed from masses of hard unaltered pitchblende. Most intermediate zones contain both uranyl silicates and phosphates; in a few deposits, minor amounts of uranyl arsenates also are present. The distribution of the uranyl silicates, phosphates, and arsenates within veins indicates that the formation of these compounds can occur essentially in place without appreciable migration of uranium or, more commonly, that the uranium has migrated short distances from the source material. Most uranyl silicates, phosphates, and arsenates occur within the vein structures, although locally some concentrations are as far as 10 feet from the veins.

A third and outermost zone, characterized by the extremely soluble uranyl carbonates and sulfates, is based largely on theoretical considerations and is not well demonstrated in veins in the United States. Ideally, for the zoning of uranium-bearing oxidation products to be complete, the most soluble uranyl compounds—dominantly schroeckingerite, johannite, zippeite, and uranopilite in veins—should be found farthest from masses of unaltered 4-valent uranium minerals and consequently should be abundant in surface exposures of uranium-bearing veins. Actually these minerals are extremely rare in the vein outcrop and, in vein deposits, are found almost exclusively as efflorescences on mine walls (Derzay, 1956, p. 140, and oral communication, 1957; Walker and Osterwald, 1956, p. 126–127; Stugard, Wyant, and Gude, 1952, p. 19 and 21); in a few caliche-like vein deposits in semiarid to arid regions (Bell, 1956, p. 385), these minerals may occur at the surface, but their relation to 4-valent uranium minerals is largely unknown.

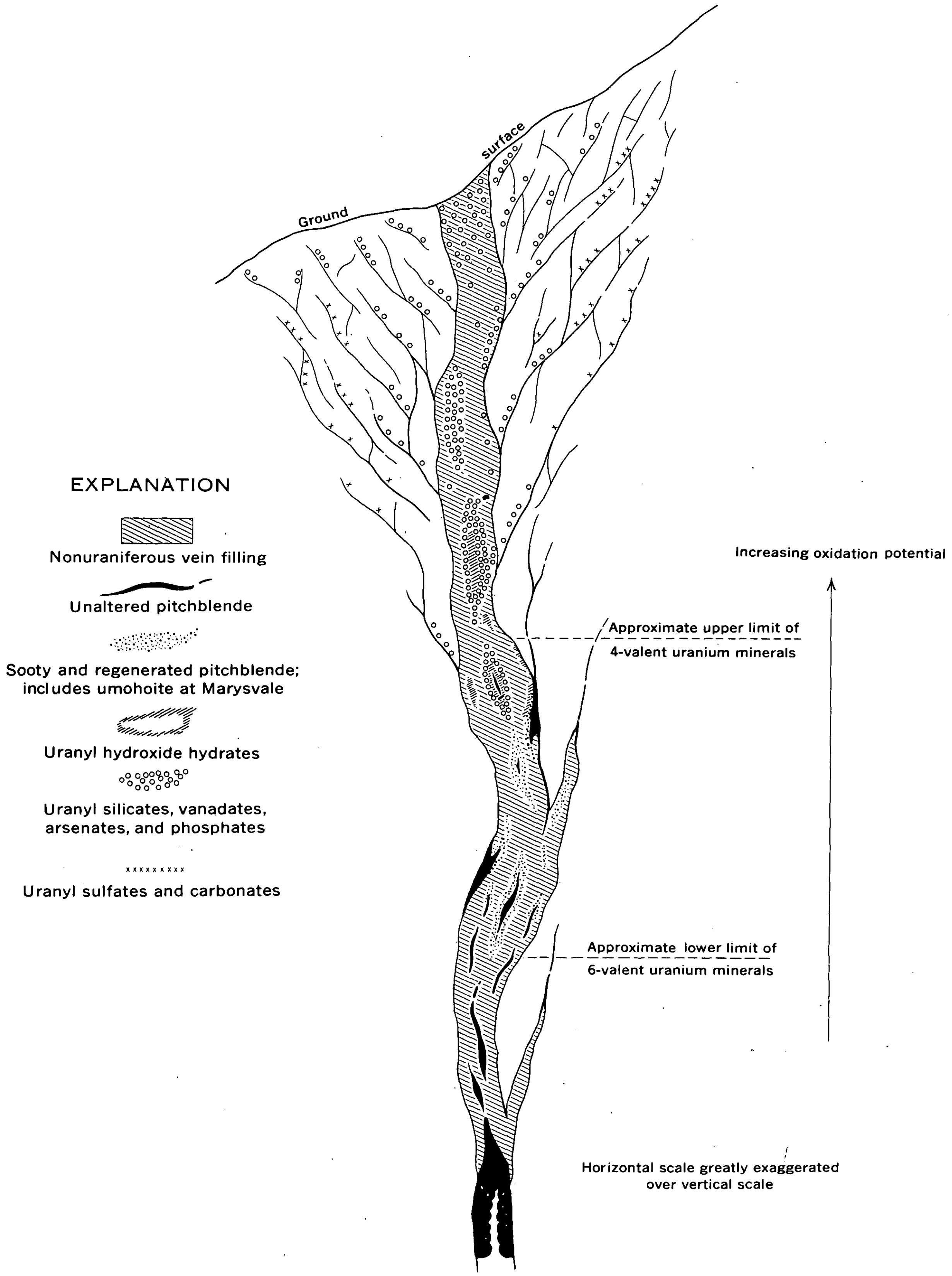

FIGURE 42.—Diagrammatic sketch showing zoned distribution of uraniferous alteration products resulting from supergene processes.

For most uranium-bearing veins, only fragmentary information is available on the distribution of supergene alteration products as related to the original hypogene uranium minerals; consequently, the zoning of these alteration products has been well demonstrated in only a very few places. Some of the best examples of the zoned distribution of uraniferous alteration products have been reported in the veins at Shinkolobwe (Thoreau and du Trieu de Terdonck, 1933; Derriks and Vaes, 1956), Marysvale, Utah (Stugard, Wyant, and Gude, 1952; Taylor and others, 1951; Gruner, Fetzer, and Rapaport, 1951; Walker and Osterwald, 1956); the W. Wilson mine, Montana (D. Y. Meschter, written communication, 1953; Wright, Bieler, Shulhof, and Emerson, 1954), and at the Moonlight mine, Nevada (Sharp, 1955; Taylor and Powers, 1955).

At Shinkolobwe, according to Thoreau and du Trieu de Terdonck (1933), the uraninite alters in place principally to becquerelite and curite and locally to ianthinite and schoepite. Farther from the uraninite, a zone composed principally of uranyl silicates gives way outward to uranyl phosphates, including torbernite, parsonite, and dewindtite. Derriks and Vaes

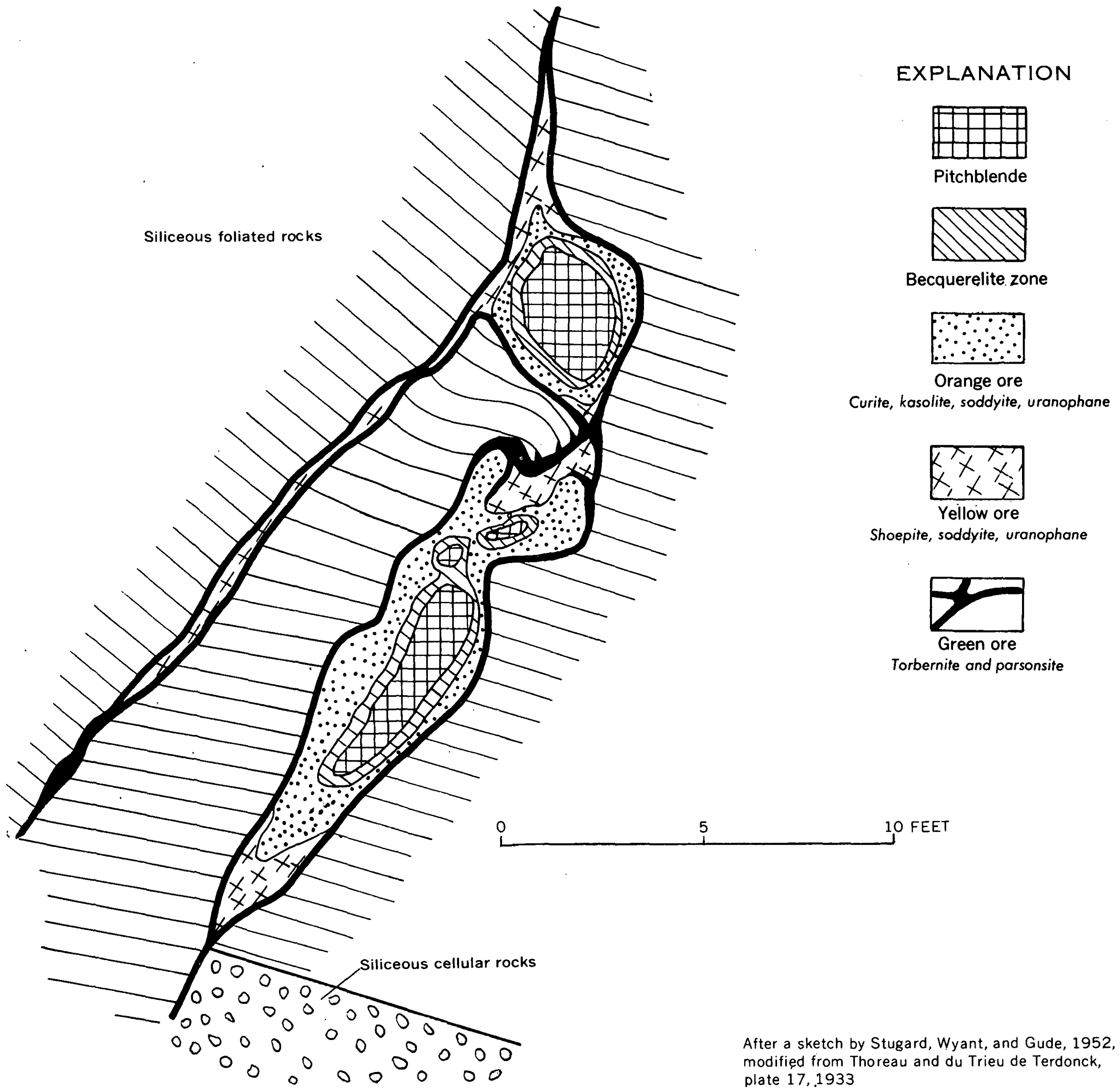

Figure 43.—Vertical section across a vein, Shinkolobwe.

(1956, p. 107) indicate that uraninite also has been altered at depth to a host of uranyl hydroxide hydrates—including billietite, vandendriesschéite and masuyite—and that dewindtite, dumontite, parsonite, and sklodowskite have not been observed at depth.

Information on the distribution of uraniferous alteration products at Marysvale, Utah, has been summarized by Walker and Osterwald (1956, p. 126–127) largely from data originally presented by Taylor and others (1951); Gruner, Fetzer, and Rapaport (1951); Stugard, Wyant, and Gude (1952); and Kerr and others (1952; 1953, p. 45–51). The alteration products tend to be distributed zonally, although it is not the "* * * typical zonation of uranium minerals * * *" as depicted by Stugard, Wyant, and Gude (1952, fig. 14, p. 21). The alteration products that occur closest to unaltered pitchblende at Marysvale are sooty pitchblende and umohoite; presumably some, and possibly all, of the sooty pitchblende and umohoite result from supergene alteration. Farther from unaltered pitchblende and extending to the ground surface is a zone of alteration products composed dominantly of uranyl silicates and phosphates. The uranyl phosphates are rare or lacking in outcrops and are found principally 10 feet or more beneath the ground surface; locally, the uranyl phosphates are as much as 400 feet beneath the surface. The uranyl silicates, on the other hand, are most abundant in surface or near-surface exposures, but they have been reported to depths of approximately 200 feet. The uranyl sulfates, zippeite, uranopilite, and johannite and the uranyl carbonate, schroeckingerite, are virtually lacking in surface outcrops and have been identified principally as efflorescences on mine walls most commonly from about 10 feet below outcrops to depths of about 100 feet.

The zonation of uraniferous alteration products in the W. Wilson mine, Jefferson County, Mont., as described first by Meschter (written communication, 1953) and later by Wright, Bieler, Shulhof, and Emerson (1954, p. 5), involves two different suites of 6-valent uranium minerals that, in general, show uranyl hydroxide hydrates nearest unaltered pitchblende, uranyl silicates in an intermediate position, and uranyl phosphates farthest from the pitchblende. Meschter (written communication, 1953) has described an inner zone of alteration in which pitchblende appears to have altered directly to "gummite" and phosphuranylite. The intermediate zone is characterized by uranophane, autunite, and uranocircite, and the outermost zone of alteration is represented by metatorbernite and metazeunerite. In the same deposit, but probably in somewhat deeper workings, Wright, Bieler, Shulhof, and Emerson (1954, p. 5) have established a zonal distribution based on a slightly different assemblage of 6-valent uranium minerals. According to them,

> Field study has indicated a zoning of secondary uranium minerals outward from primary ore shoots * * * with gummite, uranophane, beta-uranophane, meta-autunite, and torbernite occurring at successively greater distances from the vein.

Later work on the mineralogy of the W. Wilson mine by Emerson and Wright (1957) has verified the presence of metauranocircite, metazeunerite, and phosphuranylite, but their position in the zoned sequence is not given.

At the Moonlight mine, Nevada, autunite, torbernite, "gummite," and uraninite(?) exhibit a zoned distribution with depth. According to Taylor and Powers (1955, p. 12),

> Autunite is most abundant near the surface but decreases in concentration down the dip of the vein until it is almost absent at a depth of 96 feet. Torbernite and "gummite" appear as the autunite disappears. Between 80 and 120 feet on the main inclined shaft, traces of "gummite" occur as halos and coatings around small black cores presumed to be uraninite. At greater depth the only uranium mineral is probably uraninite.

Most other uranium-bearing veins in the conterminous United States either do not exhibit zoning of the 6-valent uranium minerals or the zoning is poorly defined, commonly because the veins contain only 2 or 3 species of uranium minerals.

LEACHING AND ENRICHMENT

Supergene alteration of 4-valent uranium minerals is accompanied in nearly all vein deposits in the conterminous United States by redistribution of uranium most commonly with substantial loss of uranium to migrating ground waters. In many of these deposits the processes of supergene alteration have created zones from which uranium has been leached and, in a few deposits, zones of uranium enrichment; in several deposits, leaching of uranium at or near the ground surface is accompanied by redeposition and enrichment of uranium at depth in zones of decreased oxidation potential. In only a few veins do alteration and solution of 4-valent uranium minerals and redeposition of 6-valent ones occur essentially in place.

Evidence for leaching and redistribution of uranium as a result of supergene alteration is afforded in many deposits by studies of radioactive disequilibrium relations resulting from the preferential leaching of uranium with respect to radium and other radioactive daughter products. Some insight into the intensity of leaching and the amount of redistribution of uranium also is afforded by the type and distribution of both the 4- and 6-valent uranium minerals within a deposit.

Leaching of uranium in veins as a result of near-surface oxidation is particularly prevalent in deposits characterized by common or abundant metallic sulfide minerals and is largely attributable to the chemical processes described by Phair and Levine (1953). Their work has shown that altered and oxidized pitchblende "* * * is readily susceptible to solution by the H_2SO_4 invariably present in and around sulfide mines * * *" (Phair and Levine, 1953, p. 367) and that the amount of uranium leached is relatable principally to the UO_2/UO_3 ratio in the altered pitchblende and to the amount of H_2SO_4 in solution; pitchblende high in UO_3 is most readily attacked by the sulfuric acid solutions. Commonly, where the solutions were moderately acid, virtually all the uranium was removed, and 6-valent uranium minerals are rare. Such places can be found in many of the pyritic deposits of the Colorado Front Range (Sims and Tooker, 1956; Drake, 1957; Sims, Phair, and Moench, 1958), apparently in the St. Kevin district, Colorado (Pierson and Singewald, 1954), possibly in the Cebolla district, Colorado (Burbank and Pierson, 1953), and elsewhere. Less stringent leaching of uranium in veins, commonly with associated formation of 6-valent uranium minerals, tends to be characteristic of deposits that contain only small amounts of base-metal sulfide minerals (particularly pyrite) and of those that have been altered and oxidized in an environment in which there is little migrating ground water—as in the oxidized parts of several uraniferous base-metal sulfide veins in the Goodsprings district, Nevada (Albritton and others, 1954; Barton, 1956).

Sims and Tooker (1956, p. 109), in summarizing data on supergene alteration of veins in the Central City district and adjoining areas, Colorado, make the following general comments:

> In the oxidized parts of the veins, pitchblende was leached and altered where the meteoric waters were acid, and green secondary uranium minerals were deposited where the solutions were nearly neutral. For the most part, the oxidized portions of the veins were impoverished; but locally, particularly in the lower part of the oxidized zone, the veins were enriched in uranium. The meteoric waters were relatively acid along veins of the pyritic and composite types; the pitchblende was leached and dissociated, and uranium was not reprecipitated as secondary minerals. The solutions were only slightly acid along veins of the galena-sphalerite type * * * [as for example the Carroll mine (Sims, Osterwald, and Tooker, 1955, p. 20–22)] * * *, because these sulfides provide less acid than pyrite on weathering. By reaction with the wall rocks * * * [as well as calcite gangue] * * * the solutions were locally neutralized, and uranium was reprecipitated at places as secondary minerals.

Bird and Stafford (1955, p. 82), in reviewing the geology of several uranium-bearing vein deposits in the Colorado Front Range, with special emphasis on deposits near Ralston Creek, suggested that uranium was leached for the first 10 or 20 feet below the surface and that at a depth of about 100 feet the deposits probably were enriched with "secondary" pitchblende. The suggested leaching and enrichment of uranium is based on (a) an increase in the chemical uranium—equivalent uranium ratio with depth and (b) on a transition with depth from leached outcrops to completely oxidized uranium minerals, to a zone containing mixed 6-valent uranium minerals and sooty pitchblende, and thence to a zone characterized by both sooty pitchblende and massive unaltered pitchblende.

Studies of the uranium-bearing vein deposits in the Boulder batholith, Montana, including principally the W. Wilson, Free Enterprise, and Gray Eagle mines, indicate that although alteration of 4-valent uranium minerals to form 6-valent uranium minerals locally occurs essentially in place (Roberts and Gude, 1953a, p. 79; 1953b, p. 153), redistribution and depletion of uranium is characteristic (Roberts and Gude, 1953a,b; Wright, Bieler, Shulhof, and Emerson, 1954). Considerable migration of uranium in some parts of these deposits is suggested by Thurlow and Reyner (1952, p. 27), but they (1950, p. 1) indicate that there is little, if any, enrichment of uranium at depth.

Secondary (supergene) enrichment of uranium as well as alteration in place is postulated by Wilmarth and Johnson (1954) for uraniferous veins at the Silver Cliff mine near Lusk, Wyo. They suggest that

> * * * During supergene alteration, the primary copper minerals were converted to cuprite, and the pitchblende was altered to gummite, uranophane, and metatorbernite. The deposits of uraniferous sandstone probably are the result of alteration of the primary minerals in place, whereas those in the light buff standstone result from solution and redeposition of the uranium by descending ground waters to form a commercial secondary uranium deposit.

Supergene enrichment of uranium immediately below the outcrop of an oxidized lead-zinc ore shoot has been noted at the Green Monster mine, Clark County, Nev. (Albritton and others, 1954). Kasolite and dumontite intermixed with hydrozincite, calamine, hydrated iron oxide, cerussite, and anglesite were sufficiently abundant below the outcrop to constitute uranium ore, and small patches of oxidized material contained slightly over 9 percent uranium; presumably some uranium is present as uranyl ions adsorbed on several different colloidal materials (Behre and Barton, 1954; Barton, 1956). The amount of uranium diminishes rapidly with depth. One might speculate that the 6-valent uranium minerals represent a dispersed halo around what was a small high-grade mass of pitchblende or other 4-valent uranium mineral contained in the lead-zinc ore body. On the other hand, minute amounts of 4-valent uranium originally may have been dispersed in the unaltered lead-zinc ore body and concentrated in the 6-valent state, as the ore shoot was oxidized and degraded. A similar type of surface or near-surface enrichment of uranium also is proposed by Staatz and Osterwald (1959) for most of the uraniferous fluorite deposits of the Thomas Range, Juab County, Utah. According to them,

> The increase of uranium content near the surface is believed to have been caused by slow leaching of the upper part of the ore body, in part from material being actively eroded. The uranium is carried downward and redeposited * * * [as carnotite or some other 6-valent uranium mineral] * * * at some level between a few inches and approximately 30 feet below the surface.

Secondary (supergene) enrichment of uranium in a base-metal sulfide deposit apparently has taken place in the Madonna mine, Chaffee County, Colo. (Dings and Schafer, 1953). Although the deposit contains only small amounts of uranium, the uranium appears to be concentrated in porous oxidized material that borders an ore body of primary base-metal sulfide minerals.

In a few places, uranium in veins seems to be neither enriched nor greatly depleted as a result of near-surface supergene alteration. In most vein deposits, solution, redistribution, and subsequent loss of uranium to migrating ground waters is characteristic; but, in a few veins, largely in arid to semiarid regions, alteration and oxidation occur essentially in place. At Marysvale, for example, hydrothermal pitchblende- and fluorite-bearing veins grade upward into a complex assemblage of 6-valent uranium minerals (Walker and Osterwald, 1956), including principally autunite, torbernite, metatorbernite, and uranophane; some sooty pitchblende and umohoite also are present and apparently are most abundant just below the oxidized zone. In general, the pitchblende- and fluorite-bearing veins show no marked tendency to be richer in uranium than their overlying secondary counterparts, and both the oxidized and unoxidized vein segments have yielded ore of about the same grade.

SUMMARY

In general, the causal chemical processes and the resultant geologic expression of supergene alteration of uranium-bearing veins are similar to those described for copper and other base-metal sulfide deposits.

The products of supergene alteration of uraniferous veins are many and include not only hydrated 6-valent uranium minerals but, locally, uranyl ions adsorbed on several alteration products and, in some places where reduction has occurred, on several supergene 4-valent uranium minerals. Commonly, in those vein deposits characterized by several uranyl compounds, a zoning of the uranium-bearing alteration products has been demonstrated in which hydrated oxides and hydroxides occur closest to unaltered pitchblende whereas uranyl silicates, phosphates, vanadates, molybdates, and arsenates occur in an intermediate position, and uranyl carbonates and sulfates are found farthest from unaltered pitchblende.

Solution, redistribution, and subsequent loss of uranium to migrating ground waters are characteristic of most uranium-bearings veins subjected to supergene processes and are most common at or near the ground surface. In a few veins, supergene alteration occurs essentially in place and shows no marked tendency toward uranium enrichment or depletion in the more oxidized parts of the veins. In still other veins, supergene alteration has resulted in the enrichment of uranium in zones of decreased oxidation potential; commonly, the enriched zones are characterized by sooty or regenerated pitchblende.

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Concepts of Origin of Uranium-Bearing Veins in the Conterminous United States

By GEORGE W. WALKER *and* FRANK W. OSTERWALD

GEOLOGY OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

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CONCEPTS OF ORIGIN OF URANIUM-BEARING VEINS IN THE CONTERMINOUS UNITED STATES

By George W. Walker and Frank W. Osterwald

ABSTRACT

Several different theories have been proposed to account for the formation of uranium-bearing veins. Most theories consider that vein deposits were derived directly through magmatic differentiation of magmas or, conversely, through concentration of uranium from a dispersed source in rocks of the crust as a result of the development of energy gradients through diastrophic activity; in many places it can be assumed that these different modes of origin are not mutually exclusive. The wide distribution of uranium-bearing veins in the conterminous United States and the diverse geologic characteristics of these deposits and of their structural and petrologic environments seem more compatible either with several different modes of origin or with concentration of dispersed uranium as a result of tectonic, petrologic, or hydrologic processes.

Both liquid and gaseous transport of uranium have been postulated and are described in several of the hypotheses of uraniferous vein formation. Postulated ore-transporting solutions have included magmatic, meteoric, and connate water, some unidentified liquid organic material, and liquid carbon dioxide. The uranium within these different phases may have been in true solution as ions or ion complexes, or it may have been in colloidal suspension. In some places it has been postulated that uranium has been transported in a gaseous phase, presumably as a halide.

Deposition of uranium has been attributed to several different, but commonly interrelated, physical and chemical factors largely related to changes in pH and Eh within the vein system. In some places uranium seems to have been fixed solely by evaporation of solvent, by the formation of stable metallo-organic compounds, or by adsorption.

An extremely wide range of temperature and pressure conditions of formation, essentially from near-surface deposition by cold ground water to high-temperature (about 500°C or more) deposition at great depths and confining pressures, has been demonstrated for uranium-bearing veins. In the conterminous United States, the largest number of uranium-bearing veins as well as most of the larger veins can be assigned to epithermal or middle to upper mesothermal pressure-temperature classes.

INTRODUCTION

The various concepts of origin of uranium-bearing veins are generally either the same as, or modifications of, hypotheses that have been advanced for other types of metalliferous deposits. The problem of ultimate origin of deposits in veins is related to the distribution of elements in the earth's crust and to tectonic, petrologic, and hydrologic processes that have redistributed elements to form various kinds of ore deposits. It has been postulated, on the one hand, that exploitable deposits of uranium are spatially and genetically related to parts of the earth's crust that are enriched in uranium, the enrichment presumably occurring during the formation of the crust. On the other hand, it also has been postulated that uranium deposits are ephemeral, occurring in different parts of the crust during different periods of geologic history. Interpretations regarding the mode of origin of uraniferous deposits are varied and include principally processes of magmatic differentiation, in which the uranium-bearing ore solution is a late-stage differentiate, and processes in which dispersed uranium in rocks of the crust is mobilized and transported and later concentrated in favorable environments. No single mode of origin for uranium-bearing vein deposits in the United States is adequate to account for all the diversities in the deposits and their geologic environments.

DISTRIBUTION OF URANIUM IN THE EARTH'S CRUST

Any discussion of concepts of origin of uranium-bearing veins is closely bound to considerations of the abundance and distribution of uranium in the earth's crust. The mode of occurrences of uranium in these rocks probably has considerable bearing on its availability for mobilization, transportation, and ultimate deposition to form deposits.

Estimates of the abundance of uranium in the earth's crust by Clarke and Washington (1924), Schneiderhöhn (1934), Goldschmidt (1937), Anderson (1942), Rankama and Sahama (1950), Mason (1952), and others have been summarized in tabular form by Fleischer (1953). These estimates show considerable variation in uranium abundance and range from a low of 0.0002 percent by weight to a high of 0.008 percent; several of the more recent of these estimates indicate that the abundance of uranium in the earth's crust is 0.0004 percent, although Fleischer (1953, fig. 2) apparently favors a slightly lower abundance, perhaps about 0.0002 percent. Irrespective of whether 0.0002 percent or 0.0004 percent is more nearly correct, the earth's crust contains a vast quantity of uranium; and Katz and Rabinowitch (1951, p. 71) have computed that a crust 20 km thick contains about 1.3×10^{14} metric tons of uranium, assuming an average uranium content of 4 ppm (parts per million), or 0.0004 percent. Uranium is a ubiquitous but minor constituent of all kinds of rocks, and only a very small part is concentrated into deposits.

Inhomogeneity in the distribution of uranium among different kinds or groups of rocks is well established (Evans and Goodman, 1941; Senftle and Keevil, 1947; Larsen and Phair, 1954; Adams, 1954; Bell, 1954), and many variations in uranium content are systematically related to the petrologic character of the rocks involved. Among products of magmatic differentiation, the uranium content varies widely from as little as a few tens or hundreds of parts per billion to several tens of parts per million (Phair, 1952; Larsen, 1954); most unaltered igneous rocks contain less than 7 ppm (Larsen and Phair, 1954, p. 75). Furthermore, as summarized by Klepper and Wyant (1956, p. 18–19) from data originally presented by Rankama and Sahama (1950), Billings and Keevil (1946), Adams and Saunders (1953) and others, the lower uranium contents for igneous rocks are in the earlier, more mafic varieties, and the higher uranium contents are in the later, silicic and silicic-alkalic varieties. This variation is not universal, however, because several exceptions were noted by Neuerburg (1956b, p. 56). In addition, effusive igneous rocks may be more uraniferous than their intrusive counterparts (Klepper and Wyant, 1956, p. 19; Adams, 1954), but such differences cannot yet be systematically demonstrated with analytical data (Neuerburg, 1956b, p. 57).

The uranium content of sedimentary rocks ranges from a few tens of parts per billion or less to tens or locally hundreds of parts per million. Estimates of the average uranium content of sedimentary rocks, exclusive of limestones, range from 1.2 ppm (Evans and Goodman, 1941) to 2.2 ppm (Holland and Kulp, 1954). The uranium content of marine black shales is greater than that of other sedimentary rocks (Bell, 1954, p. 106); some marine black shales in the United States contain as much as 200 ppm (Swanson, 1956), and some in Sweden contain 400 ppm (Svenke, 1956). The uranium content of carbonate rocks is very small compared with that of other rocks (Bell, 1956, p. 382). Phosphatic sedimentary rocks contain appreciable amounts of uranium (Davidson and Atkin, 1953; McKelvey, 1956; Cathcart, 1956), with content ranging from about 50 ppm or less to 300 ppm.

The uranium content of metamorphic rocks is inadequately known. Presumably, the uranium content of rocks before metamorphism was about the same as that of equivalent unmetamorphosed rocks. Metamorphic processes, however, may change not only the uranium content but also the content of other metals in rocks. As pointed out by Devore (1955, p. 188), "* * * metamorphic transformations are capable of releasing large amounts of material to a dispersed state—material which under proper conditions can become localized as ore deposits"—or which under other conditions can be removed or depleted by circulating ground waters. Much of the uranium in rocks is readily leachable, as demonstrated by Brown and others (1953), Brown and Silver (1956), Neuerburg (1955, 1956a,b), and Larsen and others (1956); hence, metamorphism probably changes the distribution of uranium within metamorphic terranes.

SOURCE OF URANIUM

Several hypotheses have been proposed to explain the origin of the uranium now found in veins and other deposits and to elucidate the methods of uranium mobilization, transportation, and deposition. Some of these hypotheses, as they pertain to veins, are reviewed in part by Everhart (1954), Nininger (1954), and Schmitt (1950, p. 194). Foremost among the several hypotheses are that the uranium has been derived from residual fluids resulting from magmatic differentiation and represents a component of the magma and that the uranium has been derived from a dispersed source in rocks of the crust.

MAGMATIC DIFFERENTIATION

Most epigenetic deposits of uranium, whether defined as veins or as some other kind of uranium deposit, have been attributed by many geologists to processes of magmatic differentation. To some of these geologists, the relation is thought to be direct in that late-stage magmatic differentiates—presumably of an aqueous nature and enriched in silica, the alkali metals, and various rare elements—have been the vehicle by which uranium was introduced into the deposits. In contrast to a direct magmatic source for uranium in the deposits, several geologists have proposed that uraniferous solutions of magmatic origin have intermixed with connate, phreatic, or vadose water and, under changing hydraulic conditions, have moved considerable distances before depositing uranium minerals in favorable geologic environments. Deposits formed in this manner might be considered telemagmatic (Lindgren, 1933, p. 121, 405) in the sense of being far removed from intrusive centers.

The spatial associations of many veins with igneous rocks, particularly in the Western United States, have been used as prima facie evidence of a genetic relationship; but at most places no such relationship can be demonstrated. Moreover, a very large proportion of uranium-bearing veins are in areas in which igneous rocks seem to be lacking or, if present, obviously are not related to uranium mineralization.

Detailed studies directed principally toward the establishment of a genetic relationship between magmatic differentiates and uranium-bearing veins in the conterminous United States are few. Phair (1952) demonstrated a spatial association and proposed a genetic relationship between some uranium-bearing veins and quartz bostonite porphyry dikes in the Central City district, Colorado. He writes (1952, p. 4–5),

> The sequence of events in the Central City district is thought to be as follows: (1) intrusion of slightly to moderately radioactive monzonite throughout the eastern half of the district, (2) intrusion of excessively radioactive, nonporphyritic varieties of quartz bostonite in the western half of the district north of what was to become the area of pitchblende deposition, (3) intrusion of the highly radioactive quartz bostonite porphyry dikes with which 15 of the 17 known occurrences of pitchblende are now associated (within 500 feet), (4) deposition of pitchblende as a local and unusual variant in the regional pyritic-gold ore deposition near, but not in, the quartz bostonite porphyry dikes.

His conclusions are based not only on the space relation, but also on inferred time relations among the several differentiates as well as the veins and on an increase in equivalent uranium, uranium, thorium, and zirconium in younger intrusive rocks of the series. Some deposits in the district are not related spatially to quartz bostonite porphyry and, according to Sims (1955, p. 202), may be derived from a different source magma. Sims (1956, p. 217) has postulated that biotite-quartz latite (magma?) may have been a source of uranium in certain vein deposits in the Front Range mineral belt but that most deposits at Central City, near Lawson, and locally elsewhere in the region are genetically related to quartz bostonite magma (Sims and others, 1957, p. 298).

Uraniferous fluorspar deposits of the Thomas Range, Utah, are closely associated in space with a series of rhyolitic and latitic flows and pyroclastic rocks. The uranium and fluorine in the fluorspar deposits and volcanic rocks probably were derived from a common magmatic source (Staatz and Osterwald, 1956, p. 135–136), as suggested by mineralogical and analytical evidence indicating that the magma for the volcanic rocks was rich in fluorine and hence the probable source for the uraniferous fluorspar deposits and by the presence of secondary uranium minerals in the volcanic rocks in the eastern part of the Thomas Range. Some geological and analytical data suggest to Staatz (1956, p. 224; 1957, p. 301) that a younger group of volcanic rocks in the Thomas Range contains more uranium than does an older group, perhaps indicating that uranium was concentrated during crystallization of the parent magma. The uranium thus concentrated could have been expelled in late fluid differentiates to form deposits. Similarly, several small uranium deposits in the Jarbidge area, Nevada, may be related to acid volcanic rocks; because, according to Coats (1956, p. 150),

> * * * the content of uranium and some other trace elements, chiefly beryllium, niobium, zirconium, tin, lead, and fluorine, increases with decreasing age * * * [of middle to late Tertiary volcanic rocks of rhyolitic to quartz-latitic composition] * * *, although the trends are irregular.

The uranium deposits in the Dripping Spring Quartzite, Sierra Ancha region, Arizona, may be related to the intrusion and differentiation of diabase (Granger, 1955, p. 188–190; 1956, p. 204–209; Granger and Raup, 1957, p. 417–418; Neuerburg, 1956a, p. 232–234). Diabase in the Apache Group in this area is spatially closely associated with many of the uranium deposits and, in general, exhibits the following patterns of uranium distribution: (a) Chilled aphanitic selvages of the diabase contain approximately twice as much uranium as does the more coarsely crystalline bulk of the diabase; (b) felsic differentiates contain the highest uranium concentrations (Neuerburg, 1956a); (c) there is a suggestion that "* * * the uranium is more closely related genetically to diabases differentiating to sodic facies than to diabases differentiating to potassic or calcic facies" (Granger, 1955, p. 190); and (d) the uranium may have been introduced into the deposits by a very late femic differentiate now represented by deuteric veinlets composed dominantly of hornblende and lesser quantities of biotite, chlorite, and zircon (Granger and Raup, 1957, p. 418). Neuerburg (1956a, p. 233) postulates that "* * * the uranium contents of the chilled selvages of these diabase bodies are probably original * * *" and perhaps are more nearly diagnostic of the uranium content of the magma than are other more coarsely crystalline differentiates. Neuerburg (1956a) calculated that about 1,000 metric tons of uranium metal was lost from each cubic kilometer of diabase during crystallization, assuming a volume of 5 percent for the differentiates and the uranium content of the chilled selvage to be that of the magma.

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Some uranium deposits may be associated with lamprophyric rocks, as suggested by studies of the relations of pitchblende and lamprophyric (or diabasic) rocks in the Montreal River (Theano Point) district of Ontario by Emmons, Reynolds, and Saunders (1953, p. 94–99). They propose (1953, p. 96–97) that "* * * Uranium halides which at most are a trace constituent of granite gather with the unmixed feldspathic, alkaline liquid * * * and drain deuterically into fractures along with accumulating lamprophyric materials."

Many uranium-bearing veins in the conterminous United States are associated with rocks of magmatic origin, but the degree and type of association vary widely among deposits. In some places, as for example in parts of the Front Range, Colorado, and in the Sierra Ancha region, Arizona, geologic and analytical data indicate that the uranium was introduced into deposits by late-stage magmatic differentiates genetically related to enclosing or nearby igneous rocks. In other places, as at Marysvale, Utah, northeast Washington, and in Lake County, Oreg., where uraniferous veins are spatially associated with igneous rocks, the implications of the association are less well known; genetic, environmental, or fortuitous relations may exist. In still other places where uranium-bearing veins and igneous rocks are spatially associated, geologic data demonstrate that a genetic relation cannot exist; and the association is, thereby, either environmental or fortuitous. Examples include deposits in the Kern River area, California, and several of the deposits in the Cochetopa district, Colorado, where hypogene uranium minerals are in sedimentary rocks of Jurassic age as well as in the underlying granitic rocks of Precambrian age.

DEPOSITS FORMED BY CONCENTRATION OF METALS FROM A DISPERSED SOURCE IN ROCKS OF THE CRUST

The study of uranium deposits in recent years has led many geologists to conclude that the uranium and associated metals in these deposits were derived from dispersed sources in rocks of the crust and were concentrated into deposits by a variety of geologic processes sometimes collectively called lateral secretion. In the conterminous United States, most studies leading to this general concept have been made on essentially stratiform deposits in clastic sedimentary rocks, particularly as exemplified by deposits on the Colorado Plateau and in several sedimentary basins of Wyoming, North Dakota, and South Dakota. A local host-rock source was ascribed for the uranium in the deposits on the Colorado Plateau after their discovery (Hillebrand and Ransome, 1900; Fleck and Haldane, 1907; Moore and Kithil, 1913), and it is still probably the most widely accepted source for all or part of the uranium in similar kinds of deposits (Denson, Bachman, and Zeller, written communication, 1951; Denson and Gill, 1956; Vickers, 1956; Vine, 1956; Gruner, 1956; Shawe, Simmons, and Archbold, 1957; Garrels, 1957). Waters and Granger (1953) conclude that leaching of volcanic debris in rocks of the Colorado Plateau may have contributed to the formation of the uranium deposits on the Plateau. Even though the concept of deriving uranium from the rocks that enclose deposits has received little consideration as applied to uranium-bearing veins both in the conterminous United States and elsewhere, such a process may be even more important as a source of uranium than magmatic sources.

As pointed out in the section on the distribution of uranium in the earth's crust, the total amount of uranium in any given rock unit is considerably larger than the amount gathered into clusters of ore deposits that represent mining districts or even large mining regions. For example, the total amount of uranium in a cubic mile of granite is about 22,000 metric tons, assuming an average uranium content of 2 ppm and a rock density of 2.65 (Holmes, 1930, p. 22, 24, fig. 1). Even for sedimentary rocks with lower densities and commonly with lower uranium contents than granitic rocks, the amount of uranium is estimated in terms of hundreds or thousands of metric tons in a cubic mile of rock. Considering the large volume of rock beneath, beside, and originally over a mining district, the total amount of uranium potentially available is tremendously large compared with that in the deposits.

By analogy with the concepts of metamorphic and metasomatic geology, the uranium in any rock can be postulated to be held within the minerals in a number of ways; and regardless of which way the uranium is held, the conditions of thermodynamic equilibrium (lowest energy state) must have been fulfilled when the rock formed. When the state of thermodynamic equilibrium is upset, the constituents of the rock become unstable; the upset may be caused by an increase in the geothermal gradient, by changes in confining pressure and in position in the earth's gravitational field, and by changes in kinetic and potential energies of particles due to stress and to motion of rock masses. These changes in energy levels can be obtained by intrusion of igneous masses, folding and faulting or other structural deformation, or deep burial. Because uranium is such a mobile element in the earth's crust, and because many of its compounds are easily soluble under surface and near-surface conditions, uranium possibly may be expelled from rocks or rock minerals under only relatively slight changes in the energy levels. After expulsion, the uranium could be moved by any circulating fluid, whether heated or unheated, and concentrated into deposits wherever lithologies and structures are favorable. The process is similar to the formation of metamorphic concretions, petroblasts, and secretions (Barth, 1952, p. 314–318). Condon and Walpole (1955) consider that many uranium deposits of Australia are a result of this kind of process or processes, in which metallic ions originally dispersed in host rocks moved to structural traps as a consequence of changes in potential energy levels. Some uranium-bearing veins in the United States that might best be attributed to concentration of uranium from a dispersed source in rocks of the crust include the deposits at Cement, Okla. (McKay and Hyden, 1956), the Huron River vein deposit in northern Michigan, several of the deposits in the Pryor Mountains–Little Mountain area of Montana and Wyoming, and deposits in the Cane Springs district, Utah. Deposits in all these areas seem to lack any relation to igneous rocks and, hence, to magmatic differentiation; however, the deposits may be attributable to some process or processes other than lateral secretion.

Both magmatic differentiation and concentration of uranium from a dispersed source in rocks of the crust may be dominant modes of origin locally, but a lack of data precludes determination of the dominant mode of origin for uraniferous vein deposits. Nevertheless, the wide distribution of uranium-bearing veins in the conterminous United States (chap. A, pl. 1) and the diverse geologic characteristics of these deposits and their structural and petrologic environments seem more compatible with either several different modes of origin or concentration of dispersed uranium as a result of the development of energy gradients through diastrophic activity (including vulcanism, intrusion, and structural deformation).

TRANSPORTATION AND DEPOSITION OF URANIUM

Several concepts of uranium transport and deposition have been presented and discussed in geologic literature during the past several decades. These hypotheses have proposed both liquid and gaseous transport of uranium and many different physicochemical processes to effect uranium deposition.

MODES OF TRANSPORT

Most concepts of uranium transport are based on the assumption that the transporting medium is meteoric, magmatic, or connate water that may be either heated or cold. In a few places, reference has been made to the possibility of transporting uranium in a gaseous phase, presumably as a halide, in some unidentified liquid organic material, and in liquid carbon dioxide. It has been postulated that the uranium within these different phases may have been in true solution as ions or ion complexes, or it may have been in colloidal suspension.

Liquid organic materials, presumably either petroleum derivatives or humic acids (Manskaïa, Drozdóva, and Emelianova, 1956; Vine, Swanson, and Bell, 1958), may have been the carrying agents for the uranium in some veins, particularly those in which part of or all the uranium is closely associated with materials variously labelled "hydrocarbons," "asphaltite," or "thucholite." Some uraniferous veins in the United States that contain these organic materials are the Black King group and the Robinson (or White Spar) property, near Placerville, Colo., the Morrison (or Pallaoro) deposit and Halfmile gulch (see chap. D, fig. 19), Jefferson County, Colo., several deposits near Cane Creek, Grand County, Utah, and several deposits in the Temple Mountain district, Utah; references to some foreign vein deposits characterized by uraniferous organic materials are given in chapter A, p. 13. Some crude oil, natural asphalt, and petroliferous rocks contain appreciable amounts of uranium as well as other metals, although the chemical nature of the metallic compounds in these materials is not definitely known (Erickson, Myers, and Horr, 1954); probably some of the metals are present as metal-organic-porphyrin compounds (Rankama and Sahama, 1950, p. 353). Further, Erickson, Myers, and Horr (1954, p. 2217) suggest that "* * * uraniferous asphaltite deposits may be formed through volatization, oxidation, and polymerization of a petroleum whose ash was enriched in uranium, vanadium, copper, arsenic, molybdenum, nickel, and other metals * * *." These organic materials may result from the polymerization of hydrocarbon gas as a consequence of its bombardment by alpha and beta radiation (Liebenberg, 1948,[1] 1955; Davidson and Bowie, 1951).

Wilmarth and Hawley (written communication, 1954) attribute the uranium in deposits at Placerville, Colo., to migrating uraniferous oils that mixed and reacted with uranium-bearing hydrothermal solutions. They suggest that the uranium in the asphaltite in these deposits occurs both as discrete mineral grains of uraninite and coffinite and as metallo-organic compounds. According to them, minor quantities of uranium and other metals were original components of oil, now represented in part by the asphaltite; and

[1] Liebenberg, W. R., 1948, Rare minerals in the banket of the Witwatersrand system: Pretoria, Transuaal, Pretoria Univ. dissertation.

during chemical reaction between hydrothermal solutions and the immiscible oil, some additional metals were adsorbed from the ore solutions and concentrated in the oil. Depositions of the highly uraniferous asphaltite resulted largely from removal of volatiles from the oil by heat and chemical reaction. Kerr and others (1957), on the other hand, apparently attribute the uranium in the highly uraniferous organic materials at Temple Mountain, Utah, solely to hydrothermal solutions from which the uranium presumably was deposited in a reducing environment high in H_2S and organic matter, in part petroliferous. This concept, however, is not substantiated by paragenetic studies of the ores at Temple Mountain (Hausen, 1956), which indicate that uranium mineralization took place prior to the introduction of the bitumens.

Although the uranium and associated metals in some veins may be transported and deposited by petroleum or humic acids, this mechanism of transport seems volumetrically unimportant either in terms of the number of deposits or in terms of tons of metal in any single uranium-bearing vein.

The concept of colloidal transport and deposition in veins of many metallic and nonmetallic minerals, locally including pitchblende, had many adherents in the 10 or 20 years prior to 1945 (for example, Boydell, 1926, 1928; Lindgren, 1933, 1936; Lasky, 1930; Kidd and Haycock, 1935; Garrels, 1944).

The concept that these materials were transported in a dispersed solid state was largely based on the following:

1. Base metal sulfides as well as uranium in the 4-valent state are soluble with difficulty either in weakly acid or alkaline aqueous solutions.
2. Several inorganic materials, particularly silica and certain compounds of iron and aluminum, are known to form colloids (Rankama and Sahama, 1950, p. 233–236; Mason, 1952, p. 147–150).
3. Many of these materials, particularly naturally occurring primary uranous oxide compounds, are in textural forms that indicate or suggest to many investigators (Roger, 1917, 1947; Kidd and Haycock, 1935; Lindgren, 1936; Bastin, 1950; Ramdohr, 1955; Robinson, 1955; Edwards, 1954; Lasky, 1930) that the material was deposited as a result of coagulation of a hydrosol. Several of these investigators also consider that part of the metal sulfides were transported as true solutes, either as ions or ion complexes of indefinitely known identity.

Wright (1954, p. 162–164) briefly reviewed data on the concept of colloidal transport of uranium with special reference to colloform pitchblende at the Caribou mine.

Deposition of pitchblende, largely in open spaces, and the general lack of replacement of other minerals by pitchblende tend to favor colloidal deposition rather than direct deposition from ions in solution. Furthermore, the colloidal or colloform textures—including principally rotund or spheroidal forms of both megascopic and microscopic dimensions, shrinkage (syneresis) cracks, and interference surfaces—perhaps are more pronounced and better illustrated by pitchblende than by any other metallic mineral; within uranium-bearing veins in the United States, these colloidal or colloform textures predominate almost to the exclusion of other textures (chap. D). Whether these textures, as found in pitchblende, indicate colloidal transport and (or) deposition from a colloid is not definitely known; conceivably, large complex uranyl ions carried in solution might act as colloidal particles, or, more likely, an intermediate colloidal stage may exist between uranium ions in solution and deposited pitchblende. Perhaps the spheroidal textures of naturally occurring pitchblende are comparable to those obtained in the laboratory by Miller and Kerr (1954) as the result of reduction of uranyl ions in an acid solution. That colloform pitchblende is crystalline and not amorphous, as demonstrated by X-ray studies, is of little significance as regards colloidal transport and deposition, because most colloidal particles are internally crystalline and many gelatine colloids possess an internal crystalline structure (Pierce and Haenisch, 1940, p. 302).

As pointed out by Hemley (1953, p. 114), the relatively high concentration of salts in solution, as deduced from liquid inclusion studies by Newhouse (1932) and from evidence of great penetration of wallrock by mineralizing solutions in many deposits, seems to militate against the concept of transport by poorly diffused colloids, particularly for the widely distributed metal sulfides that are closely associated with uranium minerals in many deposits.

Both experimental data and theoretical considerations have suggested to Emmons, Reynolds, and Saunders (1953) that uranium may be transported as some kind of halide, presumably either a fluoride or a chloride. Preliminary results of an experiment were reported by them (1953, p. 98) as follows:

> Pitchblende in the presence of gently moving chlorine gas below 200°C transferred to a cooler part of the containing chamber and deposited a translucent gelatinous and botryoidal encrustation on feldspar surfaces. The deposit is probably uranyl chloride. By introducing a very small amount of air the gelatinous encrustation was converted to a black hard botryoidal material which appears to be pitchblende.

In attempting to relate rock alteration to uranium mineralization in the Marysvale district, Utah, Kerr and others (1952, p. 51–54) and Green and Kerr (1953, p. 73–85) considered the possibility of transporting uranium in the reduced, 4-valent state combined with fluorine. The chemical processes outlined by them for hypogene deposition of fluorite and uranium—as uraninite or pitchblende—in the Marysvale deposits are: (a) The uranium was transported as uranium tetrafluoride in a fluid state; (b) these fluids were enriched in sulfur; (c) a drop in vapor pressure resulted in reaction, in the presence of water (or steam), between these fluids and components of the wallrocks to form UO_2 (uraninite or pitchblende), CaF_2 (fluorite), FeS_2 (pyrite), and HF (hydrofluoric acid). Presumably, the released hydrofluoric acid aided in the destruction of silicate minerals in the wallrocks. The concept of uranium transport as the tetrafluoride apparently is based not only on the abundant fluorite and pyrite both in the veins and in the adjoining wallrocks but also on rock analyses indicating an increase in fluorine and sulfur in altered rock adjacent to veins and, in part, to stated time relations between wallrock alteration and uranium mineralization (Green and Kerr, 1953). In contrast to this method of transport, the uranium in the colored 6-valent uranium minerals at Marysvale is thought (Green and Kerr, 1953, p. 78) to have been transported in acid, sulfate-rich waters, presumably as uranyl sulfate rather than as a tetrafluoride as for the hypogene minerals, and deposited where these solutions contacted "* * * the relatively rich * * * [in carbonte?] * * * Bullion Canyon Volcanics."

The study of uranium chemistry—insofar as it applies to possible methods of uranium transport and emplacement—together with studies of the geology and mineralogy of uranium deposits, including laboratory synthesis of uranium minerals, has focused considerable attention on the concept of transporting uranium in the 6-valent rather than 4-valent state. Even though our basic knowledge of crystallization and solution processes is somewhat limited, particularly as these processes apply to naturally occurring systems, the concensus of published opinion (in 1957) was that uranium probably is transported as the uranyl ion in aqueous sulfate or carbonate solutions. Furthermore, several recent papers (Ridge, 1956; Thompson, 1954; Krauskopf, 1951; Hemley, 1953; Barton, 1957) present evidence suggesting that many of the extremely insoluble metallic minerals commonly associated with uranium in veins, notably the base-metal sulfide minerals, are transported as complex ions, principally metal-sulfur complexes, in hydrothermal solutions.

McKelvey, Everhart, and Garrels (1955) describe in some detail the processes involved in the transport of uranium as the uranyl ion and summarized these processes (1956, p. 43) as follows:

> Little is known directly about the composition of uranium-bearing hydrothermal solutions, but from the fact that the most uraniferous natural waters are those high in sulfate or carbonate content or both, as well as from experimental data (Gruner, 1952; Miller and Kerr, 1954; Katz and Rabinowitch, 1951, p. 111–120) that indicate the solubility of uranyl sulfates and carbonates in aqueous solutions, it may be assumed that uranium is transpotred as the uranyl ion (Phair, 1952) in sulfate or carbonate solutions and that they may be either acid or alkaline. Because the physicochemical properties of CO_2 and the system CO_2–H_2O indicate that under some shallow earth-conditions CO_2 can exist as a separate phase with a density approximately that of water, liquid CO_2 has also been suggested as the ore-transporting solution (Garrels and Richter, 1955).

The dominant uranium mineral of uranium-bearing veins wherever mines have penetrated beneath the near-surface oxidized ore bodies is uraninite or, more commonly, the massive, colloform, or sooty variety, pitchblende. This poses the question of whether soluble 6-valent uranium, in whatever form, is very stable at depth, particularly where it is in association with abundant pyrite or other sulfide minerals or with organic materials such as found at Placerville, Colo., and Temple Mountain, Utah.

MECHANISMS OF URANIUM FIXATION

Several different processes for the deposition or fixation of uranium in vein deposits in the conterminous United States are suggested by the extremely variable mineral contents and geologic environments of such deposits. The nature of the ore solutions from which such uraniferous veins were formed also varied appreciably not only among the different mineralogic classes of veins but also among some veins within any one class. The uranium—in whatever form—in these ore solutions was deposited or fixed wherever a change in the chemical or physical environment caused a decrease in the solubility of the uranium or the carrying capacity of the transporting medium. Loss of solvent capacity has been attributed to several different, but commonly interrelated, physical and chemical changes including principally (a) decrease in oxidation potential and the conversion of 6-valent uranium in solution to less soluble 4-valent uranium, (b) variations in pH of the solvent, (c) changes in temperature and (or) confining pressure, (d) depletion of the solvent through evaporation, (e) formation of comparatively stable metallo-organic compounds, and (f) adsorption of uranium largely on hydroxide gels of iron but also on several other inorganic materials and possibly on some organic materials. Only one of these mechanisms of uranium deposition may have been dominant in some deposits; whereas, in other veins, several of these processes apparently operated.

McKelvey, Everhart, and Garrels (1956, p. 43–44) summarize their concepts of uranium deposition as follows:

> Precipitation of primary uranium minerals in veins may be caused solely by a reduction in the amounts of sulfate or carbonate in solution by whatever cause, by a decrease in temperature or pressure or both, or by chemical interaction with the host rock. Either pressure or chemical interaction with the host rock may result in $(U^{+6}O_2)^{+2}$ reduction, which seems to be the factor of major importance in the precipitation of uranium minerals in hydrothermal and many other types of deposits. Experiments by Miller and Kerr (1954) confirming earlier work by Gruner (1952), indicate that pitchblende may be precipitated from uranyl sulfate solutions by the use of hydrogen sulfide gas, according to the equation:
>
> $$S^{-2}+(U^{+6}O_2)^{+2}\rightarrow U^{+4}O_2+S$$
>
> Ferrous iron also may be a reducing agent for uranyl ion. The reaction:
>
> $$3H_2O+2Fe^{+2}+(U^{+6}O_2)+^{2}\rightarrow Fe_2O_3+U^{+4}O_2+6H^{+1}$$
>
> goes to completion $[(U^{+6}O_2)^{+2}<10^{-6}]$ at 25°C at pH 4 and above throughout a wide range of Fe^{+2} concentration. This may explain the widespread association of iron oxide with pitchblende in vein deposits.

Changes in pressure, causing reduction of $(U^{+6}O_2)^{+2}$, would be most effective where environmental conditions permit a free gas phase. Reduction in pressure could permit the "boiling off" of CO_2 or other gases dissolved in the ore solution and, as a result, effectively change the equilibrium of the system. Such a mechanism was postulated by Roach and Wallace (1957, p. 38–39) for uranium deposition in sandstone-type deposits of the Bull Canyon district, Utah, and possibly is an effective mechanism for the deposition of uranium in some veins.

Deposition of uranium in veins by chemical interaction of ore solutions and wallrocks is substantiated in only a few places. No specific chemical interaction between host rocks and ore solutions can be demonstrated for all deposits.

Within some districts, or deposits, characterized by several kinds of rock, the chemical and mineralogic compositions of certain rocks seem to aid in the deposition of uranium in individual veins. In part of the Central City district, Gilpin County, Colo., metatorbernite has replaced some minerals of altered biotite-quartz-plagioclase gneiss and altered amphibolite wallrocks in the supergene zone but is absent in other rock types (Sims and Tooker, 1955; Sims, Osterwald, and Tooker, 1955, p. 17–18). Hawley and Moore (1955) suggested a chemical control of uranium deposition in the Fall River area, Clear Creek County, Colo. The veins in which the uranium occurs cut several kinds of Precambrian metamorphic and granitic rock, but uranium was deposited only where the veins intersect garnet-quartz rock. Some pitchblende deposits in Golden Gate Canyon, Jefferson County, Colo., show a similar type of chemical control. According to Adams and Stugard (1956, p. 113), "The veins occupy extensive faults considered to be of Laramide (earliest Tertiary) age and normally contain pitchblende only where they cut hornblende gneiss." Many uranium-bearing veins near and in the Central City, Fall River, and Golden Gate Canyon areas, however, occur in an assemblage of host rocks that are noticeably different in mineralogy and chemical composition from those mentioned above. Uraniferous veins in amphibolite, quartz monzonite gneiss of several different compositions, biotite-quartz-plagioclase gneiss, sillimanite-biotite-quartz gneiss, granite pegmatite, granite gneiss, and several varieties of schist have been reported in the Central City district, all within a few miles of each other. A somewhat parallel situation has been noted in the Goldfields region of Saskatchewan, Canada, where, although uranium was deposited in several quite different kinds of rock, the preferred host rocks are mafic gneiss, chlorite schist, amphibolite, diabase, and granites "* * * where they [the granites] are crushed and contain carbonate and chlorite" (Robinson, 1955, p. 49 and table 1). The preferential localization of uranium in calcium- or iron-rich wallrocks has been demonstrated for deposits in these and other areas; however, the variable nature of the host rocks of most veins in the conterminous United States would seem to preclude any such general chemical relation.

Uranium-bearing veins in carbonate rocks—as for example in the Pryor Mountains–Little Mountain area of Montana and Wyoming, possibly some of the veins in the Goodsprings (Yellow Pine) district, Nevada, and at Bisbee, Ariz.—may be attributable in part to the neutralizing effect that such rocks have on slightly acid uraniferous ground waters or hydrothermal solutions (Bell, 1956, p. 381). The fixation of uranium in coaly environments—such as is found at the Leyden mine, Jefferson County, Colo.—can possibly be attributed to the formation of metallo-organic compounds or complexes (Moore, 1954, p. 656–657; Breger, Deul, and Rubinstein, 1955, p. 225–226), to the adsorption of uranium by coal, or to the reducing characteristics of the coaly material in the deposit. At the Leyden mine, part of the uranium in the deposit is in coffinite (Stieff, Stern, and Sherwood, 1956), and part is in carnotite (A. J. Gude, 3d, and F. A. McKeown, written communication, 1952); neither urano-organic compounds nor adsorbed uranium have been determined, but they might be expected in these coaly rocks.

Many uranium-bearing veins in the conterminous United States show no clear-cut relation between ore deposition and chemical composition of wallrock, possibly owing to (a) lack of adequate data, (b) inert chemical properties of ore solutions with respect to the altered or unaltered host rocks, or (c) marked differences in the nature of chemical interaction between ore solutions and host rocks from one deposit to another.

The most significant generalization that can be made about the influence of host rocks in localizing uranium is that a majority of uraniferous veins are enclosed in rocks that are dominantly silica and silicate minerals, most commonly igneous and metamorphic coarse- to medium-grained holocrystalline rocks (chap. C). These rocks, although their mineralogic and chemical compositions differ widely, do have certain physical properties in common, particularly their competence under stress. Silicate rocks lack any major plastic flow phenomena under near-surface conditions of pressure and temperature and are more apt to rupture under stress than other kinds of rock (Robertson, 1955). Conceivably this tendency to rupture and the detailed characteristics of the resultant fractures and fragmentation possibly affecting the adsorptive properties of the host rock may affect the apparent preferential deposition of uranium. Such breaking qualities would also influence the amount of surface area developed in fragmented rock and, consequently, the amount of rock material available for reaction with migrating ore solutions. Presumably, for uranium to be adsorbed on crushed wallrock or crushed preuranium vein filling and deposited directly as a 4-valent uranium mineral, the following conditions should be met. The uranium should be carried in the ore solution in the reduced state, most likely as a colloidal sol, or as the uranyl ion which is converted to a colloid composed of 4-valent uranium at or near the site of deposition. Although this is in contrast to the summary statements concerning transportation and deposition of uranium by McKelvey, Everhart, and Garrels (1956, p. 43), such a mechanism could explain many of the textural characteristics of pitchblende and the texture and distribution of some sooty pitchblende.

SOME ASPECTS OF THE DEPOSITIONAL ENVIRONMENT

Concepts of environmental conditions during uranium deposition in veins are based largely on speculative data regarding crystallization temperatures of certain minerals or mineral assemblages, on textural characteristics of veins, and on other evidence (of questionable validity) that suggests certain pressure-temperature relations. Some of these data are presented in the following pages and are briefly summarized by McKelvey, Everhart, and Garrels (1956, p. 43) as follows:

> From the mineral assemblages and some experimental evidence (Gruner, 1952; Miller and Kerr, 1954; Lang, 1953) the silica-iron-lead veins that contain sooty pitchblende are classed as epithermal; the other silica-iron-lead veins and the cobalt-nickel-silver veins are believed to be mesothermal; and some uraninite (Stevenson, 1951), brannerite (Pabst, 1954), and davidite (Nininger, 1954, p. 55) veins, which somewhat resemble pegmatite deposits, are regarded as hypothermal. The temperature of the transporting fluids and the depth and pressure at the site of deposition of the uranium veins are thus believed to have ranged widely. According to Lindgren (1933, p. 212, 45, 529, 640), epithermal deposits are believed to have formed probably at temperatures of less than 200°C, at depths of less than 4,000 feet, and at pressures of less than 140 atmospheres; mesothermal deposits probably formed at temperatures of 175° to 300°C, depths of 4,000 to 12,000 feet, and pressures of 140 to 400 atmospheres; and hypothermal deposits likely formed at greater temperatures (possibly several hundred degrees centrigrade), depths, and pressures. Field evidence strongly indicates that most of the pitchblende veins were formed at depths shallow enough and at pressures low enough to provide open spaces along regular fissures.

By analogy with postulated temperatures of pegmatite formation (Turner and Verhoogen, 1951, p. 332), some uranium-bearing veins that are perhaps partly transitional to pegmatite may have crystallized at temperatures in the range 800° to 600°C (pegmatite stage) or in the range 600° to 400°C (pneumatolytic stage). Some minerals in uranium-bearing veins that characterize these stages are allanite, monazite, uraninite, possibly brannerite, uranothorite, and davidite (pegmatite stage), and tourmaline and beryl (pneumatolytic stage). Examples of veins in the conterminous United States that contain one or several of these minerals include the California mine, Colorado, containing both brannerite and beryl; the Climax mine, Colorado, from which brannerite has been reported (Vanderwilt and King, 1955); deposits at Majuba Hill, Nevada, which contains abundant tourmaline (Trites and Thurston, 1958); the Blue Jay mine, Colorado, containing both uranothorite and colloform pitchblende; and the vein on the Black Dog claim, California, which is composed in part of monazite partly replaced by allanite. Many other examples of uranium-bearing veins characterized by thorium and rare earths minerals have been reported. Whether these minerals are diagnostic of certain temperature ranges is open to considerable question, and in some places, detailed geothermometry studies have invalidated earlier high-temperature estimates.

Several temperature estimates or determinations of temperature, particularly in the medium to high ranges, have resulted from studies of uraniferous veins or veinlike deposits in Canada, Australia, Belgian Congo, and elsewhere. Data from several of these studies are used for purposes of comparison with like and unlike deposits in the conterminous United States.

Few detailed geothermometry studies have been made of uranium-bearing veins, and most temperature assignments have been based on analogies with deposits of other metals—notably base-metal sulfide, quicksilver, and fluorite deposits—with pegmatites, and, for some vein deposits characterized by 6-valent uranium minerals, with caliche-type deposits. Most, if not all, of the temperature estimates are based on indirect evidence—including principally mineral associations and vein textures and structures—and, consequently, multiple interpretations are possible. The nearly universal occurrence of colloform pitchblende in veins in the conterminous United States and its presence largely as open-space fillings indicate low temperatures (Edwards, 1954). Commonly, higher temperatures of crystallization are assumed for those few vein deposits characterized by idiomorphic uraninite and brannerite and uranothorite and for several of the deposits that contain rare-earth minerals as well as uranium. The temperature assignments commonly are complicated by variable paragenetic positions of vein minerals; and, consequently, most deposits can be assigned only in terms of the general pressure-temperature classes—that is, the epithermal, mesothermal, or hypothermal classes of Lindgren (1933).

The association of uranium with magnetite deposits near Warick, N.Y. (Engineering Mining Journal, 1957) suggests high temperature deposition. Presumably the magnetite deposits are metasomatic replacements, and, according to Edwards (1954, p. 149), the abundant magnetite suggests that initial crystallization temperatures may have been as high as 600°C; the temperatures at which the uranium minerals crystallized is, of course, unknown. Even though davidite-bearing veins are not known in the United States, those at Radium Hill, South Australia (Spriggs, 1954; Whittle, 1954), give some insight into temperature conditions of deposits presumably of high-temperature metasomatic origin. At Radium Hill, the solutions that introduced iron and titanium were "* * * at a temperature of not less than 600°C * * *" (Whittle, 1954, p. 56) and apparently were followed by a period of mineralization related to pegmatite formation that introduced feldspar, rare-earth minerals, and probably davidite.

High-temperature pyrometasomatic deposition is postulated by Matheson and Searl (1956) for the uraninite- and allanite-bearing deposit (Mary Kathleen) in Queensland, Australia; the deposit also contains pyrrhotite and several rare-earth minerals including stillwellite, caryocerite, and rinkite. No precise estimate of the crystallization temperatures are given; but on the basis of the classification assigned to the deposit by Matheson and Searl, temperatures must have been in the range 500° to 800°C (Lindgren, 1933, p. 212).

Somewhat lower temperatures (about 500° to 300°C) might be postulated for a group of uranium-bearing vein deposits in British Columbia that are classed as hypothermal by Stevenson (1951). According to him (1951, p. 366),

> * * * the position of the deposits within bodies of batholitic rocks and their characteristic mineral assemblage, the association of the uraninite with hornblende, biotite, apatite, allanite, monazite, orthoclase, cobalt sulfarsenides, arsenopyrite, and molybdenite, are all indicative of deposition at high temperatures.

These hypothermal deposits are characterized by idiomorphic crystals of uraninite—not the colloform variety pitchblende common to mesothermal and epithermal uranium deposits—which may tend to substantiate a correlation between environmental temperature and the growth of uraninite as idiomorphic crystals or as colloform masses of pitchblende.

Somewhat comparable temperatures have been postulated for the vein deposits near Goldfields, Saskatchewan. According to Robinson (1955, p. 97–100), the initial temperatures of deposition were probably high, possibly of the order of 500°C; but most of the pitchblende was deposited at temperatures between 250° and 350°C, or essentially in the lower hypothermal or uppermost mesothermal range. The temperature assignments for these deposits are based on an evaluation of the minerals associated with the pitchblende, on exsolution textures of chalcopyrite in bornite, on decrepitation temperatures of calcite and quartz gangue, and on oxygen-isotope ratios of calcite.

High crystallization temperatures (about 600° to 400°C) might be predicted for the beryl- and brannerite-bearing vein at the California mine, Colorado, if temperature estimates were based on analogies with minerals of Turner and Verhoogen's (1951) pneumatolytic stage. Fluid inclusion studies made by Ingerson (*in* Adams, 1953, p. 112–113) indicate that some of the beryl crystallized at about 315°C, or close to the lower limit of the hypothermal range as defined by Lindgren (1933, p. 212). No data are available to establish the crystallization temperature of the brannerite. In addition, Phair and Shimamoto (1952) indicated that the uranothorite-bearing deposits near Jamestown, Colo., are not as high temperature as might be postulated solely on the basis of the uranothorite. They state (1952, p. 665), "The temperatures at which the Jamestown uranothorite was deposited may have reached the mesothermal range but was certainly no higher." This assignment to an intermediate range (about 175° to 300°C; Lindgren, 1933, p. 529) is based on the mineralogy and brecciated character of the deposits as well as on comparisons with other kinds of ore deposits in adjacent mining districts.

Most uranium-bearing veins in the conterminous United States may have formed under pressure-temperature conditions that encompass both the mesothermal and epithermal zones of Lindgren (1933)—that is, temperatures of about 300° to 50°C and pressures of several hundred atmospheres or less. A review of pertinent data regarding several deposits within this pressure-temperature range follow.

Sims, Phair, and Moench (1958) state that at the Copper King mine, Larimer County, Colo.,

> The ore-forming solutions possibly did not exceed a temperature of 135°C and may have been acid. The pyrite in the Copper King vein is anisotropic. According to Smith (1942, p. 13) anisotropic pyrite, which is sulfur-deficient, forms below a critical temperature between room temperature and 135°C. If these data hold, the pitchblende and associated vein minerals formed at a temperature below 135°C. The presence of marcasite with the pitchblende suggests, if the marcasite is a hypogene mineral, that the pitchblende formed in an acid environment and at low temperatures (Buerger, 1934).

The following brief discussion of the temperature of crystallization in the Wood and East Calhoun mines, Colorado, is given by Drake (1957, p. 167):

> It is difficult to assign these deposits to one of the usual pressure-temperature classifications. Armstrong (written communication, 1956) classified the ore deposits of Quartz Hill as xenothermal, largely on an inferred temperature of formation. His temperature-of-formation inferences were based on the presence of exsolved chalcopyrite in sphalerite (chalcopyrite and sphalerite supposedly unmix at about 350°–400°C, Edwards, 1947, p. 98) and on the UO_2–UO_3 ratio of the picthblende (pitchblende with a relatively high UO_2 percentage presumably indicates a high-temperature origin, Tomkeieff, 1946). The writer prefers to classify the deposits as leptothermal (Graton, 1933, p. 536–540). The deposits have many characteristics of the mesothermal zone, yet plentiful vugs and the growth of comb structure in some places indicate that the conditions of formation were somewhat shallower than most mesothermal types.

Somewhat similar pressure-temperature conditions apparently existed at the Caribou mine, Boulder County, Colo. Deposition is thought to have taken place under mesothermal conditions, probably in the lower temperature portion of the mesothermal range (Wright, 1954, p. 164).

Little specific information is available regarding the temperature of formation of the uranium deposits in the Boulder batholith, Montana. Roberts and Gude (1953, p. 153) consider the Free Enterprise mine to be epithermal because of the brecciated character of the siliceous vein material, the presence of argentite and primary ruby silver, and the reported presence of cinnabar in the vicinity. Thurlow and Reyner (*in* Roberts and Gude, 1953, p. 153), however, believe the vein to be a mesothermal fissure filling. According to Wright and others (1954, p. 78),

> * * * rock alteration associated with siliceous reef deposits * * * [W. Wilson, G. Washington, and Free Enterprise mines] * * * is characteristic of moderately low temperature veins in granitic rocks, probably near the low temperature end of the mesothermal range or even in the upper part of the epithermal range.

By inference, Wright and others (1954, p. 78–79) apparently also consider the Lone Eagle, Comet, and Gray Eagle mines—all characterized by base-metal sulfide minerals—to have formed under pressure-temperature conditions comparable to the siliceous reef deposits.

The temperature of formation of the uranium deposits at Marysvale, Utah, is thought to be within the epithermal range and, according to Taylor and others (1951), possibly solfataric or fumarolic. Kerr and others (1957, p. 147, 156) report that the temperature of formation of pyrite, thought to be contemporaneous with the associated pitchblende and fluorite, was 200° ± 25°C and that the hydrothermal alteration of the rocks of the area indicates a temperature of about 250° C. Adularia in the veins at Marysvale tends to substantiate temperatures of more than 200° C on the basis of experimental work by Gruner (1936) and other evidence presented by Ingerson (1955, p. 372–373). Furthermore, the uraniferous fluorite deposits of the Thomas Range, Utah, are thought to be low-temperature, epithermal deposits on the basis of mineralogy and brecciated and open boxwork structures (Staatz and Osterwald, 1959).

Several uranium-bearing veins a few miles northwest of Lakeview, Oreg., particularly the White King mine, are quite similar in geologic setting, mineralogy, and wallrock alteration to some of the epithermal quicksilver deposits that White (1955) considers are related to thermal springs. Similarities include the occurrence of mercury and arsenic minerals, widespread argillic alteration, and local fine-grained (opaline or chalcedonic) silicification that in some places converts the host rock to a dense brittle material commonly referred to as opalite. Although quantitative data are lacking on crystallization temperatures, most of these veins may represent the lower end of the epithermal range, perhaps indicating deposition temperatures on the order of 100°C or less as based in part on the amorphous character of the silica (Ingerson, 1955, p. 374).

Coleman (1957, table 1) infers a temperature of 75°C for the Cashin Copper mine on the basis of exsolution phenomena between chalcocite and covellite; he points out, however, that this method of temperature determination is of questionable accuracy. The temperature of original uranium mineralization in this deposit is undetermined and may be unrelated to Coleman's inferred temperature, because only minute amounts of uranium are in the deposit, and the relation of the uranium to the copper minerals is not stated.

Deposition from cold or only slightly warm vadose or phreatic waters has been postulated for some veins characterized by 6-valent uranium minerals; some of these deposits are commonly referred to as calichelike or caliche-type veins (Bell, 1954, p. 112). Presumably deposition occurred at or near the ground surface, largely under oxidizing conditions, and principally in arid and semiarid regions. Some uranium-bearing veins for which this type of deposition has been considered include several in the Pryor Mountains area of Montana and Wyoming (Hauptman, 1956); several in the Challis Volcanics in Idaho and the meta-autunite deposits north of Spokane, Wash. (Weis, Armstrong, and Rosenblum, 1958); the Miracle mine, California, which contains some sooty pitchblende at depth; several deposits in the Mojave Desert region of California (Walker, Lovering, and Stephens, 1956); the Buckhorn claims, Nevada; and a pitchblende occurrence in northern Michigan (Vickers, 1956). A similar low-temperature type of deposition is postulated at Mount Painter, South Australia (Stillwell and Edwards, 1954, p. 110), where the deposits are characterized largely by torbernite, autunite, uranophane, and "gummite."

These estimates of pressure-temperature conditions of uranium deposition in veins, whether considered in terms of the general depth zones of Lindgren or in quantitative temperature and pressure units, are still of doubtful accuracy and validity. Many minerals or mineral assemblages used as temperature indicators are not adequately tied paragenetically to the uranium minerals, and, consequently, the temperature estimates or determinations do not necessarily indicate the crystallization temperatures of the hypogene uranium minerals. Furthermore, in a number of veins, several stages of pitchblende mineralization have been recognized that probably represent deposition under different pressure-temperature conditions. Nevertheless, these estimates have qualitative usefulness in that they demonstrate that both large and small deposits of uranium in veins have formed over an extremely wide range of temperature and pressure conditions, essentially from near-surface deposition by cold ground water to high-temperature (about 500°C or more) deposition at great depths and confining pressures.

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