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April 18, 1956

Mr. Robert D. Nininger, Assistant Director
Division of Raw Materials
U. S. Atomic Energy Commission
Washington 25, D. C.

Dear Bob:

Transmitted herewith are three copies of TEI-433, "Paragenesis and structure of pitchblende-bearing veins, Central City district, Gilpin County, Colorado," by Paul K. Sims, January 1956.

We are asking Mr. Hosted to approve our plan to submit this report for publication in Economic Geology.

Sincerely yours,

for George N. Pipiringos
W. H. Bradley
Chief Geologist

JAN 2 2

Geology and Mineralogy

This document consists of 32 pages.
Series A

UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

PARAGENESIS AND STRUCTURE OF PITCHBLENDE-BEARING VEINS, CENTRAL CITY DISTRICT, GILPIN COUNTY, COLORADO*

By

Paul K. Sims

January 1956

Trace Elements Investigations Report 433

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*This report concerns work done on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

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PARAGENESIS AND STRUCTURE OF PITCHBLENDE-BEARING VEINS, CENTRAL CITY DISTRICT, GILPIN COUNTY COLORADO

By Paul K. Sims

ABSTRACT

Pitchblende occurs locally along early Tertiary gold-, silver-, and sulfide-bearing quartz veins in the Central City district, within the mineral belt of the Front Range. The veins cut a complex mass of Precambrian metamorphic and igneous rocks and early Tertiary intrusive porphyritic rocks.

The veins are fissure fillings that formed at intermediate temperatures and pressures. They consist mainly of pyrite, sphalerite, and galena in a quartz gangue but also contain tennantite, chalcopyrite, enargite, and pitchblende. The veins differ in quantitative mineralogy, and they can be classified as pyrite type and galena-sphalerite type veins.

Vein filling took place during three stages of mineralization, from oldest to youngest, a uranium stage, a pyritic stage, and a base-metal stage. Major periods of fracturing and vein reopening took place between the vein-forming stages.

The pyrite stage and the base-metal stage mineralization were of broad areal extent and produced a concentric zonal arrangement of the ores in the district. In contrast, the uranium-stage mineralization was local in extent and resulted in scattered clusters of uranium deposits, which show no definite spatial relation to the zoning pattern.

Pitchblende is present in only a few veins. It occurs locally along four of the six vein sets of the district, in ore shoots or small lenses and pods that are separated by vein material essentially barren of uranium. The ore shoots are small and measure at most a few tens of feet in height and length, and average less than a foot in width; they rarely contain more than 50 tons of ore. Some of the shoots are systematically arranged within the veins, but others are erratically distributed. The ore bodies are localized in structurally controlled open spaces along faults.

INTRODUCTION

Pitchblende was first discovered in the United States at the Wood mine in the Central City district in 1871. The Central City district, since the discovery, has been a source of sporadic production of uranium ore, and more than 100,000 pounds of U_3O_8 has been shipped; most of the yield was prior to World War I. Only recently this region was replaced as the country's leading producer of high-grade pitchblende ore by the Marysvale, Utah, area.

The Central City district constitutes an area of about 12 square miles in Gilpin County, Colo., about 30 miles west of Denver (fig. 1). It is the most important of several well-known precious-metal and base-metal mining camps in the mineral belt of the Front Range; and, since 1859 when gold was discovered in the area, it has yielded ores valued at more than $100 million. Most of the values have been in gold, but substantial amounts have also been recovered from silver, lead, copper, and zinc, as well as uranium. The production has come from about 500 mines, but a few mines have supplied a large proportion of the ore.

Several papers describing certain aspects of the pitchblende deposits of the Central City district have been published. The most important of these are Pearce (1895), Rickard (1913), Moore and Kithil (1913), Alsdorf (1916), Bastin (1915, 1916), Bastin and Hill (1917), Lovering and Goddard (1950), and Phair and Levine (1953). U. S. Geological Survey Professional Paper 94 (Bastin and Hill, 1917) has been the principal source of information of the deposits.

During the past several years the U. S. Geological Survey, on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission, has been restudying the Central City district and adjoining mining areas to determine the geology and economic importance of the uranium occurrences in the region. This report presents some of the new data obtained during the investigation that have a bearing on the economics of the deposits and on exploration. It describes briefly the paragenesis of the pitchblende-bearing veins and the structure of the deposits. The other mineral deposits of the district are discussed only insofar as needed to provide the geologic setting. A comprehensive report on the uranium deposits of the Central City and adjoining mining districts is in preparation for publication by the U. S. Geological Survey.

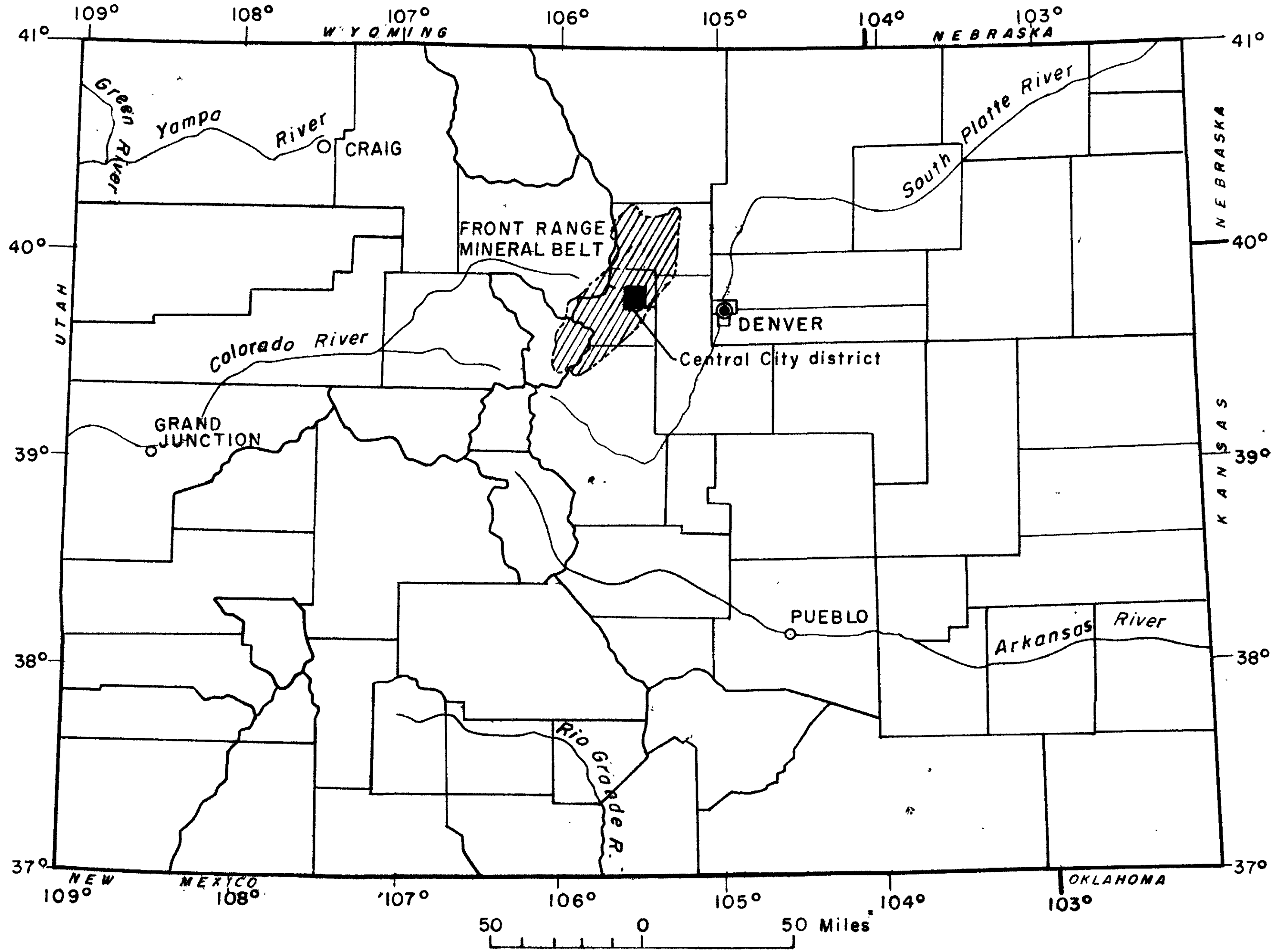


FIGURE I.—INDEX MAP OF COLORADO SHOWING LOCATION OF CENTRAL CITY DISTRICT

During the investigation of the Central City district, from 1952 to 1954, the writer was associated with several members of the U. S. Geological Survey, and their work materially aided in the preparation of this report. The writer wishes particularly to acknowledge the data contributed by A. A. Drake, Jr., E. W. Tooker, and A. E. Dearth.

GEOLOGIC SETTING

The Central City district is in the core of the Front Range of Colorado- a complex of Precambrian metamorphic and igneous rocks, early Tertiary intrusive dikes and plugs, and early Tertiary veins. The Precambrian rocks in the district consist dominantly of a wide variety of felsic gneisses and granites that are folded along northeast-trending axes. The early Tertiary intrusives are mainly quartz monzonite and bostonite. Faulting, which both preceded and followed the Tertiary intrusives, produced a mesh-like fracture pattern composed of six distinct fracture sets; these fractures were later filled with precious metal, base metal, and uranium minerals.

Precambrian rocks

The Precambrian rocks of the Central City district consist of an interlayered and generally conformable sequence of metasedimentary and igneous units, some of which are metamorphosed. The principal types, in order of probable relative age, are given in table 1.

The metasedimentary units--biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss--and quartz monzonite gneiss are dominant in the district, and they constitute more than 75 percent of the bedrock. The other units, although locally abundant, form relatively small, generally lenticular bodies in the metasedimentary biotite gneisses and the quartz monzonite gneiss. The metamorphic rocks belong to Eskola's amphibolite facies (1939).

Aside from the biotite-muscovite granite and the post-granite pegmatite, the rocks are metamorphosed and folded. The major fold axes trend northeasterly and plunge gently to the northeast or southwest. The folds are predominantly open and, except locally, the limbs dip less than 60°.

Table 1. --Principal Precambrian rock units, Central City district, in order of probable relative age.

Rock units	Comments
Pegmatite	Some pegmatite is abnormally radioactive.
Biotite-muscovite granite	Equivalent to Silver Plume granite at Silver Plume, Colorado.
Quartz diorite and hornblendite	
Granodiorite	Probably equivalent to Boulder Creek granite of Lovering and Goddard (1950).
Pegmatite and granite gneiss	Also constitute felsic layers in migmatites. Granite gneiss is sparse in district.
Quartz monzonite gneiss	Granite gneiss of Bastin and Hill (1917). Age relative to rocks below is obscure.
Cordierite-cummingtonite gneiss Biotite-quartz-plagioclase gneiss Sillimanitic biotite-quartz gneiss Lime-silicate gneiss Skarn and related rocks Amphibolite Quartzite (or quartz gneiss)	Age relations among rock units are unknown. Most of the rocks previously were grouped in the Idaho Springs formation of Ball (1906).

Early Tertiary intrusive rocks

The prophyritic igneous rocks that cut the Precambrian rocks of the Central City district are dominantly quartz monzonite porphyry and bostonite but also include granodiorite porphyry. The quartz monzonite and granodiorite form plugs and dikes, and in the southeast part of the district they constitute a substantial proportion of the bedrock. The bostonite-type intrusives can be subdivided into two distinct groups--bostonite and quartz bostonite. The bostonite commonly occurs as steep-walled, narrow dikes that trend easterly. The quartz bostonites similarly form narrow dikes, but they are more varied in orientation; most trend northwest but a few trend northeast or in other directions. The bostonite dikes are a foot or less to about 50 feet wide, and some are more than two miles long. The pattern of the bostonite dikes within a part of the district, the Eureka Gulch area, can be seen in the report by Sims, Osterwald, and Tooker (1955, pl. 1). The regional pattern is shown by Bastin and Hill (1917).

Recent studies by Phair (1952) of the early Tertiary intrusive sequence have disclosed that it is one of the most radioactive igneous series in the world. All of the porphyries are more radioactive than "the average granitic rock," and the quartz bostonite is 10 to 20 times more radioactive than "the average granitic rock."

Faults

A complex fracture system was formed during the Laramide orogeny as the result of two separate periods of faulting. Early Laramide faults formed before the emplacement of the porphyries; later Laramide faults developed after the intrusion of most of the porphyry sequence. Both periods of faulting preceded the mineralization, but recurrent movement took place during mineralization.

During the earlier period of faulting, persistent, steeply dipping, northwesterly trending fractures were formed. These are members of Lovering's "breccia reef" system. Only two faults of this system--the Blackhawk and the J. L. Emerson--are present in the Central City district. The Blackhawk fault is barren; the J. L. Emerson fault--the northwest extension of the great Gem Lode in the Idaho Springs district (Bastin and Hill, 1917, p. 290-292)--has been a minor source of ore. The faults are right-hand faults, the northeast side having moved northwest relative to the southwest side. The apparent horizontal displacement commonly is several tens to several hundred feet; the vertical component is substantial but less than the horizontal displacement.

During the later period of faulting, a complex mesh-like fracture pattern was developed. The faults generally dip steeper than 60°, and they are less continuous than the older faults; the movement was dominantly strike-slip. Five principal fault sets, distinguished by their trend, are recognized; and, although they appear to have formed essentially contemporaneously from the same regional (?) shear, they generally developed in the following sequence, from oldest to youngest: west-northwest-trending, east-trending, east-northeast-trending, northeast-trending, and north-northeast-trending. The displacement along individual faults of all sets is small; the apparent horizontal displacement rarely exceeds 10 feet. The offset of steeply-dipping porphyry dikes indicates that the component of movement is largely horizontal. The faults of this system originated prior to mineralization, but movements along the fractures took place during the filling.

SUMMARY OF MINERAL DEPOSITS

The mineral deposits of the Central City district are gold-, silver-, copper-, lead-, zinc-, and uranium-bearing veins of early Tertiary age that were formed as fissure-fillings in the faults. Most of the values are in gold. Uranium, a local constituent of the ores, occurs in the same veins as the sulfides.

The veins are similar in mineralogy and structure to the deposits classified by Lindgren (1933, p. 530-532) as mesothermal. They range from single, well-defined fissure-fillings to complex, branching lodes. Although few veins are more than a thousand feet long, some are a mile or more in length and one vein system, the California-Gardner-Mammoth lode, is at least 12,000 feet long. The California vein has been mined to a depth of 2,200 feet, the deepest penetration in the district. The veins average 1 to 3 feet in width, but locally they are 5 to 10 feet or more wide.

A narrow zone of altered wall rock surrounds the veins. A few inches of hard, bleached wall rock adjacent to the vein is partly altered to sericite and locally silica. This zone of hard, altered rock is bordered by a few inches of soft, white rock composed of montmorillonite, illite, and kaolinite that grades outward into fresh rock. Pyrite is disseminated in the hard, bleached rock adjacent to the vein and at places also occurs in the softer clay zone.

The principal metallic minerals are the sulfides and sulfosalts of iron, copper, lead, and zinc; uranium oxide, silver-bearing sulfosalts, and free gold occur locally. Quartz is the dominant gangue mineral, but fluorite and the carbonates ankerite, rhodochrosite, siderite, and calcite are locally present in a few veins.

The veins differ in quantitative mineralogy, and they can be divided into two main types, veins of pyrite type and veins of galena-sphalerite type. Although the two types are distinctive, they grade into one another through gradual changes in the proportions of the constituent minerals; some veins change along strike from one mineralogic type into the other.

The veins of the pyrite type consist mainly of pyrite and quartz, with subordinate, but locally abundant, chalcopyrite, tennantite, enargite, sphalerite, and galena, and sparse pitchblende. The base-metal sulfides and sulfosalts, where present in the veins, occur as two distinctive mineral assemblages, one consisting dominantly of copper minerals and the other consisting of intergrown sphalerite, galena, and copper minerals. The former at places can be worked for copper, and the latter can be mined for lead and zinc as well as copper. Because of these distinctive mineralogic differences, the pyritic veins can be subdivided into three subtypes. These are: subtype A--pyrite veins that consist almost wholly of pyrite and gangue, subtype B--pyrite veins that contain copper sulfides and sulfosalts as the dominant base-metal minerals, and subtype C--pyrite veins that contain roughly equal quantities of sphalerite, galena, and copper minerals. The veins that contain tellurides of gold and enargite (Bastin and Hill, 1917, p. 105) are confined to one part of the district, and they appear to be local variants of the ores, as suggested by Bastin.

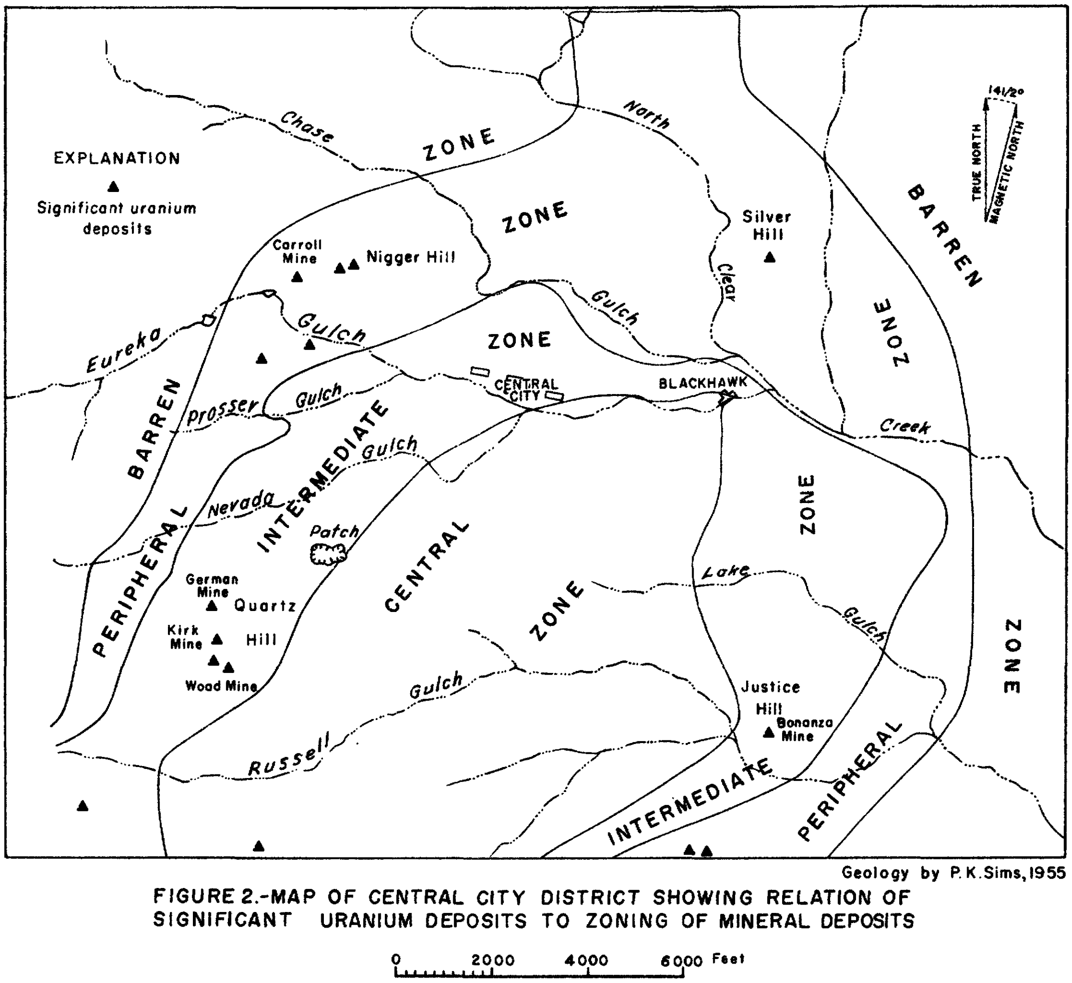
The veins of the galena-sphalerite type contain dominant sphalerite and galena. Pyrite is ubiquitous in these veins, but it is never abundant; copper minerals are minor constituents and pitchblende and silver sulfosalts are rarely present. Carbonates locally are the dominant gangue and barite is present rarely.

A concentric zonal arrangement of the ores is clearly shown by the geographic distribution of the pyrite type and galena-sphalerite type veins (fig. 2). A core area or central zone of pyritic veins, 2 to 3 miles in diameter, is surrounded by an intermediate zone of transitional veins, which in turn is surrounded by a peripheral zone of galena-sphalerite type veins. The central zone contains pyrite veins of subtypes A and B that are chiefly valuable for their gold content. The intermediate zone contains pyrite veins of subtype C. The pyritic veins of subtypes B and C were formed by composite mineralization, as described later under the section on paragenesis. The galena-sphalerite veins of the peripheral zone are mined for base metals as well as gold and silver, but except in the zone of supergene enrichment gold values generally are low. Because the veins of different mineral composition are gradational, the demarcation between zones is necessarily arbitrary. It is probable, but it cannot be conclusively demonstrated, that a depth zoning also is present in the district.

PARAGENESIS OF VEINS

The vein minerals were deposited during three stages of mineralization, from oldest to youngest, a uranium stage, a pyritic stage, and a base-metal stage. The stages probably were not separated by long time intervals, but the mineralization was interrupted by several periods of recurrent movement along the fissures; widespread and intense periods of fracturing separated each of the stages of vein filling, resulting in the local development of composite ores.

The pyritic and base-metal stages of mineralization resulted in the concentric zonal arrangement of the ores. The uranium stage of mineralization, in contrast, was local and resulted in scattered clusters of uranium deposits that show no direct correlation with the zoning pattern. It is presumed that the pyritic and base-metal mineralization stemmed from a single source, probably deep-seated, beneath the core of the district; and that the uranium stage mineralization came from several relatively shallow, separate sources.



Geology by P.K.Sims,1955

FIGURE 2.-MAP OF CENTRAL CITY DISTRICT SHOWING RELATION OF SIGNIFICANT URANIUM DEPOSITS TO ZONING OF MINERAL DEPOSITS

Stages of vein filling

A distinctive suite of minerals was deposited during each of the three stages of mineralization. During the uranium stage, pitchblende and sparse pyrite were formed; during the pyritic stage, pyrite was the only metallic mineral formed; and during the base-metal stage, galena, sphalerite, copper minerals, and rarely, pyrite and sulfosalts were deposited. Most of the gold and silver was introduced during the base-metal stage of mineralization. Quartz accompanied all stages of mineralization; carbonate minerals and fluorite were deposited only during the base-metal stage.

The generalized sequence of deposition of the principal vein-forming minerals, within faults of all fracture sets, is given in figure 3. The vein minerals for which few data are available are not shown in the diagram. Also not shown are the minor periods of fracturing which are important locally in some veins but which do not appear to be regional in scope.

During the uranium stage quartz, pitchblende, and pyrite were deposited. The quartz is gray to white and crystalline, and at most places it was the first mineral to crystallize. Pitchblende began to form somewhat after the beginning of quartz deposition, developing wholly by filling. Most of the pyrite crystallized later than the pitchblende, and in large part it veins both the pitchblende and the quartz; some of it, however, crystallized contemporaneously with the pitchblende. In some veins neither pyrite nor quartz were deposited during this stage. The pitchblende characteristically developed spheroidal forms, and a typical specimen is shown in figure 4. In addition to forming spheroidal grains or aggregates of these grains, it also occurs in vein forms and tiny pellets, and rarely irregular, dendritic forms. The outer surfaces of the veinlets are subrounded, and, like the spheroidal grains, have shrinkage cracks, particularly radial cracks. The pitchblende generally is fractured and broken; at places, as shown in figure 5, the fragments are finely comminuted and partly rotated. In the Wood vein on Quartz Hill (Drake, in press), minor fracturing took place during pitchblende formation, and as a result, brecciated fragments of pitchblende locally are cemented by later pitchblende and quartz.

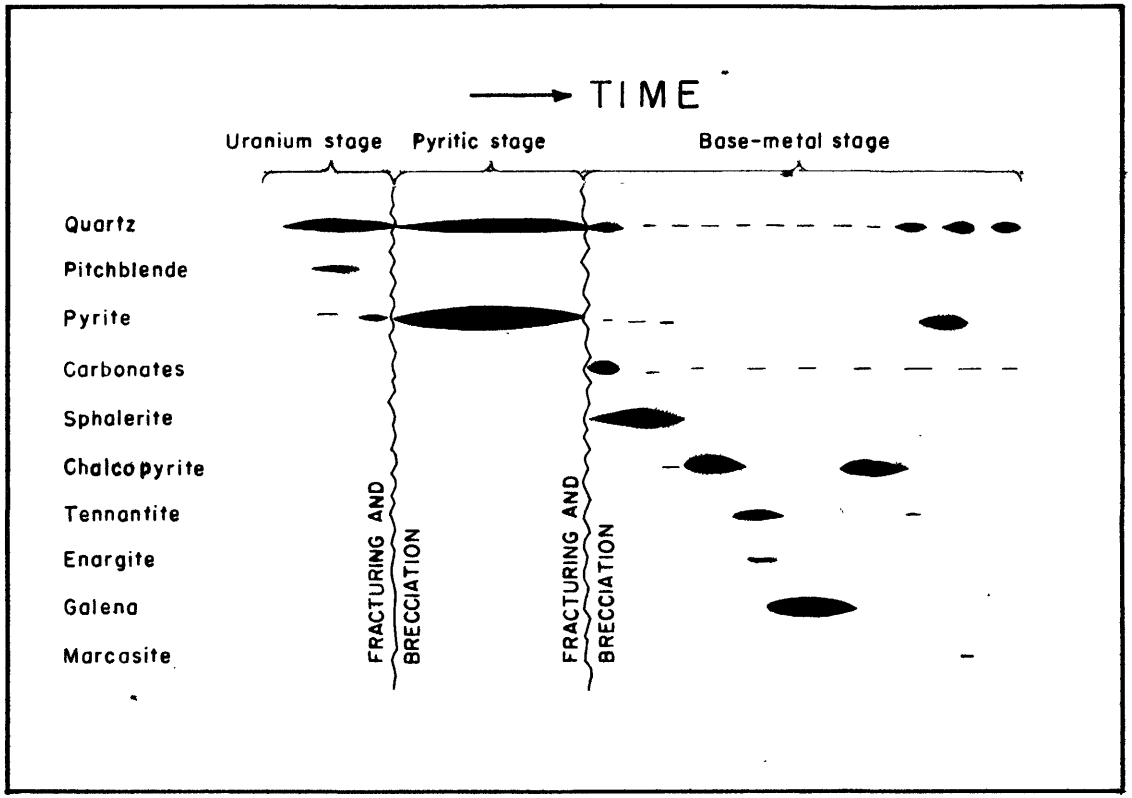


FIGURE 3.-GENERALIZED SEQUENCE OF DEPOSITION OF PRINCIPAL VEIN-FORMING MINERALS, CENTRAL CITY DISTRICT

Figure 4.--Camera lucida drawing of polished surface of pitchblende ore from J. P. Whitney mine, showing spheroidal outline of pitchblende. The pitchblende has radial shrinkage cracks; both the pitchblende and the quartz (black) are fractured and locally brecciated.

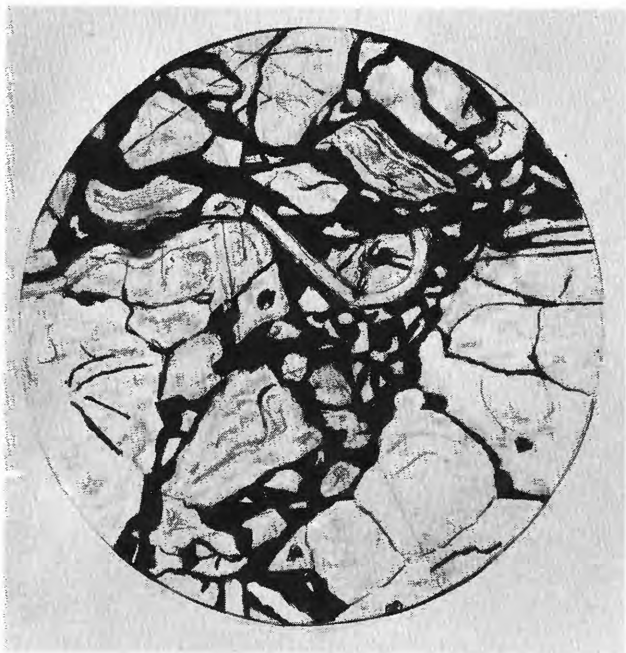


Figure 5.-- Camera lucida drawing of polished surface of pitchblende ore from Wood vein, 583 - level west, East Calhoun mine, showing brecciated pitchblende in a quartz (black) matrix.

A major period of fracturing preceded the pyritic stage of mineralization. It resulted in the brecciation of pitchblende and its associated minerals, as described above, and in the development of conspicuous, widespread, new openings on the faults. During the pyritic stage of mineralization, pyrite and quartz were deposited. Much of the pyrite that is disseminated through the altered wall rocks of the pyrite veins probably was formed before or during this stage, but some of it may have formed before the uranium stage mineralization.

Following another period of recurrent movement, which again reopened the fissures, the minerals of the base-metal stage were deposited. At places these minerals were deposited in openings that crosscut the earlier pyrite-quartz filling or the pitchblende-bearing seams, but at other places they were deposited as crustifications on the older vein minerals. Crystallization during this stage, as determined by the veining of older minerals by younger minerals, followed the commonly observed paragenetic sequence; and, in general, began with sphalerite, which was followed by chalcopyrite and copper sulfosalts, galena, chalcopyrite, and pyrite (fig. 3). In addition to quartz, the carbonates--ankerite, rhodochrosite, siderite, and sparse calcite--formed locally as gangue, and fluorite developed in a few veins in the southeastern part of the district. Some of the quartz of the base-metal stage is cryptocrystalline and colored gray, black, or brown; the fluorite is purple, white, or green, the former being dominant. The fluorite commonly is associated with gold- and silver- bearing tellurides (Bastin and Hill, 1917, p. 114), but it also is associated with base-metal ores.

Most of the gold and silver was introduced with the base-metal stage mineralization, and veins are rarely workable where minerals of this stage are absent. In most veins, only small amounts of gold were deposited during the pyritic stage, and probably little if any of the gold was deposited during the uranium stage of mineralization. The gold is in part free, occurring as extremely fine particles, and in part tied up in all of the vein-forming minerals. The occurrence of high gold values with the base-metal sulfides and sulfosalts and the low gold content of the primary pyritic vein filling was recognized early by the miners. Subsequent studies of the distribution of gold by sampling of the vein filling and by assaying pure mineral separates (Collins, 1903; Bastin and Hill, 1917, p. 116-119) have substantiated these observations.

The interpretation of paragenesis, as presented above, differs in detail from that of Bastin (1915), but in some respects is similar to the views of Alsdorf (1916, p. 270), who, although he did little or no microscopic work, did have the opportunity to examine some pitchblende occurrences in the mines on Quartz Hill. Bastin (1951, p. 4) had few opportunities to study the pitchblende ores in place, and his studies largely were of specimens submitted by the mining men of the district. Bastin (1915, p. 5) believed "that the pitchblende was deposited during the earlier or pyritic mineralization, that it was afterward fractured, and that the fractures thus formed were filled by sulphides of the later of lead-zinc mineralization." He considered the pitchblende merely a local and unusual variation of the main sulfide mineralization of the region. Alsdorf (1916, p. 270), on the basis of field examinations, noted that the "pitchblende veins are cut across, followed, and obliterated by the subsequent faulting and vein filling of the period of the precious metal veins."

Origin of vein types of contrasting mineralogy

The pyritic and base-metal stages of mineralization were of broad areal extent and resulted in the concentric zonal arrangement of the ores of the district; the uranium stage of mineralization, on the other hand, was relatively local in extent, and the deposits formed by this mineralization do not have a definite spatial relationship to the mineral zoning. The distribution of the dissimilar types of sulfide veins can be accounted for by assuming that the source of the fluids that deposited pyritic stage- and base metal stage-minerals was beneath the central zone of the district, and that the fluids changed with time from predominantly iron-depositing (pyritic stage) to predominantly base metal-depositing (base-metal stage). The uranium-depositing fluids can logically be assumed to have come from several local, relatively shallow sources asymmetrically arranged with respect to the dominant, deep-seated, central sulfide source.

The pyritic stage mineralization was most intense in the core of the central zone; to judge from the quantity of pyrite in the veins, it decreased in intensity outward from the core. Little pyrite was deposited in the peripheral zone. In the core of the central zone (fig. 2) the veins are on the average wider than most pyrite type veins of the district, the walls are poorly defined, and the wall rock and "horses" within the veins are intensely pyritized and altered. Replacement was an important process in the formation of these veins. Outward from the core, the pyrite-quartz veins become narrower, the walls become more distinct, and the wall rocks less intensely pyritized. The veins outside of the intermediate zone (fig. 2) were not filled with pyrite, and only sparse pyrite formed in the altered wall rock bounding the veins.

The minerals of the base-metal stage were deposited farther from their source than the pyrite. In the outer parts of the district, where pyrite had not been deposited in appreciable quantities, the fissures were filled by base-metal sulfides to yield galena-sphalerite type veins; inward from the periphery, the pyritic type veins, where reopened, were mineralized with base metals to produce composite ores.

The minerals deposited during the base-metal stage differed quantitatively from area to area. In the central zone, where pyrite veins were reopened, copper-bearing minerals--chalcopyrite, tennantite, and locally enargite--were deposited in the openings; sphalerite and galena rarely formed in significant quantities. In the intermediate zone, as defined on figure 2, sphalerite and galena, as well as chalcopyrite and tennantite, were deposited in varying proportions; and in the peripheral zone, sphalerite and galena were dominantly formed, and copper minerals were rarely deposited in commercial quantities. Gold was precipitated with the sulfides (and gangue) in all environments, but silver, largely as sulfosalts, was deposited predominantly with the sulfides mainly in the intermediate and peripheral zones.

The uranium stage mineralization, because it was relatively local in areal extent, formed clusters of uranium deposits, erratically distributed with regard to the mineral zoning pattern. The principal areas of uranium veins are in the Quartz Hill-Upper Russell Gulch area and the Eureka Gulch area (fig. 2). Areas containing fewer deposits are present in the Silver Hill and lower Russell Gulch areas. This concept of the relation of uranium to hypogene mineral zoning differs from that presented previously by Leonard (1952) and Armstrong (1952). These writers concluded that the uranium deposits of the Central City district occurred in the intermediate zone, for at the time of their studies the known deposits (Quartz Hill) were restricted to this part of the zoning pattern.

To account for the zonal distribution of the vein types and for the textural and structural relations of the ores, it is postulated that the pyritic and base-metal stages of mineralization resulted from fluids given off from a common, deep-seated source beneath the core of the district. Initally the fluids deposited iron, to form pyrite type veins; later they deposited mainly copper, zinc, and lead to produce composite type veins, as defined by Bastin and Hill (1917, p. 112) and galena-sphalerite type veins. The nature of the fluids changed with time at the source, and the marked change from an iron-depositing to a base-metal-depositing solution coincided with a major period of recurrent fault movement that reopened the fissures. It is the writer's belief that during the deposition of the pyritic vein filling the channelways gradually were clogged with the material and a restraining pressure was built up on the source magma. The fault movements reopened the fissures locally and facilitated the release of the restraining pressures at depth, permitting the escape of new ore fluids into the openings. In the meantime sufficient time had elapsed to change the temperature, pressure, and composition of the ore fluid so that the openings were filled with base-metal sulfides; little pyrite was deposited again until near the end of mineralization. During the base-metal stage of mineralization copper preferentially was deposited in openings near the apex of the source to yield the copper-rich pyritic veins; lead, zinc, and copper in nearly equal amounts were deposited in openings further from this source.

Evidence is strong that most of the uranium in the early Tertiary magma sequence was split off during differentiation into the magma fraction that yielded the quartz bostonites; and uranium mineralization was related to several local, probably shallow quartz bostonite magma sources. Phair (1952) has demonstrated that the enrichment of uranium (and thorium) in the Ca-poor magma, that formed quartz bostonite, was considerably greater than that of the other magmas. Further he and others, particularly Alsdorf (1916), have shown that most of the known uranium occurrences in the district are spatially associated with centers of quartz bostonite intrusion. The implication of the field and chemical evidence is that the uranium-rich fluids were given off by the cooling quartz bostonite masses. The ore fluids moved upward along the porphyry dikes and other zones of weakness and were deposited in faults within short distances of these channelways.

STRUCTURE OF URANIUM DEPOSITS

Pitchblende and, at places, secondary uranium minerals occur in several vein sets as local, generally small shoots or lenses. At places the uranium ore shoots are closely related spatially to precious-metal- bearing sulfide ore shoots, but elsewhere they are isolated. Because the pitchblende formed almost wholly as a vein filling, the ore bodies were localized by structurally controlled openings.

Relation of uranium deposits to fracture sets

Uranium deposits are present locally along four of the six principal fracture sets; no deposits have been found, within the district, in the breccia-reef-type faults or in the north-northeast-trending fracture set. Commonly within any area of uranium deposits the metal occurs in two or more different fracture sets.

Twenty-two veins in the district contain uranium deposits of known significance or of potential importance. Ten of these deposits are in veins that trend N. 75° E. to N. 80° E., five are in veins that trend N. 80° W. to N. 85° E., five are in veins that trend N. 55° to N. 70° E., and two are in veins that trend N. 70° W. The other uranium occurrences are in the same fracture sets as the significant uranium deposits.

In both the Quartz Hill and the Eureka Gulch areas, which contain the largest number and the most important deposits, the uranium occurrences are along two or more fracture sets, some of which intersect. At Quartz Hill, deposits in the German-Belcher, Kirk, and Wood veins have been mined (Bastin and Hill, 1917). At Nigger Hill, in the Eureka Gulch area (Sims, Osterwald, and Tooker, 1955, pl. 1), deposits occur in three different fracture sets; the deposits in each of the sets are proved or are of probable economic importance.

All of the fracture sets were present prior to uranium stage mineralization, with the possible exception of the north-northeast-trending fracture set--the youngest of the fractures. Mineralization of the fractures was dependent, therefore, on the presence of local openings.

Ore shoots

The pitchblende, like the precious-metal and base-metal ores of the district, is not regularly present throughout the vein, but instead occurs in ore shoots or smaller lenses, pods, and stringers that are separated by vein filling that is essentially barren of uranium. Within the shoots pitchblende forms discontinuous bodies--lenses and pods--that pinch and swell. Some of these masses mined on Quartz Hill were very high in grade, but the bodies currently (1955) being mined, for the most part, contain ore that averages less than one percent uranium.

The ore shoots in the district are small, measuring at most a few tens of feet in maximum dimension and a foot or less in thickness. Many ore shoots occur systematically within the vein. An example of deposits of this type in the Carroll mine on Nigger Hill, within the Eureka Gulch area, is described below.

The uranium ore shoots in the Carroll vein, which strikes northwest and dips about 70° NE, are arranged en echelon within a westward-plunging zone of favorable ground (or zone of ore shoots) that essentially coincides with a precious metal-base metal ore shoot (fig. 6). Individual shoots vary somewhat in size. The largest shoot, which is on the 228-level, has a height of about 50 feet, a stope length

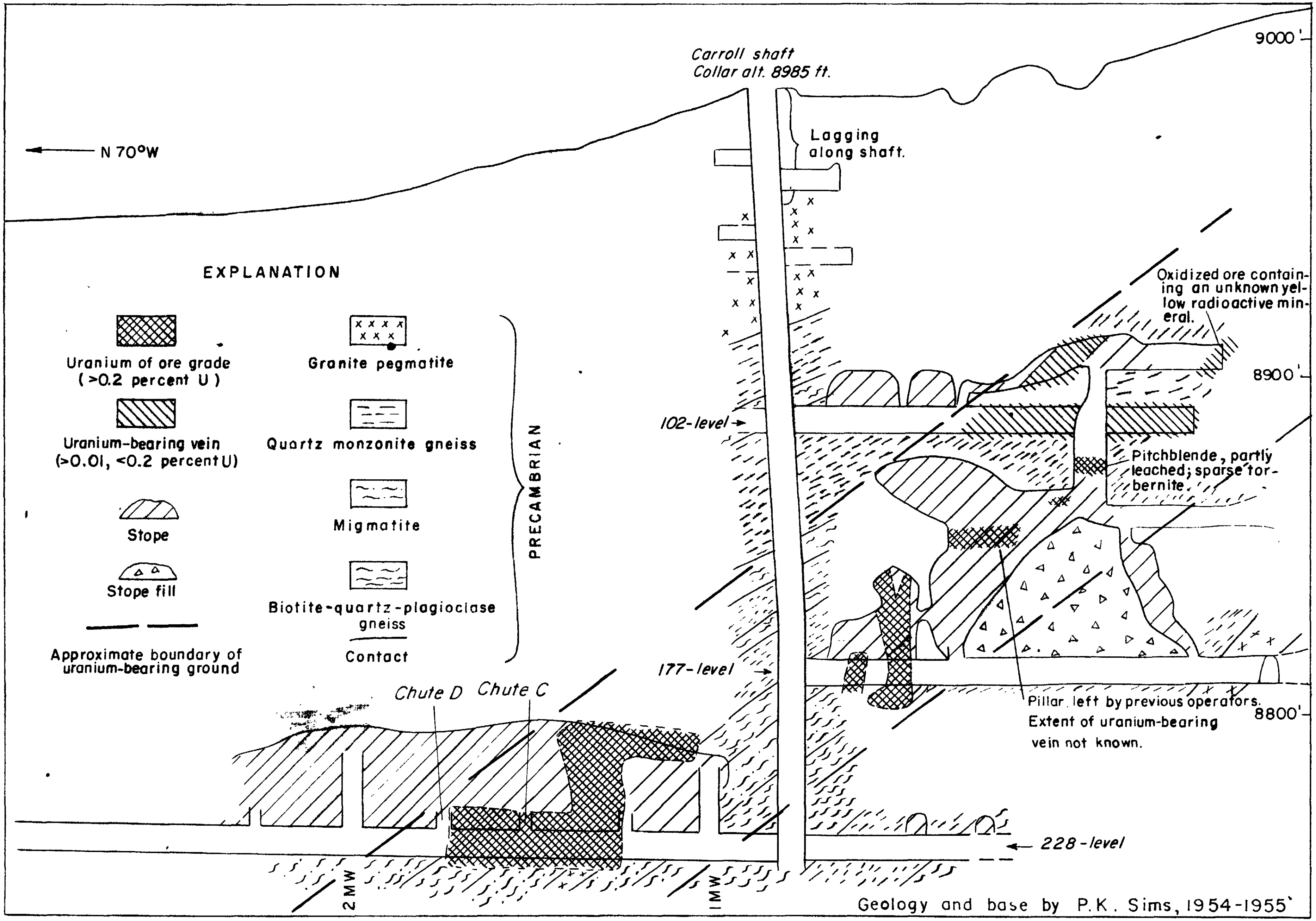
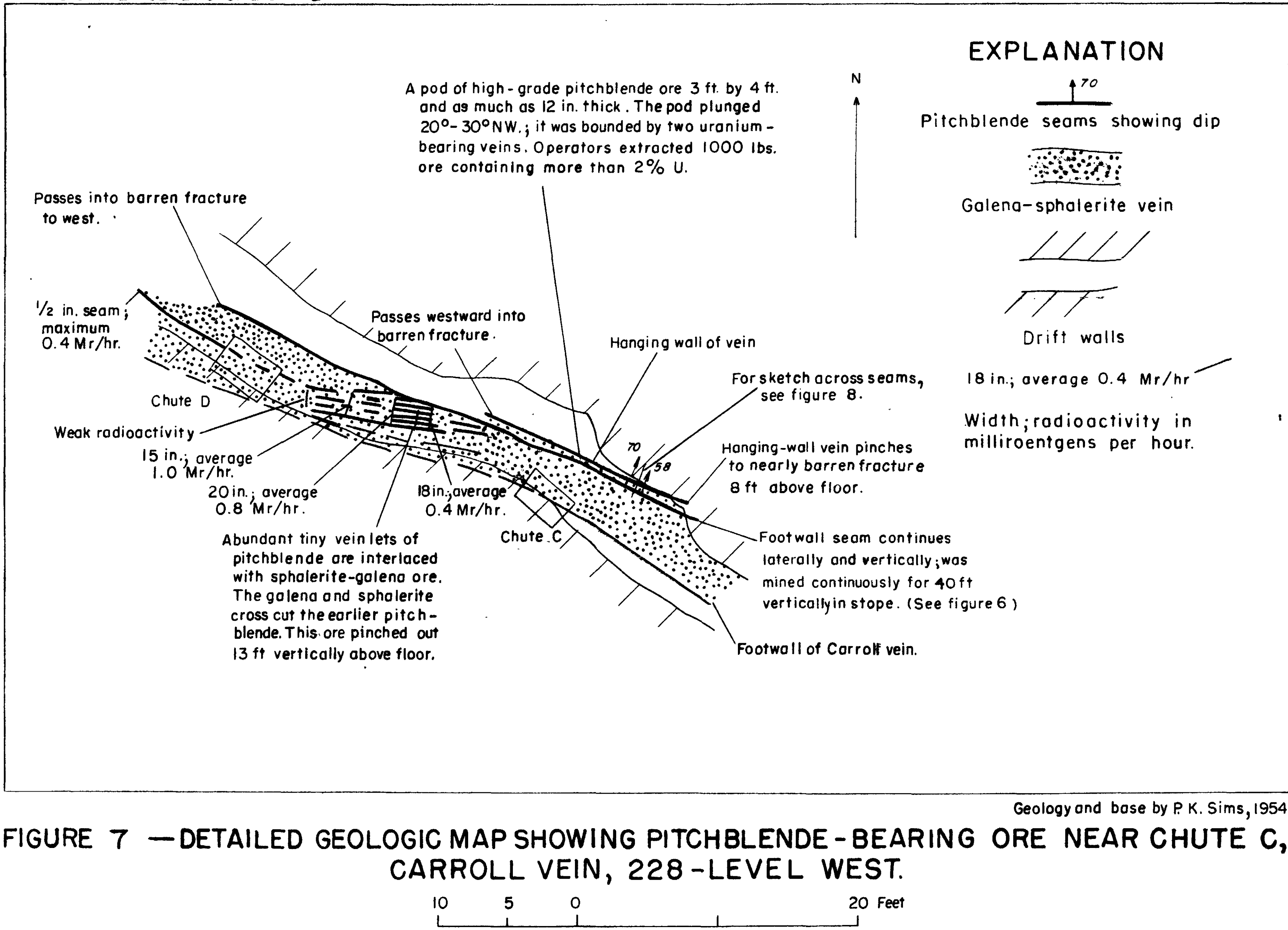


FIGURE 6 — VERTICAL LONGITUDINAL PROJECTION OF CARROLL MINE, CENTRAL CITY DISTRICT, GILPIN COUNTY, COLORADO.

of as much as 50 feet, and an average thickness of about six inches. A smaller shoot, having a maximum horizontal length of only about 11 feet, was mined east of the shaft on the 177-level. Other small shoots probably were mined previously further east along the vein. It is likely that additional shoots of comparable size and shape will be found along the projection of the zone of ore shoots at greater depths.

Within the Carroll ore shoots the pitchblende occurs in seams, veinlets, and pods. The ore within the shoot on the 177-level occurs mainly as a tabular layer that is one to four inches thick and as much as 11 feet in breadth. The ore layer lies about six inches above the vein footwall and is separated from it by radioactive gouge. In the lower part of the shoot, mined in a small underhand stope (fig. 6), a pod or kidney of pitchblende ore 12 inches in width occurs at the junction of two inch-thin pitchblende-bearing veinlets; the pod plunges 18° N. 60° W. The ore within the shoot on the 228-level is largely a tabular seam or sheet of varying thickness, but in part the ore occurs as pods at the junction of seams, and as crosscutting seams. Figure 7, a plan of the pitchblende-bearing vein on the 228-level, shows in detail the pitchblende occurrences and their relation to the galena-sphalerite vein. The pitchblende near chute C is on the hanging (or north) wall of the vein, in two closely-spaced seams. The outermost seam, which forms the hanging wall of the vein, pinches in short distances both laterally and vertically. The inner seam is more continuous and extends as a tabular layer to the top of the stope, where it pinches out. In the drift, the seam is an inch to three inches thick, but it is wider in the stope, averaging about six inches thick, and at one place is as much as 15 inches thick. Locally on the level, as shown in figure 8, steep cross-fractures between the two seams, which converge slightly near the floor, also contain small seams of pitchblende, the whole locally constituting ore. At the junction of the two seams, opposite chute C, a pod of pitchblende ore, 3 feet by 4 feet by 1 foot thick, is present. This pod plunges 20°-30° NW., in the same direction as the pod encountered on the 177-level. Between chuts C and D on the level (fig. 6) the pitchblende occurs in numerous, inch-thick seams that lie at an acute angle to the trend of the Carroll vein. This zone is as much as 15 inches wide; it pinches out above five feet above the back of the drift. The seams are cut, broken, and locally obliterated by the later galena-sphalerite ore that constitutes the bulk of the Carroll vein filling.



Geology and base by P. K. Sims, 1954.

FIGURE 7 —DETAILED GEOLOGIC MAP SHOWING PITCHBLENDE-BEARING ORE NEAR CHUTE C, CARROLL VEIN, 228-LEVEL WEST.

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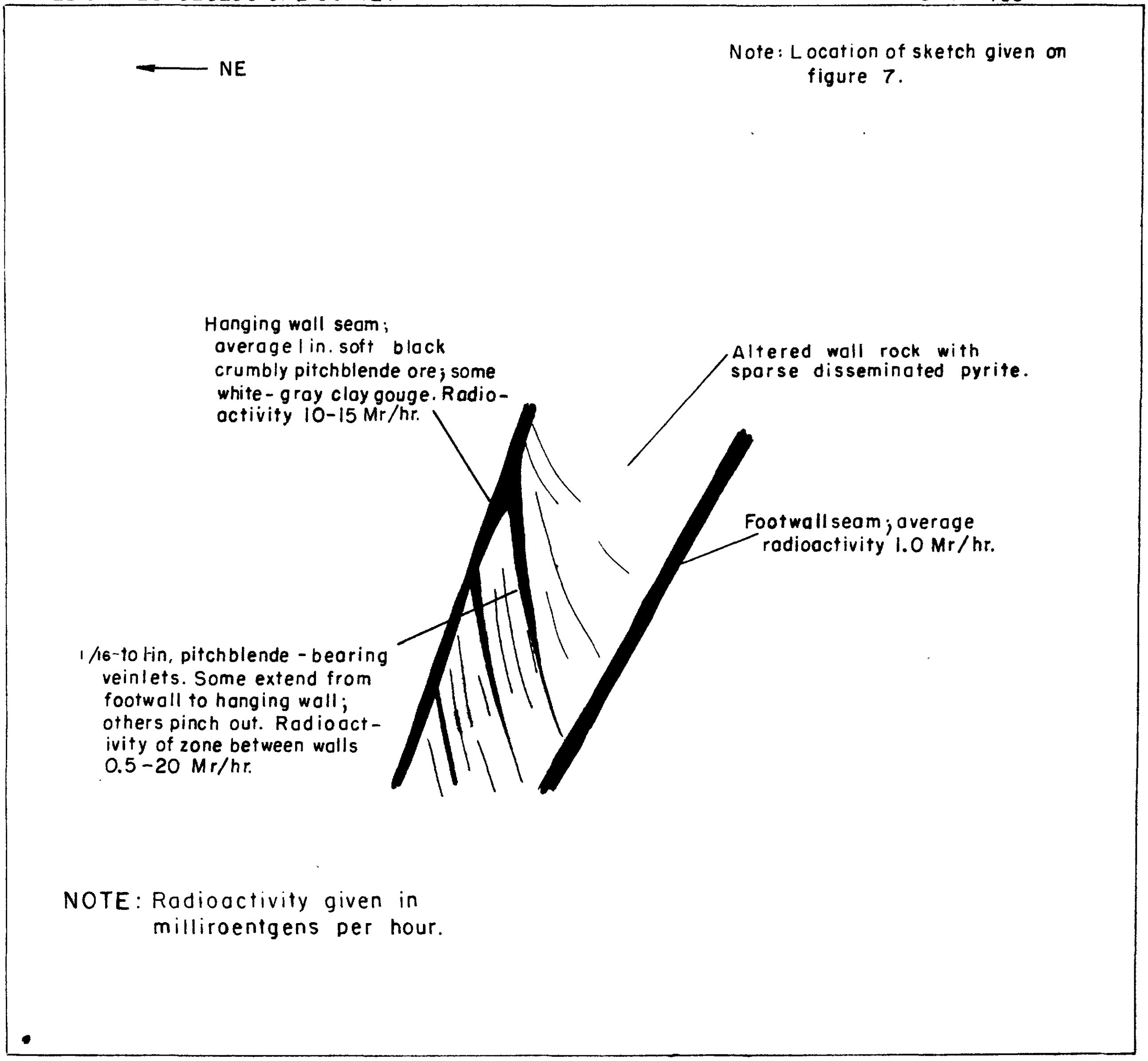
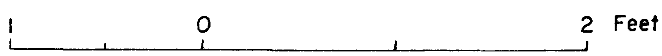


Geology by P. K. Sims, 1954

FIGURE 8. —SKETCH SHOWING CHARACTER OF PITCHBLENDE-BEARING VEINLETS BETWEEN FOOTWALL AND HANGING WALL SEAMS, 228-LEVEL WEST, CARROLL MINE.



The detailed structure of the pitchblende bodies along the veins on Quartz Hill is little known, as they were mined long ago. It is probable that most of the pitchblende was deposited in small, high-grade lenses and kidneys rather than in shoots of the size as those found at the Carroll mine; possibly, however, the kidneys were sufficiently concentrated to constitute ore shoots. In the Wood vein (Bastin and Hill, 1917, p. 245) known individual pitchblende bodies are small and range from a few pounds to about five tons in weight. Recent exploration of the vein from the 583-level of the East Calhoun mine disclosed two small bodies of pitchblende ore, one on the level 506 feet west of the crosscut from the East Calhoun shaft and the other in a small stope above the level (Drake, in press). The lenses are separated by non-uraniferous vein material. The pitchblende ore lens on the level is 8 feet long, about 8 feet high, and one to 8 inches thick; it appears to plunge about 50° W. Similarly, the deposits in the Kirk vein, which have supplied most of the uranium metal from the district, are reported (R. R. Hinckley, oral communication) to occur as small lenses, seams, and kidneys, generally adjacent to the country rock on the hanging wall of the gold-bearing vein, which are separated by non-uraniferous vein. At places the ore forms kidneys as much as a foot thick; one single piece of high grade pitchblende ore was removed that measured 2 feet 8 inches by 1 foot (Moore and Kithil, 1913, p. 44).

An oxidized ore shoot being mined on Silver Hill, consisting of kasolite, metatorbernite, and meta-autunite--alteration products of pitchblende--structurally is similar to the pitchblende ore shoots. The edges of the shoot are not as sharply defined, however, as the primary ore shoots.

Localization of ore

The structural features which provided openings for the deposition of the metal were probably most important in the localization of the uranium deposits, but proximity of the openings to the source of the fluids also was a factor, as discussed previously. There is no direct evidence within the district that any particular type of wall rock provided a more favorable chemical depositional environment than others.

The structural features that provided openings for the deposition of uranium include the direction and amount of fault movement, the irregularities of the fissures themselves, and the lithology and structure of the wall rocks. It is probable that the same types of structures that controlled the deposition of the precious metal-bearing sulfide deposits (Lovering and Goddard, 1950, p. 94-99) also were responsible for the localization of uranium deposits; for various reasons, however, the structural controls of the uranium deposits are much less well known; only a few uranium deposits have been available for detailed study; the important deposits on Quartz Hill were mined out even prior to Bastin's investigations in 1911 and 1912.

The uranium does not necessarily occur in close association with the base metal ores, and at many places it can be demonstrated that it is in different fractures within the veins than these ores. Only where the post-uranium fractures cut or follow the uranium-bearing seams, are the two types of deposits intimately associated.

Irregularities along the fissures that provided open space for uranium filling were formed at vein intersections, at the junctions of small fractures within a main vein or lode, and at the sites of small-scale deflections in strike or dip of the faults. At the Bonanza mine on Justice Hill, a pitchblende deposit occurs at the junction of two veins--the Bonanza and the Shamrock--where the ground was intensely sheared and broken. The deposit appears to rake essentially parallel to the vein junction. At many places within all of the known uranium deposits the intersections of minor fractures within the veins were the loci of ore deposition, and not uncommonly pods or other enlargements occur at these junctions. Examples from the Carroll vein were given previously. The occurrences related to deflections of the filled fissures are minor and so far as known constitute small pods and lenses rather than deposits of shoot dimensions.

In some deposits it can be shown that the structure and physical character of the wall rock, rather than irregularities along the fissures themselves, were important factors in the localization of ore bodies. At the Carroll mine the zone of favorable ground (or zone of uranium ore shoots), as well as the base-metal ore shoot (fig. 6), plunges moderately westward, essentially parallel to the trace of the intersection of the vein with the layering of the wall rocks. The wall rocks--quartz monzonite gneiss, granite pegmatite, and biotite-quartz-plagioclase gneiss--are interlayered on a fine scale. These rocks differ slightly in competence to fracturing, and the greatest weakness in this interlayered sequence occurs along the contacts. Consequently, maximum breakage and brecciation produced by the Carroll fault occurred along the intersection of the fault with the rock layering. The position of individual en echelon uranium ore shoots, which plunge down the dip of veins, however, cannot be explained wholly on this basis; possibly they owe their position to minor deflections along the filled-fault, but this has not been proved. Collins (1930, p. 260-261) has noted that all the important gold ore shoots in the Nevada Gulch area, about midway between the Eureka Gulch and Quartz Hill areas, rake parallel to the intersection of the vein with the layering in the Precambrian wall rocks; and during the current studies in the Central City district the writer has found that this structural control combined with vein intersections are the two dominant factors in base-metal ore localization within the district.

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