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

By

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## FOREWORD

This paper, "Mineralogy, internal structural and textural characteristics, and paragenesis of uranium-bearing veins in the United States" by George W. Walker and John W. Adams, is a chapter of a larger, more comprehensive report entitled, "Geology of uranium-bearing vein deposits in the United States" in preparation by George W. Walker, Frank W. Osterwald, and others. The comprehensive report will include information on tectonic and structural setting, kinds of host rocks, wall-rock alteration, mineralogy, physical characteristics, processes of deposition, and concepts of origin of uraniferous veins; but, because it will not be completed until some time in the future, some chapters of the report are being transmitted as they are finished. Three reports which are to be chapters of the comprehensive report have been transmitted: one, entitled "Classification and distribution of uranium-bearing veins in the United States" (Walker and Osterwald, 1956), defines several of the terms used herein; another is entitled "Host rocks and their alterations as related to uranium-bearing veins in the United States" by George W. Walker (1956); and the other report is entitled "Supergene alteration of uranium-bearing veins in the United States" by George W. Walker (1957).

The compilation of data leading to this report and its preparation by members of the Uranium Research and Resource Section, U. S. Geological Survey was 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 The report is based on both published and unpublished information collected principally by personnel of the U. S. Geological Survey, the U. S. Atomic Energy Commission or its predecessor organization, The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 or State agencies and by geologists in private industry. Information concerning foreign uranium-bearing vein deposits has been extracted almost exclusively from published reports; references to these and other data are included at appropriate places.

The authors wish to acknowledge the assistance of Wendell Walker of the U. S. Geological Survey who prepared all the photographic illustrations appearing in this report.

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

By George W. Walker and John W. Adams

## INTRODUCTION

The study of the many uranium deposits, that have been discovered in the 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 different 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 of the uranium minerals that have been found in vein deposits in the 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 (Czechoslovakia), Wölsendorf (Bavaria), deposits near Schneeburg (Saxony), Shinkolobwe (Belgian Congo), and Great Bear Lake (Canada). Many of the 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 new species of uranium minerals that occur in vein and other deposits, including principally andersonite, swartzite, bayleyite, umohoite, and coffinite, 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 vein deposits.

For convenience, uranium-bearing vein deposits are subdivided into 8 mineralogic classes (Walker and Osterwald, 1956, unpub. report), most of which are intergrading, and only a few of which are important commercial sources of uranium in the United States. The classification is based largely on the mineralogic characteristics of more than 400 vein deposits in the United States and to a lesser extent on the characteristics of deposits in other parts of the world. One mineralogic class of deposits--davidite-bearing veins--is not known to occur in the United States. The 8 mineralogic classes of uranium-bearing veins are: (1) Fluorite-bearing veins; (2) veins in which uranium minerals are subordinate to base-metal sulfide minerals including deposits containing sulfides and sulfarsenides of cobalt and nickel and gossans derived from alteration of such deposits; (3) veins in which uranium minerals are "dominant" but which may contain minor amounts of other introduced metallic minerals; (4) magnetite or other iron oxide-bearing veins; this excludes deposits in gossan derived from supergene alteration of base-metal sulfide deposits but does include those uraniferous deposits characterized dominantly by hypogene magnetite and hematite, or limonite derived from their alteration; (5) veins dominated by thorium or rare earths minerals; (6) brannerite-bearing quartz or siliceous veins; (7) davidite-bearing veins; and (8) veins containing uraniferous hydrocarbons._/

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_/Descriptions of the 8 mineralogic classes of uranium-bearing veins and several examples of both foreign and domestic deposits of the different classes of veins are contained in "Classification and distribution of uranium-bearing veins in the United States" by George W. Walker and Frank W. Osterwald (1956).

## URANIUM-BEARING MINERALS OF VEIN DEPOSITS

Of the many known minerals that contain uranium either as an essential or as a nonessential constituent, 55 different species have been reported from uraniferous vein deposits in the 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 of the known occurrences of these 4-valent uranium minerals indicate that deposition took place in a primary reducing environment with the exceptions of the occurrences of ianthinite and several occurrences of sooty pitchblende which contains both 4-valent and 6-valent uranium. In addition, uranium-bearing hydrocarbons, present in several deposits, probably contain mostly 4-valent uranium.

Table 1.--Minerals that contain uranium either as an essential or nonessential constituent identified from vein deposits in the United States.

| | Uranium minerals | Frequency of occurrence in vein deposits or districts a/ | Selected localities b/ | References or remarks |
|---|---|---|---|---|
| Arsenates | Metazeunerite | uncommon | Majuba Hill, Pershing County, Nev. | Trites and Thurston, in preparation. |
| | Novacekite | rare | White King property, Lake County, Oreg. | Matthews, 1955. |
| | Troegerite ? | rare | Bald Mountain district, Lawrence County, S. Dak. | George, 1949, p. 158. |
| | Uranospinite | rare | Deposits in Washoe County, Nev. | Unpublished data in files of U.S. Geol. Survey. |
| | Walpurgite | rare | Miracle mine, Kern County, Calif. | Bowes, W.A., written communication, 1957. |
| Carbonates | Andersonite | rare | Hillside mine, Yavapai County, Ariz. | Axelrod and others, 1951. |
| | Bayleyite | rare | Hillside mine, Yavapai County, Ariz. | Axelrod and others, 1951. |
| | Liebigite | rare | Midnite mine, Stevens County, Wash. and Silver Cliff mine, Niobrara County, Wyo. | Weis, 1955, p. 224; George, 1949, p.179. |
| | Rutherfordine | rare | W. Wilson mine, Jefferson County, Mont. | Roberts and Gude 3d., 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 | rare | W. Wilson mine, Jefferson County, Mont. | Roberts and Gude 3d., 1953, p. 78. |
| Molybdate | Umohoite | rare | Marysvale, Piute County, Utah. | Kerr and others, 1953. |
| Titanate | Brannerite | uncommon | Chaffee County, Colo. and Mono County, Calif. | Adams, 1953; Pabst, 1954. |
| Oxides and hydroxides | Becquerelite | rare | Billikin lode, Jefferson County, Colo. | Unpublished data in files of U.S. Geol. Survey. |
| | Ianthinite and possibly epianthinite | rare | Marshall Pass area, Saquache County, Colo. | Young, E.J., oral communication, 1956. |
| | Schoepite | rare | Abe Lincoln mine, Yavapai County, Ariz. | Raup, 1954, p. 181. |
| | Pitchblende and uraninite | common | Marysvale, Utah and Central City district, Colo. | 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; Wetland, 1955. |
| Phosphates | Autunite | common | White Signal and San Acacia districts, N. Mex. | Lovering, 1956. |
| | Bassetite | rare | Deposits in Dripping Spring quartzite, Gila County, Ariz. | Granger, 1955, p. 134. |
| | Dumontite | rare | 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 | common | Eureka Gulch area, Gilpin County, Colo. | Sims, Osterwald, and Tooker, 1955. |
| | "Meta"-uranocircite | uncommon | Deposits in Dripping Spring quartzite, Gila County, Ariz. | Granger, 1955, p. 134. |
| | Phosphuranulite | uncommon | Marysvale, Piute County, Utah. | Kerr and others, 1954, p. 44. |
| | Sabugalite | rare | Tusas Mountains, Rio Arriba County, N. Mex. | Everhart, 1956. |
| | Saléeite ? | rare | 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, Mont. | Wright, Bieler, and others, 1954. |
| | Coffinite | uncommon ? | Leyden (Jefferson County) and Copper King (Larimer County) mines, Colo. | 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 | rare | Honeycomb Hills, Juab County, Utah. | Wilmarth and others, 1952, p. 15. |
| | 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 | uncommon | Gilpin County, Colo. | Palache, Berman, and Frondel, 1944 and 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. | Armstrong, F. C. and Weis, P. L. written communication, 1954. |
| Vanadates | Carnotite | uncommon | Thomas Range, Juab County, Utah and Kern Canyon, Kern County, Calif. | Staatz and Osterwald, 1956; Everhart, 1956. |
| | Metatyuyamunite | uncommon | Huron River deposit, Baraga County, Mich. | Vickers, 1956. |
| | Tyuyamunite | uncommon | Deposits in Pryor Mountains, Carbon County, Mont. | Unpublished data in files of U. S. Geol. Survey |
| | Rauvite | rare | Marysvale area, Piute County, Utah. | Walker and Osterwald, 1956, p.127. |
| | Sengierite | rare | 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. | Wolfe, H. D., written communication, 1953. |
| | | | Pedad prospect, Jackson County, Colo. | Winterhalter, E. C., written communication, 1953. |
| | Hydrated iron oxides | common | ---------------------------------------------------- | Lovering, 1955. |
| | Hydrozincite | rare | Goodsprings district, Clark County, Nev. | Barton, 1956. |
| | Chrysocolla | rare | Goodsprings district, Clark County, Nev. | Barton, 1956. |
| | Hyalite opal | common | Marysvale, Piute County, Utah. | Kerr and others, 1952. |
| | Pyromorphite | rare | "Spelbrink" claim and Golondrina claim, Ariz. | Wright, R. J., 1950. |
| | Rutile | rare | New Years Eve mine, Pima County, Ariz. | |
| | 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, 1956. |
| | Thorite ? | | Roberts prospect, Gunnison County, Colo. | Malan, R. C., oral communication, 1956. |
| | Uranium-bearing hydrocarbons | uncommon | Golden Gate Canyon area, Jefferson County, Colo. | Sheridan 1955, p. 216. |

a/ The actual frequency of occurrence is complicated by data inadequate to distinguish between certain hexavalent-uranium minerals and their beta- and meta- varieties.

b/ 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 (1953, 1953, 1954, 1955).

A large number of uranium minerals, characterized by 6-valent uranium, have been found in the oxidized parts of vein deposits; 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 meta-uranocircite, 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 vein deposits, the latter two minerals occurring as encrustations on mine walls. In many deposits, ample evidence is available to demonstrate that these minerals have resulted from oxidation of primary, tetravalent-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, under oxidizing conditions, directly from circulating ground waters or other solutions containing uranium of unknown origin in vein structures; and, consequently, they are the primary uranium minerals of these deposits.

In some uranium-bearing vein deposits, 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-earth 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, generally less than 10 parts per million (Wright and Shulhof, 1957a). In some of the minerals containing uranium as a nonessential constituent, the uranium is probably present as microscopic or more commonly submicroscopic inclusions of unidentifiable uranium minerals. In others, the exact mode of occurrence of the uranium is unknown but probably follows one or a combination of the different modes postulated by Neuerburg (1956, p. 55); these are ..."uranium disposed in the structure of....minerals by diadochy and in structural defects in crystals, uranium held in cation-exchange positions, uranium in unknown form absorbed on surfaces of crystals, uranium dissolved in fluid inclusions within....minerals, and uranium dissolved in intergranular fluids..." Although little evidence is available to document any one of these modes of occurrence, as applied to vein deposits, several modes have been proposed for uraniferous fluorite deposits (Staatz and Osterwald, 1956; Wilmarth, and others, 1952), for uraniferous base-metal sulfide deposits (Wright, H. D. and Shulhof, W. P., 1957a), and for uranium-bearing magnetite-hematite deposits (Walker and Osterwald, 1956).

In several oxidized vein deposits, some or all of 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.

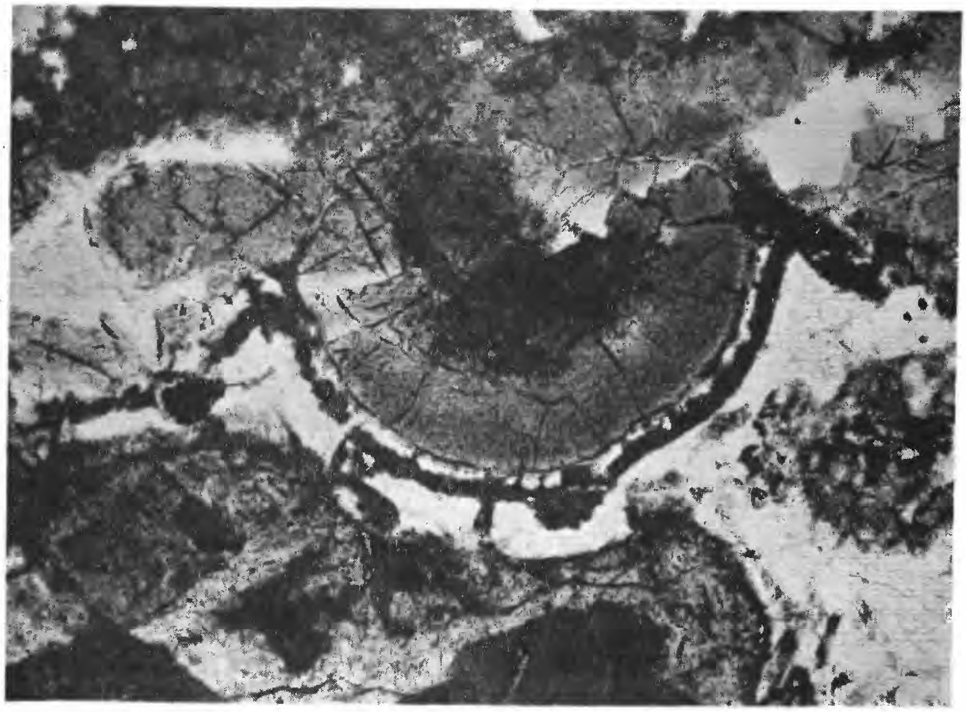
The uranium minerals listed in table 1 are 1) reported from vein deposits in the United States and 2) identified with accuracy, principally by X-ray techniques, by chemical analysis and, for many of the minerals, by both methods. Although several other hexavalent-uranium minerals could be listed, identification of a few of these is open to considerable question and for one or two 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 different minerals listed in table 1 and for the different 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," 7th edition, 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 much in the same sense as that described in Dana's "System of mineralogy" (p. 614, v. 1, 7th ed.) and in Geffroy and Sarcia's "Contribution á l'étude des pechblendes françaises" (1954, p. 4 and 145); several of the distinctive features of pitchblende and uraninite have been described and reviewed briefly by Rogers (1947, p. 90-91). 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 United States, the uranous oxide occurs as microscopic, idiomorphic crystals or fragments of crystals; and, for these occurrences, the term uraninite is applied. A similar, but more precise, distinction has been made by Croft (1954, p. 53) for the terms uraninite and pitchblende. To him...

> "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 microscrystalline aggregates."

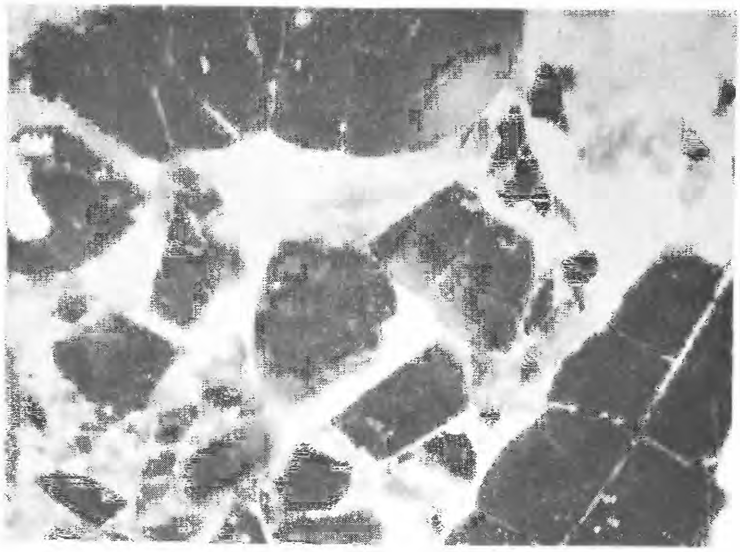
Katz and Rabinowitch (1951, p. 75 and 76) have made a further distinction between uraninite and pitchblende based on the presence of significant amounts of thorium and rare earths in uraninite and their virtual absence in pitchblende. No such chemical distinction is made by the authors of this paper because analytical data are lacking on the elemental content of pitchblende from most of the vein deposits 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 United States occurs as megascopic or microscopic colloform, submetallic to pitchlike, or dull masses that are gray to black in color. An olive-green or light brown, slightly translucent, colloform pitchblende has been identified from the North Star mine, Colorado (figs. 1 and 2), and brown, slightly translucent pitchblende spherulites have been noted in the Nigger Shaft deposit, Colorado, (Adams, Gude, and Beroni, 1953, p. 12 and 16); presumably such pitchblendes are 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, p. 429-430). In some deposits, pitchblende occurs as gray to black, minute, sootlike particles in restricted and spotty disseminations in altered or unaltered host rocks (figs. 3 and 4) 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 was deposited commonly close to masses of hard, unaltered pitchblende in transitional zones where the environment was neither strongly oxidizing nor strongly reducing; according to L. R. Page (oral communication, 1956), it is comparable to the "regenerated" pitchblende of Russian and some other European geologists.



500 microns

Figure 1. 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.



300 microns

Figure 2. Brecciated, colloform pitchblende, showing concentric banding, with interstitial secondary copper minerals from North Star mine, Jefferson County, Colo. Polarized, reflected light.

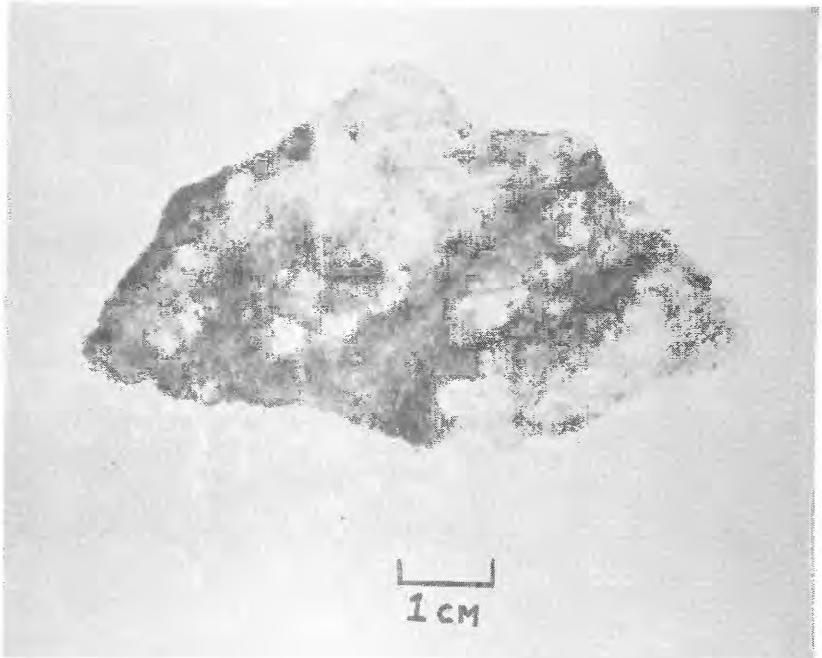



**Figure 3.** Diffuse veinlets and impregnations of sooty pitchblende in altered, fine-grained sedimentary rock from Los Ochos mine, Saguache County, Colo.

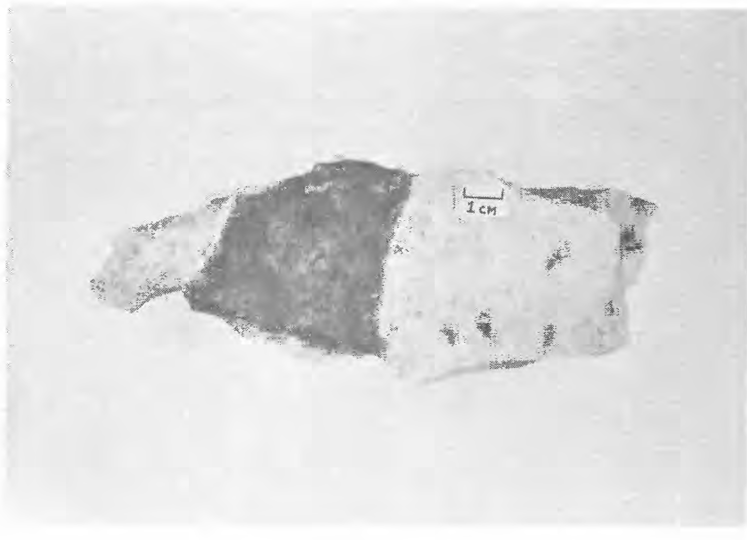



**Figure 4.** Irregular impregnations of sooty pitchblende (black) commonly with fine-grained jordisite and marcasite or pyrite in altered, fine-grained sedimentary rock from Los Ochos mine, Saguache County, Colo.

No well established correlation between different species of 4- and 6-valent uranium minerals and the 8 mineralogic classes of vein deposits can be demonstrated, with available data, beyond 1) the obvious mineralogic correlations resulting from the arbitrary classifying of uraniferous vein deposits--i.e., brannerite-bearing veins--and 2) several expectable 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; in all essential characteristics the pitchblende appears to be identical in the several mineralogic classes of deposits and differs from deposit to deposit principally in the degree of oxidation or hydration. Coffinite and uranothorite have been reported in so few vein deposits that no correlation is warranted.

In those places where uranium-bearing vein deposits 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. As for example, kasolite is characteristic of uraniferous, base-metal veins containing galena or alteration products of galena, and torbernite is most 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 VEIN DEPOSITS

The gangue minerals associated with uranium-bearing vein deposits are those commonly found in metalliferous veins and demonstrate no tendency toward abundance or rarity of any particular specie 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 the eight mineralogic classes of vein deposits. 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 vein deposits is characterized by common or abundant fluorite which 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 of the mineralogic classes of uranium-bearing vein deposits (Walker and Osterwald, 1956). A review of available data, which is most abundant for uraniferous base-metal sulfide deposits, suggests that the following assemblages most commonly occur in the various classes; the minerals are listed in order of decreasing frequency of occurrence, an arrangement that is not necessarily coincident with their relative abundance.

Class 1.—Fluorite-bearing veins.

Quartz, carbonate minerals, clays, chalcedony, opal, adularia.

Class 2.-Veins in which uranium minerals are subordinate to base-metal minerals.

Quartz, carbonate minerals, barite, chalcedony, chlorite, fluorite, microcrystalline quartz, adularia.

Class 3.-Veins in which uranium minerals are dominant.

Quartz, carbonate minerals, barite, chalcedony, opal, adularia.

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

Quartz

Class 5.-Veins dominated by 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 the United States).

Quartz, biotite, ilmenite, rutile, sphene, carbonate minerals.

Class 8.-Veins containing uraniferous hydrocarbons.

Carbonate minerals, barite, quartz, adularia.

The dissimilarities in gangue mineral assemblages results not only from the arbitrary classifying of deposits, as for example in establishing one class on the presence of significant amounts of fluorite, but also on differences related, in part, 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.

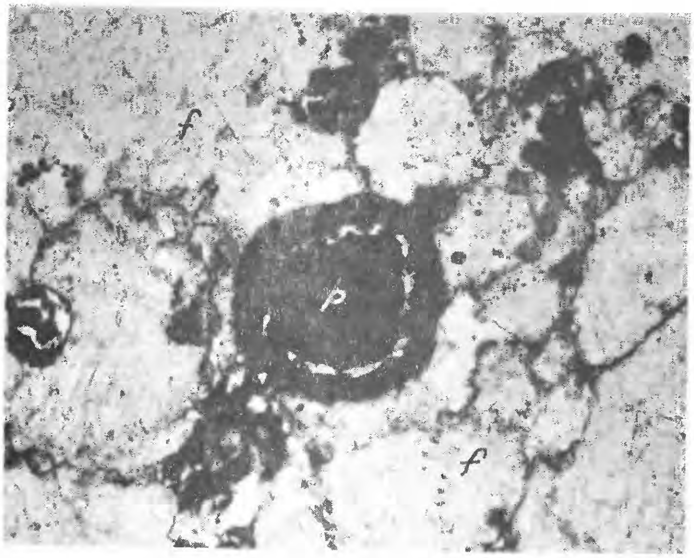
In their study of thirteen uranium-bearing vein deposits of the world, Everhart and Wright (1953, p. 91) note a correlation between the gangue minerals and the host rocks of the deposits to the extent that deposits in metamorphic rocks generally have carbonate minerals as gangue whereas deposits in intrusive rocks have a dominantly siliceous gangue. The conclusions of Everhart and Wright (op. cit.) in regard to this correlation tend to be verified by the review of published data and a study of many thin 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 vein deposits. The gangue minerals in these deposits are subjected to a greater-than-normal radiation intensity from (1) adjacent uranium minerals, (2) radioactive elements that have migrated from these minerals, or (3) 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 have been recognized for many years through the study of pleochroic halos in micas. In vein deposits, these coloration changes are best demonstrated by fluorite where 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 may be present only as irregular clots and patches. Where discrete grains of radioactive minerals are included in fluorite, darker colored halos may be produced (fig. 5) of widths nearly equivalent to the penetration ranges of the alpha particles emitted by the inclusion. 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 originally may 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.; the thorium-derived halos surrounding included uranothorite crystals are larger than halos surrounding pitchblende grains because of the greater energy of radiation from the thorium series; thus, it is possible to distinguish uranothorite from pitchblende by the size of the halos surrounding grains (Phair and Shimamoto, 1952, p. 664). A uranium-derived halo in fluorite is shown in figure 5.




300 microns

**Figure 5.** Radiation halo around pitchblende grain (p) in fluorite (f), Jamestown district, Colorado. Halo is dark purple in nearly colorless fluorite. Transmitted light.

The darkening of quartz to a smoky color has been attributed to radiation damage resulting from higher concentrations of radium and uranium than that ordinarily found in quartz (Holden, 1925, p. 240). More recently, Daniels and Saunders (written communication, 1951) have suggested that cosmic ray particles may produce some darkening in view of a correlation between the color of Alpine quartz and the altitude of the vein from which it was obtained (Holden, 1925, p. 210). Holden's observations may need verification by the more precise analytical techniques now available, and the influence of cosmic rays not only must be reconciled 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 relationship between radiation and the darkening of quartz is indicated not only by the facility with which quartz can be artificially "smoked" (Frondel, 1945, p. 432-446) 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 vein deposits is not well demonstrated, perhaps due in part to lack of data, as the distinction between colorless and smoky quartz might not be as obvious in fine-grained vein material as in coarser-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 which may have radioactive elements incorporated in its structure or is in direct contact with radioactive minerals inasmuch as migration of daughter-product elements, as well as uranium itself, may produce new radiation centers at some distance from the original source. Such a process is described by Yagoda (1946, p. 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. 6) 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.

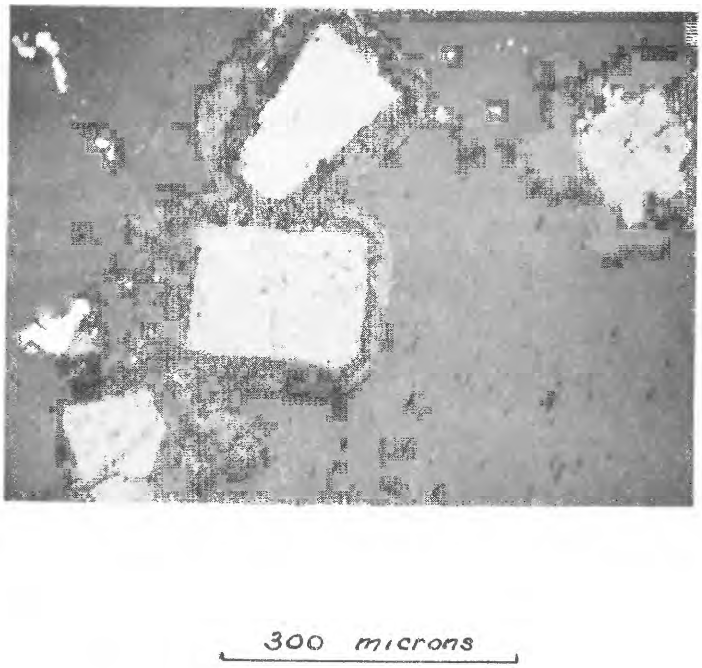



Figure 6. Idiomorphic, cubic crystals and crystal fragments of uraninite (white) in quartz (gray) exhibiting haloes probably resulting from radiation damage. Specimen from the Little Man mine, Carbon County, Wyoming. Reflected light.

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

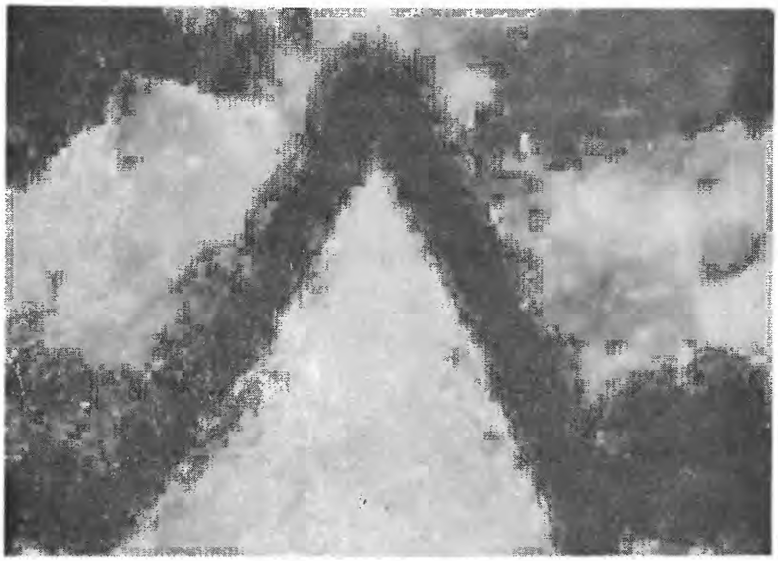
The presence of reddish brown coloration in the gangue minerals of radioactive deposits has been noted, particularly in respect to foreign uranium-bearing vein deposits, and has been considered a useful prospecting guide for both veins (Lang, 1952, p. 35; Everhart and Wright, 1953, p. 93) and pegmatites (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 to form a jasper-like material (Kerr and Robinson, 1953, p. 506-507); similar brown or reddish jasper has been reported from vein deposits in Portugal (Cavaca, 1956, p. 183).

Some of the hematite causing the reddish 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 coloration results more probably from hydrated ferric oxides, notably goethite (Lovering, 1955, p. 187), formed by supergene processes from iron-bearing wall rock and vein minerals. However, it is possible that the association of reddish 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 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 $SO_4^{=}$ ions highly soluble ferric sulfate forms and ferric iron would be 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 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 is more obvious in pegmatites than in veins, largely because more grains are of megascopic size, and has been cited in the descriptions of many deposits. Heinrich (1948, p. 68) notes that in the Yard pegmatite in Colorado pods of monazite and euxenite are surrounded by aureoles of pink to dark red feldspar, and that euxenite masses are the centers of conspicuous radial cracks. In a recent 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.

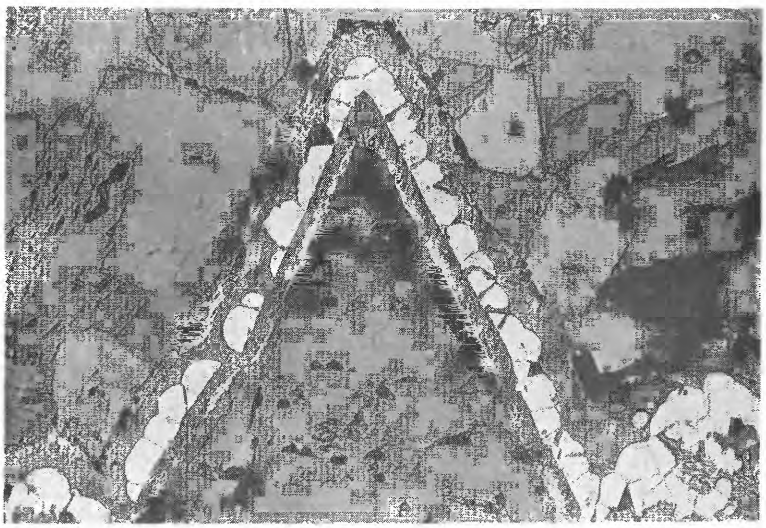
Radiation-induced oxidation of ferrous to ferric iron was proposed (Adams, and others, 1953, p. 16) to explain reddish bands in ankerite from the Nigger Shaft deposit, Colorado. The bands are along ankerite-pitchblende interfaces (fig. 7) and are of a width (about 21 microns) that is close to the calculated alpha particle range (22 microns) in ankerite. A radio-chemical 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."



300 microns

**Figure 7A.** Radiation damage bands between pitchblende (black) and ankerite (white and gray). Nigger Shaft, Colorado. Reflected light; crossed nicols.



300 microns

**Figure 7B.** Same field as shown in fig. 7A. Reflected light.

## 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 are original openings in the rocks at time of formation, some are 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 non-uranium minerals, have been reported in only a few places.

In a majority of deposits where the morphology of the primary uranium minerals has been ascertained, colloform or colloform-like textures dominate almost to the exclusion of other textures. In a minority of vein deposits the primary uranium minerals exhibit crystal form; for example, idiomorphic crystals of uraninite, uranothorite, and brannerite have been identified in only a few vein deposits. In deposits where the uranium is present either 1) as a vicarious constituent of rare earths- or thorium-bearing minerals or other minerals, or 2) as 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 term fracture or sets of fractures encompass most induced openings in rocks whether resulting from compressive, tensional, or torsional stresses related to orogenic activity (including vulcanism, intrusion, and structural deformation.) Some of the 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, post-sedimentation 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. In addition, some deposits, localized in part by fractures, are not tabular, principally those associated with 1) wall rocks that are extensively altered and replaced, 2) porous gossan zones that are intensely leached, and 3) 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 pipe-like deposits as defined by Lindgren (1933, p. 159).

The primary uranium minerals in these deposits, commonly associated with both gangue and other metallic minerals or with hydrocarbons, occur in the interstices of breccia (figs. 8, 9, 10 and 11), as breccia fragments (fig. 12), as macroscopic or microscopic well-defined veinlets either in fractured wall rocks (figs. 13, 14 and 15) or in fractured pre-uranium vein fillings (figs. 16 and 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), as diffuse veinlets (figs. 3 and 20) or spotty, irregular impregnations (fig. 4) 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 wall rock 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), as disseminated pitchblende, locally with coffinite (?), in porous sandstone (fig. 21) adjacent to arcuate fracture zones at the Orphan mine, Arizona. Uraniferous rutile is disseminated in molybdenite in quartz veins (fig. 22) at the New Years Eve mine, Arizona, and uraniferous hydrocarbons (fig. 23) in which small spheres or grains (commonly less than 5 microns in diameter) of pitchblende are disseminated, are present in several vein deposits.

(Text is continued on page 61.)

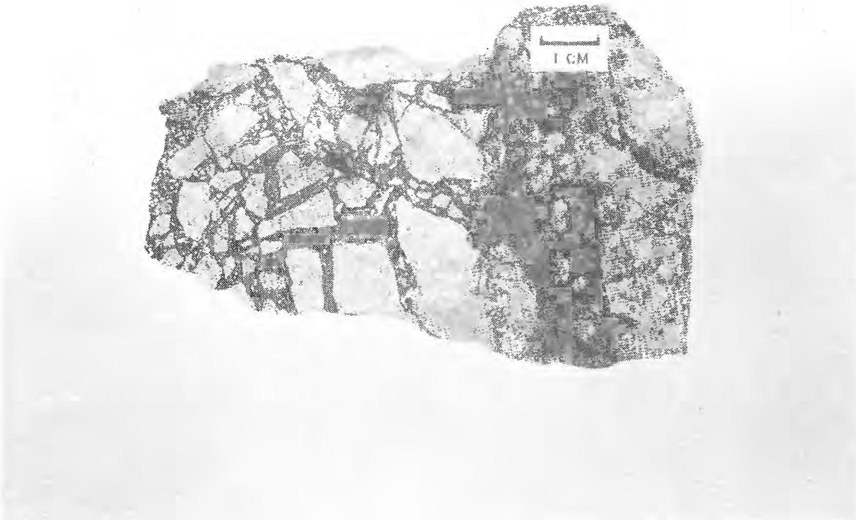



Figure 8. Breccia ore from Marysvale, Utah. Dark vein filling composed dominantly of a mixture of fine-grained purple fluorite, pyrite, and pitchblende.

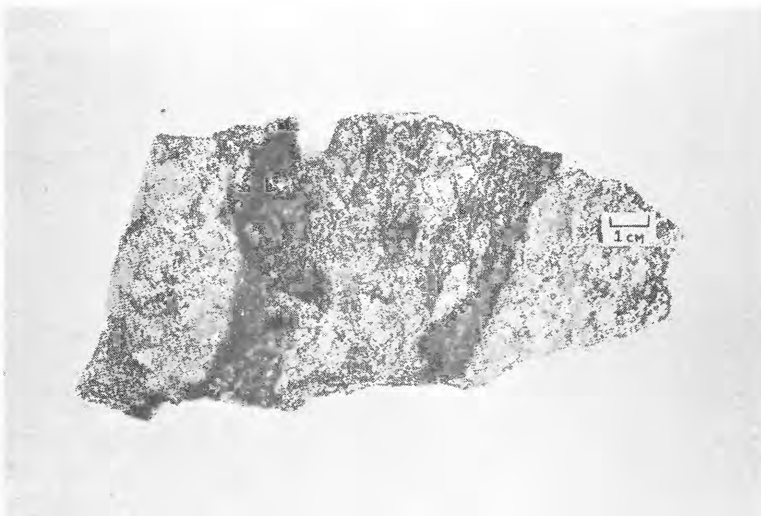
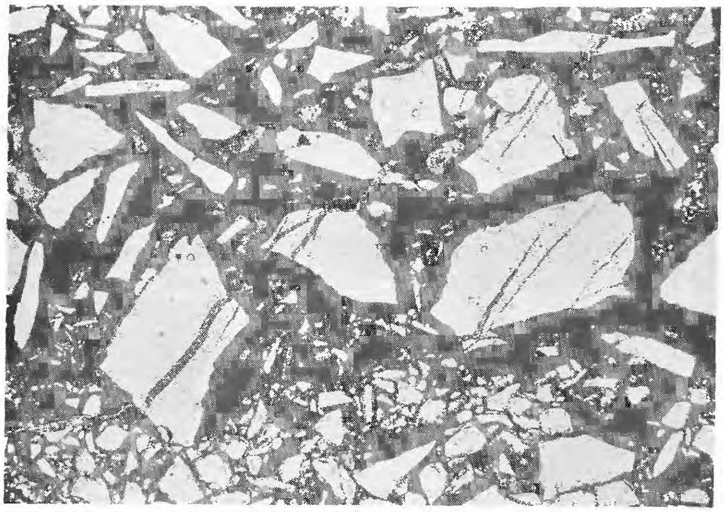
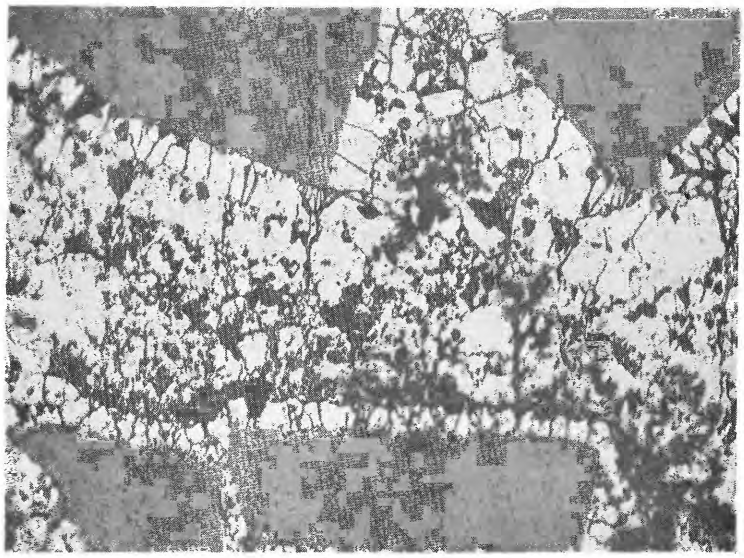



Figure 9. Specimen of uranium ore from Prospector vein, Marysvale, Utah. Dark vein filling composed of silicified gouge and breccia mineralized with fluorite, pyrite, and pitchblende.



2 millimeters

**Figure 10.** Brecciated quartz (white) with interstitial filling of pitchblende (black) from Buckman adit, Jefferson County, Colo. Transmitted light.



300 microns

**Figure 11.** Photomicrograph of piece of same specimen shown in fig. 10. Quartz fragments (gray) and interstitial pitchblende (white). Reflected light.

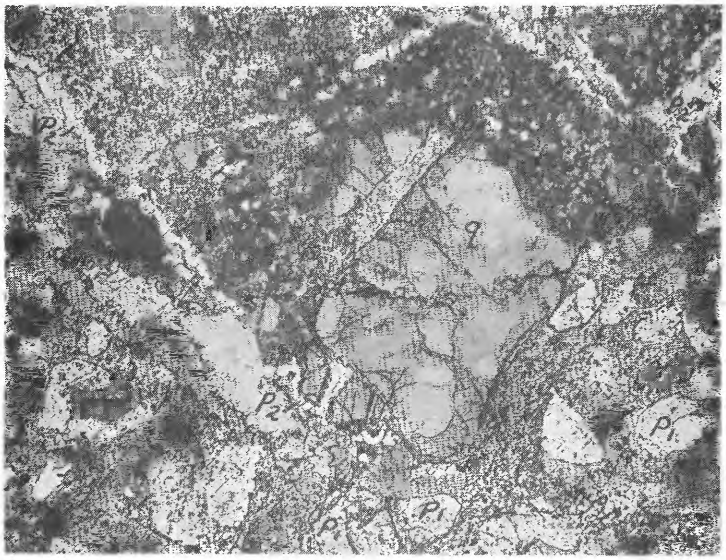



**Figure 12.** Brecciated, early-stage pitchblende ($p_1$) and late-stage colloform pitchblende ($p_2$) veinlets and spherulites in gangue composed dominantly of quartz (q) and unidentified rock minerals. Float specimen of vein material from Marshall Pass area, Saguache County, Colo. Reflected light.

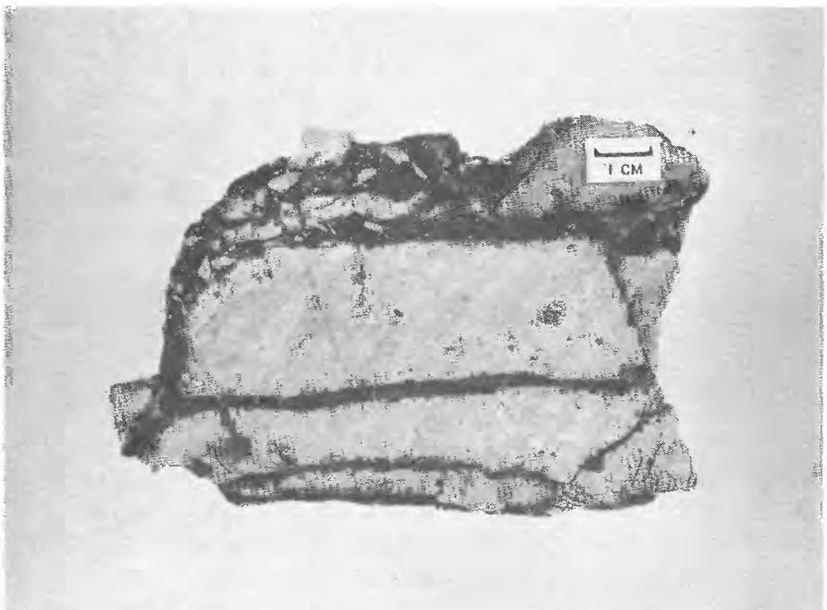



**Figure 13.** Veinlets (black) from stockwork of veinlets, Freedom No. 2 mine, Marysvale, Utah. Veinlets composed of alternating bands of purple, crystalline fluorite and purplish-black bands of fine-grained, mixed fluorite, pyrite, and pitchblende.

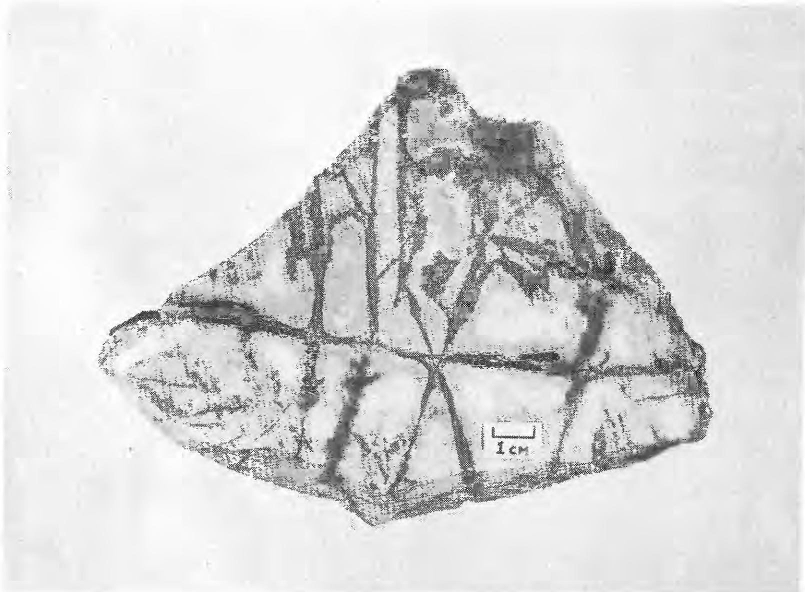
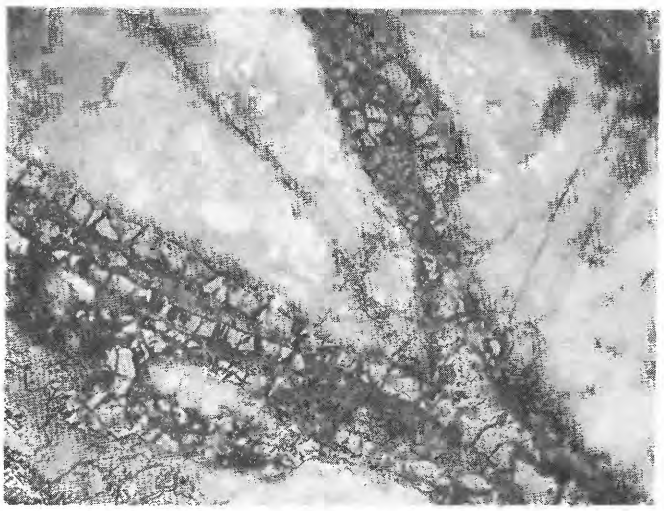



**Figure 14.** Mineralized joints in specimen of Dripping Spring quartzite, Red Bluff mine, Gila County, Ariz. Dark seams are highly radioactive and contain pyrite or marcasite, possibly pitchblende, hexavalent-uranium minerals, or radio-colloids, and probably other introduced minerals.



1 millimeter

**Figure 15.** Veinlets of pitchblende from deposit near Critchell, Jefferson County, Colo. Reflected light; partly crossed nicols.

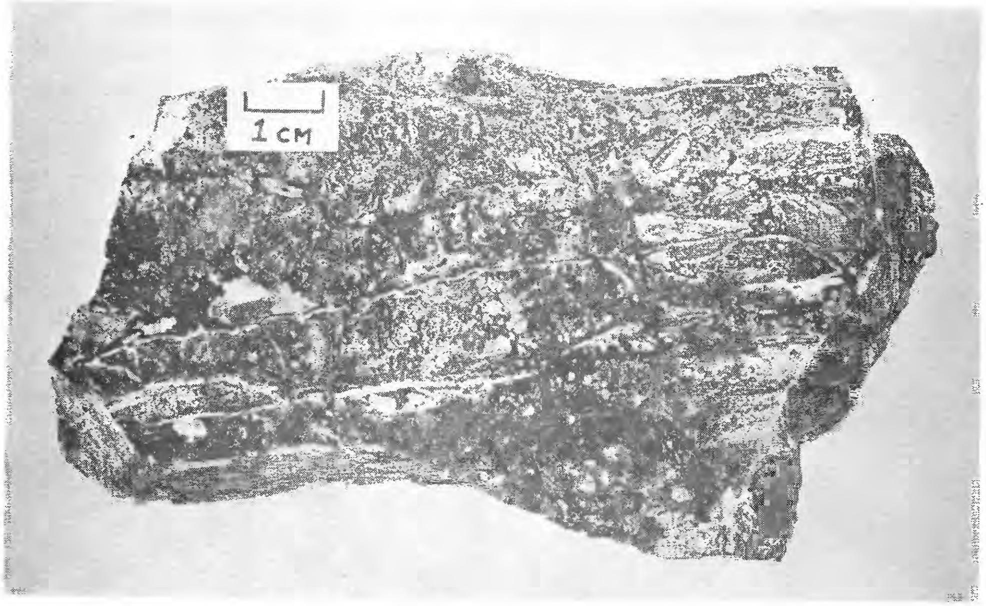



**Figure 16.** Pitchblende veining brecciated, base-metal ore from Copper King mine, Larimer County, Colo.

**Figure 17.** Autoradiograph of specimen shown in fig. 16 delineating pitchblende veinlets (white and gray areas).

/00 microns

Figure 18. Pitchblende veinlets (white) along cleavage planes in micaceous mineral from Schwartzwalder mine, Jefferson County, Colo. Reflected light.

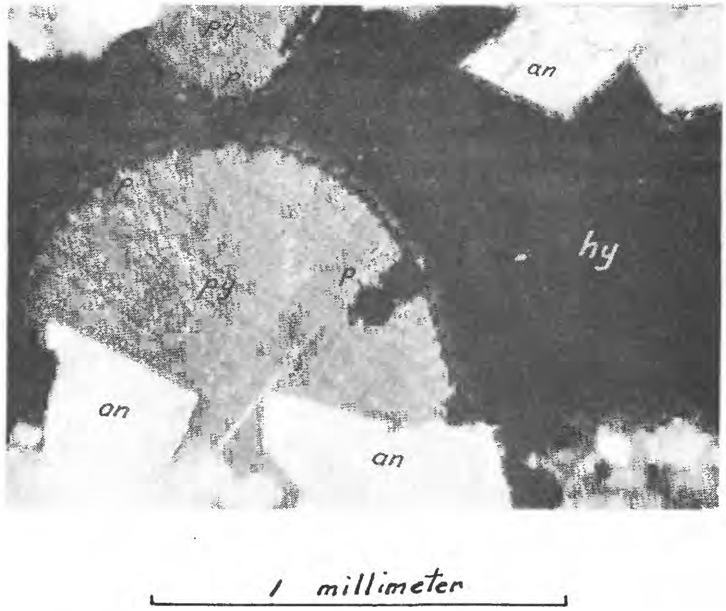



Figure 19. Pitchblende (p) as isolated spheroids and as microscopic films between pyrite (py) and unidentified hydrocarbon (hy) from Halfmile Gulch, Jefferson County, Colo. Alteration halo in hydrocarbon adjacent to pitchblende. Rhombic crystals are ankerite (an). Reflected light; crossed nicols.


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

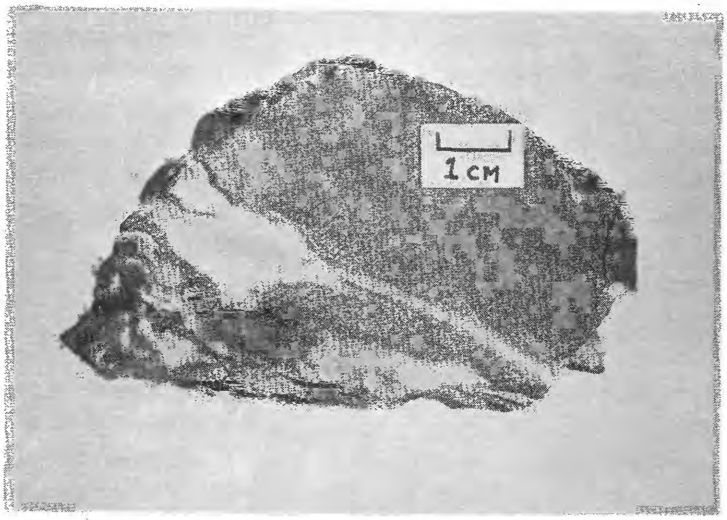



Figure 21. Disseminated pitchblende and possibly some coffinite in interstices of sandstone adjacent to fracture zones from Orphan mine, Coconino County, Ariz.

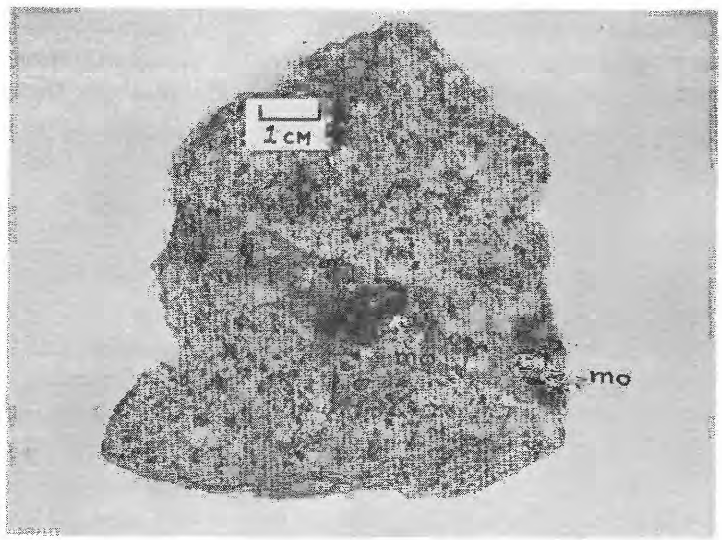



Figure 22. Quartz vein (q) containing uraniferous rutile in molybdenite (mo) from New Years Eve mine, Pima County, Ariz.

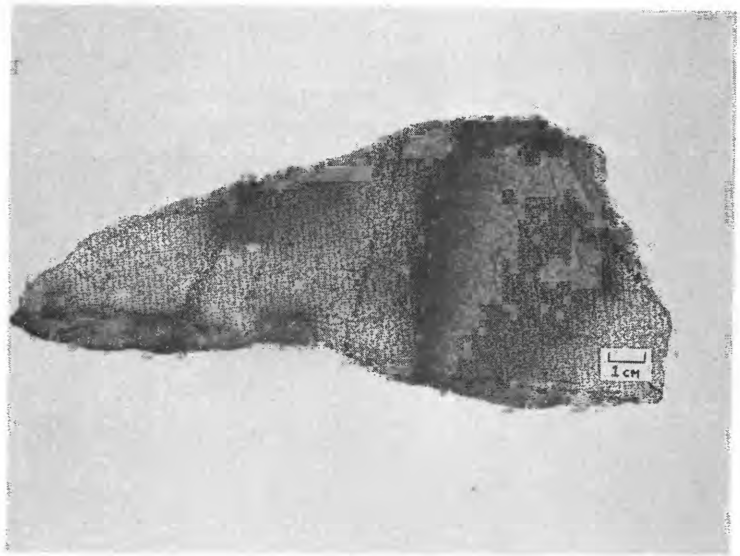



Figure 23. Veinlets and disseminations of uraniferous hydrocarbon (black) in sandstone from deposit near Morrison, Colorado. Veinlets cut sandstone bedding (not shown) at approximately 90°.

Most of the pitchblende in several of the 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, Leonard, Moore, and Pierson, 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, H. D., 1954, p. 159) and, more commonly, as soft pitchblende, coating fractures, vugs, and masses of hard pitchblende (Moore, Cavender, and Kaiser, 1957). It 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 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 of the deposits in the Dripping Spring formation, Arizona, (Granger and Raup, in preparation). Furthermore, uraniferous fluorite occurs in veins, breccia zones, pipes, or tabular to irregular replacement bodies. Dust-like particles of powdery or sooty pitchblende, probably largely derived through the alteration of hard, massive pitchblende of an earlier stage, coat vug minerals (figs. 24 and 25), surfaces of fractures or other openings in rocks and, not uncommonly, rock fragments on mine dumps.

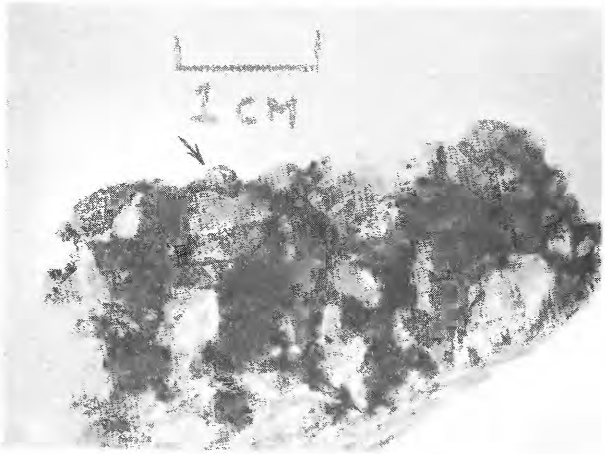



**Figure 24.** Sooty pitchblende coating quartz crystals in vug from greisen pipe, Tarryall district, Park County, Colo.

**Figure 25.** Enlargement of part of specimen shown in fig. 25.

The 6-valent uranium minerals in vein deposits 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 wall rocks, in gouge (fig. 26) or brecciated rock, in boxworks or porous gossans (fig. 27), or in vein filling. Pseudomorphous replacement and veining of primary uranium minerals by many of the hexavalent minerals are common (fig. 28), and in several places--as for example the Buckman adit and the Schwartzwalder mine--uranophane replaces siliceous constituents of the wall rocks 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 hexavalent-uranium minerals occur in microscopic veinlets between lamina 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. 29). Aggregates of crystals, rosettes (fig. 30), or spherulites (fig. 31) occur in many places and crustified banding of hexavalent-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 United States are either 1) as coatings on mineral or rock fragments in and adjacent to shear zones, 2) as pore space fillings principally in brecciated rock, or 3) a combination of both.

(Text is continued on page 69.)

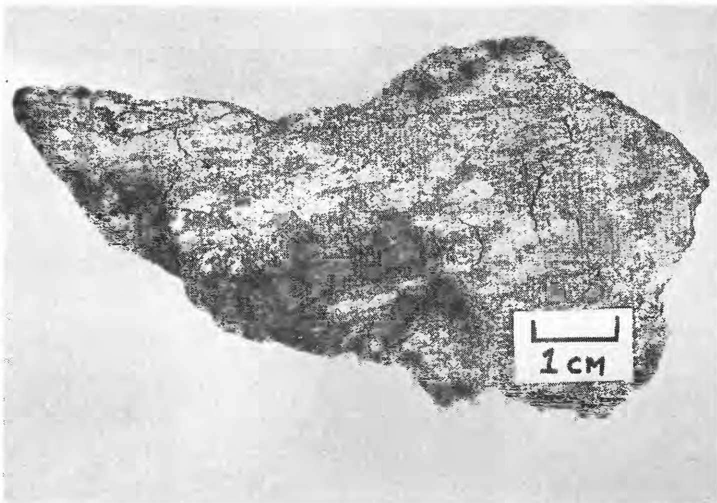



Figure 26. Crystalline and earthy carnotite (white) coating and disseminated in fault gouge from the Miracle mine, Kern County, Calif.

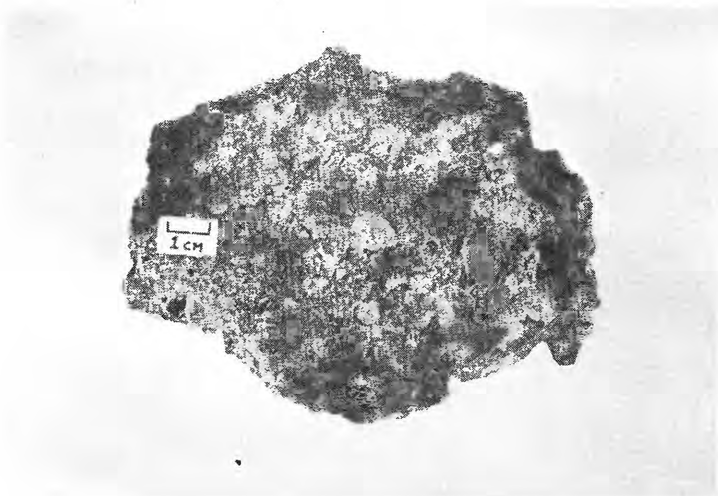



Figure 27. Carnotite (white) coating pore surfaces in fluoritic and limonitic boxworks from Thomas Range fluorspar district, Juab County, Utah.

1 millimeter

**Figure 28.** Hexavalent-uranium minerals (white and gray) that have replaced and veined spheroidal pitchblende mass (black) from W. Wilson mine, Jefferson County, Mont. Reflected light, partly crossed nicols.

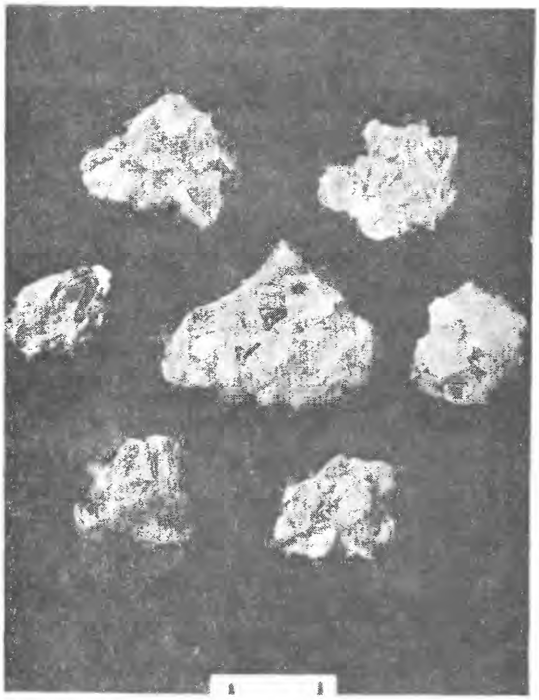
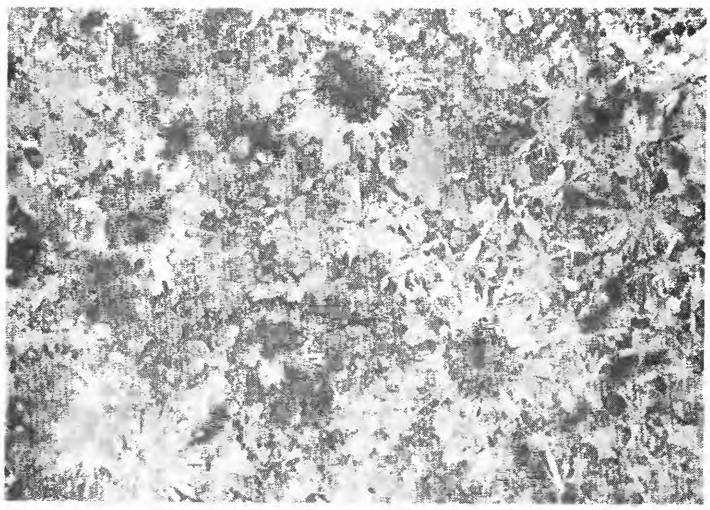


Figure 29. Coarsely crystalline aggregates of meta-autunite from Daybreak mine, Spokane County, Wash. Bar scale is 1 cm. long.



1 centimeter

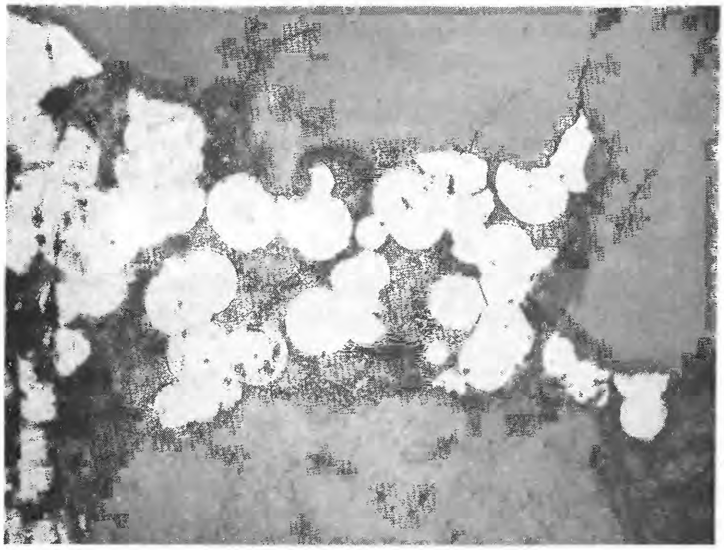
Figure 30. Rosettes of uranophane crystals on fracture in sandstone from Silver Cliff mine, Niobrara County, Wyo.

Figure 31. Spherulites of tyuyamunite on joint surface from Fuesner mine, Big Horn County, Wyo. Bar scale is 1 cm. long.

## Textural characteristics

Preliminary studies of the textural characteristics of primary uranium minerals in vein deposits in the United States, indicate that although several different textures are represented, one group is almost universally present and in many deposits dominates over all other textures. The textures within this group, which are 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 are not prepared to discuss herein the efficacy of this mode of origin for these textures, although we wish to retain the textural terms that have been applied to "colloidal" deposits because in most, if not all, essential features they are identical with the textures resulting from the coagulation of a hydrosol.

The colloform textures of the primary uranous oxide minerals in vein deposits in the 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. 32) and the Mi Vida mine, Utah (Laverty and Gross, 1956, fig. D). Many of these colloform textures have been beautifully illustrated for pitchblende from vein deposits in France (Geffroy and Sarcia, 1954, figs. 5, 6, 35, 36, 40, 41, 47, 52, and others; Carrat, 1955, figs. 9, 17, 18, 20, 24), for pitchblende from the Eldorado mine, Canada (Kidd and Haycock, 1935, plates 63, 64, 65), and for pitchblende from deposits in the Goldfields region, Canada (Robinson, 1955, figs. 4, 9, 28, 32, 33, 34, and 35). The colloform textures of pitchblende from several vein deposits in central Europe--including those near 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 different vein deposits in the United States. Among uranium-bearing vein deposits, idiomorphic crystals of uraninite apparently are common only at Shinkolobwe (Derriks and Vaes, 1956, p. 106, figs. 18 and 80) and in gold-bearing metallic veins of British Columbia, Canada (Stevenson, 1951); uraninite crystals are extremely rare in vein deposits in the United States and, according to published literature, apparently are quite uncommon in vein deposits elsewhere.



300 microns

Figure 32. Pitchblende (white) spherulites, exhibiting interference surfaces between individual spheroids, and calcite interstitial to quartz grains from specimen of high-grade uranium ore, La Sal mine, San Juan County, Utah. Reflected light.

As may be seen from the photographs (figs. 33, 34, 35 and 36) and photomicrographs (figs. 1, 2, 37, 38, 39, 40, 41 and 42) of uranium ore samples from several different vein deposits, the colloform 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 (figs. 33 and 34), in float specimens of vein pitchblende from the Marshall Pass area, Colorado, in the Nigger Shaft deposit, Colorado (figs. 35 and 36), and in deposits in the Central City district, Colorado (Sims, P. K., oral communication, 1956). Pitchblende showing microscopic colloform textures is more prevalent and has been reported in these and many other deposits.

(Text is continued on page 79.)

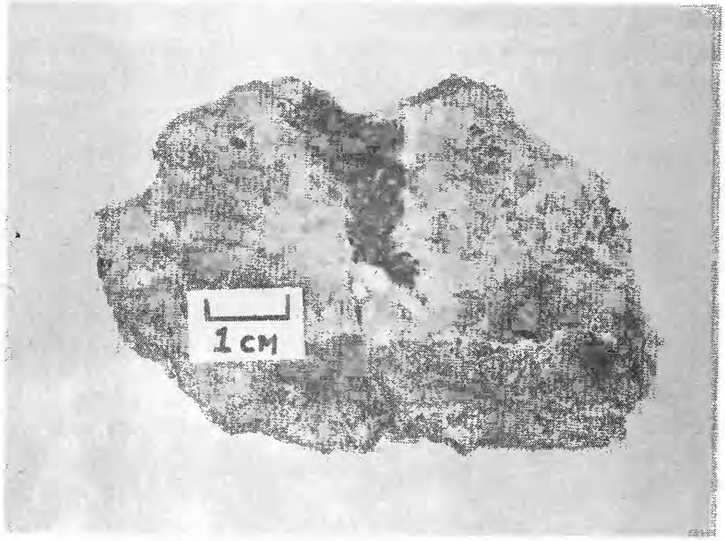



Figure 33. Rounded pellets of pitchblende (black) with intervening seams of hexavalent-uranium minerals (white) from W. Wilson mine, Jefferson County, Mont.

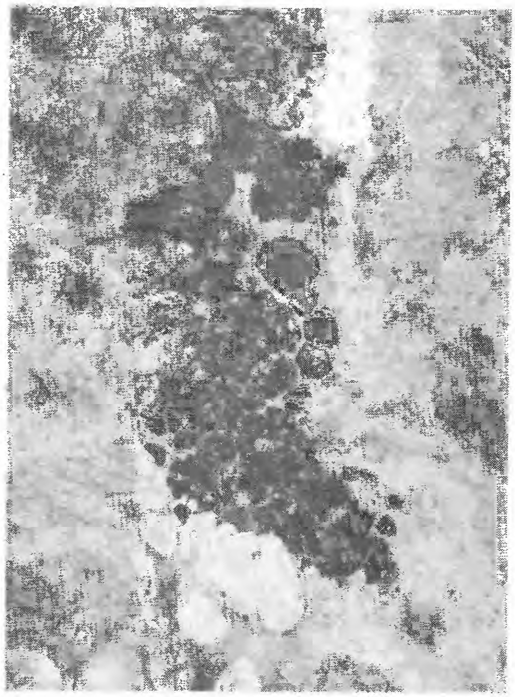


Figure 34. Enlargement of part of specimen shown in fig. 33.


Figure 35. Rounded, colloform pitchblende coating fractures from the Nigger Shaft, Jefferson County, Colo.

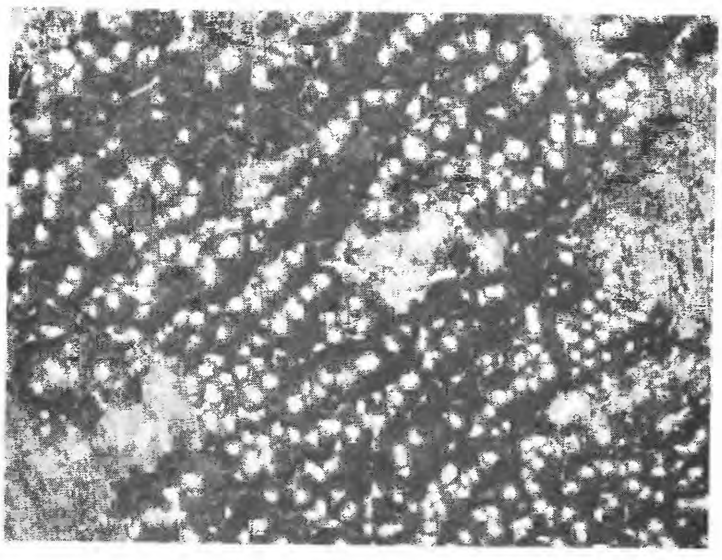


Figure 36. Enlargement of part of specimen shown in fig. 35.

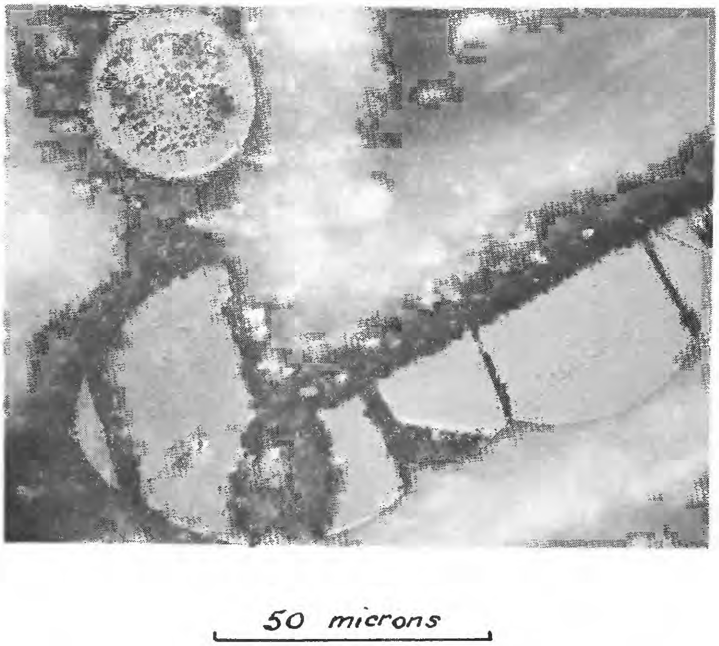



Figure 37. Spongy spherulite and veinlet of pitchblende in gangue of ankerite from Nigger Shaft, Jefferson County, Colo. Reflected light.

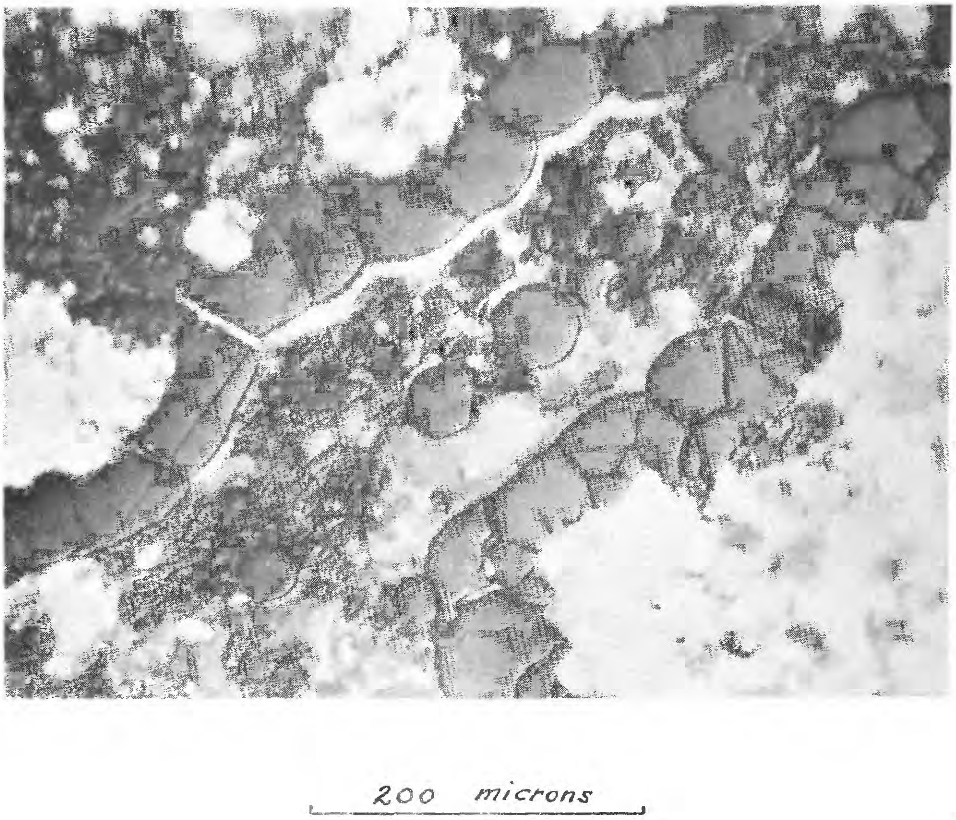
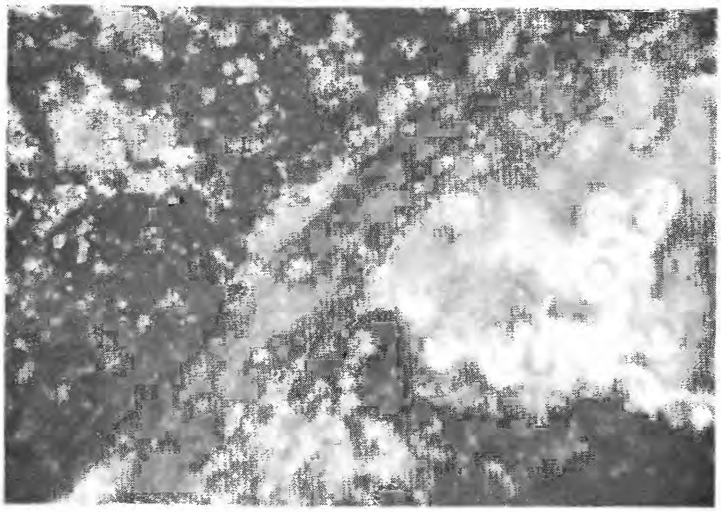
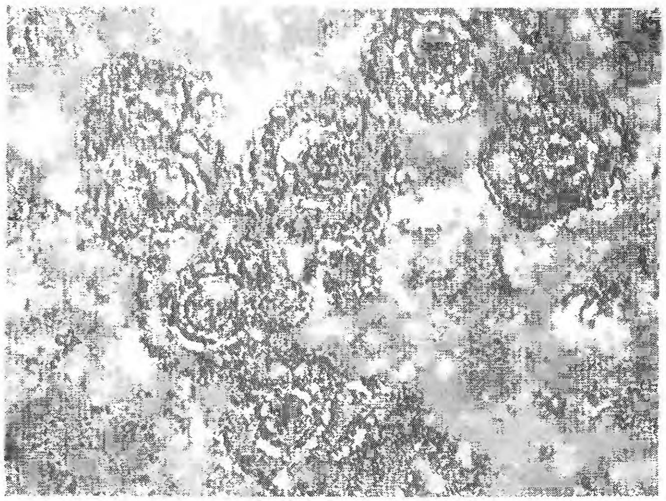



Figure 38. Spherulites and veinlets of pitchblende from float specimen of vein material, Marshall Pass area, Saguache County, Colo. Reflected light, crossed nicols.



1 millimeter

Figure 39. Pitchblende (black), exhibiting ring-like forms, replaced by "gummite" (white) from Marshall Pass area, Saguache County, Colo. Reflected light; crossed nicols.



300 microns

Figure 40. Same specimen as fig. 39 showing enlargement of ring-like forms of pitchblende. Reflected light.

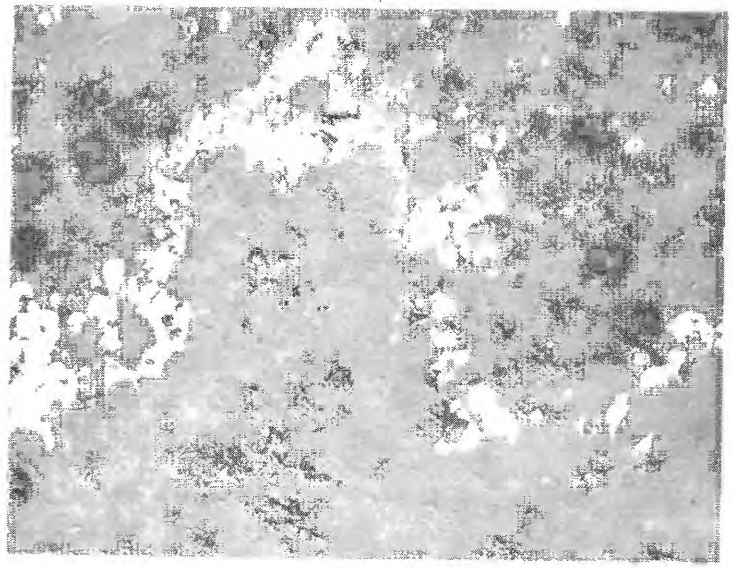




Figure 41. Pitchblende (white) spherulites and aggregates of rounded pitchblende masses from Marysvale, Utah. Reflected light.

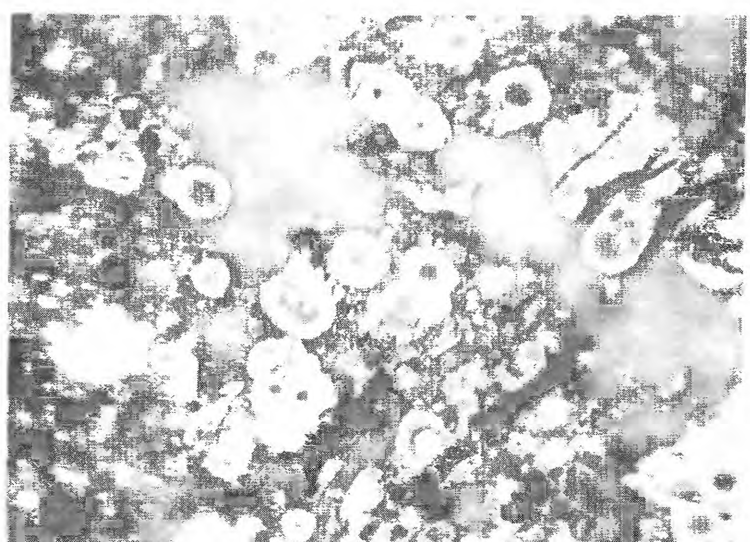




Figure 42. Pitchblende (light gray) spherulites with cores of darker gray pitchblende and, locally, with cores of galena (white) from Huron River deposit, Baraga County, Mich. Reflected light.

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 vein deposits in the United States. These include cellular or ring-like forms (figs. 39, 40, and 43), spherulitic forms (figs. 41, 42, and 44), and seams or veinlets exhibiting rounded surfaces. Not uncommonly the seams or thin veinlets appear to be composed of many individual hemispheres (figs. 45 and 46) or spheroids that have coalesced into chain-like 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 in figures 7B, 32, 38, and 45. Locally, pseudo-framboidal textures (fig. 47), that resemble the form of a head of cauliflower, are present. Concentric banding in pitchblende (fig. 2), and radial, concentric and net-like shrinkage (or syneresis) cracks, as illustrated by photomicrographs of specimens from the Caribou mine (Wright, H. B., 1954, figs. 6, 7, 13, 21, and 23) and from deposits in the Central City district (Bastin, 1914; Sims, P. K., 1956, fig. 4) are almost universally present; none has been observed, however, in those deposits characterized by pitchblende spherulites or pellets, (Bastin, 1950, p. 30) of very small size (less than 10 or 15 microns in diam.); and they are uncommon in spherulites less than 50 microns in diameter.

(Text is continued on page 85.)

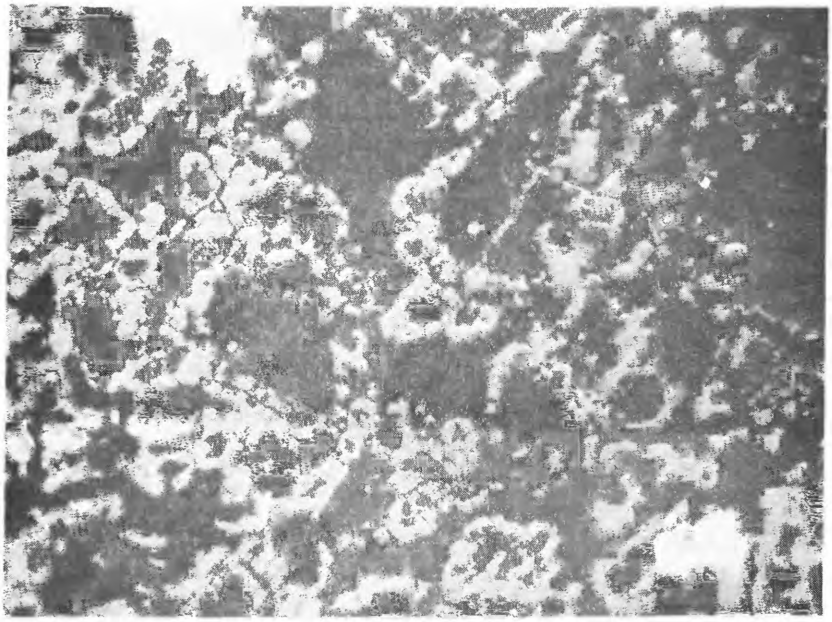



Figure 43. Cellular pitchblende (gray) principally on margins of or interstitial to crystals of ankerite (black) from Union Pacific prospect, Jefferson County, Colo. Reflected light.

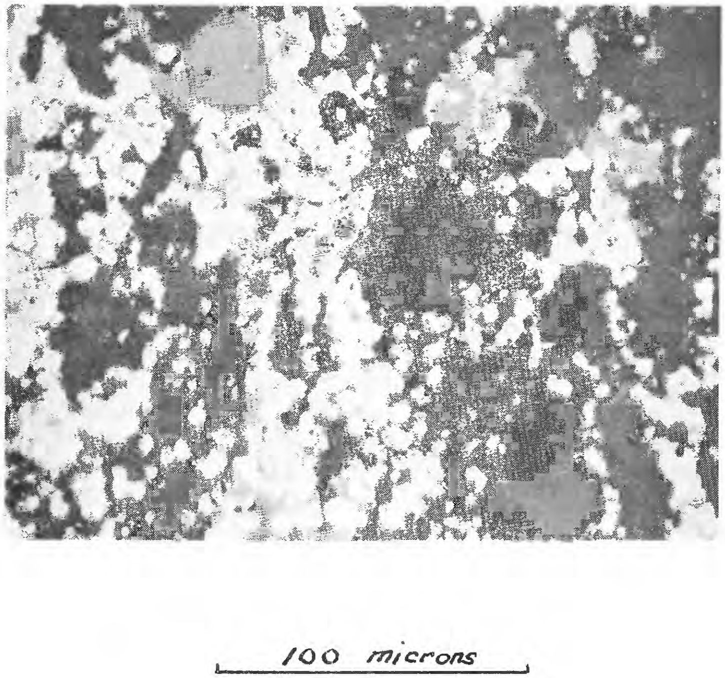



**Figure 44.** Pitchblende (white) spherulites and aggregates of spherulites in chalcopyrite (gray) and siliceous gangue (dark gray) from Hope mine, Gila County, Ariz. Reflected light.


Figure 45. 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.

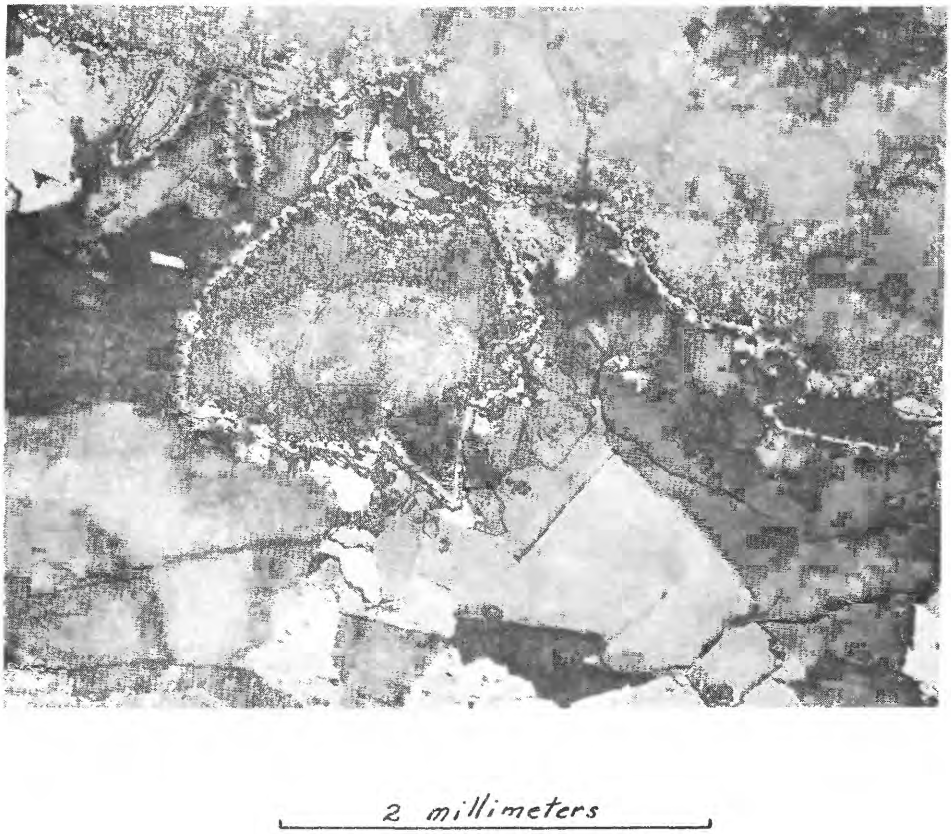



Figure 46. Veinlets and coatings composed of hemispheres of pitchblende from Nigger Shaft, Jefferson County, Colo. Reflected light; partly crossed nicols.

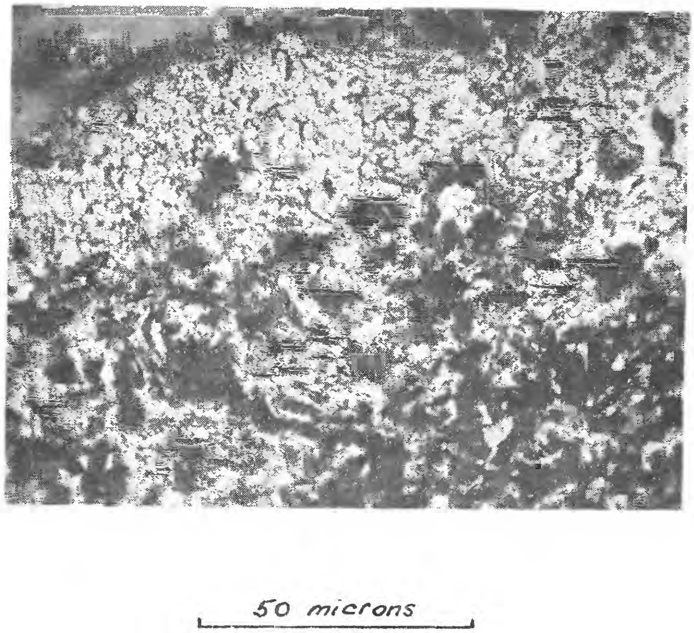
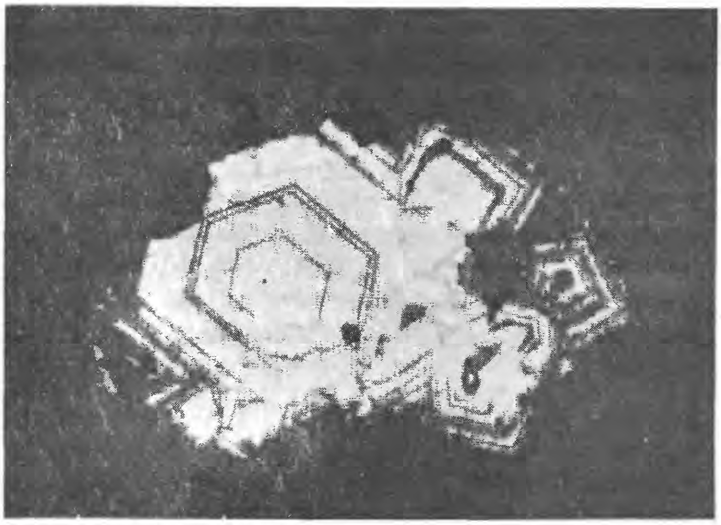



Figure 47. Pitchblende (white) showing pseudo-framboidal textures. Specimen from the Annie Laurie prospect, Santa Cruz County, Ariz. Reflected light.

The morphology of some of the primary uranium minerals in several vein deposits, particularly in the Boulder batholith and in the Sierra Ancha region, Arizona, has been described as microscopic, 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 of the grains, which are commonly about 10 microns in diameter, are pitchblende spherulites but whether the bulk of the equidimensional grains tends toward spheroidal or colloform shapes or toward microscopic idiomorphic shapes has not been established. A stage of uranium mineralization later than the equidimensional grains has been recognized in several of the 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 macro- or micro-breccias (fig. 2). 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 vein deposits are rare; 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 of the 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 state 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. 6). 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 (see fig. 44); some of the 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, has been described by King (1957, p. 648-656). In a specimen from this locality, pyrite and uraninite(?) occur as thin alternating layers paralleling crystal faces of a pyrite nucleus to form a two-phase single crystal (fig. 48) 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 hubnerite in the molybdenite deposits at Climax, Colo. (Vanderwilt and King, 1955, p. 48), and are 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.



50 microns

Figure 48. Alternating 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 vein deposits. 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 vein deposits, demonstrate the following relationships: 1) limited replacement of uraninite or pitchblende by gangue minerals or non-uraniferous ore minerals, in a few deposits, 2) replacement of siliceous gangue minerals and pyrite by pitchblende in two deposits, 3) replacement of pitchblende by sphalerite, argentite, and proustite in one deposit and by galena in another deposit, and 4) the replacement of ore, gangue, and host rock minerals by hexavalent-uranium minerals in several deposits. The 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 of the replacement relationships and textures, pertaining to pitchblende, have been described and illustrated by Wright (1954) for the vein deposits 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, H. D., 1954, figs. 16 and 17) and is replaced by sphalerite (Wright, 1954, figs. 19 and 21) and, less commonly, by proustite and argentite. Wright's evidence for replacement apparently is based largely on the presence of caries 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, 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 constituent 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. Hexavalent-uranium minerals replace primary uranous oxide minerals in an essentially pseudomorphous form in specimens from the Marshall Pass area, Colo. (fig. 39) and in several deposits where aggregates of hexavalent-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 vein deposits 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 vein deposits 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 vein deposits. 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 1) the inhomogeneity in distribution of the metallic minerals within vein deposits and, consequently, the sampling difficulties attendant with this kind of distribution, 2) the largely unpredictable distribution of many non-essential elements within common vein minerals, and 3) 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 Ni, Co, Ag, and Bi, commonly with little consideration of whether these few data are representative of a deposit (or group of deposits) and, furthermore, whether the apparent positive correlations are fortuitous spatial associations or, conversely, whether they have geologic and geochemical significance in terms of source of metals and methods of transport and deposition.

In those places where metals occur together but no functional or genetic relationship 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 relationship between the introduced metals probably exists; in these places a correlation as well as an association between 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 relationship 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 1) precise geographic location, or 2) the environment from which the sample was taken, or 3) 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 1) few, if any, of the samples are representative of the deposit from which they were taken, 2) essentially no data are available regarding the background level of metal content in the host rocks, except for only a few deposits, 3) the analyses differ in type, completeness, and accuracy, and 4) 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 of the 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 Fe, Pb, Zn, Ni, and Cu (Fleischer, 1953), and of several less common elements, including Ag, As, Co, and Mo are present in the greatest number of uranium deposits or districts listed in table 2. However, paragenetic studies of the common minerals in uranium-bearing veins indicate that the deposition of minerals containing Pb, Zn, Cu, Ag, As, and Co 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 Pb, Cu, Zn, Ag, As, and Co; and, consequently, the common occurrence of these elements with uranium perhaps is best interpreted as a spatial associatior rather than as a correlation which implies a functional relationship. Examples of deposits in which paragenetic data suggests that the uranium was introduced independently of the bulk of the base-metal sulfide minerals include those in the Central City district, the Copper King mine, and the Sunshine mine; these are discussed in the following section on paragenesis. The association of iron and uranium in most vein deposits also is thought to be a fortuitous spatial relationship; however, in several vein deposits part of the iron, principally in the form of pyrite but locally as magnetite or primary crystalline hematite, seems to show a nearly identical pattern of distribution to 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 vein deposits but also are coincident in time of deposition to uranium. 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 Fe, Cu, Mo, Pb, Zn and possibly Ag, As, Ni, and Co. The assemblage of these metals tends to vary from deposit to deposit. Most of these metal relationships cannot be explained or interpreted because of lack of data, but in a few places correlations of uranium with Mn, or Be, or W, or Nb, or Y, or Zr 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 of the 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 of the uranium deposits of the district are closely related in space to bodies of the quartz bostonite (Alsdorf, P. R., 1916; Phair, 1952). Concentrations of yttrium appear to be associated with concentrations of uranium in deposits in Kern Canyon (California), the Almaden mine

(Colorado), the Wonder Lode mine (Montana). 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 miles of each other in Jefferson County, Colo. Analyses of pitchblende from Marshall Pass and a pitchblende concentrate from vein deposits in Avery County, N. C., suggest an association of Nb, Y, and Zr to uranium. A spectrographic analysis of hard, unaltered pitchblende from the Copper King mine, Larimer County, Colo., indicates the presence of about 20 times as much Zr and 10 to 15 times as much Y 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 with available data. 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 (Osterwald, F. W., oral communication, 1956); this is one of the few districts where a positive correlation between Be and U 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 U, Pb, Cu, Ni, Co, Yb, and Be. In addition, Ce, Dy, Er, Nd, Pr, and La 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 adit and in one of the Lucky Stop veins.

Positive correlations of uranium to Mo, Ni, Mn, Be, W, Nb, Y, or Zr are suggested for some uranium deposits; conversely, most of the deposits characterized by unusually high concentrations of Mo, Ni, Mn, Be, and W--largely those deposits containing economic quantities of these metals--apparently fail to show an analogous correlation with minor concentrations of uranium. Vein deposits characterized by unusually high concentrations of Nb, Y, and Zr 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 review of data on the occurrence of uranium and vanadium in hydrothermal vein deposits, as well as other kinds of uranium deposits, has been made by Fischer (in preparation). To him, the data suggest ..."that vanadium does not tend to concentrate in the common hydrothermal environment, and specifically that it does not concentrate in most veins containing uranium ore." Several exceptions to these generalizations have been noted by Fischer (op. cit.): included are 1) the Schwartzwalder mine, Jefferson County, Colo., and the Miracle mine, Kern County, Calif.--in which the relationship between uranium and vanadium is unexplained--and 2) some titanium-bearing veins--i.e., deposits containing davidite and parts of the pitchblende-bearing Ace mine, Saskatchewan, Canada (Robinson, 1955).

In many other deposits, which fall within the definition of vein as used in this report (Walker and Osterwald, 1956), vanadium also accompanies uranium as demonstrated by the presence of uranyl vanadates in several of the deposits. The authors consider the deposits at Tyuya Muyun as veins, as does Pavlenko (1933), and also some, if not all, of the geologically similar deposits in the Pryor Mountains of Montana; deposits in both areas are characterized by uranyl vanadate minerals. Shoemaker (1956a, p. 183), has reported uranyl and cupric vanadates as well as copper carbonates in 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. Furthermore, either uranyl vanadate minerals or what appears 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 property and Rajah mine (Shoemaker, 1956b), Colorado, in a vein deposit in Huerfano County, Colorado (Moore and Kithil, 1913), in the Nigger Shaft deposit, Colorado, and elsewhere. The occurrence of uranium and vanadium in some vein deposits and not in others is unexplained but may result largely from differences in the petrologic environment of the deposits rather than to 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, the Pryor Mountains, and the Thomas Range.

The positive correlation of certain metals--notably Mo, Mn, Be, W, V, Nb, Y, and Zr--to uranium in vein deposits appears 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 Pb, Zn, Cu, Ag, and Co 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 Bisbee, Ariz., in many deposits in the Front Range of Colorado, 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 of the vein deposits, however, that have yielded hundreds or thousands of tons of uranium ore, including the Schwartzwalder and Los Ochos mines (Colorado), Marysvale deposits (Utah), Daybreak and Midnight 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, in general contain less than economic quantities of metals other than uranium.

# PARAGENESIS OF URANIUM-BEARING VEIN DEPOSITS

## Introduction

Detailed paragenetic studies have been made of relatively few of the uranium-bearing vein deposits of the United States. The lack of such studies has resulted largely from the time limitations on the scientific investigations that could be made of individual deposits during the past few years when the national interest has 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 relationships that permit only partial paragenetic interpretation. Some of these 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 particular phase of the geology of uranium deposits.

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 a 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 in 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 vein deposits in the 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, those in which uranium minerals are subordinate to base-metal sulfide minerals (Class 2) predominate, but examples of fluorite-bearing veins (Class 1) and hydrocarbon-bearing veins (Class 8) as well as veins in which uranium minerals are dominant (Class 3) are included.

The available data are summarized as follows:

Table 3. —Paragenetic position of pitchblende in single stage vein deposits.

| Deposit | Class a/ | Age of mineralization | Position of pitchblende in mineral sequence | Remarks | Reference |
|---|---|---|---|---|---|
| Marysvale, Utah | 1 | Tertiary | Intermediate | District composite, see fig. 53. | Leverly and Gross, 1956. |
| Jamestown, Colo. (Blue Jay Mine) | 1 | do. | Early and intermediate | Uranothorite and some pitchblende are early. | Phair, George and Onoda, Kiyoko, written communication, 1950. |
| Buck mine, Michigan | 2 | Ordovician ? | Intermediate | Pyrite earlier. | Vickers, R. C., written communication, 1956. |
| Francis mine, Michigan | 2 | do. | do. | do. | Do. |
| Union Pacific prospect, Colo. | 2 ? b/ | Tertiary | Early | See fig. 48. | Adams and Stugard, 1956. |
| Wigger Shaft, Colo. | 2 ? b/ | do. | do. | Ankerite earlier. | Adams, Gude and Beroni, 1953. |
| Deposits in Sierra Ancha region, Ariz. | 3 and 2 | Pre-Devonian | do. | District composite. | Granger and Raup, in preparation. |
| Schwartzwalder mine, Colo. | 3 | Tertiary | do. | See fig. 51. | Kuehnel, F. W., written communication, 1956 |
| Los Ochos mine, Colo. | 3 | do. | Late | Marcasite earlier. Pitchblende probably regenerated. | Derzay, R. C., 1956. |
| W. Wilson mine, Mont. | 3 | do. | Intermediate | Pyrite earlier; galena, sphalerite contemp. with pitchblende. | - - - |
| G. Washington mine, Mont. | 3 | do. | do | Pyrite earlier, no other sulfides. | Wright and others, 1954. |
| Sherwood mine, Michigan | 2 ? b/ | Ordovician ? | do | Pyrite earlier. | Vickers, R. C., written communication, 1956. |
| Placerville, Colo. | 8 | Post-Triassic | do c/ | Pitchblende precedes most sulfides; pyrite contemporaneous or earlier. | Wilmarth, V. R. and Vickers, R. C., written communication, 1952. |

a/ Mineralogic classes of veins: 1) Fluorite-bearing veins; 2) veins in which uranium minerals are subordinate to base-metal sulfide minerals; 3) veins in which uranium minerals are "dominant"; 8) veins containing uraniferous hydrocarbons.

b/ Data on relative abundance of minerals not adequate to definitely establish mineralogic class.

c/ Represents paragenetic position of uraniferous hydrocarbon and included pitchblende.

Table 4.--Paragenetic position of pitchblende in vein deposits in which multiple stages of mineralization recognized.

| Deposit | Class | 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 |
| Almaden, Colo. | 2 | do. | do. | do. | Pitchblende and Ni minerals in early pyrite stage. Base-metal stage later. | Sims, P. K., 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, Fe-sulfides precede pitchblende. | Sims, Phair, and Moench, in preparation. |
| Lone Eagle, Mont. | 2 | do. | do. | Early | With chalcedony, minor pyrite. (Also see comments, p. 74 text). | Wright and others, 1954. |
| Mooney claim, Mont. | 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 | Cret. | Early | do. | Crystallized uraninite associated with quartz and hematite. | Bain, 1952. |
| de la Fontaine, Ariz. | 2 | Late Meso. | Late | do. | Uranium deposition thought to follow brecciation of base-metal vein. Wright, H. D. and Schulhof, W. P., (written communication, 1956) think pitchblende is late mineral of pre-breccia suite. | Hart and Hetland, 1953. |
| Huron River, Mich. | 2 | Ordiv. (?) | do. | Intermediate | See fig. 52. Pyrite earlier. | Vickers, R. C., 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. | - - - |

a/ Mineralogic classes of veins -- entire assemblage of multiple stage veins used as a basis for classification: 2) veins in which uranium minerals are subordinate to base-metal sulfide minerals; 8) veins containing uraniferous hydrocarbons.

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* 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).

*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.

Moore, Cavender, and Kaiser (1957, p. 537) indicate that most of the 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 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).

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, Phair, and Moench, in preparation).

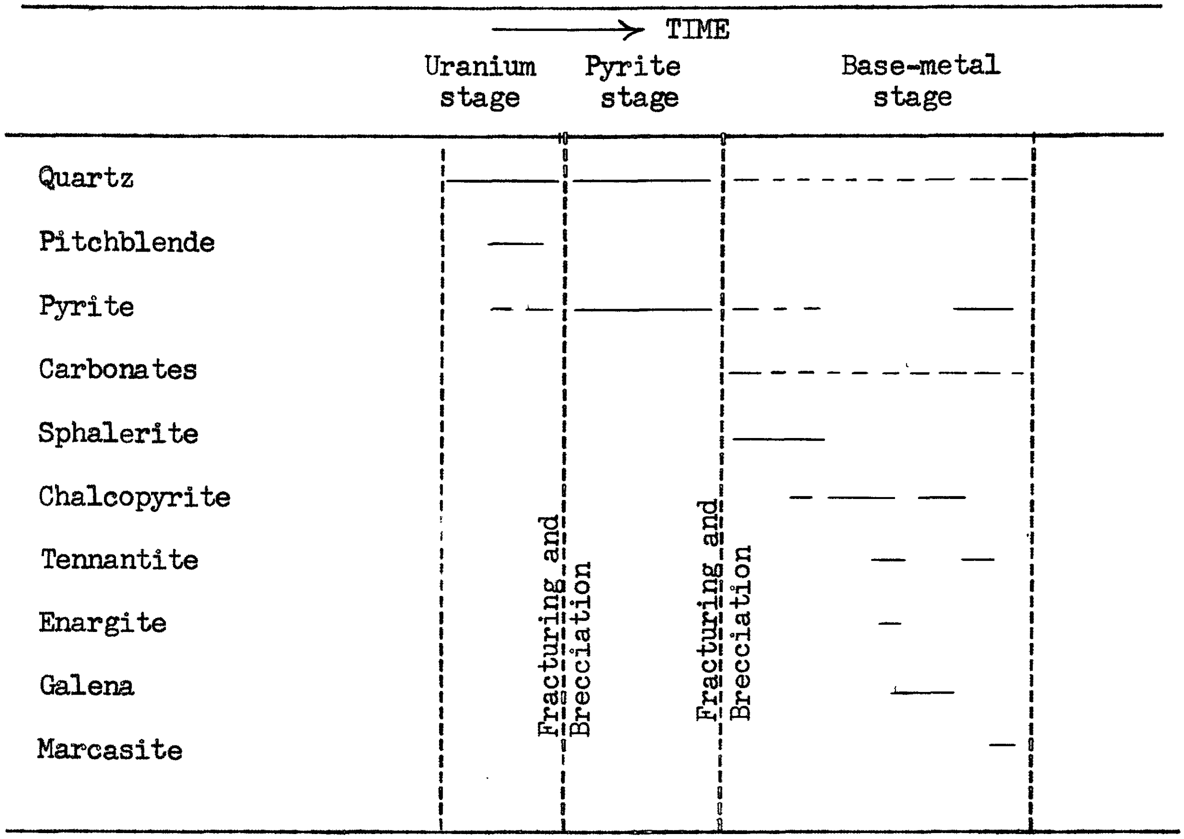
During or after a period of brecciation of the skarn ore and the enclosing rocks, a second period of mineralization began with the introduction of siderite, pyrite, marcasite, and minor quartz. Some sphalerite and chalcopyrite may also have formed at this time. Fracturing of these minerals was followed by a third period of deposition at which time pitchblende and fine-grained siderite veined the earlier minerals and filled openings between them (figs. 16 and 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, Phair, and Moench, in preparation). Coffinite is intimately intergrown with both the early and late pitchblende.

Evidence supporting the concept of two widely-spaced periods of mineralization at the Copper King mine is afforded by age determinations. Two specimens of magnetite from the skarn ore gave ages of 700 to 740 million years (Precambrian) by the alpha-helium method (Sims, Phair, and Moench, in preparation) whereas lead-uranium ratio 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 long recognized (Bastin and Hill, 1917; Lovering and Goddard, 1950); these show a spatial distribution considered to be the result of hypogene zoning. The pattern is essentially one of an inner zone about two 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 predominate. Composite veins have formed where quartz-pyrite-filled structures were re-opened and minerals of the galena-sphalerite type assemblage introduced. Pitchblende occurs locally in the district, as in the composite-type lode at the Wood-Calhoun mine (Moore and Butler, 1952; Drake, in press). Recent detailed studies (Sims, 1956) indicate that the uranium minerals are unrelated to the 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 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 49.

Figure 49.--Generalized sequence of deposition of principal vein-forming minerals, Central City district, Colorado. (after Sims, 1956)



## 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 the Belt Series sedimentary rocks, 2) early emplacement of uraninite-pyrite-quartz accompanied by local penetration of the wall rocks 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, and 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 post-tetrahedrite and hence late in the mineral sequence.

Evidence supporting an early period of uranium deposition is afforded by chemical and lead isotope analyses which suggest a Precambrian age for pitchblende from the Sunshine mine (Kerr and Kulp, 1952). The lead-silver mineralization of the Coeur d'Alene district has been 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 only be separated 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 important in establishing the age of the main period of mineralization in the Coeur d'Alene district.

## Jefferson County, Colorado

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. 50, 51), the Union Pacific prospect (Adams and Stugard, 1956, p. 200-202, fig. 49) and the Schwartzwalder (Ralston Creek) mine (Kuehnel, F. W., written communication, 1956) indicate that pitchblende was deposited prior to the introduction of most of the sulfides. In both of these deposits, pitchblende deposition is separated from deposition of most of the sulfide minerals by a period of fracturing; however, mineralization is thought to have been essentially continuous.

Figure 50.--Paragenetic sequence of minerals at the Union Pacific prospect, Jefferson County, Colo. (from Adams and Stugard, 1956).

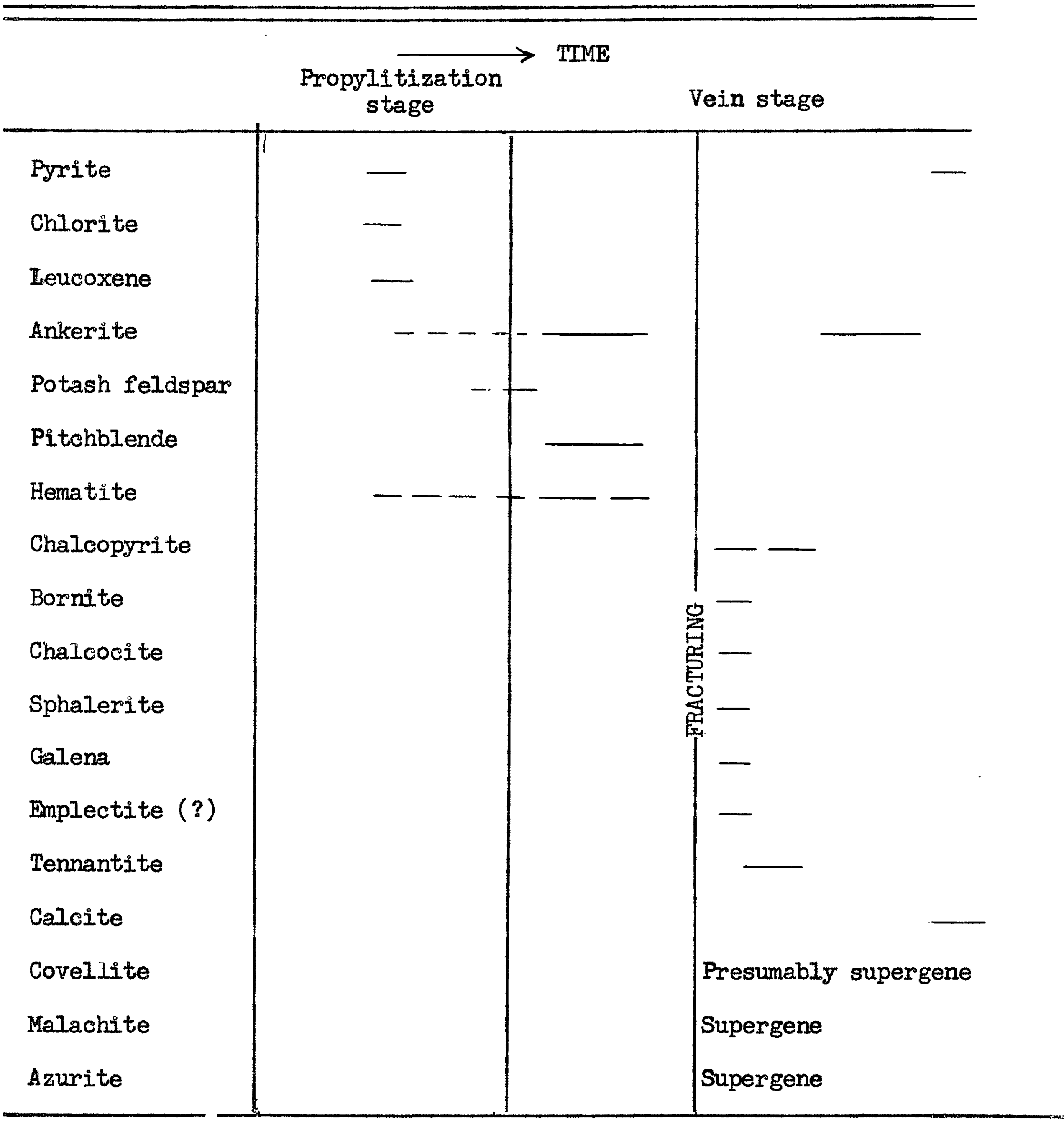
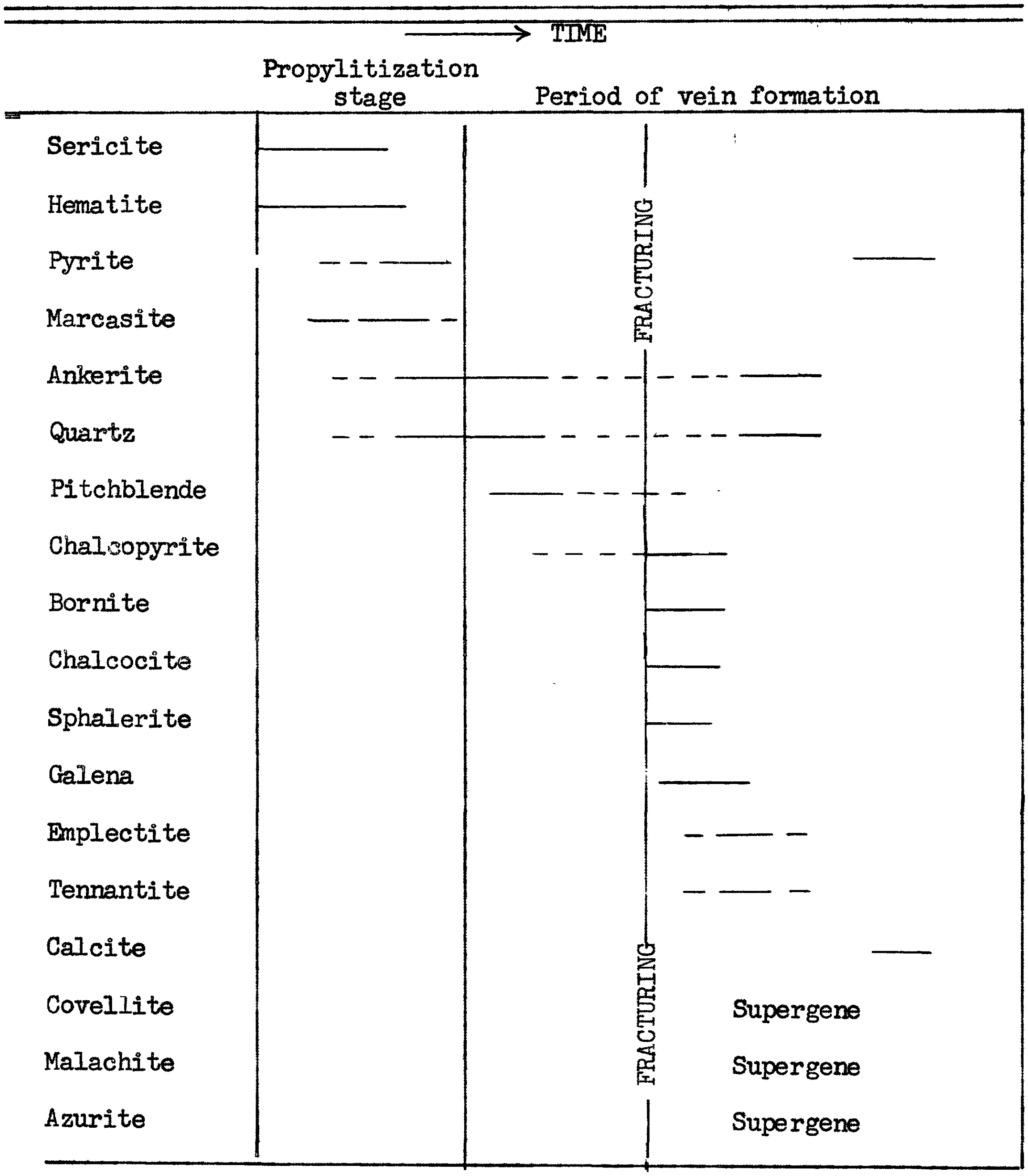


Figure 51.--Paragenetic sequence of minerals at the Schwartzwalder (Ralston Creek) mine, Jefferson County, Colo.

(after F. W. Kuehnel, written communication, 1956)



## 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 of the so-called "siliceous reef" type which are chalcedonic vein zones in which metallic minerals are sparse. A tentative paragenetic sequence by Wright and others (1954) 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 1) essentially contemporaneous with pyrite and chalcopyrite in the deposit and 2) is probably intermediate in the sequence if both metallic minerals and non-metallic 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 of vein showing characteristics of both the chalcedonic and 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).

Wright and Shulhof (1957b) present a slightly revised paragenetic sequence of vein minerals for the Lone Eagle mine 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 others, 1953). The most detailed paragenesis is that given for the Huron River deposit (fig. 52) where Vickers (op. cit.) 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 pene-contemporaneous sulfide minerals; deposition of calcite was continuous throughout the stage. Pitchblende from this deposit commonly encloses small grains and idiomorphic crystals of galena (fig. 42) 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. 52) with deposition orders analogous to that given for the second stage of the Huron River vein.

Figure 52.--Paragenetic sequence of the minerals at the four pitchblende occurrences in northern Michigan. (after Vickers, R. C., written communication, 1956)

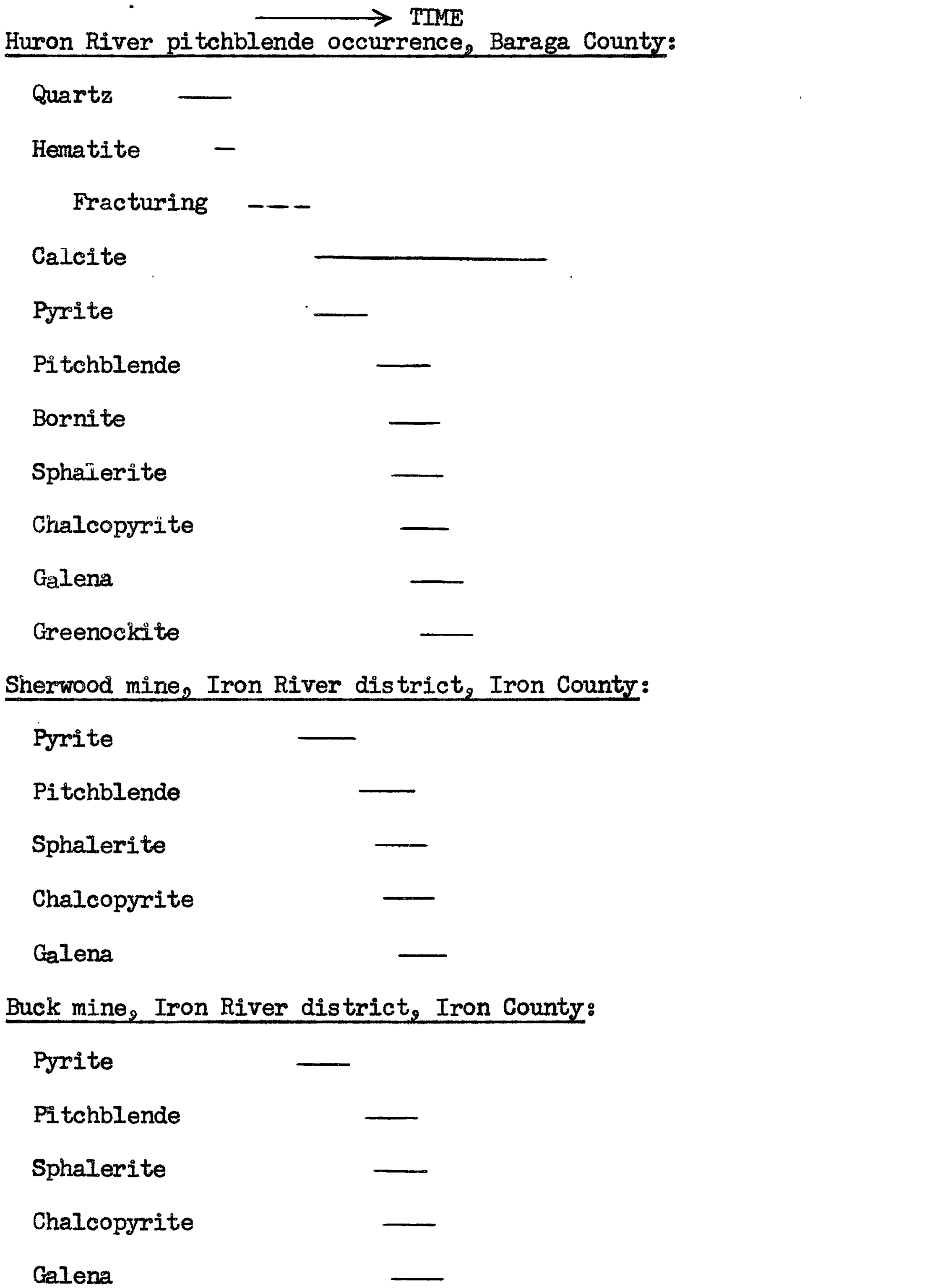


Figure 52.--Paragenetic sequence of the minerals at the four pitchblende occurrences in northern Michigan.--Continued.
(after Vickers, R. C., written communication, 1956)

→ TIME

Francis mine, Gwinn district, Marquette County:

| | |
|---|---|
| Pyrite | —— |
| Pitchblende | —— |
| Chalcopyrite | —— |

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, locally, have been metamorphosed to hornfels adjacent to diabase bodies, and the ore deposits are best developed in the hornfels (Granger and Raup, in preparation). These deposits as yet have not been dated radiochemically, but they are believed to be genetically related to the diabase bodies of pre-Devonian age.

Polished section studies suggest that pitchblende formed before any of the sulfide minerals (op. cit.) 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, clay-like material.

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

Bisbee, Arizona

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

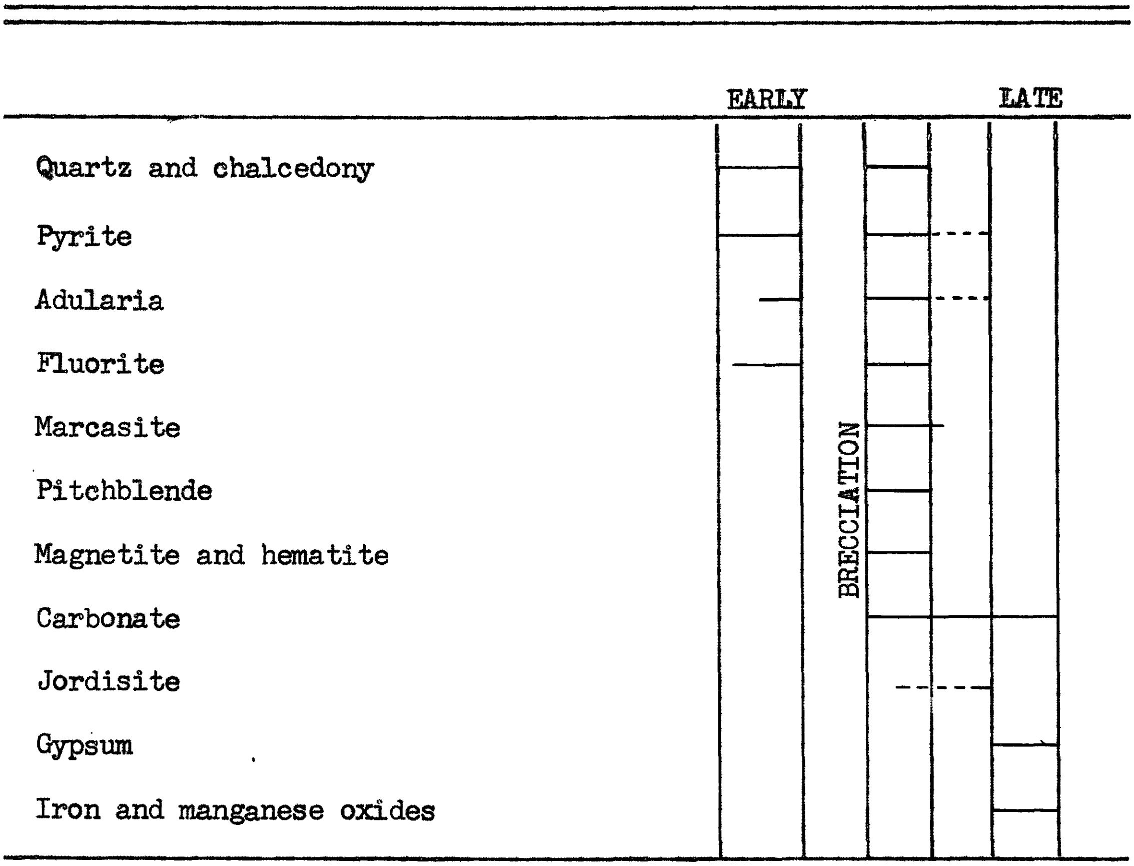
That euhedral uraninite is early in the paragenetic sequence has been substantiated by S. R. Wallace (oral communication, 1956), although he also has established later stages of colloform and sooty pitchblende mineralization.

## 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, Brophy, and others, 1952; Gruner, and others, 1954; Walker and Osterwald, 1956; 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. 53) given by Laverty and Gross (1956) it would appear 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 re-working of early hard pitchblende (Stugard, Wyant, and Gude, 1952, p. 21).

Figure 53.--Paragenetic sequence of the minerals at Marysvale, Utah. (after Laverty and Gross, 1956).



Jamestown, Colorado

Fluorite deposits of Tertiary age at Jamestown, Colo. (Goddard, E. N., 1946) contain pitchblende that is largely concentrated in an assemblage of fine-grained minerals cementing coarse fluorite breccia (Phair, George and Onoda, Kiyoko, written communication, 1950). According to Goddard (1946), deposition of fluorite, quartz, pyrite, galena, and other sulfide minerals took place at about the same time. Due 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 of the uraninite of the second stage may have been derived from uranium leached from uranothorite (Phair, George, personal communication, 1956) or uraninite during the period of fluorite solution. Colloform uraninite coating pyrite has been reported as inclusions in fluorite by Phair and Onoda (op. cit.), but no detailed paragenesis is available.

In districts other than Jamestown, fluorite-bearing veins in which only hexavalent-uranium minerals have been found are not uncommon (Wilmarth and others, 1952; Vickers, 1953; Lovering, 1956); fluorite veins are also known where these hexavalent 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 hexavalent-uranium minerals and perhaps some sooty pitchblende were derived from uraniferous fluorite.

## Placerville, Colorado

In the vicinity of Placerville, Colo., two hydrocarbon-bearing veins have been studied in some detail by Wilmarth and Vickers (written communication, 1952). These veins cut sedimentary rocks of late Paleozoic and early Mesozoic age and contain both uraniferous and non-uraniferous 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 (op. cit.) the following relationships 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, and (5) deposition of calcite. Locally, euhedral quartz crystals were deposited prior to the early calcite-barite stage and show replacement by these minerals. Quite 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 (op. cit.), and minute specks believed to be uraninite were noted in similar material by Kerr and others (1951). However, megascopic uraninite or pitchblende has not been recognized in these deposits, and most of the uranium is presumably dispersed in the hydrocarbon material as discrete microscopic to submicroscopic uraninite and coffinite grains or possibly, in part, as a metallo-organic complex.

The direct precipitation of the uranium as a metallo-organic complex is favored by Wilmarth and Vickers (op. cit.) 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 partially or completely fills vein cavities in which marcasite, pyrite, and pitchblende are interstitial to crystals of pink ankerite. Some of the 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 has not been established for the deposit, but observed relationships indicate an early pyrite stage, followed by brecciation, 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 vein deposits is the relation of the time of deposition of the primary uranium minerals to that of the associated ore and gangue minerals. With the exceptions of the crystallized uraninite at Bisbee and the Little Man mine, Wyoming, uraniferous hydrocarbon at Placerville, and uranothorite at Jamestown, the primary mineral in all of 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 of the 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. We are, however, afforded an example in which the individual stages have been demonstrated to be widely separated; this is the Copper King deposit in Colorado (Sims, Phair, and Moench, in preparation) 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 those 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) or intense brecciation (Blue Jay) 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 pre-pitchblende mineral in some deposits.

Except for the pitchblende itself, there appears to be nothing unique in the mineral assemblage of uranium-bearing veins. The paragenetic sequence of the minerals, exclusive of pitchblende, is essentially that of non-uraniferous veins in which the minerals tend to follow a depositional order not too different from that proposed by Lindgren (1926, p. 88) and tabulated in a somewhat abbreviated form by McKinstry (1948, p. 150).

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

The paragenetic studies of deposits in the 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, Ni-Co sulfosalts), but its deposition commonly starts before most of the associated metallic minerals and the bulk of the gangue in any single stage of mineralization.

The close association of pitchblende and pyrite, in the vein deposits 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 Ni-Co 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 relationship. That some relationship 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 found at the Copper King and Los Ochos mines (table 3) and at the Caribou mine (table 4), as well as elsewhere, and can be expected to show apparently anomalous paragenetic relationships.

In tables 3 and 4, summarizing the paragenetic position of pitchblende, most of the deposits included belong to the mineralogic class of uranium-bearing veins characterized by dominant base-metal sulfide minerals (class 2). Other deposits or districts listed include two representing fluorite-bearing veins (class 1), four in class 3 in which uranium minerals are "dominant," two in class 8 characterized by uraniferous hydrocarbons, and four in which either the mineralogic class has not been clearly established or deposits within a district belong to 2 different classes. The paragenetic position of pitchblende is almost invariably early or intermediate in 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 has been restated in a more recent publication by McKelvey, Everhart, and Garrels (1955, p. 487).

Presently 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 vein deposits shown on tables 3 and 4 are based on geologic or radio-chemical dating or both; the paragenetic positions of pitchblende shown on 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 the 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 different uranium-bearing minerals have been identified from vein deposits in the United States. Of these, 43 different 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 hexavalent-uranium minerals, particularly uranyl phosphates and silicates, are probably more characteristic of veins than other kinds of uranium deposits. Several minerals, such as rutile and pyromorphite, containing 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 vein deposits are those commonly found in metalliferous veins and demonstrate no tendency toward abundance or rarity of any particular specie that could be considered distinctive. Changes in coloration, as a result of radiation damage, are distinctive characteristics of gangue minerals in some uranium-bearing vein deposits.

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 Mo, Mn, Be, W, V, Nb, Y, and Zr--with uranium in vein deposits appears 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 8 mineralogic classes of vein deposits can be demonstrated beyond 1) the obvious mineralogic correlations resulting from the arbitrary classifying of uraniferous vein deposits and 2) 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 at Bisbee, Ariz. and the Little Man mine, Wyoming. In general, pitchblende or uraninite is commonly 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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