

CARBONATIC NIOBIUM-RARE EARTH DEPOSITS,
RAVALLI COUNTY, MONTANA*

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ABSTRACT

Carbonatic Nb-RE deposits of Ravalli County, Montana contain chiefly dolomite and Sr-Ba calcite and variable amounts of biotite, chlorite, actinolite, allanite, quartz, barite, apatite, monazite, pyrite, magnetite, and columbite. Rarer unusual constituents are ancylite, fersmite, niobian rutile, eschynite, andradite, glaucophane and wollastonite. The tabular deposits which are in pre-Beltian (?) hornblende metamorphic rocks are an inch to 10 feet thick, as much as 450 feet long, and crosscutting as well as conformable. They range in texture and composition from metasomatized marble layers to banded, comb-structure veins, resulting from the action of hydrothermal solutions of alkalic derivation, which supplied mainly Sr, Ba, RE, Nb, and S.

INTRODUCTION

General Statement

Mineral deposits of unusual characteristics occur in the southwestern corner of Montana in Ravalli County, in the headwaters of the West Fork of the Bitterroot River along the eastern flank of the Bitterroot Range. The area is approximately 38 miles by road south of Darby. Deposits have been discovered in the general area of Woods, Beaver, and Sheep Creeks, all tributaries to the West Fork Bitterroot River (Fig. 1). The purpose of this investigation has been to study the mineralogy and paragenesis of these deposits and to formulate conclusions regarding their origin.

History

Rare-earth minerals from western Montana were first described by Penfield and Warren (1899), who analyzed parisite crystals which were reportedly found near the ghost settlement of Pyrites, east of Florence, in northern Ravalli County. The description of the matrix material containing the parisite, apparently an altered rhyolite or trachyte, indicates, however, that this occurrence of a rare-earth carbonate is not directly related to the deposits described in this report.

Sahinen (1957) states that columbite was discovered at Sheep Creek in 1953. Fersmite was first detected in the columbite ore in January 1954 (Hess and Trumpour, 1959) in a sample submitted by Mr. Louis Eriksen

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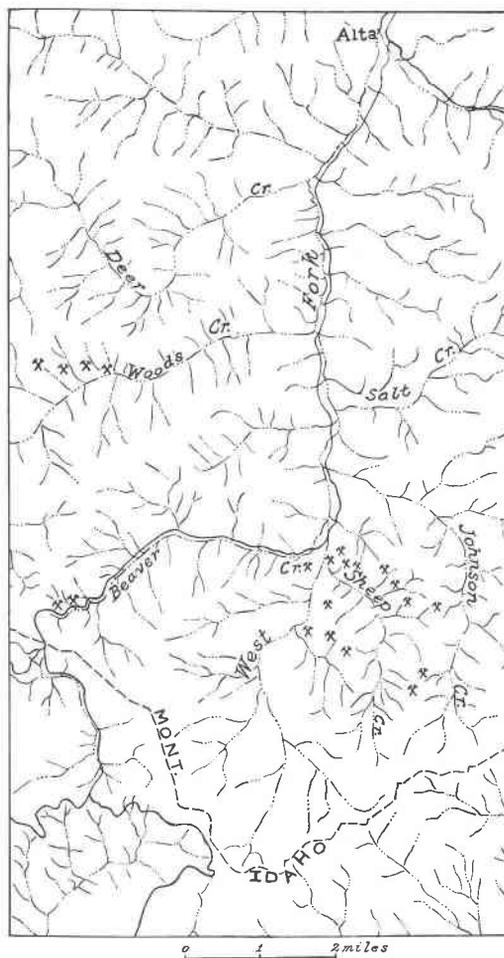


FIG. 1. Outline map of the niobium-rare earth district, Montana and Idaho.

of Corvallis to the U. S. Bureau of Mines Petrographic Laboratory at Albany, Oregon.

Only the Sheep Creek deposits have been actively developed; all of the other Montana occurrences have been merely prospected. The former are owned by the Sheep Creek Mining Company, a subsidiary of the Continental Columbian Corporation of California, which began activities in 1957, driving four adits. The Idaho counterparts, first described by Abbott in 1954, have since been studied in detail by Anderson (1958, 1960).

The senior author studied the deposits during the early summer of

1957 and again in August 1958, when he also examined a number of the Idaho occurrences. The Montana Bureau of Mines and Geology also has investigated the deposits (Crowley, 1958, 1960).

The field work and part of the laboratory work has been supported by Michigan Memorial-Phoenix Project, No. 150. The writers gratefully acknowledge assistance from the following individuals: for laboratory aid, R. A. Borup, J. A. Greear, R. W. Vian, R. W. Deane, and E. B. Gross; for information and specimens, Dr. Charles Milton and Dr. Mary Mrose, Professor Clifford Frondel and Frank A. Crowley. The writers are grateful to Dr. E. R. Wright and The Dow Chemical Company for their encouragement and permission to publish the results of this study.

GEOLOGY

Definition of the District

The district lies in the southwestern corner of Montana, continuing generally southward into Idaho (Fig. 1). Deposits are known in a north-northwest-trending belt that extends from near North Fork, Idaho, to Deer Creek, just north of Woods Creek in Montana (Fig. 1). The belt is approximately 18 miles along its northwesterly axis and 3 or 4 miles across the axis.

General

The mineralized area is underlain chiefly by metamorphic rocks, shown on the geological map of Montana (Ross *et al.*, 1955) as metasediments of the Ravalli group, Belt Series. Reconnaissance study suggested however, that the rocks might be pre-Beltian in age. This is supported by Sahinen (1957, p. 6). Crowley (1958, 1960) also regards these rocks as pre-Beltian. In many respects their lithology resembles that of the Cherry Creek group, a unit widespread elsewhere in southwest Montana (Heinrich, 1953). The other possibility is that these rocks represent higher-grade metamorphic facies, grading northward into more typical Belt rocks.

Main rock types noted near the deposits include: 1) Hornblende gneiss and amphibolite, weakly foliated to coarsely gneissic; some banded or streaked. This is the most common wall rock of the deposits. 2) Light colored quartz-feldspar gneiss streaked with biotite-rich lenses. 3) Augen gneiss, a relatively dark hornblende rock studded with ovoid feldspar metacrysts, an inch long. This may represent local, partly granitized amphibolite. 4) Biotite and muscovite schists, highly fissile, light gray to dark. 5) Biotitic and feldspathic quartzite. 6) Iron formation—banded quartz-magnetite rock. This rock is characteristic of the Cherry Creek group elsewhere in Montana. 7) Marbles. Crowley (1958, 1960) also reports diabase dikes cutting these metamorphic rocks.

Along Woods Creek the metamorphic foliation strikes generally N. 30–50° W., dipping rather uniformly northeast at 40–70°. Near the mouth of Sheep Creek it strikes N. 60–70° W. and dips steeply northeast. The West Fork Bitterroot River north of Sheep Creek apparently follows a major north-south fault that passes just west of the Sheep Creek deposits.

The metamorphic rocks are intruded by scattered, relatively small, undifferentiated, granitic pegmatites and are also cut by a few small quartz and quartz-chlorite veins. These pegmatites and veins are probably related to granodiorite of the Idaho batholith, which intrudes the metamorphic rocks at the very southern tip of the West Fork area. Locally fine-grained felsic dikes (Laramide or Tertiary?) transect the metamorphic complex.

Deposits

Most of the smaller deposits generally are parallel with the metamorphic foliation and most of them occur within hornblendic rocks. Some of the thicker ones transect the foliation at slight angles, or locally send off apophyses that cut across at considerable angles. The deposits range in thickness from about an inch to as much as 10 feet (Fig. 2). Some have been traced for only several feet, whereas others are known to be continuous along the strike for as much as 450 feet. The thinner deposits tend to occur in closely spaced subparallel clusters of three or more, separated by a few inches to several feet of wall rock.

Most deposits have sharply defined walls. Most are tabular; a few of the larger ones are lensoid to irregular, showing branching as well as pinch-and-swell structures. The deposits appear to have been formed

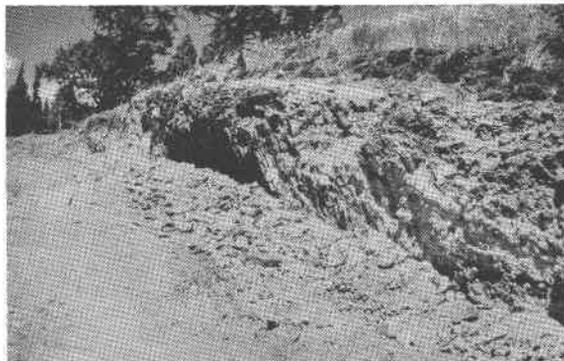


FIG. 2. Hanging-wall part of thick baritic carbonatic deposit, Rocky Point No. 5, Woods Creek, Montana.

chiefly along two types of structures: 1) the metamorphic foliation, and 2) contacts between hornblende gneiss and other metamorphic rocks. Some of the cross-cutting deposits may also have been emplaced along faults.

On the basis of texture, the deposits are divisible into three types: 1) Very fine grained, essentially aphanitic, showing a very weakly developed gneissoid texture. This is characteristic of some of the deposits along Woods and Beaver Creeks. This carbonate-rich rock resembles a fine-grained limestone, with a porcelanoid fracture and an average grain size of 1 mm. or less. Thin-sections show a well developed foliation, with the carbonate in highly elongate, equigranular, subparallel spindles that are conspicuously twinned. 2) A somewhat coarser-grained, megascopically granular and streaked texture occurs in Rocky Point No. 5 and some of the other Woods Creek deposits. The gneissoid texture results from the alignment of barite lenses within a dominantly carbonate matrix. The grain size ranges from 3 to 10 mm. Under the microscope the carbonates are seen to be heterogranular, poorly to non-foliated, with but minor twinning. 3) More variable and much coarser-grained structures characterize the Sheep Creek veins. Irregular comb structures may be developed marginally, and the interiors vary greatly in grain size, from coarse grained (4 cm.) to fine grained (1 mm. or less). Gneissoid structure is only locally and marginally present.

A few small vugs (several mm. to several cm. across) were found in the lower Beaver Creek deposits and in some parts of the Sheep Creek vein. They are generally partly filled with calcite rhombohedra. Some vugs in the lower Beaver Creek deposits have an outer lining of small quartz crystals, central crystals of clear calcite, corroded by very fine-grained hematitic carbonate which fills the remaining space.

Thus the deposits range in appearance from some resembling fine-grained limestones, through others that look like coarse-grained, weakly foliated marbles, to several that have the textural characteristics of ordinary veins.

Post-consolidation disturbance of the deposits is shown by 1) numerous late veinlets of clear calcite and/or of quartz, and 2) slickensided surfaces (in the Sheep Creek deposits) across all of the minerals including ancylite. The Sheep Creek veins have been offset and displaced by at least two sets of faults.

Exomorphic and Endomorphic Effects

Most of the deposits are characteristically surrounded by thin envelopes of altered wall rock, in which much of the hornblende has been transformed to biotite (Table 1, A and B). Metacrysts of biotite as large

TABLE 1. MODES OF WALL ROCKS

	A	B	C
Hornblende	49.6%	31.9%	70.0%
Biotite	2.4	23.2	—
Quartz	15.6	9.6	3.6
Plagioclase	30.8	32.8	6.2
Epidote	tr	—	13.8
Barite	—	—	4.4
Magnetite	0.5	—	1.4
Apatite	0.4	2.5	—
Rutile	tr	—	—
Sphene	0.7	—	—
Pyrite	—	—	0.6
	100.0	100.0	100.0

- A. 6—RP2 Amphibolite, Rocky Point No. 2, several feet from deposit.
 B. 4—RP2 Altered amphibolite, Rocky Point No. 2, directly adjacent to deposit.
 C. 11—RP5 Altered amphibolite, Rocky Point No. 5, directly adjacent to deposit.

as 1 cm. in diameter appear in the selvages of carbonate layers that are only a few inches thick. Subsequently much of the biotite directly at the contacts was chloritized. These biotitized selvages also have been impregnated by considerable calcite, which appears both as fine-grained disseminated aggregates and as hair-like, crisscrossing veinlets.

Along the Rocky Point No. 5 the amphibolite has been coarsened, epidotized, and has had barite introduced (Table 1, C). The hornblende also shows unusual greenish blue pleochroism and abnormal interference tints, indicating a transition toward glaucophane.

Many carbonate bands contain small inclusions of altered wall rocks or aggregates of amphiboles formed by the alteration of incorporated wall-rock hornblende. Angular pieces of chloritized biotite amphibolite as much as several centimeters across have been noted.

MINERALOGY

General

The chief minerals are rhombohedral carbonates, which usually constitute 80–95% of the deposits. Present also in most of the occurrences, but in variable amounts, are biotite, chlorite, actinolite, allanite, quartz, barite, apatite, monazite, pyrite, magnetite and columbite. Of these, the Fe-Mg silicates, barite, monazite and apatite become major constituents (>10%) in some parts of deposits.

TABLE 2. CHARACTERISTICS OF THE RHOMBOHEDRAL CARBONATES
(ANALYSES BY EMISSION SPECTROGRAPH)

Deposit	Max. grain size of carbonate	Fabric	Appearance and paragenetic positions	X-ray diffraction identities	Composition (in weight per cent)
Calhoun	1 cm.	Heterogranular, non-foliated, no twinning	Main = Clear (Carb. I)	Dolomite	—
			Minor = dusty, interstitial (Carb. II)	?	
Rocky Pt. No. 1	6 mm.	Equigranular, strongly foliated, sheared (?), twinning strong	Main = Dusty (Carb. I)	Dolomite	—
			Vein = Carb. III	Calcite	
Rocky Pt. No. 2	2 mm.	Foliation moderately well developed, twinning minor, heterogranular	Clear (Carb. I)	Dolomite	—
			Dusty (Carb. II) Ratio 1:1	Calcite	
Rocky Pt. No. 3 (Cresthill)	3 mm.	Heterogranular, non-foliated	Main = Clear (Carb. I)	Dolomite	Calcite (Carb. II); Sr-1.1, Ba-0.51, Mn-0.55
			Minor = dusty and brown-weathering (Carb. II)	Calcite	
Rocky Pt. No. 3—West	3 mm.	Equigranular, well foliated	Clear (Carb. I)	Dolomite	—
			Dusty (Carb. I)	Calcite	
Rocky Pt. No. 4	1 mm.	Heterogranular, poor foliation in clear grains	Clear (Carb. I)	Dolomite	—
			Dusty (Carb. II)	Calcite	
Rocky Pt. No. 5	1 cm.	Heterogranular	Clear (Carb. I)	Calcite	Calcite (Carb. II) Sr-1.4, Ba-0.11, Mn-0.46
			Dusty (Carb. II)	Calcite	
			Clear, vein (Carb. III)	Calcite	
Upper Beaver Creek (Jackie)	1 mm. or less	Equigranular, well foliated twinning common	Clear (Carb. I)	Dolomite	—
			Dusty (Carb. II)	Calcite	
		Heterogranular, non-foliated	Vein (Carb. III)	Calcite	
Lower Beaver Creek	1 cm.	Non-foliated, highly twinned, twin lamellae are bent	Dusty (Carb. II)	Calcite	—
Sheep Creek (Columbine, Van Matre)	4 cm.	Comb, at vein margin	Clear (Carb. I)	Dolomite	—
Sheep Creek (Columbine, Van Matre)	2 cm.	Remnants in ancyllite	Dusty (Carb. II)	Calcite	Sr-0.35, Ba-0.59, Mn-0.42
Sheep Creek (Columbine, Van Matre)	3 cm.	Bladed	Dusty (Carb. II)	Calcite	Sr-1.3, Ba-0.42, Mn-0.42
Sheep Creek (Columbine, Van Matre)	3 cm.	Bladed	Dusty (Carb. II)	Calcite	Sr-1.2, Ba-0.32, Mn-0.19
	3 mm.	Equigranular	Veined by Carb. III	Calcite	—
Sheep Creek (Columbine, Van Matre)	1 cm.	Equigranular vein	Clear (Carb. III)	Calcite	Sr-0.07, Ba-0.37, Mn-0.73

The complete list of minerals found is:

Sulfides: pyrite, pyrrhotite, chalcopyrite, molybdenite

Oxides: magnetite, hematite, rutile, niobian rutile, ilmenite, columbite, fersmite, eschynite

Halide: fluorite

Carbonates: dolomite, strontian-barian calcite, calcite, ancylite, malachite

Sulfate: barite

Phosphates: apatite, monazite

Silicates: quartz, albite, andradite, biotite, chlorite, muscovite, hornblende, actinolite, soda-actinolite, glaucophane, allanite, wollastonite

NOTES ON INDIVIDUAL MINERALS

Rhombohedral carbonates: The rhombohedral carbonates show a considerable variation in grain size, texture, and composition. On the basis of paragenetic position, three main types are recognizable:

Carbonate I—Earliest. Microscopically clear, megascopically gray to blue-gray if unweathered. With weathering, it first develops films of limonite along cleavage surfaces and finally turns entirely brown, resembling siderite megascopically. It is usually dolomite, rarely calcite (Table 2).

Carbonate II—Of intermediate position. Microscopically dusty to "dirty"; in hand specimen gray, pale buff or greenish. It is the only carbonate present in a few veins or locally in parts of some veins. If it occurs subordinate to Carbonate I, it is interstitial to I; if it exceeds I, it embays and replaces it (Fig. 3). It is invariably a strontian and/or barian calcite also containing Mn (Table 2).

Carbonate III—A megascopically snow-white carbonate forms veinlets across nearly all other species (post-ancylite and post-sulfide). In thin section it is clear. The veinlets may consist solely of this carbonate or of quartz-carbonate (Fig. 3), or, rarely, of quartz, carbonate and a second generation of barite (Fig. 4). They range



FIG. 3. Sr-Ba calcite (II) enclosing corroded remnant of iron stained dolomite (I), Rocky Point No. 5 deposit. 70X.

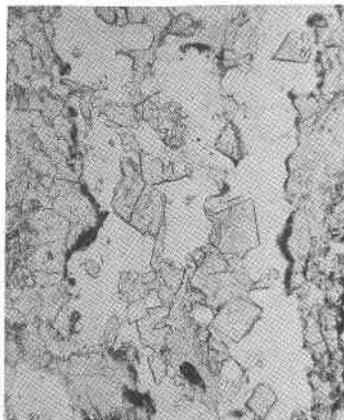


FIG. 4. Veinlet of chlorite (dark marginal fringe), quartz (clear), barite euhedra, and calcite (III) (central, gray), cutting Sr-Ba calcite (II), Sheep Creek vein. 42X.

in thickness from less than a millimeter to about 1.3 cm. This carbonate is invariably calcite, and the one analysis shows it to be Sr-low (Table 2).

This carbonate also forms coarse rhombohedra in vugs of the Lower Beaver Creek deposit, which also contain a fourth carbonate that fills the remainder of the vugs, corroding the white calcite (III). This youngest carbonate is uniformly very fine grained and deep brick-red in color owing to included hematite.

Textural relations and compositions of the carbonates indicate that the initial carbonate (I) was chiefly dolomite, which in some of the thinner deposits displays a strongly foliated fabric. In some deposits or parts of some deposits dolomite was 1) recrystallized, or 2) recrystallized and partly replaced by Sr-Ba calcite, or 3) nearly entirely replaced by Sr-Ba calcite (Fig. 3).

Ancylite: Ancylite has been found by the writers only in the Sheep Creek vein. The ancylite content varies considerably, with the color of the specimen serving as an index to the rare earth carbonate content: specimens low in ancylite are faintly pink; higher grade material is colored light cherry red; the highest grade rock, containing slightly less than 50% ancylite, is dark reddish-lilac in color. The Sheep Creek vein contains material relatively rich in ancylite in masses as much as several feet across, generally segregated in the central parts.

Most of the ancylite is very fine grained (0.007–.030 mm.) and is intimately intergrown with quartz of similar grain size and with Sr-Ba calcite and some barite, both of which are replaced by the ancylite-quartz aggregates (Fig. 5). Veinlets of quartz and of clear calcite (III) transect the ancylite aggregates (Fig. 6). Ancylite varies considerably in form: most is anhedral (Fig. 5); some is euhedral (Fig. 7) and in a few cases it forms radial aggregates (Fig. 8). *X-ray* data are given in Table 4.

Complete purification of an ancylite sample for analysis proved impossible. Analysis of a high-grade specimen containing ancylite, strontian calcite, quartz and a little barite gave the results of Table 3A. Since no other rare-earth mineral was present, all of the rare-



FIG. 5. Corroded remnants of Sr-Ba calcite (II) in fine-grained ancylite quartz aggregate. Late veinlet of calcite (III) cuts both. Sheep Creek vein. 70X.

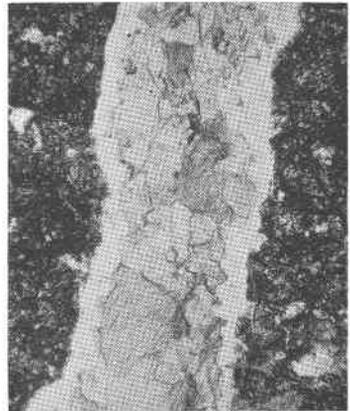


FIG. 6. Veinlet of marginal quartz and central calcite (III) cutting very fine-grained ancylite (dark)-quartz-carbonate aggregate. Sheep Creek vein. 42X.



FIG. 7. Anhedral ancyllite in quartz matrix, with irregular Sr-Ba calcite (II) remnants (gray) and a late calcite (III) veinlet. Sheep Creek vein. 70X.

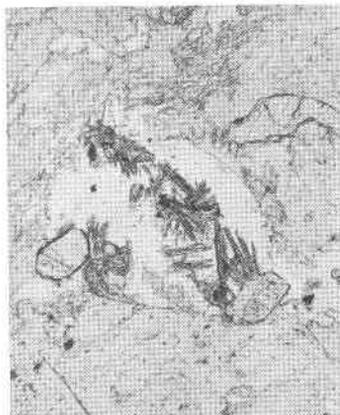


FIG. 8. Radial groups of ancyllite in quartz. Also rounded monazite (gray, high relief) in Sr-Ba calcite (III). Sheep Creek vein. 70X.

earth elements are assignable to ancyllite. By comparing the amount of rare-earth elements in the sample to that required by pure ancyllite, the sample can be calculated to contain 44% ancyllite. The ratio

$$\frac{\text{Wt}\% \text{ Sr}}{\text{Wt}\% \text{ RE}} = 0.25.$$

For pure strontium ancyllite this ratio (Palache *et al.*, 1951, p. 292) is calculated to be 0.47. Since some of the Sr in the Ravalli sample is contained in the calcite (Table 2) and a little in the barite, there is considerable substitution of Ca for Sr in the ancyllite, certainly sufficient to regard the Sheep Creek mineral as a calcian ancyllite. Probably the small amount of Ba reported may be assigned entirely to barite.

Barite: Barite is especially abundant in the Rocky Point No. 5 deposit, in which it occurs in irregular to lensoid snow-white, coarsely crystalline aggregates, many grains of which are 3 mm. across. Nearly all barite is pre-calcite II, being veined and corroded by it (Fig. 9). Parts of the Sheep Creek deposit contain microscopic quartzose veinlets containing scattered barite euhedra (Barite II) (Fig. 4). The Rocky Point No. 5 barite (by x -ray fluorescence) contains 0.4% Sr.

Monazite: Monazite was identified in nearly all the deposits studied, in most cases microscopically. However, in the Rocky Point No. 1 and in the Sheep Creek vein it appears in coarse, rounded anhedra, in the former as much as 8 mm. across and in the latter as much as several centimeters in diameter. These tend to be concentrated in marginal parts of veins. The color is somewhat variable, ranging from a light honey-yellow to a deep orange-red. Microscopically monazite appears most commonly as irregular to ellipsoidal and rounded grains intergrown with carbonate. Some grains are skeletal; others are lobate, markedly embayed by carbonate II (Fig. 10). In the Sheep Creek vein some monazite, which forms overgrowths on subhedral apatite, is dactylicly intergrown with strontian calcite (Fig. 11).

TABLE 3. PARTIAL ANALYSES OF THE RE MINERALS, BY X-RAY FLUORESCENCE

A	B	C
Ancylite ore ¹	Monazite ³	Allanite ⁴
Ce —9.0%	Ce ₂ O ₃ —35.8%	Ce ₂ O ₃ —12.9%
La —6.8	La ₂ O ₃ —26.5	La ₂ O ₃ —10.1
Nd —1.7	Nd ₂ O ₃ — 6.4	Nd ₂ O ₃ — 2.0
Pr —0.5	Pr ₂ O ₃ — 2.7	Pr ₂ O ₃ — 1.1
Sm —0.1	Sm ₂ O ₃ — tr.	Y ₂ O ₃ — tr.
Y —0.01	Gd ₂ O ₃ — tr.	ThO ₂ — tr.
Gd — tr.	Y ₂ O ₃ — tr.	SrO — tr.
Th —0.05	ThO ₂ — 0.7	TiO ₂ — tr.
Ca —34		
Sr —4.6	Total—72.1	Total—26.1
Ba —1.3		
Fe —0.2		
Mn—0.1		
W ² —0.3		

Analysts: A. A. Levinson and R. A. Borup.

¹ Sheep Creek vein. Estimated to be 44% ancylite, rest mainly Sr-Ba calcite and minor quartz.

² By emission spectrography.

³ Rocky Point No. 1 deposit. Average of three analyses.

⁴ Sheep Creek vein. Average of two analyses.

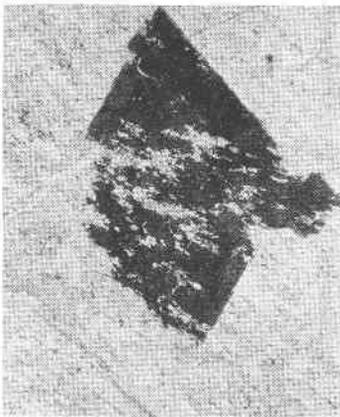


FIG. 9. Zoned, euhedral barite, partly replaced by Sr-Ba calcite (II). Sheep Creek vein. 70X. Crossed polars.



FIG. 10. Lobate monazite embayed by Sr-Ba calcite (II). Sheep Creek vein, 70X.

Monazite is intergrown with both allanite and columbite. Much of it is veined by clear calcite and less commonly by pyrite. For the composition of the monazite see Table 3B; it is but feebly radioactive.

Apatite: Apatite is widespread as microscopic anhedral to subhedral intergrown with dolomite and with Sr-Ba calcite, which may vein it. It is especially abundant in the Western Rocky Point No. 3 vein in which it forms thin phosphate-rich layers.

Fluorite: Small, very rare anhedral of fluorite, pale lilac in color, were noted in two specimens from the deposits in the upper part of Beaver Creek. Microscopic colorless fluorite occurs in the Lower Beaver Creek deposits associated with the altered andradite and wollastonite.

Sulfides: Pyrite is widespread as minute subhedral to euhedral but is locally abundant only in the Sheep Creek vein in which it forms coarse-grained masses as large as 7 cm. across. The other sulfides, chalcopyrite, pyrrhotite and molybdenite appear to be largely restricted to the Sheep Creek vein. Molybdenite is very rare, having been noted as small flakes in but two specimens. Pyrrhotite, only slightly more abundant, was identified only in polished sections. In the Sheep Creek vein the sulfide-rich material also contains much coarse magnetite. Quartz and calcite veinlets transect all of the sulfides.

Columbite: Columbite forms ellipsoidal to irregular aggregates as much as 5 cm. long, with all of the masses over 0.5 cm. in size coming from the Sheep Creek vein. Smaller particles are widespread but not common in many of the other veins, but it is not always possible to distinguish them from grains of niobian rutile by inspection.

The larger columbite aggregates are polycrystalline, composed of numerous un-oriented subhedral having a maximum length of about 2 mm. The aggregates include considerable intergrown carbonate as well as some barite and a little monazite and fersmite. Columbite particles from acid insoluble residues therefore are highly porous and resemble minute "clinkers" (Fig. 12). In some instances columbite euhedra project into the included carbonate. These interlaced crystals are of stout prismatic habit, showing closely



FIG. 11. Apatite grain with dactylic overgrowth of monazite in Sr-Ba calcite (II). Sheep Creek vein. 42X.

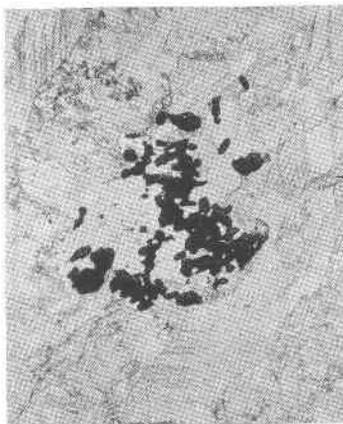


FIG. 12. Skeletal columbite in carbonate I, with scattered biotite flakes. Rocky Point No. 1 deposit. 70X.

spaced vertical striations and simple terminal development, with {001} dominant. By emission spectrograph the mineral was determined to be tantalum-free, agreeing with Sahinen (1957).

Fersmite: The second world occurrence of fersmite is represented by that in the Sheep Creek vein (Hess and Trumpour, 1959). Small amounts of fersmite also were found intergrown with columbite from the Rocky Point No. 1 deposit. Fersmite occurs as irregular to angular inclusions in columbite, commonly close to larger calcite particles. Some fersmite is distinctly vein-like in form.

Eschynite: Crowley (1958, 1960) found a dark brown, radioactive, submetallic mineral in aggregates of parallel fibers as much as 6 inches long and 4-5 inches across in a deposit in the upper part of Sheep Creek. A 200 mg. specimen of the mineral, which he suggested might be euxenite, was analyzed by wet methods by J. A. Greear and found to contain 2.8% barite, 0.7% SiO₂ and 0.4% H₂O as impurities. The original analysis (total 102.7%), excluding the impurities, recalculated to 100% yields:

CaO = 4.2%	ThO ₂ = 3.3%	TiO ₂ = 15.7%
RE ₂ O ₃ = 25.4%	Nb ₂ O ₅ = 49.4%	Fe ₂ O ₃ = 2.0%

By *x*-ray fluorescence analysis it was found that (1) the rare-earths are chiefly of the cerium sub-group, (2) the mineral contains no Ta or U and (3) Greear's chemical separations were good. ThO₂ was precipitated with RE₂O₃ and determined by *x*-ray fluorescence.

Microscopically the mineral is partly metamict. The crystalline remnants are brown, feebly pleochroic, biaxial (-), 2V moderate. $\alpha > 2.00$; $\gamma - \alpha = 0.010 - 0.015$. $G = 4.20$. *X*-ray data are given in Table 4. These data, together with the analytical results, indicate the mineral is eschynite, low in Ti and Th. Eschynite has not been found up to now in carbonate-rich deposits.

TABLE 4. X-RAY DIFFRACTION DATA FOR ANCYLITE AND ESCHYNITE FROM SHEEP CREEK, RAVALLI CO., MONTANA. FILTERED Fe RADIATION

Ancylite				Eschynite	
<i>d</i> Å	I	<i>d</i> Å	I	<i>d</i> Å	I
4.3	1	1.83	3	1.66	ms
3.7	1	1.74	4	1.62	s
2.95	5	1.72	4	1.54	w
2.65	5	1.68	5	1.50	w
2.53	5	1.65	2	1.44	ms
2.44	4	1.62	3	1.37	m
2.35	10	1.59	5	1.34	w
2.18	1	1.55	2	1.28	m
2.14	3	1.53	6	1.24	m
2.09	10+	1.49	5		
2.05	3	1.46	2		
2.02	10	1.42	5		
1.95	8	1.38	4		
1.90	2	1.32	10		
1.85	6				



FIG. 13. Twinned allanite with inclusions of monazite, cut by calcite veinlets (III). Sheep Creek vein. 42 \times Crossed polars.



FIG. 14. Partial pseudomorph of chlorite (dark gray) and calcite (clear blades) after zoned and sector-twinned andradite (high relief). Sheep Creek vein. 70 \times .

Iron and titanium oxides: Magnetite occurs in all the deposits, appearing in the narrower carbonate bands of Woods and Beaver Creeks as minute disseminated octahedra. In the Sheep Creek vein it also forms irregular to ellipsoidal aggregates as large as 5 \times 9 cm. Polished sections show that these are replaced by metallic hematite, particularly along fractures. Minor amounts of supergene red hematite coatings occur in several other veins. Minute morphologically complex hematite crystals also were found in insoluble residues from the upper Beaver Creek deposits.

Niobian rutile, the most abundant niobium mineral of the Idaho deposits, appears to be much less common in the Montana counterparts. It was identified with certainty only in the Rocky Point No. 4 by its x-ray powder pattern. However columbite is present in the same vein. The Idaho niobian rutile contains 13% Nb and <0.1% Ta (Heinrich, *et al.*, 1958). Small grains of golden rutile were noted in thin sections of the Rocky Point No. 1 deposit. Crowley (1958, 1960) also reports ilmenite in the Beaver Creek deposits.

Allanite: Nearly all the deposits contain some allanite; locally in several it forms conspicuous clusters of prismatic subhedra, several centimeters long, concentrated near the walls. It is commonly intergrown with some monazite. The allanite crystals are segmented by veinlets of clear calcite and marginally replaced and corroded by actinolite and chlorite. None of the allanite shows any metamictization whatsoever, and its thorium content is very low (Table 3C). It is strongly pleochroic in shades of deep red, brown and dark green. Some of the larger crystals show color zoning with darker shades in the central parts of crystals. Twinning is conspicuous (Fig. 13).

Amphiboles: Hornblende and actinolite, which are widespread, are concentrated in the thicker deposits near the walls but in thinner ones are disseminated, with the former showing sub-parallel orientation. Dark green hornblende forms single crystals; light green actinolite forms clusters of fibers, usually in radiating groups.

Glaucophane, black in hand specimen, is locally abundant in outer parts of the Sheep Creek vein, forming subparallel bundles as much as 4 cm. long. It also occurs in the

Rocky Point No. 4 deposit. Several amphiboles, which from their optical properties are member of soda-actinolite—glaucofane series, appear in minor amounts as disseminated prismatic subhedra in the Rocky Point No. 4 and 5 deposits.

Micaceous minerals: In the larger deposits much of the biotite forms single foils as much as several centimeters across in marginal parts of veins. It shows varying degrees of alteration to chlorite. In the narrower bands biotite usually is disseminated and may show parallel orientation. Most of it is pleochroic in shades of brown, rarely green. It is veined by strontian calcite along cleavage directions. Biotite is generally more abundant in deposits that contain strontian calcite rather than dolomite as the principal carbonate. Muscovite is an uncommon, late mineral in a few deposits.

There are three types of chlorite: 1) a variety pseudomorphous after biotite, 2) a type which, together with fine-grained carbonate, replaces zoned andradite (Fig. 14), and 3) a variety forming spherulitic aggregates interstitial to calcite (Lower Beaver Creek deposit).

Andradite: Garnet occurs as remnants of partly replaced euhedra in the Lower Beaver Creek and Sheep Creek deposits. It was observed only microscopically. Its properties are: very pale golden yellow in color; isotropic or very weakly birefringent with B as much as 0.004; $n = 1.85-1.86$. The former euhedra are zoned concentrically and show sector twinning. The x-ray powder diffraction pattern has the spacings of andradite, with a $a_0 = 11.98 \text{ \AA}$. The crystals have been largely replaced in the Sheep Creek vein by a very fine-grained chlorite-carbonate-hematite mixture (Fig. 14) and in the Lower Beaver Creek deposit they are corroded by wollastonite.

Wollastonite: Wollastonite was discovered in the Lower Beaver Creek deposit in which it forms fibrous, pink lenses as much as 5 cm. long and 1 cm. thick. Under the microscope it appears as finely felted aggregates of radial or irregular aspect. It is minutely intergrown (and replaced) by fine-grained calcite, quartz, and fluorite. Wollastonite corrodes andradite, actinolite, and carbonate I. The wollastonite is also replaced by several very fine-grained unidentified hydrated calcium silicates.

Other silicates: Quartz is a minor constituent of many of the deposits, occurring in four ways: 1) As disseminated ellipsoidal grains. 2) As very fine-grained lacy aggregates with ancyllite replacing Sr-Ba calcite (Sheep Creek only). 3) In late veinlets. 4) As euhedral crystals lining small vugs in the Lower Beaver Creek vein.

Rounded relicts of sodic plagioclase corroded by a strontian calcite appear in the Rocky Point No. 4 vein.

PARAGENESIS

Clearly defined textural relations indicative of age differences (cross-cutting veinlets, corroded relicts, pseudomorphs, crustification and overgrowths) abound in the veins, and their interpretation leads to a generally consistent paragenetic sequence which is divisible into the following stages (oldest to youngest; a question mark indicates a doubtful positional assignment):

Metamorphic

- I. Dolomite, apatite, magnetite I, hornblende, quartz I, plagioclase, andradite, wollastonite, hematite

Metasomatic replacement

- II. Silicate stage: biotite, actinolite, Na-actinolite, glaucophane
- III. RE-Nb stage: allanite, monazite, barite, columbite, Nb-rutile, eschynite (?)
- IV. Carbonate stage: Sr-Ba calcite
- V. Sulfide stage: Pyrite, magnetite II, molybdenite, chalcopyrite, pyrrhotite
- VI. Ancylyte stage: chlorite, muscovite, ancylyte, quartz II, fersmite (?) hematite, fluorite (?)

Veinlet stage

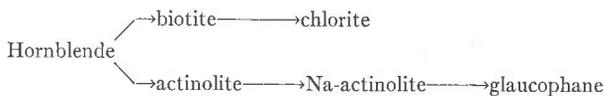
- VII. Quartz III, calcite III, barite II, chlorite, hematitic calcite

Supergene

- VIII. Hematite, limonite, malachite

For the metasomatic stages it is noteworthy that this sequence agrees well, although not exactly, with that first determined by Anderson (1958, p. 30), independently for the similar Idaho deposits: 1) silicates, 2) phosphates, 3) sulfates, 4) oxides, 5) carbonates, 6) sulfides. In his later publication (Anderson, 1960, p. 1196) he changes the order to 1) silicates, 2) phosphates, 3) carbonates, 4) sulfates, 5) oxides, and 6) sulfides. In our sequence the position of the sulfide phase is in considerable doubt. Pyrite is clearly post-monazite, but may be as late as post-ancylyte.

Within individual stages, save that of the sulfides, age relationships among member species are less clearly defined than between stages. It appears that wall rock hornblende was altered in the sequences:



There is also the possibility that allanite represents the final mineral in the alteration of wall rock plagioclase which locally has been transformed to epidote along vein margins (Table 1C). The alteration, andesine→epidote, would release Na for the change, actinolite→glaucophane. Allanite appears to overlap the silicate and RE-Nb stages; some of it is included in monazite, whereas some of it contains monazite inclusions. Monazite is at least in part post-apatite (Fig. 11).

Strontian-barium calcite, which forms the bulk of many of the veins, is an excellent reference mineral. Most of the other species can readily be determined as older or younger than it.

The sequence within the sulfide stage is: 1) pyrite, 2) magnetite, 3)

GEOCHEMICAL CONSIDERATIONS

General

Analyses of vein samples (Table 5) show that the principal determined elements of the deposits are Ca, Ba, Sr, and Fe. Other known major constituents not sought in the analyses are CO₂, P, S, Si, Al, and H₂O. Of lesser quantitative significance are Nb, Ti, Mn, K, Na and several rare earths of the cerium group. Also present but in very minor amounts are yttrium-group rare earths, Zn, Cu, and Th.

The group of elements concentrated in these deposits resembles strongly the assemblage characteristic of carbonatites (Heinrich, 1958, pp. 225-226). Like carbonatites radioactivity is low and stems almost entirely from Th. Also like carbonatites the deposits are essentially Ta-free. However, these deposits appear to be somewhat lower in F and possibly Zr than most carbonatites. The columbite is Zr-free.

Rare Earths

Rare earths are represented almost entirely by the cerium group, with La and Ce predominating greatly, Pr and Nd subordinate, and Sm minor. The yttrium group is represented only by Y and Gd. Noteworthy also is the rare-earth distribution on atomic weight per cent basis for the three chief rare-earth minerals.

	<i>Allanite</i>	<i>Monazite</i>	<i>Ancylite</i>
La	39	37	38
Ce	49	50	50
Pr	4	4	3
Nd	8	9	9
	<hr/>	<hr/>	<hr/>
	100	100	100

These species, within the experimental, measurable limits, show no rare-earth fractionation. The individual rare-earths of the Ravalli fersmite have not been determined. In the eschynite the principal RE elements also are Ce, Nd and La.

Niobium

The presence of columbite in these deposits represents an essentially unique occurrence of this mineral. Previously it has been recorded as 1) a widespread accessory mineral in granite pegmatites; 2) a rare accessory in a few aplites, e.g., the Meldon aplite of Devonshire (von Knorring, 1951); 3) an accessory in some alkalic granites, e.g., the famous biotite granite of the Jos-Bukuru younger granite complex of Nigeria and the alkali granites of the Erzin Massif of Eastern Tuva, U.S.S.R. (Pavlenko *et al.* 1958); and 4) pseudomorphs after pyrochlore in two Tanganyika

carbonatites (James and McKie, 1958). In the Ravalli deposits its occurrence represents a rare example of a Nb-Ca-CO₂ association in which most of the Nb does not occur as a Ca-Nb oxide or silicate (pyrochlore, betafite, niobian perovskite, niocalite). Likewise this occurrence of eschynite is unique.

Strontium

Gundlach (1959) has determined the Sr contents of many hydrothermal carbonate-rich veins from several German districts and reports their Sr content to range from 0.1–0.7%. These are chiefly sulfide-bearing veins with gangues of variable amounts of quartz, fluorite, barite, and calcite, dolomite, siderite, and ankerite. In this type of deposit 95–100% of the Sr occurs in barite. The Ravalli County veins contain 0.24–1.7% Sr (Table 5), with the rhombohedral carbonates containing 0.07–1.4% Sr (0.35–1.4% if the late clear vein calcite is excluded) (Table 2). The barite contains but 0.4% Sr. Thus the Montana veins not only contain from 2 to nearly 2.5 times as much Sr as typical sulfidic hydrothermal veins, but also have most of the Sr in carbonate rather than in sulfate species. The Sr content of these deposits also is in the order of 400–2800 times that of normal limestones (Turekian and Kulp, 1956). Such high Sr contents, are, however, characteristic of feldspathoidal rocks (Gerasimovskii and Lebedev, 1958).

The presence of such, apparently unusually, large amounts of Sr and Ba in calcite aroused the suspicions of the writers. The analyzed material was carefully checked for 1) strontianite and 2) aragonite. Neither was detected. That not all Ba- and Sr-rich calcium carbonates need have the orthorhombic (aragonite) structure has been demonstrated by Terada (1952), who synthesized rhombohedral Ba-Ca and Sr-Ca carbonates.

ORIGIN

General

Ideas on the origin of the Montana-Idaho RE-Nb deposits are highly diverse. Abbott (1954) believed that originally clastic rare earth-bearing minerals, deposited in argillaceous and arenaceous Belt sediments, were destroyed during regional metamorphism and the liberated RE elements migrated to beds of phosphatic marble, where they reacted to form monazite. Kaiser (1956) likewise favored the idea that, during metamorphism, solutions carrying RE elements, derived either from an unknown source or from the rocks themselves, precipitated monazite selectively in carbonate rocks in certain favorable structural settings. Sahinen (1957) refers to the Sheep Creek deposit as a "dike" or "vein."

Hess and Trumpour (1959, p. 1) state simply "The fersmite . . . occurs . . . with a tantalum-free columbite associated with monazite, ancylite,

barite, quartz, and apatite in a fine-grained buff-colored marble." Crowley (1958) has summarized arguments for and against three hypotheses: 1) carbonatites, 2) hydrothermal replacement in marbles, and 3) lateral secretion (actually metamorphic segregation).

Anderson (1958) classed the Idaho deposits as replacement veins and lodes, and pointed out (p. 24) that, "Although others have regarded the carbonates as representing beds of crystalline limestone or marble replaced by the monazite and associated minerals, . . . much of the carbonate intimately associated with the mineralization is younger than the marble beds and indeed younger than the monazite and most of the other minerals." This conclusion is supported by the observations of the writers for the Montana deposits. Anderson (1958, 1960) believes that RE, Ba, Nb, Ti and other substances were introduced by fluids from a deep, probably magmatic, source and that these fluids entered the rocks not long after metamorphism to deposit their minerals along structurally favorable channelways.

Similar Deposits

The mineralogy and composition of these deposits are totally unlike those of most other types of metalliferous veins that have predominantly carbonate gangues. However, a few other occurrences have been described to which the Montana-Idaho deposits show similarities. Pecora (1942, 1948; Pecora and Kerr, 1953) has described deposits in the Bearpaw Mountains of Montana which are calcitic veins also containing essential sanidine, biotite, aegirine, pyrite and pyrrhotite in varying abundance, with lesser amounts of other sulfides (chalcopyrite, galena, tetrahedrite), ilmenite, barite, pyrochlore, and rare-earth carbonate minerals (ancylite, lanthanite, burbankite and calkinsite). The deposits are crudely zoned, 1-8 inches thick, cutting shonkinite, mafic monzonite, and syenite of the Bearpaw Mountains alkalic complex.

In the Salmon Bay area of Prince of Wales Island, southern Alaska, rare-earth carbonate veins cut graywacke (Houston *et al.*, 1958). The chief minerals are ankerite, ferroan dolomite and dolomite, with appreciable amounts of alkali feldspar, hematite, pyrite, and locally siderite and magnetite. Small amounts of the following also have been identified (in decreasing order of abundance): quartz, chlorite, calcite, parisite, bastnaesite, muscovite, fluorite, apatite, thorite, zircon, monazite, epidote, topaz, garnet, chalcopyrite, and marcasite. Niobium minerals are apparently absent. The veins appear to be related genetically to lamprophyre dikes which ". . . may be associated with alkalic rocks which have not yet been exposed by erosion." (Houston *et al.*, 1958, p. 21.)

Zoned phosphatic veins occur 35 miles northeast of Uranium City,

Saskatchewan, cutting chiefly quartz-feldspar gneisses (Hogarth, 1957). Marginal amphibole-rich zones (hornblende, diopside, sphene, biotite, and allanite) are succeeded by phosphatic zones (cerian and yttrian apatite with inclusions of monazite, uranothorite and allanite), with central units that are feldspathic (chiefly hyalophane) and carbonatic (chiefly calcite, quartz and barite). Lamprophyres occur on the flanks of the area; syenite and a barium-rich syenitic gneiss also are present.

Also similar in many respects to the Montana-Idaho veins are the carbonate-rich veins and mineralized zones adjacent to and genetically related to the Iron Hill, Gunnison County, Colorado, alkalic intrusive complex, in which carbonatite body occurs (Olson and Wallace, 1956). These Th-RE veins contain rhombohedral carbonates (calcite, dolomite, ankerite, siderite), minor sulfides (pyrite, sphalerite, chalcopyrite, galena), barite, phosphates (monazite, xenotime, apatite), fluorite, quartz, alkali feldspars, phlogopite, sodic amphiboles, thorite, bastnaesite, cerite (?) and synchisite (?).

Age

Age determinations have been made on three monazites from the Idaho deposits (Jaffe *et al.*, 1959, pp. 96-97). The lead-alpha ages are 99, 95, and 90 (mean 95) m.y. The mean age of rocks from the main mass of the Idaho batholith has been determined as 108 ± 12 m.y. by Larsen *et al.* (1958), who conclude that the batholith was emplaced within a short time, not over a few million years, in early Late Cretaceous. Anderson (1958, p. 32) suggests that the mineralizing fluids came ". . . from some deep, probably magmatic, source, possibly the root region of the Idaho batholith." The age difference between the monazite mineralization and the Idaho batholith rocks appears to be too great to support the idea that the solutions were derivatives of the batholith. Geochemical considerations further hamper linkage of the two: the batholith being of calc-alkalic character, whereas the deposits are alkalic in nature.

CONCLUSIONS

The Montana-Idaho RE-Nb deposits are primarily of metasomatic origin. They grade in structure, texture, mineralogy and chemical composition from nearly undisturbed phosphatic dolomitic marbles through recrystallized and reconstituted marbles to typical veins formed by combined replacement and fracture filling. Even the carbonate layers of the Upper Beaver Creek deposits, which most closely resemble marbles in structure, and mineralogy, contain abnormal Sr concentrations and small amounts of monazite. Crowley (1960, p. 42) also distinguishes two types of carbonate bodies: mineralized and unmineralized ("blue marble").

In addition to the textural evidence, other factors supporting the thesis that the deposits are epigenetic are: 1) Some are slightly discordant to the metamorphic foliation and some have apophyses that transect the foliation. 2) The deposits are usually enclosed in selvages of altered wall rocks, and in a general way the intensity of this alteration appears to be more pronounced around the thicker, more persistent veins. A few even contain what are apparently altered wall rock inclusions. 3) The deposits are characterized by assemblages and concentrations of elements that are anomalous to dolomites, limestones and their metamorphosed equivalents. 4) The monazite, at least, is much younger than the wall rocks of the carbonate deposits. Furthermore, in Idaho, the host rocks are probably of Beltian age, whereas those in Montana may be pre-Beltian.

The writers believe that the deposits were formed by hydrothermal solutions that may well have been derivatives of an alkalic subsilicic magma. Although rocks of this character are not known in the vicinity of the deposits, a small peridotite-syenite complex occurs to the north, east of Hamilton (Heinrich, 1948), and the region as a whole contains other deposits suggesting the imprint of alkalic mineralization (*e.g.*, barite veins in Missoula County to the north and thorite-rare earth veins at Lemhi Pass to the south).

The chief extrinsic elements supplied by the solutions were Sr, Ba, RE, Nb, and S, and minor K, Cu, Mo, Th. Largely available to the solutions from the marbles or the adjacent gneisses were Ca, Mg, Fe, Al, Si, PO₄, and CO₃.

Anderson (1958, p. 24) has aptly stated that "The deposits possess all the compositional characteristics of . . . carbonatites, differing from the type only in the apparent absence of usually associated alkaline rocks," and he further (p. 32) characterizes ". . . the deposits as hypothermal, occurring as hypothermal replacements in carbonate and other rocks. They should, perhaps, be classed as carbonatite veins and lodes."

The writers conclude that the deposits are alkalic-type hydrothermal lodes and veins generally developed in compositionally favorable layers of marble. The presence of such species as columbite, eschynite, rutile, allanite, and actinolite certainly suggests that at the beginning of their formation temperatures were high, probably, as Anderson believes, within the hypothermal range. Terminal stages, characterized by chlorite, fine-grained quartz, ancylite, and ordinary calcite, were marked by much lower temperatures.

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Manuscript received February 1, 1961.