# Thorium and Rare Earth Minerals in the Powderhorn District, Gunnison County, Colorado

By Jerry C. Olson and Stewart R. Wallace



*Trace Elements Investigations Report 353*



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# GUNNISON COUNTY, COLORADO

By Jerry C. Olson and Stewart R. Wallace

## ABSTRACT

Thorium has been found since 1949 in at least 33 deposits in an area 6 miles wide and 20 miles long in the Powderhorn district, Gunnison County, Colo. The district is composed largely of pre-Jurassic metamorphic and igneous rocks, which are chiefly if not entirely pre-Cambrian in age. The metamorphic and igneous rocks are overlain by sandstone of the Morrison formation of Jurassic age, and by volcanic rocks of the Alboroto group and Hinsdale formation of Miocene and Pliocene (?) age, respectively.

The thorium deposits occur in or near alkalic igneous rocks in which such elements as titanium, rare earths, barium, strontium, and niobium occur in greater-than-average amounts. The greatest mass of the alkalic igneous rocks -- the Iron Hill composite stock -- occupies an area of 12 square miles in the southeastern part of the district. The age of the thorium deposits, like that of the alkalic igneous rocks, is not known other than pre-Jurassic.

The thorium veins and mineralized shear zones range from a few inches to 18 feet in thickness and from a few feet to 3,500 feet in length. The veins are composed of calcite, dolomite, siderite, ankerite, quartz, barite, pyrite, sphalerite, galena, goethite, apatite, alkali feldspar, and many other minerals. The thorium occurs at least partly in thorite or hydrothorite. Sparse xenotime has been tentatively identified in one deposit.

Several minerals containing rare earths of the cerium group as major constituents are found in carbonate veins near Iron Hill. Bastnaesite has been identified by X-ray methods, and cerite and synchisite are probably present also. The fluorapatite in some veins and in parts of the carbonate rock mass that occupies 2 square miles in the central part of the Iron Hill complex contains rare earths of the cerium group, generally in amounts of a fraction of a percent of the rock.

The radioactivity of the deposits appears to be due almost entirely to thorium and its daughter products. The $ThO_2$ content of selected high-grade samples from the Little Johnnie vein is as much as 4 percent. The $ThO_2$ content of the veins is generally less than 1 percent, however, and is only 0.05 to 0.1 percent in many of the veins studied.

The Little Johnnie vein, which was mapped in detail, can be traced discontinuously for a distance of more than 3,500 feet. The thorium-bearing material occurs as irregular veinlets and thin films introduced into the fault zone. The mineralized shear zone ranges from less than 6 inches to 5 feet in thickness. Near its west end the vein is broken by many faults in a zone that marks the edge of a roughly circular fault block, $1\frac{1}{2}$ miles in diameter, that has dropped 1,000 feet or more since the deposition of Miocene volcanic rocks that now floor the Milkranch basin.

## INTRODUCTION

Thorium deposits were discovered in the Powderhorn district in 1949. This district has long been known for its occurrences of alkalic igneous rocks, of which the best known is the Iron Hill complex (Larsen, 1942).

Some of these alkalic rocks contain titanium, barium, strontium, rare earths, thorium, and niobium in greater percentages than those of most igneous rocks. A study of the thorium deposits was undertaken to obtain more information on the geologic relation of minor elements, particularly rare earths and thorium, to alkalic igneous rocks, and to evaluate the economic significance of the thorium deposits.

## Geographic setting

The Powderhorn district is an elongate area about 20 miles long and 6 miles wide that trends northwestward from the vicinity of Iron Hill to the Lake Fork of the Gunnison River, in the southwestern part of Gunnison County, Colo. (fig. 1). Powderhorn, a small settlement in the south-central part of the district, is about 30 miles by road southwest of Gunnison, the nearest town.

The district is drained by three northward-flowing tributaries of the Gunnison River: Willow Creek, Cebolla Creek, and the Lake Fork of the Gunnison. These streams and their tributaries are deeply incised and in places have cut canyons as much as 1,000 feet deep in the pre-Cambrian rocks which underlie much of the district. The interstream areas consist of dissected mesas that slope gently northward toward the Gunnison River. Many of these are capped by remnants of nearly flat-lying Mesozoic sedimentary rocks and Tertiary volcanic rocks. The altitude ranges from 7,500 feet on the Lake Fork of the Gunnison to more than 10,000 feet in the southeastern part of the district.

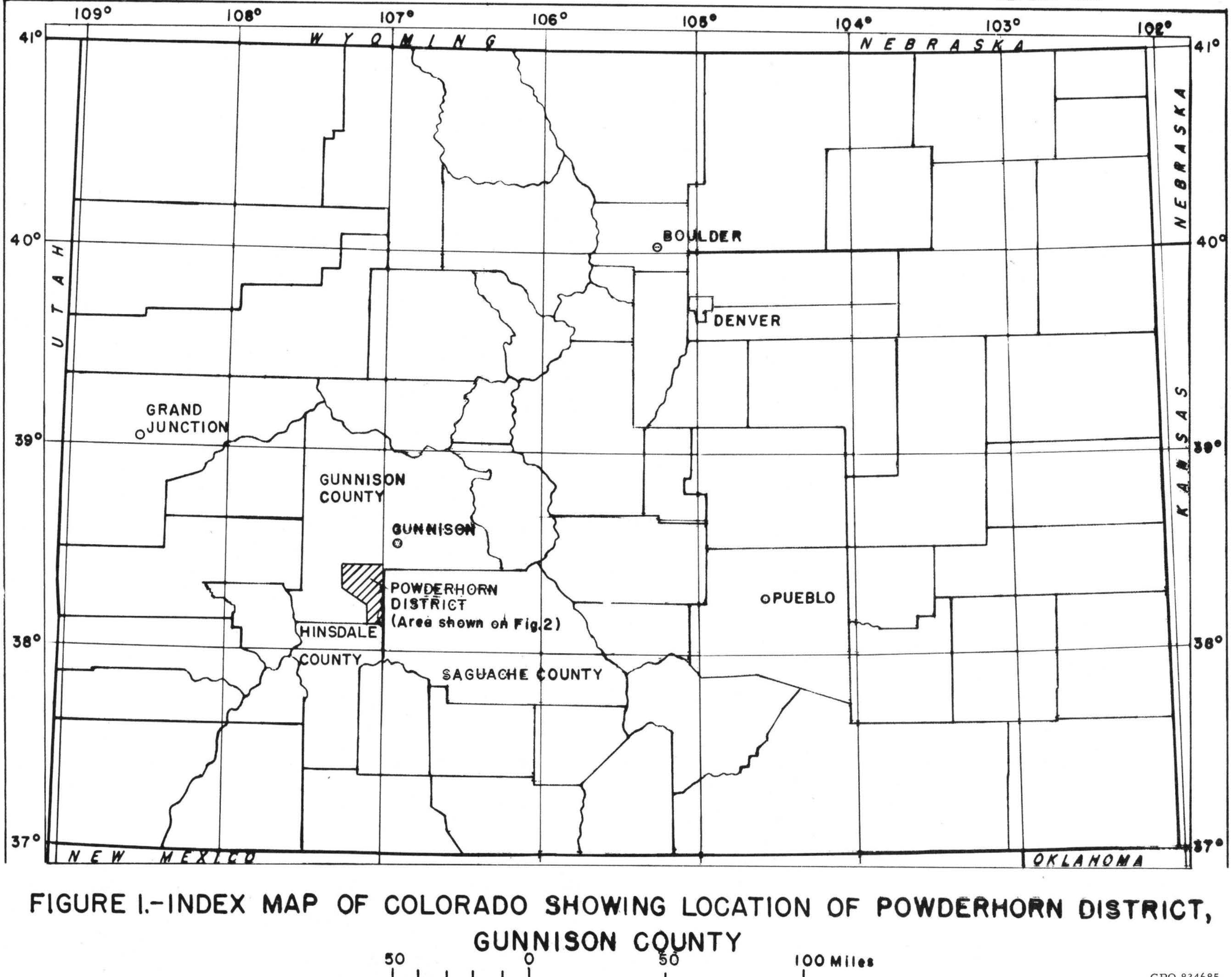


FIGURE 1.-INDEX MAP OF COLORADO SHOWING LOCATION OF POWDERHORN DISTRICT, GUNNISON COUNTY



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## Previous work

The first comprehensive geologic study of the region embracing the Powderhorn district was made by Hunter (1925), who studied the pre-Cambrian rocks of the Gunnison River region in 1911-1913. In part of this work Hunter was associated with E. S. Larsen, Jr., and Whitman Cross (Cross and Larsen, 1935). Larsen also studied the area subsequently, and his Professional Paper (Larsen, 1942) on the Iron Hill complex contains a wealth of data on the petrography, mineralogy, and geochemistry of the alkalic rocks.

In 1950, soon after the discovery of thorium deposits in the district, J. W. Adams and F. B. Moore of the U. S. Geological Survey examined the Little Johnnie, Jeanie, and Red Rock claims. In 1951, during reconnaissance for radioactive materials in the San Juan Mountain region, W. S. Burbank examined thorium deposits in the Lake Fork-Dubois area and veins in the vicinity of Iron Hill (Burbank and Pierson, 1953).

## Field work and acknowledgments

This report is the result of a brief reconnaissance for thorium-bearing deposits by J. C. Olson during the period August 11-25, 1952, and plane-table mapping of the Little Johnnie thorium deposit by S. R. Wallace and J. E. Roadifer from July 1 to August 6, 1953, with the assistance of J. C. Olson for 8 days. Notes, sketch maps, and other unpublished data obtained by W. S. Burbank in 1951 and J. W. Adams and F. B. Moore in 1950 contributed much to the field study and the preparation of the report. In the laboratory, samples from the Powderhorn district were studied by chemical, spectrographic, and X-ray methods.

The investigations of the Powderhorn thorium deposits were made by the U. S. Geological Survey on behalf of the Division of Raw Materials of the U. S. Atomic Energy Commission.

## GENERAL GEOLOGY

Thorium deposits have been found in an area 6 miles wide and 20 miles long, extending from the Iron Hill complex to the Lake Fork of the Gunnison River (fig. 2). The area is underlain chiefly by pre-Cambrian metamorphic and igneous rocks. The metamorphic rock complex is intruded by pre-Jurassic alkalic igneous rocks. Flat to gently dipping strata of the Morrison formation, of Jurassic age, overlie the complex of metamorphic and igneous rocks. Tertiary volcanic rocks were deposited on an early Tertiary erosion surface that in places nearly coincides with the late Paleozoic or early Mesozoic erosion surface on which the Morrison formation was deposited.

### Pre-Cambrian metamorphic complex

The pre-Cambrian rocks, as mapped by Hunter (1925), are divided into the Black Canyon schist, the Dubois greenstone, and the Powderhorn granite group. In the Powderhorn district (fig. 2) the Black Canyon schist of Hunter (1925) is dominantly biotite schist, quartz-mica schist, and micaceous quartzite. Granite gneiss and amphibole schist make up a small part of the Black Canyon schist.

The Dubois greenstone occurs in an east-trending band 1 to 4 miles wide in the north-central part of the district. The dark green rocks of this formation consist chiefly of hornblende schist, hornblende gneiss, amphibolite, metadiorite, and chlorite schist.

The Black Canyon schist occupies most of the pre-Cambrian area north of the belt of Dubois greenstone, whereas rocks of the Powderhorn granite group predominate to the south.

The Powderhorn granite group of Hunter (1925) comprises granitic rocks of relatively uniform composition but includes such diversified textural varieties as schistose rhyolite porphyry, coarsely porphyritic granite, and aplite. The Powderhorn granites cut and are, therefore, younger than the Dubois greenstone, but some foliated amphibolite appears to form dikes cutting Powderhorn granite. The porphyritic texture and quartz phenocrysts of the metarhyolite porphyry suggest that this variety was either extrusive or intruded at relatively shallow depth. Other facies of the Powderhorn granite group are almost certainly plutonic.

With the exception of some facies of the Powderhorn granite, all the rocks described above are well foliated and have been metamorphosed to a much higher degree than any of the lower Paleozoic sedimentary rocks of central Colorado and the San Juan Mountain.

## Intrusive rocks

Many dikes and small irregular bodies of poorly foliated to massive igneous rock intrude the pre-Cambrian metamorphic and igneous complex. These igneous rocks include diorite, quartz diorite, gabbro, syenite, augite syenite, shonkinite, and the alkalic rocks of the Iron Hill complex (fig. 2). The Iron Hill complex (Larsen, 1942) is a composite stock that occupies an area of about 12 square miles in the southeastern part of the district. It is composed of about 70 percent pyroxenite, 17 percent dolomitic carbonate rock, and uncompahgrite (melilite rock with pyroxene and magnetite), ijolite (nepheline-pyroxene-garnet rock), soda syenite, nepheline syenite, nepheline gabbro, and quartz gabbro.

The Iron Hill stock has been dated as pre-Jurassic (Larsen, 1942, p. 2) on the basis of heavy minerals in the basal Morrison beds that are characteristic of those found in the Iron Hill alkalic rocks. The age relations of the Iron Hill rocks to the dikes and irregular masses of non-foliated diorite, gabbro, and the variety of syenitic rocks ranging from leucosyenite to shonkinite is unknown. The chemical and structural features of this group, however, are generally similar to those of the Iron Hill rocks and indicate a probable genetic relationship. According to Hunter (1925, p. 78), quartz diorite and augite syenite in Wildcat Gulch are cut by pegmatites. If these pegmatites are pre-Cambrian in age, as is commonly believed for pegmatites in this region, the quartz diorite and the augite syenite may also be pre-Cambrian. The age is speculative, however, for the pegmatites in the district may be of more than one age.

## Marble of Iron Hill

A mass of marble occupies about 2 square miles near the center of the Iron Hill complex. The carbonate mineral in the marble is chiefly dolomite, but some calcite is present (Larsen, 1942, p. 5). Apatite, which contains small amounts of rare earths, makes up several percent of the carbonate rock; other accessory minerals locally present include phlogopite, magnetite, aegirite, and soda amphibole.

The marble is generally massive but locally has a conspicuous steeply-plunging to vertical lineation formed mainly by streaks of apatite along shear planes; the lineation is especially well developed near the margins of the carbonate mass. The marble is not bedded, but in a few places, as at locality 13 (fig. 2) and in the isolated mass (locality 12) south of the mouth of Beaver Creek, it has a layering or banding resulting from streaks of such minerals as phlogopite and magnetite.

Numerous carbonate veins similar in composition to the large carbonate mass of Iron Hill cut the pyroxenite and other intrusive rocks of the Iron Hill stock. Several small isolated bodies of carbonate rock, generally similar to the marble of Iron Hill, occur both in the pyroxenite and in the pre-Cambrian rocks outside the Iron Hill complex; a mass of white marble at least 200 feet in diameter is enclosed in Powderhorn granite at the locality indicated by a prospect pit 1 mile N. 45 E. of Powderhorn (fig. 2).

Carbonate rocks are locally both older and younger than the alkalic dike rocks. The numerous carbonate veins that cut the pyroxenite and other igneous rocks are clearly younger than the main mass of the stock. The reverse age relations are shown at a prospect pit in Sammons Gulch 1.3 miles east of Powderhorn, where a carbonate body about 20 feet wide is cut by pyroxenite dikes 1 to 8 inches thick (Larsen, 1942, p. 4-5). At a locality just south of the mouth of Beaver Creek (no. 12, fig. 2), an outlying body of carbonate rock and the pyroxenite adjacent to it are cut by thin micaceous dikes. The relations at these two localities show that at least some dikes are younger than some carbonate rock.

The age relationships of the large Iron Hill carbonate mass are not known because of inadequate exposures, and the origin is controversial. Larsen favored the concept that the main mass represents a large hydrothermal deposit formed in the throat of a volcano, though it may have been intruded as a carbonate magma or it may be an inclusion of pre-Cambrian marble (Larsen, 1942, p. 6-9).

## Sedimentary and volcanic rocks

The metamorphic rock complex is overlain unconformably by thin remnants of sandstone and siltstone of the Morrison formation of Jurassic age, which were deposited on a nearly flat surface. The Mancos shale of Cretaceous age occurs in two small areas on the Lake Fork of the Gunnison River. Volcanic rocks of the Alboroto group of the Potosi volcanic series of Miocene age lie unconformably on the Morrison formation, and in turn are overlain unconformably by rhyolite of the Hinsdale formation of Pliocene (?) age (Cross and Larsen, 1935). The sedimentary and volcanic rocks are found chiefly as erosional remnants on mesas and ridges and have been removed from most of the district by erosion.

## Structure

The foliation and individual layers of the pre-Cambrian metamorphic rocks strike generally within 45 degrees of east and dip steeply throughout most of the district. Many of the dikes and veins in the district were emplaced parallel to this foliation and layering. The Mesozoic and Cenozoic sedimentary and volcanic rocks dip gently northward except locally where disturbed by faults.

The largest fault known in the region (fig. 2), the Cimarron fault of Hunter (1925, p. 88), is a southward-dipping normal fault that has a throw of more than 1,500 feet in the Powderhorn district (Hunter, 1925, p. 90). It extends at least 35 miles northwestward from Powderhorn but has not been mapped southeast of Powderhorn. Its probable location in the valley of Cebolla Creek is marked by hot springs and spring deposits. The movement on this fault occurred chiefly in late Cretaceous or early Tertiary time, but the fault has also been active in post-volcanic time. Several other northwest-trending faults in the district were mapped by Hunter (1925).

## MINERAL DEPOSITS

Mineral deposits in the Powderhorn district are related to at least three distinct periods of mineralization: pre-Cambrian sulfide-bearing vein and replacement deposits; various types of veins and segregations associated with the Iron Hill composite stock and its related intrusive rocks in other parts of the district; and small veins and fissure deposits whose source was the Tertiary volcanic rocks.

Sulfide-bearing quartz veins in the vicinity of Dubois, Spencer, Midway, and Vulcan were mined or prospected principally during the period 1870-1900. The veins are composed chiefly of quartz and chlorite but tourmaline is present in some. Similar veins in the Cochetopa district to the east are considered pre-Cambrian by Hill (1909, p. 29); accordingly, the quartz veins of the Powderhorn district are probably of pre-Cambrian age. The dominant metallic minerals are pyrite, chalcopyrite, and sphalerite, but the deposits were worked for the gold and minor silver they contained. A small quantity of sulfur was produced from massive sulfide (pyrite, chalcopyrite, sphalerite) bodies which replace chloritic schist near Vulcan.

Iron and manganese oxides, vermiculite, and minerals containing titanium, rare earths, thorium, and niobium are associated with the alkalic igneous rocks and are present in sufficient quantity to encourage some prospecting. With the exception of a small production of vermiculite and manganese, the output of these materials in the Powderhorn district has been insignificant.

The vermiculite, an alteration product of biotite, has been mined at several places from biotite-rich facies of the pyroxenite. Iron occurs in hematite- and limonite-bearing veins and irregular bodies in the marble of Iron Hill, and in lenticular concentrations of magnetite and very fine-grained perovskite in the pyroxenite which are commonly 20 feet to as much as 75 feet wide. The iron-bearing veins in the carbonate rock are relatively small and contain abundant phosphorus in the form of apatite.

Titanium minerals are abundant in some of the pyroxenite of the Iron Hill complex, and considerable exploratory work and investigation of recovery methods has been done, chiefly by the Humphreys Gold Corporation, during the past three years. Many cuts have been excavated by bulldozer, and large samples have been obtained for study of beneficiation of the titanium ore.

Titanium oxide averages 7.4 percent in the pyroxenite and exceeds 35 percent in some of the perovskite iron ore bodies (Larsen, 1942, p. 57-58).

The bulk of the titanium occurs as the calcium titanate, perovskite, but some is present as sphene and ilmenite, and small amounts are contained in melanite, biotite, pyroxene, and other minerals.

Titanium-rich alkalic rocks commonly contain a relatively high percentage of niobium, and the Iron Hill complex contains niobium in amounts greatly exceeding those of average igneous rocks. Analyses to date, however, indicate somewhat lower niobium percentages than have been found in certain other alkalic rock complexes. (See Fleischer and others, 1952.) Perovskite concentrates from the pyroxenite of Iron Hill generally contain 0.X to 0.0X percent niobium. Spectrographic analyses of 11 samples of veins and carbonate rocks are given in table 1.

Table 1.--Niobium content of 11 samples of veins and carbonate rocks, Powderhorn district

| Type of rock | No. of samples | Nb (percent) |
|---|---|---|
| Little Johnnie thorium-bearing vein | 1 | 0.X |
| Do. | 2 | .0X |
| Iron Hill marble, apatite-bearing | 1 | .X |
| Do. | 1 | .0X |
| Calcite-apatite-martite vein in Iron Hill marble | 1 | .X |
| Do. | 1 | .0X |
| Carbonate vein in pyroxenite east of Iron Hill | 3 | .0X |
| Do. | 1 | .00X |

Spectrographic analyses by R. G. Havens and P. R. Barnett, U. S. Geological Survey.

## Thorium deposits

The known radioactive deposits in the Powderhorn district are of 3 types: (1) mineralized shear zones in pre-Cambrian foliated rocks, (2) carbonate-rich, tabular veins formed along fractures; these are especially abundant in and adjacent to the Iron Hill intrusive complex; and (3) weakly radioactive zones in non-tabular masses of carbonate rock such as the marble of Iron Hill.

The radioactivity appears to be due almost entirely to thorium and its daughter products, mostly in the form of thorite and hydrothorite. Of 33 samples analyzed chemically for uranium, the maximum uranium content found in any sample is 0.005 percent; most contain 0.001 to 0.002 percent. Radium has been determined in four samples of thorium-bearing veins, and the highest radium content obtained is $2.7 \times 10^{-11}$ percent. The $ThO_2$ content of selected high-grade samples from the Little Johnnie vein is as much as 4 percent. The $ThO_2$ content of the veins is generally less than 1 percent however, and is only 0.05 to 0.1 percent in many of the veins indicated on the geologic map (fig. 2) as abnormally radioactive.

The highest radioactivity in the district is found in mineralized shear zones a foot to several feet thick in which the introduced material forms numerous closely-spaced films and streaks in fractures in the country rock. Near the veinlets the wall rock is commonly partly replaced and greatly altered. Masses of wall rock, generally iron-stained, are found in many places within the mineralized shear zones,which are commonly discontinuous and variable in thickness.

The large carbonate mass of Iron Hill is radioactive in at least two areas, localities 12 and 13 (fig. 2), where readings on a scintillation counter were locally as high as 0.3 and 0.14 mr/hr[1], respectively (background 0.03 mr/hr). In general, the Iron Hill marble and several smaller carbonate masses, such as the ones in Sammons Gulch, which is 1.3 miles east of Powderhorn, and on the ridge south of Milkranch Gulch, have negligible radioactivity.

[1] Milliroentgens per hour

## Structural features

The thorium-bearing veins are a few inches to 18 feet thick and a few feet to more than 3,500 feet long. Most of the veins are essentially vertical and few dip less than 60 degrees. The strikes of the veins are not consistent throughout the district. In general, the veins near Iron Hill have a crude radial arrangement with respect to the central Iron Hill carbonate mass. The veins and mineralized shear zones near the Little Johnnie claims generally strike northeast to east, and those in the Dubois-Lake Fork area strike variably northwest to northeast.

The thorium deposits have not been exposed at depth, with the exception of a few exposures underground in adits at Dubois. The length and tabular form suggest that some thorium veins persist to depths of hundreds of feet. Thorium-bearing veins are exposed in the bottom of Lake Fork Canyon, 1,000 feet below exposures of similar veins on the mesa to the east; the Little Johnnie vein is exposed through a vertical range of more than 700 feet.

Well-defined carbonate veins are particularly common in the Iron Hill complex. Locally these veins contain fragments of wall rocks. The great lengths, 3,500 feet or more, of some of these veins, and the rather even widths, suggest that they were emplaced in fractures. Many of the carbonate veins have a foliation or banding, shown by the concentration of various minerals in streaks parallel to the walls of the vein.

Among the deposits outside the Iron Hill complex, the impression was gained that veins or mineralized shear zones in relatively massive granite, such as No. 31 (fig. 2), may be shorter and less persistent than veins in foliated or layered rocks such as amphibole and chlorite schists and gneisses near Dubois and the interlayered quartzite, schist, and metarhyolite porphyry in the vicinity of the Little Johnnie claims.

## Mineralogy

The thorium-bearing veins are composed of calcite, dolomite, siderite, ankerite, quartz, barite, pyrite, sphalerite, galena, hematite, goethite, apatite, thorite or hydrothorite, xenotime (?), and alkali feldspar. In addition, rare-earth minerals including bastnaesite, cerite (?) and synchisite (?) were found in carbonate veins near Iron Hill. The carbonate veins in the Iron Hill complex also contain a number of silicate minerals including aegirite, sodic amphibole, phlogopite, zeolites, idocrase, melilite, diopside, garnet, and other minerals (Larsen, 1942, p. 31).

Thorium is known to occur as thorite or hydrothorite in some of the deposits, but many of the radioactive deposits have not been studied sufficiently to establish the thorium-bearing mineral or minerals. Among the carbonate-rich veins near Iron Hill, the more radioactive deposits appear to be those containing fresh sulfide minerals such as pyrite, but unoxidized material is not common in surface exposures. The more oxidized veins and mineralized shear zones in near-surface exposures, characterized by abundant powdery goethite, also are appreciably radioactive, and the thorium is apparently chiefly associated with the iron oxides, perhaps in part as thorite or hydrothorite.

Several minerals in which rare earths of the cerium group are major constituents occur in carbonate veins east of Iron Hill. The fluorapatite in parts of the large mass of Iron Hill marble and in many of the carbonate veins contains rare earths of the cerium group. In addition to the widespread rare-earth-bearing apatite, X-ray patterns by A. J. Gude, U. S. Geological Survey, show that bastnaesite is one of the rare-earth minerals present in a sample from a prospect 0.2 mile SW of locality 10 (fig. 2). Another mineral in this same sample has an X-ray pattern that matches the pattern of cerite (?) from Jamestown, Colo., although the identity of the Jamestown cerite (?) used as a reference standard is not certain. A third mineral containing abundant rare earths of the cerium group was found in samples from localities 8 and 10 (fig. 2). This mineral is provisionally considered to be synchisite (?) on the basis of X-ray powder patterns by Fred A. Hildebrand of the U. S. Geological Survey. It seems likely that several other minerals containing rare earths as major constituents, such as monazite and rare earth carbonates and fluocarbonates, may be found by additional detailed mineralogical studies.

Hematite and goethite are sufficiently abundant in some deposits, particularly the mineralized shear zones such as the Little Johnnie, to impart a red- to yellow-brown color that is an aid in prospecting. This color is not an infallible guide to thorium, however, for some zones relatively rich in hematite and goethite are not radioactive.

## Relation to alkalic igneous rocks

The map of the district (fig. 2) indicates a spatial relation between thorium-bearing deposits and alkalic igneous rocks. Most of the known thorium deposits are in 3 areas: near Dubois, near the Little Johnnie claims, and in the Iron Hill complex. In each of these areas alkalic igneous rocks are present.

Among the elements that characterize the mineralized shear zones, the carbonate veins, and the alkalic igneous rocks are Ti, Ba, Sr, Nb, P, and the rare earths. The abundance of these elements in the mineralized shear zones and the carbonate veins is indicated in table 2. These elements are also present in greater than average amounts in the alkalic igneous rocks, and the geographic and geochemical relations of the thorium-bearing veins and the alkalic rocks strongly suggest a genetic tie between them.

Table 2. Abundance of certain minor elements in spectrographic analyses of mineralized shear zones and carbonate veins.

| | Number of samples in which element exceeds 0.1 percent | |
|---|---|---|
| Element | Mineralized shear zones (6 samples analyzed) | Carbonate veins (8 samples analyzed) |
| Ba | 6 | 8 |
| Ti | 5 | 4 |
| Sr | 0 | 4 |
| Th | 4 | 0 |
| La | 0 | 4 |
| Ce | 0 | 4 |
| Nd | 0 | 4 |
| Sm | 1 | 0 |
| Y | 3 | 0 |
| Nb | 1 | 1 |
| P | 0 | 3 |
| V | 0 | 2 |
| Zr | 0 | 2 |

Spectrographic analyses by R. G. Havens and P. R. Barnett, U. S. Geological Survey.

Larsen (1942, p. 29) has pointed out the abundance of potash in many of the alkalic rocks outside the Iron Hill complex, in contrast to the relative abundance of soda and lime in the igneous rocks within the complex. However, some sodic dikes such as soda syenite have also been found outside the Iron Hill complex. Thorium appears to be associated with both the potassic and sodic types, and this suggests that other thorium deposits may be found by prospecting in the vicinity of syenitic rocks in Wolf Gulch, Wildcat Creek, and Willow Creek.

## Age

The thorium deposits are known to be older than the Alboroto group of the Potosi volcanic series of Miocene age. Thorium-bearing veins cut the pyroxenite and other igneous rocks in the Iron Hill complex. The affinity of the veins with the Iron Hill complex and other alkalic igneous rocks in the district suggests that the thorium-bearing veins formed during the late stages of the Iron Hill igneous activity. The vein on the Little Johnnie claims, however, may be cut by a gabbro dike. The contacts between the Little Johnnie vein and the dike are not exposed, but no abnormal radioactivity was detected across a 100-foot width of the dike along the projected strike of the vein. The gabbro contains anatase and brookite along fractures, and the presence of these titanium minerals suggests that the dike is related to the Iron Hill complex. Accordingly the thorium mineralization may predate some of the alkalic rocks.

## Effects of weathering and alteration

The rocks of the district have been altered through weathering during pre-Jurassic, pre-Miocene, and present erosion cycles. Oxidation, leaching, and jasperization of the vein material during one or more of these erosion cycles may have dispersed part of the radioactive material in deposits that lie near the erosion surfaces.

The veins on the mesa between Dubois and Lake Fork are altered in places to a jaspery material, which has chiefly replaced the carbonate gangue, locally forming pseudomorphs of carbonate of the veins (Burbank and Pierson, 1953, p. 3). The jasper retains some of the radioactivity of the original vein matter. In some places where the veins are exposed beneath the volcanic capping of the mesas, jasperization extends to depths of 50 to 100 feet beneath the volcanic rocks; veins exposed on the lower slopes of recently-cut valleys are not jasperized where examined. The volcanic rocks rest on an early Tertiary erosion surface which is closely coincident with the late Paleozoic or early Mesozoic erosion surface on which the Jurassic sedimentary rocks were deposited (Burbank and Pierson, 1953, p.2). Thus, the jasperization of the veins probably resulted from weathering and leaching during one or both of these earlier cycles of erosion; it may be partly related to hot-spring activity.

Several deposits show some evidence of increase in amount of radioactivity, and presumably an increase in thorium content, with depth. The apparent variation may be an effect of oxidation and leaching, as well as jasperization of veins near the pre-Miocene erosion surface. At locality 20 (fig. 2), much of the vein outcrop shows radioactivity of 0.07 - .10 mr/hr (background 0.03 mr/hr), whereas less altered rock on the dump of a 30- to 40-foot shaft has a maximum radioactivity of 0.5 mr/hr. Locality 20 is just below the pre-Miocene erosion surface on which the volcanic rocks were deposited, hence this vein has been subjected to both pre-Miocene and Recent periods of weathering and leaching. At locality 10 (fig. 2), a carbonate vein 1,500 feet or more in length shows radioactivity of about 0.07 to .10 mr/hr (background .03 mr/hr) in much of the oxidized surface outcrop, but fresh carbonate vein material containing abundant siderite and pyrite, on the dump of a shaft slightly more than 25 feet deep, shows radioactivity of 0.15 to .20 mr/hr. The highest radioactivity found by Burbank in the Dubois area was 500 feet underground in one of the adits at Dubois, in a relatively unoxidized carbonate vein containing sulfide minerals. Vein exposures in the adit nearer the portal were more limonitic and lower in radioactivity, suggesting the possible significance of oxidation of the veins and dispersal of radioactive material related to the present erosion surface.

The jasper that has replaced part of the carbonate vein material on mesas is locally radioactive, but the most radioactive material in the district is not jasperized, and it is possible that some of the radioactive material in the jasperized veins was dispersed at the time of jasperization. At locality 25 (fig. 2), higher radioactivity was noted in vein matter containing some carbonate mineral than in more thoroughly jasperized rock.

Although the high radioactivity of deposits in the district is due to thorium, it is conceivable that some uranium was leached from the surficial parts of veins, especially those near the erosion surfaces on which the Mesozoic and Tertiary rocks were deposited. Although there are indications that some radioactive material may have been dispersed near the surface, and that fresher rock at depth may contain a somewhat greater concentration of radioactive material, the fact that relatively fresh radioactive rocks that have been analyzed contain no more than 0.005 percent uranium suggests that the variations in radioactivity probably result from variations in thorium content.

## DISTRIBUTION OF RARE EARTHS

Rare earth-bearing minerals have been found in the Powderhorn district in carbonate rocks, pyroxenite, and thorium-bearing veins. Rare earths of the cerium group predominate and were detected by field observation of absorption bands, due to neodymium, in a hand spectroscope.

The most widespread rare earth-bearing mineral in the carbonate rock is apatite, which constitutes several percent of the carbonate rock. The hand spectroscope indicates that the rare earth content of the apatite varies in different parts of the Iron Hill carbonate mass. In some areas several hundred feet wide the apatite contains rare earths, but in other areas the apatite apparently contains little or no rare earths according to the hand spectroscope.

The apatite is pale green to white and occurs in linear streaks along shear planes in the carbonate rock. The apatite grains commonly stand in relief on weathered surfaces. Apatite in apatite-martite veins a few inches to 3 feet thick that cut the carbonate body also contains rare earths. Near the top of Iron Hill, 4 pits have been dug in a zone of carbonate rock at least 10 feet wide and 300 feet long that is richer in rare earth-bearing apatite and more iron-stained than the average carbonate rock. Rare earth-bearing apatite also occurs in some of the carbonate veins both in the pyroxenite and in pre-Cambrian rocks outside the Iron Hill complex.

Rare earths have been found in small percentages in apatite from many localities, probably substituting for calcium in the apatite structure. Apatites having a range in rare earth content from a trace to 3.18 percent have been reported by Starynkevich-Borneman (1924, p. 41). The rare earth content ranges from a trace to about 5 percent in apatite samples from various types of occurrences tabulated by Fersman (1924, p. 43-44).

Spectrographic, chemical, and radioactivity analyses of carbonate rock containing rare earth-bearing apatite are summarized in table 3.

In addition to the apatite, five samples of perovskite concentrates from the pyroxenite all have La, Ce, and Nd in amounts of tenths of a percent, and Y in the hundredths, according to spectrographic analyses by A. T. Myers, P. J. Dunton, and J. D. Fletcher, of the U. S. Geological Survey. Sm and Pr were determined in 3 of these perovskite samples in amounts of hundredths of a percent. All the samples from the vicinity of Iron Hill, whether of apatite-bearing carbonate rock, perovskite concentrates from the pyroxenite, or carbonate veins, show a high ratio of cerium group to yttrium group of rare earths.

The results of six spectrographic analyses indicate that mineralized shear zones at localities 18, 17, 16, and 15 (fig. 2) several miles northwest of the Iron Hill contain more Y than Ce, La, and other metals of the cerium group of rare earths. Of the 6 samples, two have 0.X percent yttrium, one

Table 3--Analyses, in percent, of carbonate rock containing rare-earth-bearing apatite

| Location of sample | Equivalent uranium[a] | Combined rare-earth and thorium oxides[b] | La[c] | Ce[c] | Nd[c] | Y[c] | $P_2O_5$[b] |
|---|---|---|---|---|---|---|---|
| 1. West side carbonate mass, Cebolla Creek | .001 | ___[d] | .OX | .OX | .OX | .OOX | ___ |
| 2. South side carbonate mass, Beaver Creek | .001 | ___ | .X | .X | .X | .OX- | ___ |
| 3. Northeast side carbonate mass, Deldorado Creek | .014 | ___ | .X | .X | .X | .OX | ___ |
| 4. Area at least 100 by 300 ft., south side carbonate mass, Beaver Creek | .001 | .07 | ___ | ___ | ___ | ___ | 3.6 |
| 5. Apatite-rich zone at least 10 X 300 ft., on ridge near top of Iron Hill | .002 | .07 | .X | .X | .X | .OOX | 7.4 |
| 6. Apatite-martite vein 2 to 3 ft. thick, adit on west slope of Iron Hill. | .005 | .10 | .X | .X | .X | .OOX | 13.8 |
| 7. Apatite-martite vein 150 ft. east of sample 6 | .002 | .09 | ___ | ___ | ___ | ___ | 13.4 |
| 8. Lens 4 by 18 in., largely coarse apatite, on ridge west of top of Iron Hill | .001 | .09 | ___ | ___ | ___ | ___ | 35.1 |

a/ Determined radiometrically by S. P. Furman, U. S. Geological Survey

b/ Determined chemically by J. W. Meadows, W. Mountjoy, and J. P. Schuch, U. S. Geological Survey

c/ Determined spectrographically by P. R. Barnett, R. G. Havens, U. S. Geological Survey

d/ Dashes indicate element not looked for.

has 0.0X percent, and three have 0.00X percent. These values may be compared with the lanthanum content which is 0.0X percent in three of the samples, 0.00X percent in one, and only a trace in the other two. Yttrium also constitutes 0.X percent of one sample collected by Burbank (Burbank and Pierson, 1953, p. 8) from the vein at locality 21 (fig. 2).

Although these analyses do not indicate rare-earth concentrations of commercial grade, they are of geologic interest for they show, together with the large area in which the rare earth-bearing apatite and perovskite occur, that the Iron Hill alkalic complex as a whole contains a relatively large quantity of rare earths. The presence of rare earths is reflected also by the presence of bastnaesite, cerite (?) and synchisite (?) in carbonate veins in the pyroxenite east of Iron Hill.

## LITTLE JOHNNIE CLAIMS

The Little Johnnie group of claims (no 18,fig. 2) is in secs. 14, 15, and 22, T. 47 N., R. 2 W., near the northeastern margin of the Milkranch Gulch drainage basin; the west end of the area shown in fig. 3 is about a quarter of a mile east of the Lot mine. Radioactivity was discovered on the Little Johnnie claims in 1949 by Neil Foreman and J. A. McGregor of Powderhorn. Analyses of samples by the U. S. Geological Survey in 1950 indicate that the radioactivity is due chiefly to thorium and its daughter products.

## General Geology

Most of the Little Johnnie area is underlain by pre-Cambrian metasedimentary and meta-igneous rocks. The foliation of these rocks strikes N. 50° - 65° E. and dips steeply north or south, commonly within 15 degrees of vertical. The metamorphic rocks are cut by carbonate-rich veins, small alkaline intrusives, and a large gabbro dike of alkaline affinities, which are believed to be related to the Iron Hill intrusive complex about 4 miles to the south. The Alboroto rhyolite of the Potosi volcanic series (Tertiary) and sandstones of the Morrison formation are exposed in the southwestern part of the Little Johnnie area. These rocks are in fault contact with one another and with pre-Cambrian metamorphic rocks.

The thorium deposit is a mineralized fault that strikes at a small angle to the foliation of the enclosing metamorphic rocks, and is offset at several places by post-Alboroto rhyolite faults.

## Pre-Cambrian rocks

The pre-Cambrian rocks on the Little Johnnie claims include quartz-biotite schist, quartzite, and amphibolite belonging to Hunter's Black Canyon schist, and metarhyolite and granite of the Powderhorn granite group (Hunter, 1925).

### Quartz-biotite schist and quartzite

The oldest and most abundant rock exposed in the area is a quartzitic metasedimentary rock that includes several closely related types. The most common facies is a medium-gray, fine- and even-grained, biotitic quartzite which contains an estimated 5 percent biotite. With increasing biotite this rock grades into a quartz-biotite schist and with decreasing biotite into an almost pure, massive quartzite. Some specimens appear feldspathic, and fine-grained feldspar is probably a constituent of most of the quartz-biotite rocks. A few specimens contain a small quantity of amphibole, and these are difficult to distinguish from some of the feldspathic varieties of amphibolite.

Outcrops are scarce or lacking in many parts of the area, and some metarhyolite, syenite, and various types of amphibolite are included in the quartz-biotite rock unit shown on the map (fig. 3).

## Metarhyolite

Metarhyolite is one of the lithologic types included by Hunter (1925, p. 41-44) in the granite porphyry of the Powderhorn granite group. Within the map area (fig. 3) it forms dikes that generally parallel the foliation and layering of the quartzitic metasediments. Pinch-and-swell features are common; in a few places the dikes bifurcate. At the eastern end of the area a metarhyolite body of unknown size and shape cuts sharply across the foliation of the quartzose metamorphic rocks. A similar discordant mass occurs on the southern edge of the area about 800 feet to the west.

The metarhyolite is readily distinguished from the quartz-biotite schist and quartzite by the presence of oval masses of quartz from 1 mm to more than 1 cm in diameter which commonly have a characteristic grayish-blue cast. Under the microscope many of these masses of quartz appear to be distorted phenocrysts, and the degree of distortion appears to vary with the size of the original crystals. Some of the smaller crystals have the outline of perfect bipyramids. Medium-sized crystals commonly have broken and displaced crystal faces, and some of the larger masses exhibit strong granulation.

The porphyritic texture of the rock varies with the size and abundance of the quartz masses. Individual phenocrysts are as small as 1 mm but commonly range from 3 to 6 mm; at the Lot mine they attain a maximum length of nearly 2 cm. The quartz phenocrysts constitute 10 to 15 percent of the typical metarhyolite.

The quartz crystals are set in a fine granular aggregate of quartz, alkali feldspar, and biotite. A thin section of a specimen collected by J. W. Adams from the sheared and silicified wall of a vein on the Jeanie No. 6 claim (no. 16, fig. 2) shows orthoclase; albite; quartz, in part secondary; biotite, partly altered to chlorite; and sericite as the principal constituents. Apatite, zircon, pyrite, iron oxides and allophane are present in minor amounts.

## Amphibolite

Amphibolite forms dikes and irregular bodies that intrude both the quartz-biotite rocks and the metarhyolite. Most of the dikes parallel the foliation of the country rocks, but several discordant dikes strike nearly east.

The amphibolite is typically a dark green hornblende-rich rock containing as much as 85 percent hornblende in crystals 1 to 5 mm long. Less common, lighter-colored types contain plagioclase feldspar in varying amounts.

A dark-gray amphibolite from the west end of the area contains an estimated 40 percent hornblende, 25 percent oligoclase, 20 percent quartz, and 10 percent biotite, with minor sericite, clinozoisite, apatite, and magnetite. Both the feldspar and the mafic minerals are corroded and embayed by quartz, which may have been introduced into the rock. Much of the amphibolite at the west end of the area is light- to medium-gray and contains small crystals of amphibole in a quartz-feldspar matrix. These rocks are transitional in appearance to some of the amphibole-bearing quartz-biotite schist. Schistosity is poorly developed in the amphibolites.

The darker amphibolites probably represent metamorphosed intrusive rocks of basic to intermediate composition. In a few places the light- to medium-gray amphibolites appear to be cut by metarhyolite. These older amphibolites are of unknown origin but may be metasedimentary.

## Granite

In the southwestern part of the area (fig. 3) the rocks designated as undivided pre-Cambrian include the metarhyolite, the quartz-biotite rocks, and a few fragments of pink, coarse-grained equigranular and porphyritic granite. The granitic rocks are similar to those described and mapped by Hunter (1925, p. 44-46) as the porphyritic biotite granite of the Powderhorn group.

## Quartz veins

Quartz veins ranging from a few inches to slightly more than a foot in width occur in the pre-Cambrian rocks in and adjacent to the map area (fig. 3). The veins cut the amphibolite, the quartz-biotite rocks, and the metarhyolite.

The quartz veins are chiefly of two kinds, quartz-chlorite and quartz-tourmaline, and are probably of pre-Cambrian age.

## Rocks related to the Iron Hill complex

The rocks described below occur as dikes and veins that cut the pre-Cambrian metamorphic rocks. The composition of these rocks is varied, but all show some chemical or mineralogic affinity -- titanium minerals, sodic amphibole, sodic pyroxene, abundant alkali feldspar, and abundant carbonate -- with one or more of the rock types of the Iron Hill complex, and they are probably the same age as the Iron Hill intrusives. The age relations of the different rock types in the Little Johnnie area (fig. 3) could not be determined because of poor exposures.

### Gabbro

A gabbro dike cuts the quartzose metasedimentary rocks, the meta-rhyolite porphyry, and the amphibolite near the east end of the area. The dike is about 75 feet thick and strikes about N. 60° W. At one place the gabbro appears to cut a linear concentration of fragments of breccia that probably marks the location of a breccia vein.

The most common facies of the gabbro is a medium-gray equigranular rock that contains 30 to 40 percent labradorite as lath-shaped crystals about 2 mm long. The feldspar laths are randomly oriented and intergrown with pyroxene, giving the rock a coarse ophitic texture. Magnetite is abundant and makes up an estimated 8 percent or more of the rock. This medium-gray facies grades into a dark-gray rock that probably contains only

10 to 15 percent plagioclase, but which is otherwise similar to the more feldspathic varieties.

The pyroxene in all specimens examined microscopically has a 2V of 20 to 30 degrees and is probably pigeonite. Primary accessory minerals include abundant prisms of apatite, magnetite, and a few small scattered phenocrysts of orthoclase. Several grains of greenish-brown hornblende, probably uralite, are present. Both the hornblende and the pigeonite are replaced locally by a fibrous, dark-blue, pleochroic soda-amphibole. Other alteration products include sericite, epidote, allophane, iron oxides, and carbonate. Except for the lack of quartz, this rock is similar to the quartz gabbro that Larsen (1942, p. 28-29) has described from the Iron Hill area.

In contrast to the equigranular rocks described above, a few specimens from the dike area are porphyritic. These rocks contain an estimated 10 percent labradorite as phenocrysts approximately 1 mm long which are set in dark-gray aphanitic groundmass.

The distribution of the textural and compositional varieties within the dike is unknown, but the equigranular types are believed to be differentiates of approximately the same age. The association of the equigranular gabbro and the fine-grained porphyritic facies, and the similar composition of the plagioclase in these rocks, indicate a genetic relationship between them. The texture and relative scarcity of the porphyritic rocks suggest that they occur as small dikes within the main gabbro body.

Thin films of brookite and anatase coat fracture surfaces in parts of the gabbro dike where it crosses the ridge. Associated with these titanium minerals on the fracture surfaces are minor amounts of aegirine, quartz, albite, and potash feldspar (?). Both the quartz and the feldspar appear reddish brown with the hand lens because of small amounts of included iron oxides (?). The aegirine ranges from medium green to very light green; under the microscope fragments as much as 0.04 mm thick are almost colorless with very little pleochroism. The quartz is biaxial and has a 2V estimated at 15-30 degrees. The occurrence of anatase is similar to that described by Larsen and Hunter (1914, p. 479) about half a mile northeast of the Lot mine.

Samples of the anatase and brookite contain 0.06 percent niobium and 2 percent niobium respectively, according to spectrographic analyses by Paul R. Barnett of the U. S. Geological Survey. The striking difference in niobium content of these polymorphs from the same geologic environment may be due in part to a difference in crystal structure. Anatase is tetragonal, whereas brookite and columbite are orthorhombic, dipyramidal. The X-ray powder pattern of brookite matches that of columbite much more closely than does the anatase pattern. These facts suggest that niobium may substitute for titanium in the brookite structure more readily than it does in the anatase structure.

## Syenite

Pink to reddish-orange, fine-grained, porphyritic syenite dikes intrude the pre-Cambrian metamorphic rocks at several places in the area, and probably correspond to some of the syenites described by Hunter (1925, p. 76). No outcrops of syenite were found, but the linear pattern of syenite fragments in the float and a well developed primary foliation in many of the fragments indicate that the syenite occurs as dikes. Potash feldspar, as phenocrysts 1 to 3 mm long, is the only identifiable mineral in most hand specimens. In some rocks these phenocrysts are closely packed; in others they are sparsely disseminated. Under the microscope, material from the fine-grained groundmass is seen to be almost entirely cloudy alkali feldspar. Specimens from the syenite dikes near the west end of the area are altered, porous, and contain an unidentified mafic mineral.

## Carbonate veins

At 3 localities in the area there are linear concentrations of fine-grained carbonate rock in the float. These probably represent veins similar to those in the vicinity of Iron Hill. The vein material is predominantly fine-grained carbonate in grains less than 0.5 mm in diameter, mixed with and stained by iron oxides which color the specimens yellowish-brown. In thin section sparse euhedral crystals of potash feldspar are seen to be surrounded and embayed by the carbonate, which is irregularly mottled in various shades of yellow and brown. Apatite is abundant, both as anhedral masses which in part replace the feldspar, and as euhedral crystals surrounded and in places embayed by the carbonate matrix. Small nests of quartz enclosing needles of apatite are sparingly present and appear to be older than the carbonate. A single immersion mount revealed the presence of a green pleochroic pyroxene and a little chlorite in addition to the minerals noted above.

## Breccia veins

Several breccia veins occur in the east-central part of the area (fig. 3). The veins contain angular to subangular fragments, as much as 3 inches in diameter, of pre-Cambrian rocks in a matrix composed chiefly of carbonate. The most abundant fragments are pink coarse-grained granite similar to the porphyritic biotite granite of Hunter (1925, p. 44-46), but amphibolite and quartz-biotite (?) rock have both been observed. The fragments commonly constitute 40 to 50 percent, rarely as much as 80 percent, of the rock.

The fine-grained reddish- to chocloate-brown matrix contains a large percentage of carbonate, effervesces violently in acid, and is altered to a soft brown porous coating on weathered surfaces. The groundmass contains pink feldspar in euhedral tabular crystals and irregular fragments, many of which were probably derived from the granite inclusions. Fine-grained pyrite and galena (?) are sparsely disseminated in the groundmass of a few specimens.

In thin section the breccia veins are seen to be similar to the fine-grained carbonate veins except for the presence of the included fragments. Most of the fragments are quartz, potash feldspar, or aggregates of these two minerals. The minerals and rock fragments commonly are embayed and partially replaced by the carbonate matrix. Feldspar is the most strongly attacked, but the quartz grains in an inclusion of quartzite are also rimmed and partially embayed by the carbonate.

The abundant coarse-grained granite inclusions are unlike any of the rocks exposed near the breccia veins and have probably been transported hundreds of feet, presumably by fluids of considerable viscosity rather than the dilute solutions responsible for the formation of typical hydrothermal veins.

## Sodic amphibole rock

A small vein or dike about 2 inches thick, containing abundant blue amphibole, cuts the quartz-biotite schist in the north-central part of the area. Where fresh, the rock is bluish gray; altered specimens are bluish gray, chalky gray, and light brown. Crushed fragments examined in index liquids show a fibrous pleochroic amphibole intergrown with a fine granular substance, either isotropic or very faintly birefrigent.

Other minerals include potash feldspar, apatite, chlorite, carbonate, soda-pyroxene, clay minerals, and iron oxides.

A small filled vug about 1 inch long in the sodic amphibole rock contains aegirite, dahllite, brookite, iron oxides, thompsonite (?) as fine botryoidal films, and probably other zeolites. The dahllite occurs as tiny hexagonal crystals about 0.3 mm across, with the following optical properties: biaxial negative, 2V about 15°, $\underline{n}^Y = 1.632$, $\underline{n}^Z - \underline{n}^X = 0.008$.

## Sedimentary and volcanic rocks

Sandstone and a little siltstone of the Morrison formation of Jurassic age crop out in the southwestern part of the Little Johnnie area. The sandstone is medium- to coarse-grained, well cemented, and commonly reddish brown and dark reddish purple; some specimens are light gray. Banded and mottled rocks are common.

Light-gray to buff Alboroto rhyolite flows crop out along the southwestern margin of the area.

## Structure

The drainage basin of Milkranch Gulch is a roughly circular depression about $1\frac{1}{2}$ miles in diameter floored with Alboroto rhyolite flows and surrounded by hills composed of pre-Cambrian rocks. The east end of the map area (fig. 3) is on the divide which forms the northeast side of the basin; the southwestern part of the map area extends into the basin and includes the northeastern edge of the central area of volcanic rocks. Here, Jurassic sandstone is in fault contact with both the volcanic rocks and the pre-Cambrian rocks. Outside the map area (fig. 3), the periphery of the central volcanic area was examined at 4 places, and discontinuous outcrops of Jurassic sandstone were found at 3 places along the north contact of the volcanic rocks and at 1 place on the south contact.

The closest exposures of the Jurassic sandstone outside the Milkranch Gulch basin are on Huntsman Mesa, (See fig. 2) about 1 mile east of the Little Johnnie claims at an altitude of nearly 10,000 feet. Here the sandstone is almost horizontal and extends along the top of the mesa for about 4 miles. This probably represents the normal position and attitude of the Jurassic sediments, and the sandstone in the basin is thought to mark the edge of a roughly circular fault block of Morrison beds and overlying volcanic rock, $1\frac{1}{2}$ miles in diameter, which has dropped at least 1,000 feet.

Where mapped, the margin of the subsided block is marked by a complex fault zone. In a few places the presence of individual faults is indicated by silicified breccia, altered and pyritized rock, and zones of sheared rock and gouge exposed in some of the bulldozed cuts. In general the faults are poorly exposed, therefore only approximately located, and probably the true pattern is even more complex than that shown.

The overall structure in the fault zone is a jumble of tilted blocks bounded by faults which are irregular in strike, dip, and displacement, and the resultant pattern is difficult to interpret except in a general way. Probably the major breaks are normal faults which dip toward the center of the basin. The net displacement of the zone is down on the south (basinward) side, but along many of the faults the northern block was downthrown. Many of the subsidiary faults probably dip to the north and some are thought to be reverse faults.

The full width of the fault zone is not shown on the map (fig. 3). South of the southernmost outcrops of pre-Cambrian rock, the Alboroto rhyolite contains several well-defined zones of altered and iron-stained rock. These zones are roughly parallel to the faults shown on the map and are believed to be related faults. The few faults that are shown in the central and eastern parts of figure 3 are also probably related to the fault zone between the volcanic rocks and the pre-Cambrian rocks.

## Thorium deposit

The little Johnnie vein is a steeply-dipping mineralized fault zone at least 3,500 feet long. Irregular veinlets and seams containing quartz, hematite, goethite, alkali feldspar, thorite or hydrothorite, and other minerals have been introduced along the fault in a mineralized zone ranging from less than 6 inches to 5 feet thick.

The Little Johnnie vein strikes N. 65° E., dips commonly within 10 degrees of vertical, and is exposed through a vertical range of 700 feet in a distance of 3,500 feet. At the bulldozed cut near the west end of the area the vein dips 38° N., but this departure from the generally steep dip is probably due to post-Alboroto rhyolite faulting. The vein is nearly parallel with the foliation of the enclosing pre-Cambrian rocks, but in general it strikes a little more easterly than the strike of the foliation, and in a few places it cuts across the foliation of the country rock at an angle of as much as 15 degrees.

The vein is poorly exposed and in most places it was located by scintillation counter. Points where radioactivity is above normal are shown on the map (fig. 3). Readings are given in milliroentgens per hour; background radiation for the area on the counter used was approximately 0.025 milliroentgens per hour. The best exposure of the vein is in a 35-foot drift on the vein in the central part of the area; here a small dike of altered and bleached amphibolite on the north wall of the drift is cut off by the vein, but there is insufficient evidence to indicate the direction or amount of movement. In places the vein is brecciated, indicating movement during or following mineralization.

Where exposed in trenches, the Little Johnnie vein ranges from less than 6 inches to about 5 feet in thickness; the average thickness over a length of 3,500 feet probably does not exceed 2 feet. At the east end of the map-area (fig. 3) the vein either pinches out or contains no thorium. At the top of the ridge just northeast of the map-area, the projection of the vein passes through an exposure of bedrock in which the vein does not crop out and the radioactivity does not appear to be above background. East of the ridge the bedrock is covered, but several abnormal radioactivity readings along the presumed vein projection suggest that the vein probably persists. About 1,100 feet eastward along strike from the east end of the vein shown on the map (fig. 3), a narrow vein is exposed in a bulldozed cut (no. 19, fig. 2). This is probably a continuation of the Little Johnnie vein, although it possibly is a separate but related vein. Another vein about 6 inches wide and of unknown length strikes about N. 35° E. at the east end of the map area (fig. 3).

Exposures of the vein are commonly of a reddish- to yellowish-brown color that contrasts sharply with the dull hue of the pre-Cambrian wall rocks. The vein material is heterogeneous in composition and grain size. Three thin sections, provided by J. W. Adams of the U. S. Geological Survey, show potash feldspar, albite, and quartz as the dominant constituents. Typically these are intimately mixed in a fine-grained aggregate clouded with fine hematite, goethite, and some allophane; the percentages of quartz and the alkali feldspar vary, and parts of two thin sections contain little quartz. Euhedral crystals of hematite, as much as 0.5 mm across, are common. Many are partly altered to goethite. Associated with the hematite and goethite are small subhedral to anhedral masses of thorite or hydrothorite. Apatite, as a felted mat of needles in the feldspar, is abundant in one slide but is rare in the other two sections examined. Coarse-grained barite and carbonate are abundant in a few places in the vein but were not identified in thin-section. Some of the barite fluoresces pink.

Accessory minerals in the vein include clinozoisite (?), tourmaline, fluorite, and rutile. Small euhedral crystals of a uniaxial positive mineral are tentatively identified as xenotime and probably account for much of the yttrium content of the veins. An unidentified brownish-yellow mineral having high indices, moderate birefringence, probably biaxial (-) with moderate 2V, is present in small anhedral grains.

The $ThO_2$ content of chip samples ranges from less than 0.03 percent to nearly 5 percent. Veinlets and thin stringers of thorium-bearing material are irregularly distributed in the mineralized fault zone. In the drift in the central part of the area of fig. 3, several small thorium-bearing stringers branch from the main vein into the south wall. A similar subsidiary veinlet may account for the anomalous radioactivity about 18 feet south of the main vein 365 feet N. 70° E. of the portal of the drift.

Bedrock is not exposed where the vein intersects the gabbro, and the relative ages of vein and gabbro are unknown. Inasmuch as no anomalous radioactivity was detected within the gabbro along the line of strike of the vein, the thorium mineralization may predate the gabbro, but this is uncertain because of poor exposures.

The vein is offset at many places by faults that formed during the subsidence of the fault block that constitutes the Milkranch Gulch basin. Most of these faults are near the west end of the Little Johnnie map area.

## OUTLOOK FOR FUTURE EXPLORATION

With the exception of the Little Johnnie claims, the district has been studied only in a brief reconnaissance. The conclusion seems warranted, however, that the district is a promising one in which to search for veins containing thorite and hydrothorite. Many of the 33 radioactive deposits listed in table 4 appear to contain about 0.1 percent or less $THO_2$, but some higher-grade samples contain 0.5 to as much as 4.9 percent $ThO_2$. The finding of the thorium deposits over a large area in reconnaissance indicates that other veins, possibly containing on the order of 0.5 percent $ThO_2$ might be found by more detailed studies. Thorium deposits of this type have not been mined because of the limited market for thorium.

Because the known thorium deposits are related spatially to the alkalic igneous rocks, the areas in or near the bodies of alkalic igneous rocks are considered most favorable for prospecting. Other minor elements such as rare earths and niobium are commonly found in the same geologic environment. Although commercial rare earth deposits are not known in the district, the discovery of rare earth minerals suggests that they should also be considered in future exploration.

Table 4.--Notes on localities showing abnormal radioactibity, Powderhorn district

| Locality number (fig. 2) | Known dimensions of deposit | Attitude of vein | Wall rock | Vein mineralogy | Field[a] readings mr/hr | Sample data percent eU | Sample data percent $ThO_2$[b] |
|---|---|---|---|---|---|---|---|
| 1 Prospect pit | 3 to 4 ft thick | N. 55° W. strike; 80° NE. dip | Magnetite-rich pyroxenite | Carbonate vein, rare earth mineral present | .10 common<br>.30 maximum | | |
| 2 Prospect pit | Poorly exposed. Probably 1 ft thick | Not exposed | Soda syenite(?) | Carbonate, hematite | .30 maximum | | |
| 3 25-foot shaft | Poorly exposed. 3 to 4 ft thick | Easterly strike; 75°-80° N. dip | Pyroxenite | Carbonate, quartz, purple fluorite, pyrite, hematite, goethite | .25 maximum | | |
| 4 Vermiculite prospect pit | 1.3 ft thick | Easterly strike; vertical | Vermiculite-rich pyroxenite | Carbonate vein | .10 maximum | | |
| 5 Vermiculite prospect pit | Numerous thin veins 0.5 to 3.5 ft thick | Easterly strike; steep dip | Vermiculite-rich pyroxenite | Carbonate veins | .05-.15 common | .043<br>.026<br>.011<br>.008<br>.006<br>.017<br>.067<br>.006 | .24<br>.15<br>.04<br>.04<br>.02<br>.08<br>.36<br>.03 |

a/ Milliroentgens per hour on scintillation counter. Background for this district generally 0.03-0.04 mr/hr.

b/ $ThO_2$ content approximated by multiplying equivalent uranium by 5.6, the factor determined by U. S. Geological Survey. Assumes radioactivity due entirely to thorium and its daughter products; maximum uranium content of 33 samples is only 0.005 percent.

Table 4.--Notes on localities showing abnormal radioactivity, Powderhorn district--Continued

| Locality number (fig. 2) | Known dimensions of deposit | Attitude of Vein | Wall rock | Vein mineralogy | Field readings [a] mr/hr | Sample data percent [b] eU | $ThO_2$ |
|---|---|---|---|---|---|---|---|
| 6<br>Outcrops near edge of Iron Hill complex | Fault zone with hematite staining | Northwesterly strike | Pyroxenite | Hematite staining along faults. Some thin carbonate-quartz-goethite veins | .05 common<br>.15 maximum | | |
| 7<br>Two pits | 3 to 5 ft thick. Length exceeds 350 ft | Easterly strike; 75°-80° N dip | Pyroxenite | Siderite, goethite, quartz, apatite, pyrite, magnetite, rare earth mineral | .2 common<br>.7 maximum | .025<br>.031<br>.014 | .14<br>.17<br>.08 |
| 8<br>Prospect pit | 5 ft thick | N. 78° E. strike; vertical | Pyroxenite | Carbonate, pyrite, hematite, pyrite, phlogopite, chalcedony, rare earth mineral | .2 common | | |
| 9<br>Bulldozer cuts for titanium in pyroxenite | Several thin veins 1 to 1.5 ft thick | N. 70° W. strike; steep dip | Pyroxenite | Carbonate veins | .10 common<br>.40 Maximum | | |
| 10<br>Shaft 25 ft deep to water | 10 to 15 ft thick. Length exceeds 1,500 ft | N. 70° W. strike; 75° N. dip | Pyroxenite | Siderite, pyrite, goethite, apatite, zeolite(?) | .07-.20 common<br>.25 maximum | .011 | .06 |
| 11<br>Trench | 1 ft thick? | Not exposed in place | Pyroxenite | Carbonate vein | .3 maximum | | |

Table 4.--Notes on localities showing abnormal radioactivity, Powderhorn district-- Continued

| Locality number (fig.2) | Known dimension of deposit | Attitude of vein | Wall rock | Vein mineralogy | Field readings mr/hr | Sample data percent b/ eU | ThO$_2$ |
|---|---|---|---|---|---|---|---|
| 12 Prospect pit | Carbonate rock in large satellitic carbonate body | Not determined | Pyroxenite | Carbonate, magnetite, rare earth bearing apatite, colorless mica | .09 common<br>.3 maximum | | |
| 13 Prospect pit | Part of Iron Hill carbonate body | Foliation in carbonate rock dips 50°-60° SE. toward Iron Hill | Pyroxenite | Carbonate, rare earth-bearing apatite martite | .05-.10 common<br>.14 maximum | | |
| 14 Prospect pit | 8 to 10 ft thick | N. 52° E. strike; vertical | Granite gneiss | Silicified zone, chiefly quartz | .09 common<br>.10 maximum | .002 | .01 |
| 15 2 pits, Red Rock claim | 3 ft maximum thickness. Faulted. Only a few ft in exposed length | Probable easterly strike | Chlorite amphibolite, quartzite, granite porphyry | Quartz, hematite, pyrite, goethite, carbonate | | | |
| 16 7 pits, Jeanie No. 6 claim | 1 to 2.5 ft thick; pits over 600-ft length | N. 60° E. strike | Quartzite, schist | Quartz, hematite, minor actinolite | | .007<br>.014<br>.018 | .03<br>.07<br>.10 |
| 17 5 pits, Jeanie No. 2 claim | 1 to 5 ft thick 300 or more ft long (outcrops and radioactive float) | N. 55° E. strike; dip 75° NW, to 70° SE. | Granitic gneisses and schist | Quartz, hematite, barite, carbonate | | .026<br>.009<br>.029<br>.007 | .15<br>.05<br>.16<br>.03 |

Table 4.--Notes on localities showing abnormal radioactivity, Powderhorn district-- Continued

| Locality number (fig. 2) | Known dimension of deposit | Attitude of vein | Wall rock | Vein mineralogy | Field readings mr/hr | Sample data percent eU | $ThO_2$[b] |
|---|---|---|---|---|---|---|---|
| 18<br>Little Johnnie claims (see fig. 3) | 0.5 to 5 ft thick<br>Length at least 3,000 ft, exposed discontinuously | N. 65°-70° E. strike; nearly vertical | Quartz-biotite schist, quartzite, metarhyolite porphyry | Quartz, hematite, goethite, thorite, barite, carbonate, alkali feldspar, apatite | 0.1-3.0 common | 0.13 | 0.73 |
| | | | | | | .045 | 0.25 |
| | | | | | | .12 | .67 |
| | | | | | | .12 | .67 |
| | | | | | | .11 | .61 |
| | | | | | | .88 | 4.9 |
| | | | | | | .019 | .10 |
| | | | | | | .034 | .19 |
| | | | | | | .20 | 1.12 |
| | | | | | | .031 | .17 |
| | | | | | | .15 | .84 |
| | | | | | | .009 | .05 |
| | | | | | | .014 | .08 |
| 19<br>Bulldozer cut 70 ft long | Thin veins, 2 to 6 inches thick, in a zone 4 ft wide | N. 70° E. strike | Schist | Quartz, hematite | 0.2 maximum | .009 | .05 |
| 20[c]<br>30-40 ft shaft and pit | 6 to 18 ft wide(10 ft average). Length exceeds 240 ft | N. 52° W. strike; vertical | Chlorite amphibolite | Quartz, jasper, hematite, goethite | .09 common<br>.5 maximum | .004 | .02 |
| 21[c]<br>Prospect pit | 3 to 4 ft thick<br>Not traceable beyond pit | Pod with northerly strike and steep dip | Chlorite amphibolite | Carbonate, goethite, quartz, hematite | .09 common<br>.2 maximum | | |

c/ Data in part from Burbank and Pierson (1953, p. 8-9).

Table 4.--Notes on localities showing abnormal radioactivity, Powderhorn district--Continued

| Locality number (fig. 2) | Known dimension of deposit | Attitude of vein | Wall rock | Vein mineralogy | Field[a] readings mr/hr | Sample data percent eU | $ThO_2$ [b] |
|---|---|---|---|---|---|---|---|
| 22[c] Prospect pit | 1 or 2 ft thick Not traced beyond pit | Northerly strike steep dip | Chlorite amphibolite | Quartz, goethite | maximum less than 0.2 | | |
| 23[c] Prospect pit | Not known | N. 35° W. strike | Aplite in dominantly greenstone area | Quartz, jasper goethite | .05-.25 | | |
| 24[c] 3 pits | 6 ft thick, ranging 2 to 8 ft thick More than 365 ft long | N. 13° W. strike; 80° W. dip | Chlorite schist and amphibolite | Quartz, jasper, hematite, goethite, thorite(?), minor chlorite | .3 maximum .05 to .2 common | | |
| 25 Prospect pit | 2 ft thick | N. 55° W. strike; 85° S. W. dip | Chlorite schist and amphibolite | Jasper, hematite, goethite, thorite(?), carbonate | .2 maximum | | |
| 26 Prospect pit | 1 to 2 ft thick | Not determined | Hornblende gneiss | Carbonate, quartz, goethite | .2 maximum | | |
| 27 Adits & prospect pit | Dumps only examined | Not determined | Hornblende gneiss | Carbonate vein | .15 maximum | | |
| 28[c] Adair group Adits & dumps | Dumps | Easterly strike; 75° S. dip | Dubois greenstone | Quartz, carbonate, pyrite, sphalerite, galena | | .04 | .22 |

Table 4.-- Notes on localities showing abnormal radioactivity, Powderhorn district--Continued

| Locality number (fig. 2) | Known dimension of deposit | Attitude of of vein | Wall rock | Vein mineralogy | Field [a] readings mr/hr | Sample data percent eU | $ThO_2$ [b] |
|---|---|---|---|---|---|---|---|
| 29[c] Adair group Adits & dumps | Not known | Easterly strike; 75° S. dip | Dubois greenstone | Quartz, carbonate, pyrite, sphalerite, galena | 2.0 maximum | .23<br>.086 | 1.3<br>.48 |
| 30 Shert drift | 2 ft thick? | N. 75° W. strike; Steep dip | Dubois greenstone | Quartz, carbonate, hematite | .05 to .2 common<br>.4 maximum | | |
| 31 15-ft pit | Small pod, not traceable in granite outcrops nearby | Long dimension probably N. 45° E. | Gneissic granite | Quartz, jasper hematite, goethite, Quartz crystals common | .2 common<br>.6 maximum | .010 | .056 |
| 32[c] 25-ft adit | 10-ft zone containing veins 6 to 18 in. thick and thinner veinlets, most of which are in part of zone 4 ft thick; at least 1,000 ft long | N. 88° W. strike; 88° N. dip | Mica schist and quartzite | Hematite, quartz, weathered carbonate, sphalerite, galena, thorite(?) | .2 maximum | .015<br>.016<br>.023<br>.041 | .08<br>.08<br>.13<br>.23 |
| 33[c] 25-ft adit | 4 to 6 inches thick | N. 75° W. strike; 88° N. dip | Schist and pegmatite | Quartz, carbonate, sphalerite, galena | .2 maximum | .050<br>.034 | .28<br>.18 |

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## ABSTRACT

The Little Johnnie vein is exposed discontinuously over a length of at least 3,500 feet, and is about 1.5 feet in average thickness. Thus the deposit is estimated to contain about 44,000 tons of thorium-bearing vein per hundred feet in depth. An average grade of 0.5 percent $ThO_2$ is indicated by 11 analyses of samples taken at points where the vein is well exposed. Whether these samples are representative also of concealed parts of the vein can be determined only by additional exploration.

Most of the other known thorium deposits in the district probably contain much smaller quantities of material exceeding 0.1 percent $ThO_2$ in grade. If the demand for thorium in the future should warrant the development of the Little Johnnie vein, some of the lower grade deposits should be tested by physical exploration and the district should be examined for additional thorium deposits.

## LITTLE JOHNNIE VEIN

The richest known thorium deposit in the district, the Little Johnnie vein, is at least 3,500 feet long and 1.5 to 2 feet in average thickness where exposed. The vein has not been prospected underground, except in one 35-foot drift, but a tabular form of the vein is suggested by its great length and over 700 feet of relief along the trace of the vein. Assuming the smaller thickness figure of 1.5 feet, the deposit has 440 tons of inferred ore per foot of depth, or 440,000 tons to a depth of 1,000 feet.

An average grade of 0.5 percent $ThO_2$ is indicated by 11 radiometric analyses of samples taken at points where the vein is well exposed. Whether concealed parts of the vein are of the same grade can be determined only by additional exploration, but if so the deposit may contain about 2.2 tons of $ThO_2$ per foot of depth.

## OTHER THORIUM DEPOSITS

The data obtained in brief reconnaissance are not sufficient to permit more than a very general statement of size and grade of other deposits. Aside from the Little Johnnie vein, the other thorium deposits shown on figure 2 appear to be either of small size or low grade. The richest samples from other deposits in the district are those obtained by W. S. Burbank in veins of unknown size in underground workings (no. 29, table 1 and fig. 2) at Dubois.

The Jeanie No. 2 and No. 6 veins (nos. 17 and 16, fig. 2) are each exposed discontinuously over lengths of 400 to 500 feet. Each probably contains on the order of 50 to 100 tons of vein material per foot of depth. The highest of 5 representative analyses of these veins contains 0.16 percent $ThO_2$ (calculated from eU), and it is doubtful if the average $ThO_2$ content exceeds 0.1 percent for the tonnage estimated.

Several of the carbonate veins east of Iron Hill have relatively large tonnages, but the grade of surface samples is not very high. At locality 10 (fig. 2) the carbonate vein is known to be at least 1,500 feet long and 10 to 15 feet thick, and contains at least 1,500 tons of vein matter per foot of depth that is probably less than 0.1 percent $ThO_2$ in average grade at the surface. The one sample of this vein was calculated to contain 0.06 percent

$ThO_2$. Veins No. 7 and No. 8 (fig. 2) were not traced along strike, but each is known to contain more than 150 tons of vein material per foot of depth, probably much more. Three samples from No. 7, containing 0.14, 0.17, and 0.08 percent $ThO_2$ (calculated) indicate that very little of this rock exceeds 0.2 percent $ThO_2$, and much of it is less than 0.1 percent, unless the surface samples are not representative of fresher rock at depth.

Several of the jaspery veins on the mesa between Dubois and Lake Fork probably contain on the order of 100 to 200 tons of rock per foot of depth, but the analyses such as nos. 20, 24, and 31 (table 1) indicate that very little of the vein material exceeds 0.1 percent in $ThO_2$ content. Because of the extensive jasperization near the mesa surface, these samples may be of lower grade than would be found in nonjasperized material at depth, but drilling would be necessary to determine any variation of grade with depth.

## CONCLUSIONS AND RECOMMENDATIONS

Thorium is known to occur in at least 33 deposits in the Powderhorn district. Although in most of these the average grade appears to be less than 0.1 percent $ThO_2$, the deposits and the district as a whole are worthy of exploration if the demand for thorium should become sufficient to encourage development of the higher grade ( 0.5 percent) deposit on the Little Johnnie claims.