Petrography and Origin of Xenotime and Monazite Concentrations Central City District Colorado

GEOLOGICAL SURVEY BULLETIN 1032-F

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By E. J. YOUNG *and* P. K. SIMS

GEOLOGY AND ORE DEPOSITS, CLEAR CREEK, GILPIN, AND LARIMER COUNTIES, COLORADO

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PETROGRAPHY AND ORIGIN OF XENOTIME AND MONAZITE CONCENTRATIONS, CENTRAL CITY DISTRICT, COLORADO

By E. J. Young and P. K. Sims

ABSTRACT

Xenotime and monazite are uncommonly abundant in Precambrian biotite gneiss and migmatite at three localities near Central City, Gilpin County, Colo. The occurrences are in the lower part of a thick layer of migmatized biotite gneiss in a sequence of rocks that have been metamorphosed to the almandine amphibolite facies. The zones of concentration are a maximum of about 5 feet thick and a few hundred feet long, and contain about 1 to 5 percent by volume combined xenotime and monazite.

The rare-earth minerals occur dominantly as aggregates of sand-size crystals in thin layers and clots of biotite, which are much coarser than the mica in the typical biotite gneiss. Xenotime is more abundant than monazite in 2 of the 3 occurrences. Both minerals are subrounded to rounded and crystal faces are rare. The two minerals appear to have crystallized contemporaneously. Except for magnetite, other accessory minerals that are common to the country rock are not concentrated with the xenotime and monazite.

The field and laboratory data are consistent with the hypothesis that the rare-earth minerals were concentrated at their present sites during migmatization of the biotite gneiss country rock, in a period of Precambrian plastic deformation. Presumably, granitic fluids derived during the deformation selectively mobilized rare-earth cations and phosphate from the biotite gneiss country rock. These ions crystallized with biotite and locally with magnetite to form zones of xenotime and monazite concentrations in migmatized parts of the gneiss.

INTRODUCTION

Xenotime and monazite, which are common accessory minerals in some of the Precambrian crystalline rocks of the Front Range of Colorado, are sufficiently abundant at places near Central City, in Gilpin County, to have attracted the interest of private mining companies. The occurrences that have been investigated are in migmatized biotite gneisses which are within a thick sequence of biotite gneisses that has been called the Idaho Springs formation (Ball, 1906; Lovering and

Goddard, 1950). They were discovered by radiation-detection instruments because of their high abnormal radioactivity, locally as much as 10 times as great as the average radioactivity of the country rock.

Because of the potential economic importance as well as scientific interest in these unusual occurrences of rare-earth minerals, they were studied as part of the U.S. Geological Survey's geologic investigations in the central part of the Front Range. Field studies were done largely by Sims in conjunction with geologic mapping of the Central City district that was started in 1952; the field studies were done partly on behalf of the Division of Raw Materials, U.S. Atomic Energy Commission. Laboratory studies were done by Young in 1957–58. In this report we describe the petrography of the rock units containing the xenotime and monazite occurrences, with particular emphasis on these accessory minerals. We also propose a mode of origin for these concentrations of rare-earth minerals.

J. C. Hamilton and R. G. Havens of the Geological Survey did the semiquantitative spectrographic analyses. J. W. Adams of the Geological Survey made a preliminary petrographic study of samples containing monazite and xenotime from the region.

Cogeneric monazite and xenotime have been reported in the literature from several localities and various geologic environments, but generally xenotime is sparse and the two minerals are less abundant than associated rare-earth and multiple-oxide minerals. Most of the described occurrences are in pegmatites. Brögger (1885) and Bjørlykke (1935) have described xenotime and monazite from pegmatites in Scandinavia; Scharizer (1888) has reported these same minerals from pegmatites in Germany; and Meixner (1938) has reported them from pegmatites in Austria. Occurrences of the rare-earth minerals in the southeastern United States have been noted by Hidden (1893) and Mertie (1953) in pegmatitic and metamorphic rocks. Hussak (1899) has described intergrowths of monazite and xenotime in diamond-bearing sands in Brazil.

Concentrations of cogeneric monazite and xenotime similar to the Gilpin County occurrences in having several percent of the combined minerals with virtual exclusion of other accessory minerals are rare, so far as known. The only occurrence known to us to be closely similar is in a granite augen gneiss from near Mesquite, Nev. H. W. Jaffe of the Geological Survey reports (written communication, 1951) that a sample from this gneiss contained an estimated 5 percent xenotime and 2 percent monazite. Hornblende, limonite, magnetite, zircon, and allanite(?) are sparse associated accessory minerals in the rock. An occurrence in rock similar to the host rock of the deposits in the Central City district, but containing xenotime alone in association with garnet and biotite, has been described from Charlevoix County, Quebec (Shaw, 1957).

Although described occurrences of cogeneric xenotime and monazite in high-grade metamorphic rocks are rare, this type of deposit probably is widespread. It is difficult to recognize these deposits in the field, for the host rock containing moderately large quantities of the rare-earth minerals is similar in physical appearance to the barren gneisses. They can best be distinguished in the field by their abnormally high radioactivity.

LABORATORY METHODS

To extract the accessory minerals from the rocks about 50 grams of each rock type was crushed to pass through a 20-mesh sieve. The rock particles then were separated into four size ranges by sieving to facilitate separation in methylene iodide. Each of the size fractions was washed ultrasonically to remove fine objectionable rock dust. Methylene iodide (specific gravity=3.3) was used to separate xenotime, monazite, and zircon from the other heavy minerals in preference to bromoform to prevent biotite from flooding the desired separation. The fraction that floated in methylene iodide was examined for accessory minerals such as apatite and allanite. Magnetite was removed with a hand magnet from all size fractions. The 200- to 270-mesh fraction of the minerals heavier than methylene iodide represents about 12 percent of the heavy minerals. This fraction was chosen in each case for a quantitative count, made by point counting grain mounts. Oil having an index of refraction of 1.72 was very useful for mounting as the ω index of xenotime is close to 1.72. An alternative to thin-section modal analysis was used to determine the composition of the microcline-bearing gneiss. A sawn slab of rock was immersed in hydrofluoric acid for 5 seconds, washed in water, stained with sodium cobaltinitrite and washed again. This treatment imparted a deep-yellow to the potassium feldspar, a milky-white to the plagioclase, and did not affect the color of the quartz. This technique is different from that of Gabriel and Cox (1929) in that immersion in hydrofluoric acid is used. After the rock slab was stained a point count was easily made using reflected light and a petrographic microscope.

GEOLOGIC SETTING

The biotite gneiss and migmatite that contain the abnormal concentrations of xenotime and monazite occur in the lower part of a layer of biotite gneisses that overlies a layer of contrasting lithology, composed chiefly of microcline, quartz, plagioclase, and biotite (fig. 66).

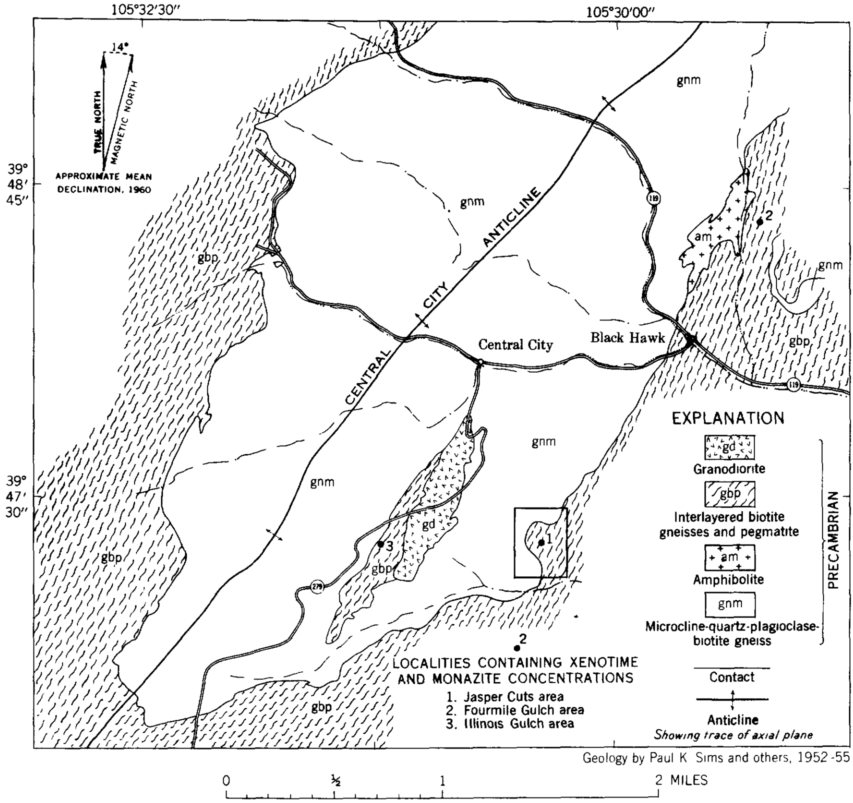

FIGURE 66.—Generalized geologic map of the Central City district, Colorado. Outlined area is shown in figure 67.

The biotite gneiss layer is one of several thick layers of this rock that are interlayered with equally thick layers of microcline-quartz-plagioclase-biotite gneiss in this part of the Front Range. Both the biotite gneisses and the microcline-bearing gneiss are interpreted as paragneisses. Previous workers (Bastin and Hill, 1917; Lovering and Goddard, 1950) referred to the microcline-bearing gneiss as granite gneiss and inferred it to be of igneous origin. All the rocks are metamorphosed to the upper range of the almandine amphibolite facies (Fyfe, Turner, and Verhoogen, 1958, p. 228).

The paragneisses in this part of the Front Range are intruded by granodiorite, correlative with the Boulder Creek granite (Lovering and Goddard, 1950), quartz diorite and associated hornblendite, and rarely biotite-muscovite granite, correlative with the Silver Plume granite at Silver Plume, Colo. Only the granodiorite, however, occurs in moderately close proximity to the area containing the rare-earth mineral deposits (fig. 66).

The localities where xenotime and monazite concentrations have been prospected are on the east side of the Central City anticline (fig. 66). Deposit 1, at the Jasper Cuts, is in migmatite; deposit 2, at Fourmile Gulch, and deposit 3, at Illinois Gulch, are in biotite-quartz gneiss. Each occurrence is about 100 feet stratigraphically above the base of the biotite gneiss layer; therefore, they are approximately in the same part of the layer.

The biotite gneiss layer consists dominantly of biotite-quartz-plagioclase gneiss and sillimanitic biotite-quartz gneiss that are interlayered on a scale ranging from an inch or less to several tens of feet, but garnet-bearing varieties and quartz-rich varieties are present locally. Migmatite, as used in this report, refers to a rock consisting of an intimate interlayering of roughly equal quantities of biotite gneiss and pegmatite.

Migmatization of the biotite gneisses took place during a period of plastic deformation that produced the major folds of the Precambrian rocks in the region. The origin of the pegmatite that constitutes the felsic phase of the migmatite is problematic, but possibly it was generated from the country rock by the heat and pressure that accompanied deformation of the deeply buried rocks.

JASPER CUTS AREA

The principal deposits of xenotime and monazite known in the region are in the Jasper Cuts area, about a mile south-southeast of Central City (fig. 66). The deposits were explored in 1957 by the Michigan Chemical Co., and about 100 tons of rock were mined as a source of yttrium-group rare earths. Previously, other companies had explored the area for radioactive minerals. The source of the radioactivity was identified by George Phair of the U.S. Geological Survey (oral communication, 1952) as mainly thorium in monazite.

OCCURRENCE

The geology of the Jasper Cuts area is shown in figure 67. The xenotime and monazite deposits occur in the layer mapped as interlayered biotite gneisses and migmatite. This layer overlies microcline-quartz-plagioclase-biotite gneiss. All the rocks are deformed into small, open anticlines and synclines that plunge gently northeast or southwest, subparallel to the axis of the Central City anticline.

The host rock of the xenotime and monazite concentrations is migmatite, which lies between 2 layers of pegmatite a few tens of feet thick, about 100 feet vertically above the underlying microcline-quartz-plagioclase-biotite gneiss (fig. 67). The migmatite is gradational both

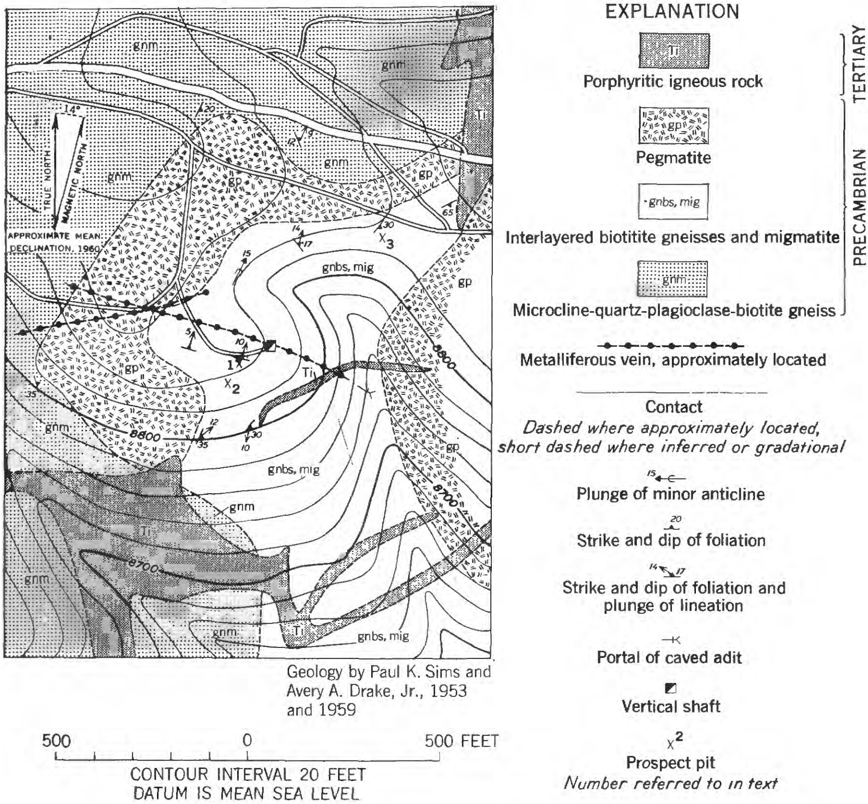

Figure 67.—Geologic map of the Jasper Cuts area, Gilpin County, Colo.

vertically and laterally into biotite gneiss on the one hand and pegmatite on the other.

The zone of concentration of xenotime and monazite, herein called the rare-earth zone, is about 5 feet thick in pit 1 (fig. 67) and contains 3 to 5 percent by volume of the rare-earth minerals. A photograph that shows the character of the rare-earth zone and the overlying migmatized biotite gneiss in pit 1 is shown in figure 68. The rare-earth zone is the blocky rock in the lower left part of the photograph. The pegmatite layers appear light gray in the photograph; they range from less than 1 to 6 inches in thickness.

It is probable that xenotime- and monazite-rich parts of the migmatite at pit 3 (fig. 67) occur at about the same stratigraphic position as the occurrences in pit 1, but the rare-earth zone cannot be traced continuously between the pits because of folding.

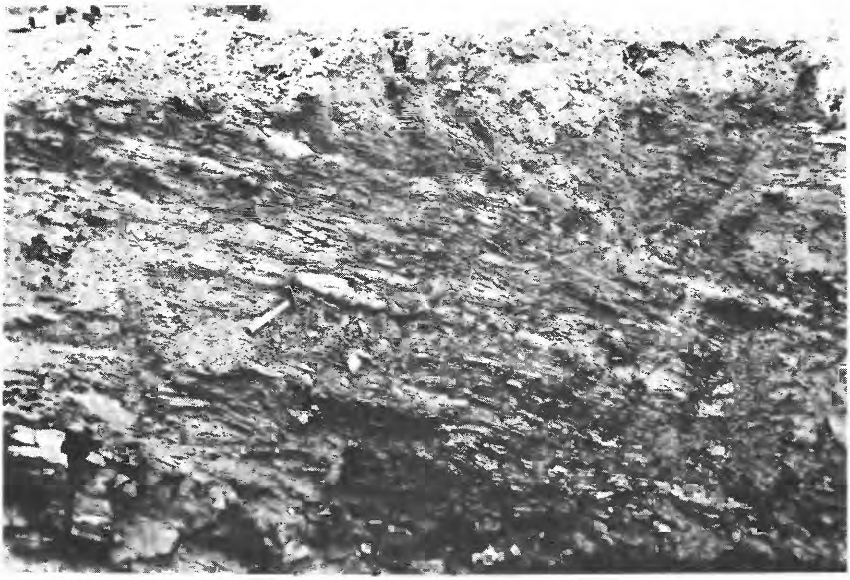

FIGURE 68.—Exposure of migmatite at pit 1, Jasper Cuts area. The rare-earth zone is in the lower left part of the photograph. The conformable light-gray layers (plagioclase-rich pegmatite) are from less than 1 to about 6 inches thick.

The migmatite in the rare-earth zone is similar in appearance to the overlying and underlying migmatite, but can be distinguished from it by its high abnormal radioactivity and abundant inch-thick lenses and clots rich in biotite. The biotite in these lenses is coarse grained in contrast to the typical fine-grained biotite of the barren migmatite, and most of it is not foliated, in contrast to the well-oriented biotite of the barren gneiss. At places in the rare-earth zone the crystals of xenotime and monazite are sufficiently large and abundant to be visible with a hand lens, particularly in the coarse-grained biotite.

PETROGRAPHY OF ROCK UNITS

Modal analyses of the rock units exposed in the Jasper Cuts area and of the intrusive grandiorite exposed about half a mile west of the area (fig. 66) are given in table 1. The locations of the samples relative to pit 1 (fig. 67) are also given in the table. Only the range in variation of the minerals is given for migmatite and pegmatite, for the essential minerals in these rocks vary from place to place.

TABLE 1.—*Modes (volume percent) of rock types in the Jasper Cuts area*

	1	2	3	4	5
	Migmatite	Biotite-quartz-plagioclase gneiss	Pegmatite	Microcline-quartz-plagioclase-biotite gneiss	Granodiorite
Plagioclase	20–60	30.9	5–50	44.6	43.9
Composition	(An_{17})	(An_{19})	(An_{17})	(An_{17})	(An_{43})
Quartz	10–25	53.2	10–40	32.8	20.7
Microcline	Tr.	Tr.	10–50	18.1	5.9
Biotite	10–80	15.2	----	3.5	21.3
Muscovite	----	.6	[1] Tr.	----	----
Hematite	----	.1	(2)	.8	----
Total accessory minerals	----	----	----	.2	8.2
Xenotime	1–10	----	----	----	----
Monazite	1–10	----	----	----	----
Zircon	Tr.	----	----	----	----

[1] Tr.=trace.
[2] ----= not found or not determined in thin section.
1. Migmatite from rare-earth zone in pit 1 (fig. 67). The oligoclase has maximum extinction angles to the (010) trace of −5° to −6°; 2V ranges from 75° to 78°(−); α' (lower index of refraction on (001) or (010) cleavage flakes suggested by Tsuboi (1923)) is 1.537±0.002. The optic angle indicates that the feldspar is midway between a low and a high structural state, according to data by Smith (1958). The biotite has indices of refraction (β and γ) ranging from 1.66 to 1.68 and is siderophyllite according to Winchell (1951).
2. Sample taken approximately 350 ft north-northeast of pit 1. 670 point counts were made over an area of 240 sq mm. Gneiss is fine grained. The oligoclase has an α' index of 1.538±0.003; 2V=77°(−); maximum extinction angles to the (010) trace are −8° to −9°.
3. Sample taken 150 ft S. 70° W. from pit 1.
4. Sample taken about 550 ft West-Southwest of pit 1. 1,329 point counts were made over an area of 525 sq mm. Gneiss is fine grained to medium grained. The α' index of oligoclase is 1.537 ±0.003; maximum extinction angles to the (010) trace are −5° to −6°. The heavy accessory minerals, in addition to hematite, are mainly apatite and zircon.
5. Average of 11 modal analyses by R. H. Moench of the U.S. Geological Survey of different specimens from granodiorite body shown on figure 66. The plagioclase in one specimen has an α' index of 1.550±0.003. The accessory minerals are mainly magnetite, sphene, and apatite. Neither xenotime nor monazite has been noted.

ACCESSORY MINERALS

The data obtained from a quantitative study of the accessory minerals in the different rock types in the area are given in table 2. The weight percent of the accessory minerals heavier than methylene iodide and the number percent of the several minerals constituting this group are given for the 200–270-mesh fraction of the different rocks studied. Quantitative data on other size fractions were not obtained during this investigation.

Both xenotime and monazite occur in more than trace amounts in the 200–270-mesh fraction (table 2) in biotite gneiss and pegmatite country rock as well as in the migmatite of the rare-earth zone. Although the microcline-quartz-plagioclase-biotite gneiss contains some monazite (3.8 number percent in the 200–270-mesh fraction), xenotime is rare. Neither monazite nor xenotime are present in the granodiorite. It should be noted that the migmatite has more than 200 times as much total accessory minerals as the pegmatite. The xenotime-monazite ratio (~3:1) within the 200–270-mesh fraction of both rocks is similar, however. According to point counts of the xenotime-monazite ratio in thin sections from the rare-earth zone xenotime is slightly more abundant than monazite on a volumetric basis (1.2:1). Where the slightly higher specific gravity of monazite is taken into account, the comparison ratio on a weight percent basis is slightly less (1.1:1).

TABLE 2.—*Accessory minerals heavier than methylene iodide in the different rock types from the Jasper Cuts area*

[Samples are the same as those described in table 1. The granodiorite sample was collected half a mile west-northwest of pit 1]

Rock type	Number of grains counted	Weight percent of heavy minerals including magnetite	Weight percent of magnetite	Number percent in 200–270 mesh fraction minus magnetite							
				Hematite [1]	Zircon	Xenotime	Monazite	Garnet	Sphene	Allanite	Epidote
Migmatite	730	7.3	Tr.	1.1	1.2	71.0	26.7	0	0	0	0
Biotite-quartz-plagioclase gneiss	439	.05	0	74.8	14.9	1.8	8.3	.2	0	0	0
Pegmatite	128	.03	Tr.	6.3	50.9	32.9	9.9	0	0	0	0
Microcline-quartz-plagioclase-biotite gneiss [2]	550	.95	.84	73.3	22.9	[3] Tr.	3.8	0	0	0	0
Granodiorite [4]	284	6.65	4.73	4.3	8.9	0	0	0	78.7	6.9	1.2

Tr.=trace.

[1] Hematite possibly contains some ilmenite.
[2] The heavy minerals in the 150–270 mesh fraction having sp. gr. >bromoform, but <methylene iodide consist of biotite, apatite, anatase (leucoxene), and hematite in decreasing order of abundance. No allanite was seen.
[3] Two grains of xenotime were seen in a slide of several thousand grains.
[4] The heavy minerals in the 150–270 mesh fraction having a sp. gr. >bromoform, but <methylene iodide contain apatite and some allanite.

The xenotime from this deposit is easily distinguished from monazite by color. The xenotime is virtually colorless, whereas the monazite is yellow, and the strong color difference is apparent in the photomicrograph in figure 69.

Although monazite and xenotime range in grain size from 0.4 mm to slightly less than 0.05 mm, more than 95 percent by weight of these accessory minerals are between 0.2 and 0.05 mm (65–270 mesh). In general, monazite tends to be somewhat coarser grained than xenotime, the mode of the monazite grains being close to 0.12 mm and that of the xenotime 0.09 mm. Both minerals are subrounded to rounded and crystal faces are rare. Xenotime is uniaxial positive, $\omega=1.724\pm0.003$ and $\epsilon=1.815\pm0.005$, and the birefringence is 0.091 ± 0.008. Pleochroism is weak with ω colorless and ϵ pale yellow. Monazite is biaxial positive and 2V ranges from 10°–15° (average 12°), as determined on the universal stage. α, β and γ are 1.790 ± 0.003, 1.795 ± 0.003 and 1.840 ± 0.003 respectively, and the birefringence is 0.050 ± 0.006. No pleochroism was noted between α, β and γ, which are all pale yellow.

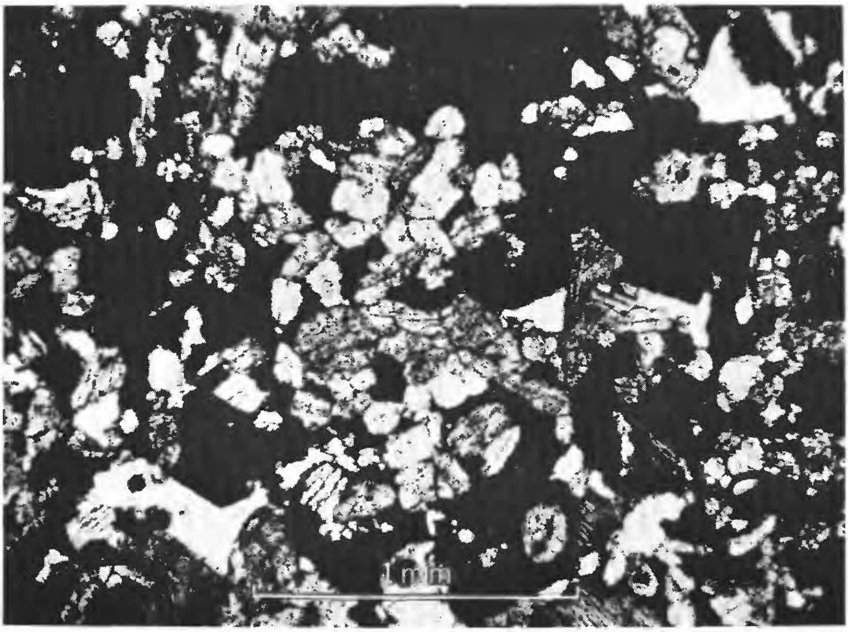

FIGURE 69.—Photomicrograph showing monazite (light-gray) and xenotime (white) in rare-earth zone at the Jasper Cuts area. Both minerals are subrounded. The white lathlike mineral in the lower left corner is muscovite. Some of the white irregular shapes, as in the upper right corner, are quartz. The black opaque-appearing background is biotite darkened by radiation damage. Plane polarized light.

In contrast to the xenotime and monazite, zircon from the rare-earth zone has conspicuous overgrowths, most of which show zoning (fig. 70). The cores of zircon grains are rounded and in general darker and pinker than the overgrowths; also, they generally contain notably more inclusions than the overgrowths, as shown in figure 70*A*. In some zircons (fig. 70*A*) the cores are cracked whereas the rims are not, probably indicating that the cracks occurred before overgrowth age. In other zircon grains, however, the overgrowths are cracked (fig. 70*B*), indicating that the cracking occurred after overgrowth age. Under crossed nicols (not illustrated) optical continuity from core to overgrowth is shown for the grain illustrated in figure 70*B* by the fact that the interference colors cross boundaries between core and overgrowth without apparent change. An unusual zircon is shown in figure 70*C*. The two rounded, innermost cores are pink and contain abundant tiny inclusions; they are enveloped by pale-yellowish-brown, zoned zircon. This is enveloped completely, in turn, by an outermost overgrowth of pale pink to colorless zircon.

The paragenesis of the heavy accessory minerals is controversial in view of the fact that Bjørlykke (1935) postulated simultaneous crys-

A—Note crack in core which does not penetrate overgrowth.

B—Note cracks confined to overgrowth.

C—Single crystal containing two cores and two overgrowths.

0.1 mm

FIGURE 70.—Zircons from rare-earth zone, Jasper Cuts area, showing overgrowths.

tallation of monazite and xenotime in granite pegmatites, whereas Carron and others (1958) have indicated that xenotime should fractionally crystallize first. The latter authors, however, do not preclude the possibility of prior deposition of monazite. At the Jasper Cuts area xenotime and monazite mutually interfere with each others growth, that is, xenotime grains truncate adjacent monazite grains, but the reverse is equally true, indicating that the two minerals crystallized almost simultaneously.

SPECTROCHEMICAL ANALYSIS OF THE RARE-EARTH ZONE

Two samples of migmatite, taken from the rare-earth zone, were spectrographically analyzed semiquantitatively (table 3). MCC–1 represents an average sample from this zone, whereas MCC-2 is markedly richer in xenotime and monazite than the average sample.

It can be noted in table 3 that both samples contain about nine times as much thorium as uranium. Also, the yttrium-group rare earths are more abundant than the cerium-group rare earths, as shown in the following tabulation:

	MCC–1 (percent)	*MCC–2 (percent)*
Total rare earths	3.8	8.0
Yttrium group (Y, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu)	2.2	4.5
Cerium group (La, Ce, Nd, Pr, Sm, and Eu)	1.6	3.5
Yttrium group-cerium group ratio	1.4	1.3

PETROFABRICS

To determine the degree of orientation of xenotime in the migmatite, 100 xenotime *c* axes (optic axes) were measured and plotted on a Schmidt equal-area net (fig. 71*A*, *B*). So far as known to us, petrofabric diagrams of xenotime have not been published previously. All the *c* axes were measured from a podlike aggregate of several hundred grains in an area of 0.5 by 0.5 cm in a thin section of sample MCC–2. The pod also contains monazite; these 2 minerals comprise about 80 percent of the pod, the remainder being biotite. The thin section is roughly perpendicular to biotite cleavage, but much of the biotite is disoriented with respect to foliation in the rock. Unfortunately orientation of the thin section in space is not known with certainty.

It can be seen from the contoured diagram (fig. 71) that xenotime optic axes have no striking preferred orientation. To acquire some idea as to the randomness of the xenotime *c* axis plot, 100 random points were chosen from a random number table and plotted similarly on a Schmidt equal-area net. Figure 71*B* illustrates the result. As would be expected no preferred orientation is shown. Although the xenotime *c* axes maxima are disposed somewhat symmetrically around

TABLE 3.—*Semiquantitative spectrographic analyses of migmatite (rare-earth zone) from the Jasper Cuts area*

[Analysts, J. C. Hamilton and others]

Element	MCC-1 (percent)	MCC-2 (percent)
Radioactive:		
U, equivalent [1]	0.065	0.22
U, chemical [2]	.022	.070
Th, radiochemical [3]	.18	.66
Th	.15	.7
Rare-earth:		
Y	1.5	3.0
La	.3	.7
Ce	.7	1.5
Pr	.15	.3
Nd	.3	.7
Sm	.15	.3
Gd	.15	.3
Dy	.15	.3
Ho	.07	.15
Er	.15	.3
Tm	.015	.07
Yb	.15	.3
Lu	.015	.07
Major and minor:		
Si	M	M
Al	7	7
Fe	3	7
Mg	.7	.7
Ca	1.5	1.5
Na	3	3
K	3	3
Ti	.3	.7
P	.3	.7
Trace:		
Mn	.07	.07
Ba	.03	.03
Be	.00015	0
Co	.0007	<.001
Cr	.015	.015
Cu	.015	.015
Ga	.003	.007
Ni	.007	.007
Pb	.03	.07
Sr	.015	.015
V	.007	.015
Zr	.07	.15

NOTES.—Looked for but not found: Ag, As, Au, B, Bi, Cd, Eu, Ge, Hf, Hg, In, Ir, Li, Mo, Nb, Os, Pd, Pt, Re, Rh, Ru, Sb, Sc, Sn, Ta, Tb, Te, Tl, U, W, and Zn.
Figures are reported to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, in percent.
Sixty percent of the reported results may be expected to agree with the results of quantitative methods.

M=major constituent, greater than 10 percent.
[1] Radiometric analyses by G. S. Erickson.
[2] Chemical analyses by D. L. Ferguson and W. W. Niles.
[3] Radiochemical analyses by J. N. Rosholt, Jr.

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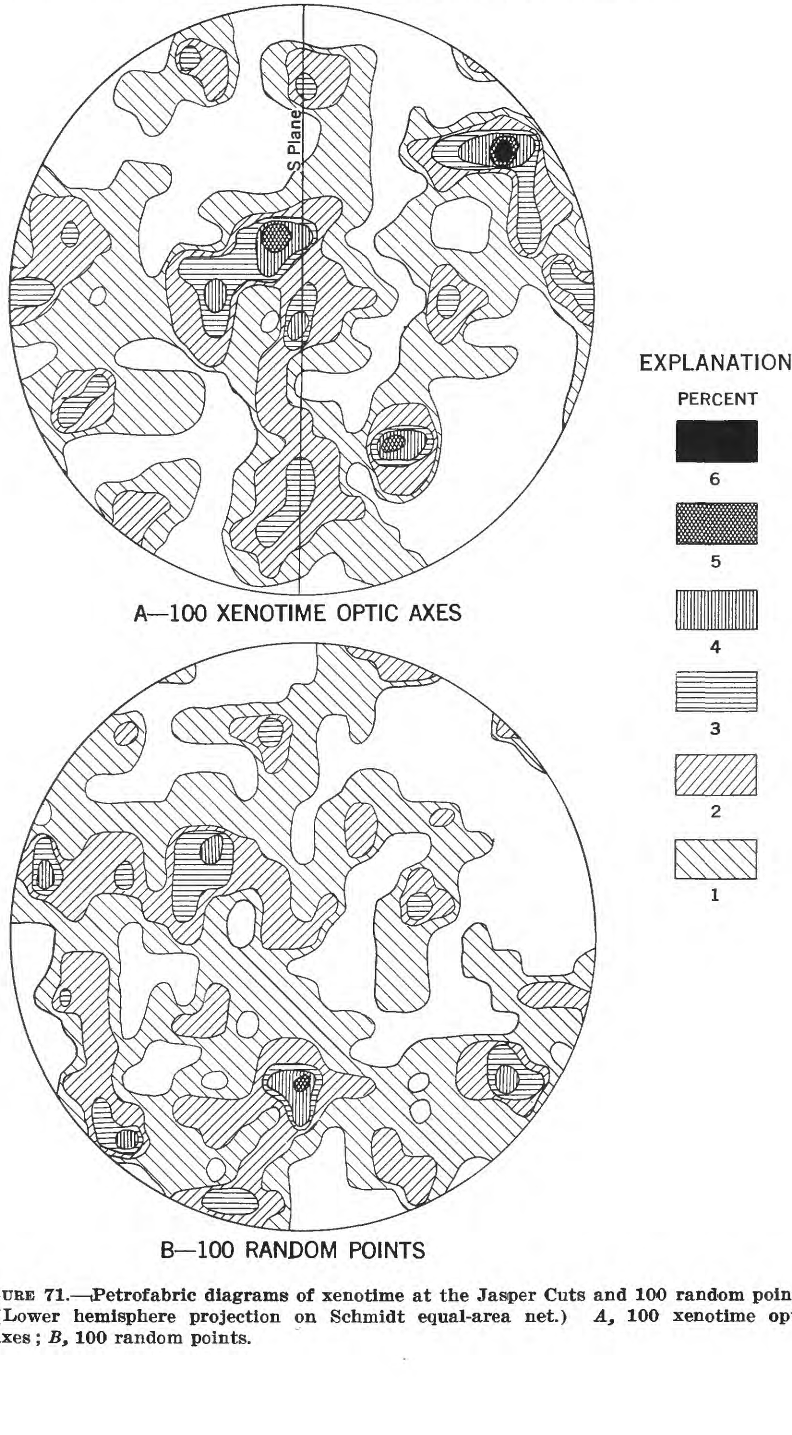

FIGURE 71.—Petrofabric diagrams of xenotime at the Jasper Cuts and 100 random points. (Lower hemisphere projection on Schmidt equal-area net.) *A*, 100 xenotime optic axes; *B*, 100 random points.

the principal **S**-plane (plane of biotite foliation) of the thin section, this may be happenstance, as shown by the following maxima analysis:

Clusters (percent)	*Xenotime* C *axes*	*Random points*
6	1	0
5	3	1
4	5	5
3	10	10
2	9	12

FOURMILE GULCH AREA

Concentrations of xenotime and monazite of a similar order of magnitude to those at the Jasper Cuts but in biotite gneiss rather than migmatite are present at the Fourmile Gulch area (loc. 2, fig. 66). This occurrence is exposed on the steep hill east of Fourmile Gulch, about three-fourths of a mile northeast of Black Hawk. It has been explored by shallow bulldozer cuts, and small samples have been collected for milling and metallurgical tests; however, no rock has been mined for shipment as an ore.

OCCURRENCE

The biotite gneiss in the area of the surface cuts varies in mineralogic composition and contains but little pegmatite. One lens of pegmatite similar in mineralogy and structure to that in the Jasper Cuts area occurs in the biotite gneisses about 15 feet stratigraphically above the zone of xenotime and monazite concentrations; other scattered lenses crop out sporadically both stratigraphically below and above the occurrence. At the surface cuts, the biotite gneiss strikes about N. 30° E. and dips about 30° SE. Lineations in the rock plunge gently northeast or locally southwest.

The exposed zone of rare-earth concentrations is about 3 feet thick and has a probable maximum strike length of less than 100 feet. The zone is estimated to contain 1 to 3 percent by volume of xenotime and monazite. The radioactivity of the rare-earth zone is about 10 times that of the surrounding country rock. Similar to the Jasper Cuts occurrence, the xenotime and monazite are mainly associated with coarse biotite that constitutes thin lenses in the rock; the biotite lenses also contain abundant magnetite.

PETROGRAPHY

The host rock containing the concentrations of xenotime and monazite is a fine-grained magnetite-bearing quartz-biotite gneiss (table 4), a local variety of the biotite-quartz-plagioclase gneiss. The overlying and underlying gneiss is typical biotite-quartz-plagioclase gneiss with thin interlayers of sillimanitic biotite-quartz gneiss. A mode of a typical specimen (3, table 4) of biotite-quartz-plagioclase gneiss collected near the rare-earth zone is given for comparison with the xenotime-monazite-bearing gneiss.

TABLE 4.—*Modes (volume percent) of biotite gneisses from the Fourmile Gulch area*

	1	2	3
Quartz	51.0	61.5	40.1
Biotite	25.5	28.6	9.2
Plagioclase	3.6	0	48.1
Composition	(An_{28})	----------	(An_{30})
Magnetite (and hematite)	14.2	7.3	1.4
Muscovite	2.6	1.5	----------
Accessory minerals	3.1	1.1	1.2

1. Sample (SH-1A) taken from rare-earth zone; 1,156 point counts were made over an area of 325 sq mm Accessory minerals are xenotime, monazite, and sparse zircon. α' of the plagioclase is 1.543±0.002.
2. Sample (SH-2A) taken from rare-earth zone; 1,143 point counts were made over an area of 300 sq mm. Accessory minerals are xenotime, monazite, and sparse zircon.
3. Sample taken about 800 ft. southwest of rare-earth zone. Modal analysis by D. J. Gable of the U.S. Geological Survey. Accessory minerals are mainly apatite and allanite.

ACCESSORY MINERALS

The accessory minerals in the rare-earth zone, the enclosing biotite gneiss, and the nearby pegmatite were extracted and studied in the same manner as those in the Jasper Cuts area. The data are recorded in table 5.

Several similarities and some differences can be noted between this occurrence and that in the Jasper Cuts area. The biotite gneiss and the pegmatite at the two localities are similar in that both contain monazite and xenotime; also, the pegmatite has the same preferential concentration of xenotime over monazite. The size and shape of xenotime and monazite and the cores of many zircons in the rare-earth zone at this locality are similar to those at the Jasper Cuts area. The major mineralogic differences between the two localities are the abundance of magnetite at the Fourmile Gulch area, the predominance of monazite over xenotime in the rare-earth zone at the Fourmile Gulch area, and the presence of more monazite relative to xenotime in the biotite gneiss (country rock) at Fourmile Gulch.

Although monazite exceeds xenotime in abundance in the rare-earth zone at the Fourmile Gulch area, spectrographic analyses of the rocks from this locality indicate that the yttrium-earth elements predominate over the cerium-earth elements, as shown in table 6. Accordingly we conclude that the monazite at Fourmile Gulch contains more yttrium than the monazite at the Jasper Cuts area.

In contrast to the Jasper Cuts area, xenotime and monazite are virtually impossible to distinguish in thin section in the Fourmile Gulch area, both being pale yellow, probably as a result of a higher percentage of yttrium in the Fourmile Gulch monazite. As shown in figure 72, a photomicrograph taken in plane polarized light, the xenotime and monazite are closely similar in appearance. Under crossed nicols some xenotime grains that have their optic axes more nearly in a horizontal than a vertical position are distinguishable from monazite, however, because of their greater birefringence. Xenotime and monazite can be distinguished in thick sections (approximately 0.3 mm) of rocks from the rare-earth zone with a calibrated absorption microspectroscope, for the two minerals give completely different absorption spectra. The following absorption spectra are especially diagnostic:

Xenotime—at 668mμ—a strong, broad line in the red, at 523 and 525mμ—a strong doublet in the green.
Monazite—572 to 592mμ—a very strong band in the yellow.

It might be noted that the data for xenotime do not match that given by Wherry (1915). Unfortunately the ordinary thin section is too thin for this instrument to be used successfully.

The optical properties of the xenotime and monazite are similar but differ slightly from those in the Jasper Cuts area. The xenotime from Fourmile Gulch is uniaxial positive with $\omega=1.723\pm0.004$ and $\epsilon=1.821 \pm0.005$; the birefringence is 0.098 ± 0.009; pleochroism is faint with ω colorless and ϵ pale yellow. Monazite is biaxial positive and $2V$ ranges from 8° to 11°; the average of three measurements on the universal stage and two measurements using Mallard's constant was 10°. The monazite is not perceptibly pleochroic; all orientations appear pale yellow. $\alpha=1.785\pm0.004$, $\beta=1.787\pm0.004$, and $\gamma=1.835\pm0.005$; the birefringence is 0.050 ± 0.009. These indices are somewhat lower than

TABLE 5.—*Accessory minerals heavier than methylene iodide in rocks from the Fourmile Gulch area*

Rock type	Number of grains counted	Weight percent of accessory minerals heavier than methylene iodide, including magnetite	Weight percent of magnetite	Number percent in 200–270 mesh fraction minus magnetite				
				Hematite	Zircon	Xenotime	Monazite	Epidote
1. Biotite gneiss in the rare-earth zone	352	34.8	31.4	7.2	4.9	26.4	61.5	0
2. Biotite gneiss	395	2.12	2.03	62.5	9.4	2.3	24.9	.9
3. Pegmatite	256	.28	.21	22.0	14.0	33.0	31.0	0

NOTES.—No apatite or allanite was found in the fractions lighter than methylene iodide. Sillimanite is present in the biotite gneiss.
1. Sample taken from same outcrop as sample 1 of table 4.
2. Sample taken 30 ft stratigraphically above sample 1.
3. Sample taken 15 ft stratigraphically above sample 1.

those of the monazite from Jasper Cuts, possibly because of its higher yttria content. Such an interpretation is partly substantiated by monazite from Bolivia, described by Gordon (1939), that has similar indices and contains 5.08 percent Y_2O_3 and virtually no thoria.

SPECTROCHEMICAL ANALYSIS

Semiquantitative spectrochemical analyses of a selected sample (SH–2) from the rare-earth zone and a composite chip sample (4–1) over a 5-foot width are given in table 6.

As in the rare-earth zone at Jasper Cuts, yttrium-group rare earths predominate over the cerium-group rare earths despite the predominance of monazite at Fourmile Gulch, as mentioned earlier. This is shown in tabular form as follows:

	SH–2 (percent)	*4–1 (percent)*
Total rare earths	3.3	0.8
Yttrium group (Y, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu)	2.2	.4
Cerium group (La, Ce, Nd, Pr, Sm, and Eu)	1.0	.3
Yttrium group-cerium group ratio	2.2	1.3

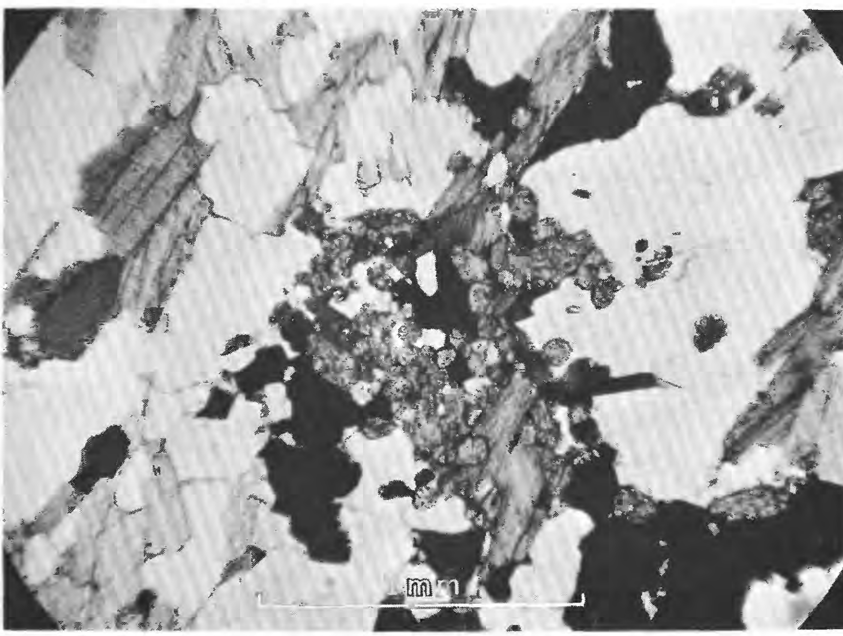

FIGURE 72.—Photomicrograph showing xenotime and monazite in rare-earth zone in biotite gneiss at Fourmile Gulch. Both minerals are rounded, gray, and indistinguishable, unlike those in figure 69. White mineral is quartz. Pale-gray laths are biotite. Most of the black mineral is magnetite. Plane polarized light.

TABLE 6.—*Semiquantitative spectrographic analyses of rare-earth zone in biotite gneiss from the Fourmile Gulch area*

[Analyst, Raymond G. Havens]

Element	SH-2 (percent)	4-1 (percent)
Radioactive:		
U	[1] 0	[1] 0
Th	.3	.07
Rare-earth:		
Y	1.5	.3
La	.3	.07
Ce	.3	.15
Pr	.07	.15
Nd	.3	.07
Sm	.07	0
Gd	.15	.03
Tb	<.07	0
Dy	.15	.03
Ho	.03	.015
Er	.15	.03
Tm	.015	.007
Yb	.15	.03
Lu	.03	.007
Major and Minor:		
Si	M	M
Al	3	M
Fe	M	7
Mg	1.5	1.5
Ca	.15	1.5
Na	.3	3
K	3	3
Ti	.7	.7
P	[2] .15	0
Trace:		
Mn	.15	.15
Ba	.03	.03
Co	.003	.003
Cr	.07	.015
Cu	.0015	[3] .7
Ga	<.007	.003
Nb	.003	.003
Ni	.015	.015
Pb	.03	.015
Sc	.003	.003
Sn	.007	.0015
Sr	.0015	.015
V	.03	.015
Zr	.15	.07

NOTE.—Looked for but not found: Ag, As, Au, B, Be, Bi, Cd, Eu, Ge, Hf, Hg, In, Ir, Li, Mo, Os, Pd, Pt, Re, Rh, Ru, Sb, Ta, Te, Tl, W, and Zn.

Figures are reported to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, in percent. Sixty percent of the reported results may be expected to agree with the results of quantitative methods.

M=major constituent, greater than 10 percent.

[1] Less than 0.05 percent U may not be detected with this method.
[2] Determined chemically by John P. Schuch, U.S. Geological Survey.
[3] The high value for Cu probably represents contamination.

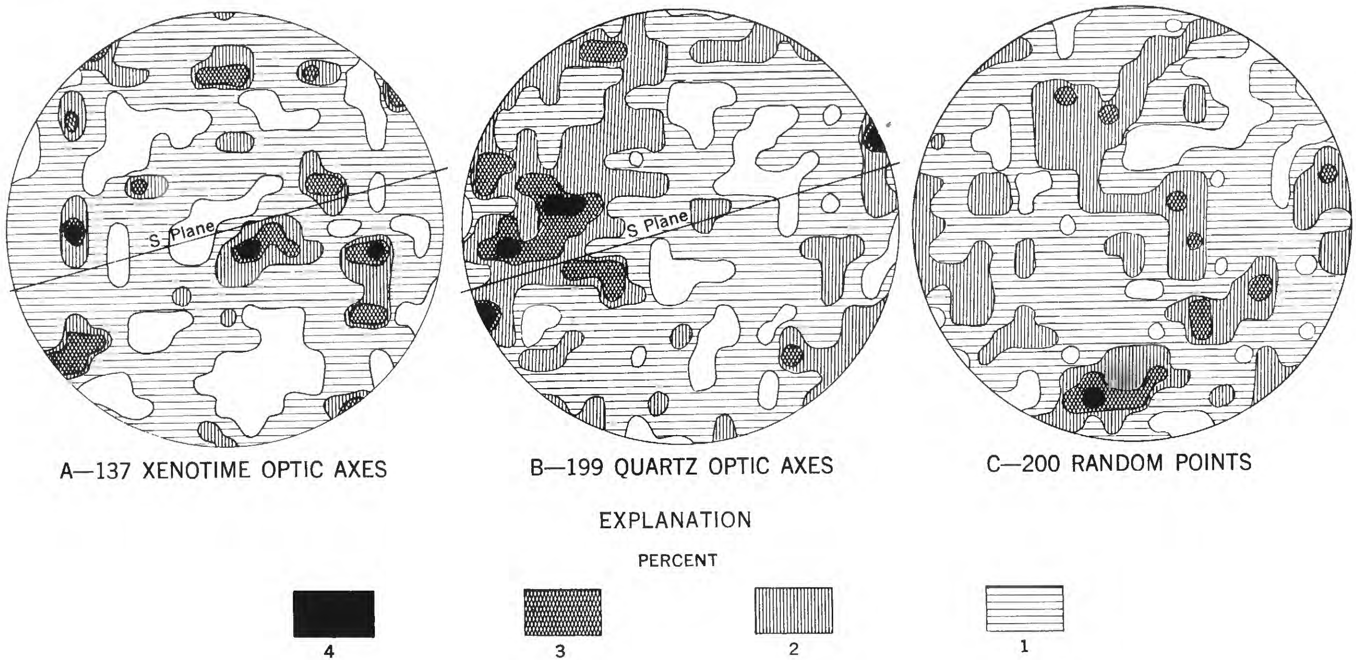

FIGURE 73. Petrofabric diagrams of xenotime and quartz at Fourmile Gulch and 200 random points. (Lower hemisphere projection on Schmidt equal-area net.) *A*, 137 xenotime optic axes. *B*, 199 quartz optic axes. *C*, 200 random points.

PETROFABRICS

Figures 73*A* and 73*B* illustrate contoured plots of the *c* axes maxima of xenotime and quartz from thin section SH-2b from Fourmile Gulch, which was cut normal to the biotite foliation. The principal *S*-plane of the foliation is shown. Figure 73*C* gives a contoured plot of 200 random points, selected and contoured as noted previously for figure 71. Diagrams in figure 73 *A*, *B* show slightly more preferred orientation for xenotime and quartz than the diagrams for the Jasper Cuts area, owing to a tendency for 4-percent maxima to be close to the principal *S*-plane. The maxima in the three diagrams show the following relations:

Clusters (percent)	*Xenotime c axes*	*Quartz c axes*	*Random points*
4	3	3	1
3	11	6	8
2	14	7	11

ILLINOIS GULCH AREA

A third known occurrence, apparently lower in tenor than the Jasper Cuts and Fourmile Gulch deposits, is about a mile south-southwest of Central City (fig. 66, loc. 3). It has been prospected by several shallow bulldozer cuts. The host rock is a migmatitic garnetiferous biotite-quartz gneiss that forms small interlayers in migmatitic sillimanitic biotite-quartz gneiss. These rocks are infolded into the layer of microcline-quartz-plagioclase-biotite gneiss along the axis of a small syncline on the southeast flank of the Central City anticline (fig. 66), and are stratigraphically approximately equivalent to the biotite gneiss and migmatite in the Jasper Cuts area.

The accessory minerals heavier than methylene iodide extracted from a sample of the host rock are listed in table 7. Garnet is the dominant accessory mineral. Xenotime and monazite are not concentrated to the extent they are in the other two occurrences; xenotime is nearly twice as abundant as monazite.

TABLE 7.—*Accessory minerals heavier than methylene iodide in migmatitic biotite gneiss from the Illinois Gulch area*

Number of grains counted	Weight percent of accessory minerals heavier than methylene iodide, including magnetite	Weight percent of magnetite	Number percent in 200-270 mesh fraction minus magnetite					
			Hematite	Zircon	Xenotime	Monazite	Garnet	Epidote
300	3.6	0.06	2.4	3.4	9.3	4.8	79.1	1.0

NOTE.—No apatite or allanite was found in the fraction lighter than methylene iodide.

ORIGIN OF XENOTIME AND MONAZITE CONCENTRATIONS

To account for the local occurrences in this region of abnormal quantities of combined xenotime and monazite without appreciable amounts of other heavy accessory minerals except magnetite, it seems that two principal hypotheses must be considered, first, an original mechanical concentration such as a placer, and second a selective mobilization of rare-earth ions from the country rock and recrystallization of xenotime and monazite in local zones of concentration within migmatized biotite gneisses.

The mineral concentrations occur at three widely separated localities at approximately the same stratigraphic position within a single layer of biotite gneiss. These concentrations could indicate that the minerals were concentrated locally at the time of deposition of the original sediments, perhaps as small lenticular placers on a moderately uniform surface of deposition. Possibly such concentrations could accumulate during normal weathering processes. Hence a placer hypothesis seems plausible. At least two objections to this hypothesis can be raised, however. One objection is that the mineral suite is much simpler than that in most known placer deposits. In the Jasper Cuts area xenotime and monazite predominate, with much smaller amounts of zircon and hematite. The Fourmile Gulch area differs in that magnetite predominates over monazite and xenotime, and zircon and hematite are relatively unimportant. All known unconsolidated monazite placer deposits have much more complex mineral suites containing rutile, sillimanite, staurolite, and other common heavy minerals. A possible exception is a deposit classified as a consolidated placer by Vickers (1956) from the Precambrian Goodrich quartzite in the Palmer area, Marquette County, Mich. It contains monazite, hematite, magnetite, ilmenite, and rutile. The second and more serious objection to the placer hypothesis is that a mechanical concentration of heavy accessory minerals similar to those contained in the enclosing rocks would yield a concentrate richer in zircon than xenotime, for the enclosing biotite gneisses both at Jasper Cuts and at Fourmile Gulch contain more zircon than xenotime (tables 2 and 5).

Much evidence supports the contention that xenotime and monazite were deposited at their present sites from fluids that selectively mobilized rare-earth cations and phosphate from the biotite gneiss country rock. The field data clearly indicate that concentration of the rare-earth minerals at their present sites took place during migmatization of the gneissic country rock. Presumably the agent of concentration was the liquid or silicate melt that crystallized as pegmatite; the character of this fluid is not known, but certainly its properties were such that it could intimately diffuse through the country rock, dominantly along the planar structure, in part replace the country rock, and in turn incorporate material from it.

The assumption that the pegmatite was the dominant concentrating agent for the rare-earth minerals is based upon two observations: (a) pegmatite is closely associated with the occurrences as the felsic component in migmatite and as larger distinct bodies; and (b) the pegmatite contains xenotime and monazite in approximately the same proportion as the host rock in the rare-earth zone, although in much smaller amount (tables 2 and 5). Also, pegmatite is closely associated with the lenses of coarse biotite that contain the xenotime and monazite. The field relations indicate that the xenotime and monazite crystallized with this coarse biotite, presumably from the same fluid that yielded the pegmatitic phase of the migmatite. This biotite is unoriented, in contrast to the mica in the biotite gneisses, indicating that it crystallized relatively late in the deformation of the rocks. Zircon must have been a stable mineral in this environment; the original mineral seems to have persisted and changed only by the development of overgrowths.

The biotite gneiss country rock is adequate as a source for the xenotime and monazite, for samples of this rock taken in the vicinity of the rare-earth deposits contain both accessory minerals (tables 2 and 5); the country rock at both the Jasper Cuts and Fourmile Gulch localities, however, contains more monazite than xenotime. The greater xenotime-monazite ratio in the rare-earth zone and in the pegmatite than in the country rock is evidence that xenotime was preferentially mobilized with respect to monazite. Along this line of reasoning, the greater monazite-xenotime ratio in the rare-earth zone at Fourmile Gulch than at the same zone at Jasper Cuts is attributable to the fact that the country rock at Fourmile Gulch contains more monazite relative to xenotime than the country rock at Jasper Cuts.

It seems improbable that either the microcline-quartz-plagioclase-biotite paragneiss or the intrusive granodiorite could have been the ultimate source of the rare-earth elements, for the microcline-bearing gneiss contains only traces of xenotime and sparse monazite (table 2) and the granodiorite lacks both minerals, so far as known. Also, known granodiorite is not present in close proximity to the deposits. A biotite-muscovite granite that occurs in this region, particularly south of Central City (Harrison and Wells, 1956; 1959), also can be ruled out as a potential source even though the rock is known to contain monazite as a common accessory mineral, for this granite is absent in this part of the Central City district; also it was emplaced after the formation of the migmatite (Moench, Harrison, and Sims, 1958, p. 1737).

One implication of these data is that both xenotime and monazite are mobile minerals in environments of high-grade metamorphic rocks and migmatite, whereas zircon probably remains as a relic, stable mineral but is modified by the development of overgrowths.

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