GEOLOGY AND MINERALIZATION CONNECTED WITH THE INTRUSION OF A QUARTZ MONZONITE PORPHYRY, IRON MOUNTAIN, IRON SPRINGS DISTRICT, UTAH

Thesis by

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ABSTRACT

Iron Mountain is one of three intrusive bodies exposed in the Iron Springs district approximately 15 miles west of Cedar City, Utah. It is the erosional remnant of a quartz monzonite porphyry, intruded into Mesozoic limestone and clastic rocks probably at a depth of less than one mile. The quartz monzonite was intruded in large part along the base of the Carmel formation and has pushed aside the overlying sedimentary rocks as if they were a trap-door hinged on the southeast.

Metamorphism is very weak and is confined for the most part to the Sandy member at the base of the Carmel formation. The Homestake limestone member of the Carmel formation is locally replaced by massive bodies of iron ore, consisting chiefly of magnetite, specularite, carbonates and phlogopite. The mineralization is associated with the quartz monzonite but was not necessarily derived from it. Chemical analyses and the mineralogy of the limestone and the ore show that Ca and CO_2 have been removed and important amounts of Fe, Si, Mg, Al and K have been added with no change in volume during replacement of the limestone.

A high temperature and a low confining pressure during mineralization may have permitted the transport of iron halide in a gas phase, but the addition of some of the other constituents and the removal of Ca are not easily accounted for by such a mechanism.

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I INTRODUCTION

Iron Mountain is an erosional remnant of a quartz monzonite porphyry of Tertiary age intruded into sedimentary rocks of Mesozoic age. It is located approximately 15 miles west of Cedar City, Utah, in the Iron Springs district. The district lies in the transition zone between the Colorado Plateau to the east and the Basin and Range province to the west.

Iron ore occurs as magnetite and specularite replacement bodies in the Homestake limestone member of the Carmel formation where this formation is in contact with quartz monzonite, and as fissure fillings within the intrusives. The iron in the fissures is of little commercial importance at present.

All the intrusives shown on the index map (figure 1) are closely related with respect to composition, mineralogy, texture and probably time of intrusion. Iron mineralization is associated with the three intrusives in the Iron Springs district and the Bull Valley intrusive, all of which intrude the Carmel formation. Other intrusives in the region intrude units higher in the stratigraphic sequence and are accompanied by no known iron mineralization. The depth of the cover under which the intrusions were emplaced probably ranged from approximately 1,000 feet to 8,000 feet.

The earliest work in the district was done by Leith and Harder (1908). The most extensive recent work has been done by Mackin (1946, 1947a, 1947b, 1948, 1952, 1954) and Mackin and Nelson (1950). Other workers in the district and nearby areas are Wells (1938), Young (1947), K. L. Cook (1950) and E. F. Cook (1954).

A topographic map at the scale of 400 feet to the inch, with a 10 foot contour interval, and aerial color photos at a scale of approximately 825 feet to the inch were provided by the Columbia Iron Mining Company.

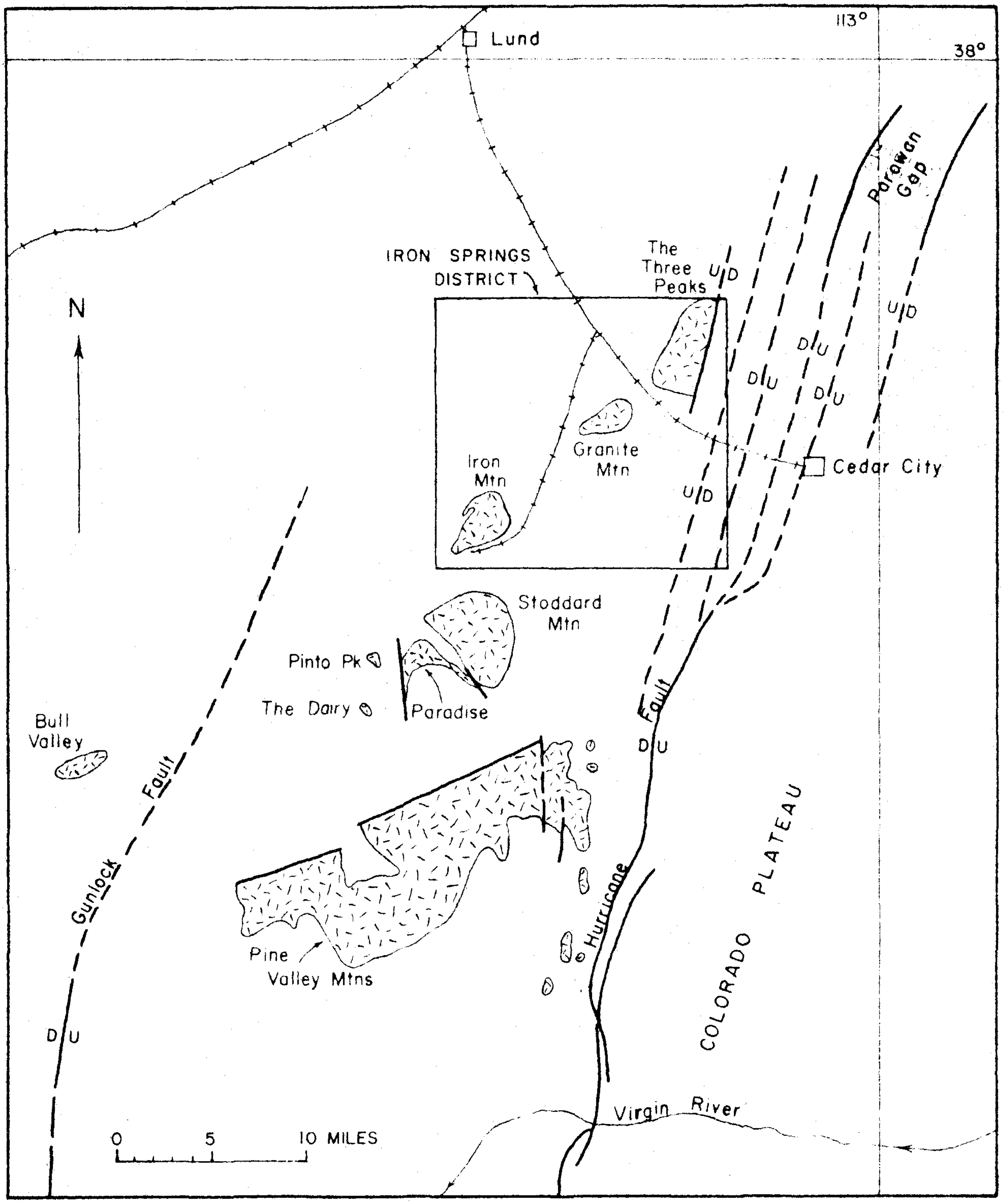


Figure 1. Index map - Intrusive rocks are indicated by random dash pattern. All are Tertiary quartz monzonite porphyries.

The topographic map was reduced to a scale of 825 feet to the inch and used as a base for geologic mapping. Parts of the area were mapped on a scale of 400 feet to the inch and transferred to the smaller scale. Other parts of the area including all of the open pits were mapped with a plane table by the staff of the Columbia Iron Mining Company and transferred directly to the base. I assisted with a small part of the plane table mapping while employed by the Columbia Iron Mining Company. In almost all of the areas mapped by others I have visited the outcrops and in many places I have made changes in interpretation.

Information from diamond drill holes was provided by the Columbia Iron Mining Company and proved very useful, particularly in the study of the McCahill ore body, where drilling was in progress during the summers of 1955 and 1956 and the core was available for study and sampling.

II SEDIMENTARY AND VOLCANIC ROCKS

In the descriptions of the sedimentary and volcanic rocks I have followed the most recent usage of the U. S. Geological Survey (Mackin, 1954) as to the age and names of formations, with one exception. Mackin calls the lowermost member of the Carmel formation exposed in the Iron Springs district, the Siltstone member. Leith and Harder (1908, pp. 25 and 36) called this member an altered contact phase of the Homestake limestone. The member consists of fine-grained meta-sedimentary rocks, interbedded with impure quartz sandstones relatively unaffected by metamorphism. Because the original nature of the fine grained meta-sedimentary rocks is unknown and the member contains sandstone I have named this member the Sandy member.

The Carmel formation is discussed in more detail in section V-Mineralization and contact metamorphism, and is described only briefly in this section.

Carmel formation

Sandy member

The oldest rock exposed around Iron Mountain is the Sandy member of the Jurassic marine Carmel formation, composed of greenish- and brownish-gray interbedded quartz sandstones and fine-grained metamorphic rocks. The member appears massive, and close inspection or the use of a microscope is required to observe the rounded detrital quartz grains which distinguish the sandstone from the metamorphic rock.

Because the lower contact of the Sandy member is observed everywhere only as an intrusive contact, it is impossible to determine accurately the original thickness of the Sandy member. Its observed thickness ranges from 0 to approximately 100 feet, with an average of about 50 feet, the range being due to the intrusive contact. This member is poorly exposed away from the pits, but in some places it can be traced as a yellowish-brown soil, topographically lower than the more resistant quartz monzonite porphyry and Homestake limestone with which it is in contact.

Homestake limestone member

The Homestake limestone member of the Carmel formation is a gray to bluish-gray, thin- to thick-bedded, cryptocrystalline limestone, ranging in thickness from 150 to 300 feet around Iron Mountain. The bottom of this member is argillaceous and grades upward within 5 to 10 feet into massive and thick-bedded limestone which constitutes most of the total thickness of the Homestake limestone. The massive and thick-bedded limestone grades upward into a very thin-bedded, ripple-marked, argillaceous limestone as much as 20 feet thick. This thin-bedded unit grades upward into a thin-bedded, non-calcareous shale arbitrarily taken as the basal part of the Entrada formation.

The Homestake limestone contains scattered brachiopod shells and some brown-weathering, weakly cross-bedded, argillaceous limestone layers less than an inch thick. The limestone is commonly bleached along tiny fractures or bedding planes, and vugs containing a minor amount of recrystallized calcite occur within the bleached part of the limestone. The bleaching and the vugs probably did not result from the action of fluids associated with the intrusive, as similar features are found in the limestone of the Carmel formation cropping out near Shurtz Creek six miles south of Cedar City, and far removed from any intrusive.

Entrada formation

The marine Entrada formation of Jurassic age consists of interbedded gray and maroon siltstones and fine-grained sandstones, greenish-gray and maroon shales, and a few lenses of coarse, green arkose. The formation ranges in thickness from 0 to 300 feet but averages between 150 and 200 feet. Some of the gray sandstones and siltstones contain maroon streaks and spots which are diagnostic of the Entrada formation. The spots may be due to ferruginous concretions. There is an increase in coarseness within the formation from bottom to top, shales predominating in the lower half and sandstones predominating in the upper half. The arkose lenses are not more than a few feet thick and are generally restricted to the upper half of the formation.

The smooth transition from thin-bedded, shaly limestone of the Carmel formation into thin-bedded shale of the Entrada formation shows that deposition was uninterrupted locally. In some places, however, channeling has removed the thin-bedded rocks of the Carmel formation, and sandstone or siltstone of the Entrada formation rests directly on thick-bedded limestone of the Carmel formation. An intraformational conglomerate, consisting of angular fragments of thin-bedded limy shale in a matrix of sandstone, was found at the base of the Entrada formation in several drill holes in the McCahill area.

Marshall Creek breccia

In the section described by Mackin (1947a, p. 9, and 1954) in the vicinity of The Three Peaks and Granite Mountain, the Marshall Creek breccia of probable Cretaceous age consists of very angular fragments of Homestake limestone in a matrix of impure limestone of the same general appearance as the Homestake limestone, and the breccia ranges in thickness from 0 to 50 feet. In the Iron Mountain area between Crystal Springs and Oak Springs it is poorly exposed but probably ranges in thickness from 0 to 10 feet. Locally, there are no breccia fragments present; the "matrix" of impure limestone is thin- and irregularly-bedded and contains red chert.

Mackin (1947a, p. 9 - 11) has inferred that in the area around the Three Peaks intrusive the Marshall Creek breccia was derived from Homestake limestone, which was locally uplifted, brecciated and stripped of the overlying Entrada formation. East of Iron Mountain near Oak Springs, the Homestake limestone is brecciated and weakly stained red where the Entrada formation is thin or absent. The distribution of the brecciated Homestake limestone, the thin or absent Entrada formation, and the Marshall Creek breccia, east of Iron Mountain is satisfactorily explained by Mackin's interpretation of the origin of the Marshall Creek breccia. The abnormal thinning or removal of the Entrada formation was due to erosion, whereas the probable absence of some of the lowermost members of the Iron Springs formation was due to nondeposition on uplifted areas.

Iron Springs formation

The nonmarine Iron Springs formation of probable late Cretaceous age (Mackin, 1947a, P. 7 - 8) ranges in apparent thickness from 3,500 to 5,000 feet in the Iron Mountain area. If the apparent thickness differs from the original thickness it is because of faults not detected.

The Iron Springs formation consists predominantly of sandstone, siltstone, and shale, with minor lenses of conglomerate and fresh water limestone. Most of the sandstone is gray or brown, thick-bedded, fine- to medium-grained, and contains calcareous cement. Some of the sandstone contains carbonaceous material, some is cross-bedded, and some is feldspathic although none would be mistaken for arkose. The siltstone is similar to the sandstone; locally it grades vertically or horizontally into sandstone or shale. The shales are reddish-brown, greenish-gray, and black. Some are very carbonaceous, and all are poorly exposed. Limestone is virtually absent in the Iron Springs formation in the Iron Mountain area, although it is commonly found in the lower part of the formation elsewhere in the district.

Conglomerate lenses ranging in thickness from 0 to approximately 30 feet are distributed irregularly through the formation. A basal conglomerate, present locally on the west side of Iron Mountain, is composed predominantly of white to black pebbles and cobbles in a matrix of light gray quartzite. This conglomerate is hard and fractures across the clasts. East and northeast of Iron Mountain a conglomerate, consisting of pebbles and cobbles of quartz and gray limestone in a matrix of gray calcareous sandstone, is inferred to be a conglomerate at some horizon above the base of the formation. A sandstone cropping out stratigraphically below this conglomerate looks like Iron Springs sandstone.

Sandstones and shales of the lower Iron Springs formation are difficult or impossible to distinguish from sandstones and shales of the upper Entrada formation unless the basal conglomerate of the Iron Springs formation or the Marshall Creek breccia is present. Pebble sandstone or conglomerate, carbonaceous shale or carbonaceous material in sandstone, and limestone, are diagnostic of the Iron Springs formation; arkose, sandstone or siltstone with maroon spots or streaks and dark maroon shale and sandstone, are diagnostic of the Entrada formation.

Claron formation

The nonmarine Claron formation consists of pinkish-gray and white impure limestones, conglomerates, red shales, and red, gray and brown, locally cross-bedded sandstones. It is easily distinguished in most places by its bright red and white colors and is undoubtedly equivalent to the Eocene Wasatch formation of the Colorado Plateau (Mackin, 1954).A basal conglomerate of irregular thickness consists predominantly of poorly sorted quartzite cobbles and boulders. The conglomerates other than the basal conglomerate are characterized by an abundance of well-rounded, dark gray limestone pebbles. The formation is about 1,600 feet thick southeast and northeast of Iron Mountain. Northwest of Iron Mountain the Claron formation appears to be considerably thinner, but mapping was not extended far enough to determine the effects of possible faulting or pre-volcanic thinning.

The Claron formation overlies the Iron Springs formation with strong angular unconformity in Parowan Gap, 15 miles northeast of The Three Peaks. On the western edge of the Colorado Plateau, the Wasatch formation, equivalent to the Claron formation, rests unconformably (Gregory, 1950, p. 58) on Upper Cretaceous sedimentary rocks equivalent to the Iron Springs formation. Mackin (1947a, p. 12, and 1954) reports an angular unconformity between the Iron Springs formation and the Claron formation in the Granite Mountain and The Three Peaks areas. Leith and Harder (1908, plate II, in pocket) interpreted these "unconformable contacts" as fault contacts in their mapping of the Iron Springs district. I know of no place in the Iron Springs district where the contact between the Iron Springs and the Claron formations is exposed well enough to positively ascertain the nature of the contact.

Northwest of Iron Mountain, on the western end of the contact between the two formations, the Claron formation is conformable with the Iron Springs formation, and because of a close similarity there of some members of the two formations, it is difficult to decide where in the section to draw the contact. Southeast of Iron Mountain the two formations are apparently conformable for a distance of almost 4 miles. East of Oak Springs Flat, according to my interpretation, a conformable contact between the Iron Springs and Claron formations is buried beneath the edge of an early intrusive thrust sheet, moved eastward from Iron Mountain. The relationship between the Iron Springs and the Claron formations is considered further in part IV (Structure).

Volcanic rocks

Only a few volcanic rocks appear on the map of the Iron Mountain area, but they are widespread in the district and the surrounding region, where they range in thickness from about 1,000 to 2,000 feet (Leith and Harder, 1908, p. 46). The composition and mineralogy of the volcanic and intrusive rocks are very similar. All the volcanic rocks are of post-Claron age. The relationship between the volcanic rocks and the underlying Claron formation is controversial. Leith and Harder (1908, p. 46) said:

> "The lavas rest on the eroded and upturned edges of the Eocene and Cretaceous sediments, indicating a considerable period of erosion between the intrusion of the biotite andesite and the outpouring of the effusives."

Mackin (1954) said:

> "The Claron is overlain conformably by a sequence of lava flows and pyroclastic rocks, now largely removed by erosion from the Granite Mountain area, that attains a thickness of at least 1,500 feet elsewhere in the district."

E. F. Cook (1954, p. 14) said:

> "Deposition of the lacustrine limestones and sandstones of the Claron was followed by a short interval of uplift and local crustal disturbance before the first volcanic rocks were laid down...... Numerous unconformities within the volcanics, some of them marked by deposits of lacustrine limestone and quartzite gravel, may record either orogenic disturbances or periods of great intrusive folding - - probably the latter."

According to Cook's map, the Paradise intrusive and the Pinto Peak intrusive (see figure 1 for location) are later than the older members of the volcanic sequence. If these intrusives are of the same age as the intrusives in the Iron Springs district then the Iron Mountain intrusive is younger than the oldest of the volcanic rocks. The few volcanic rocks mapped in the Iron Mountain area probably correlate with this older group of volcanic rocks and are therefore older than the Iron Mountain intrusive.

III IGNEOUS ROCKS

Quartz monzonite porphyry

In hand specimen the quartz monzonite porphyry is light gray and consists of phenocrysts of plagioclase, biotite, augite and hornblende in a light gray aphanitic groundmass. Outcrops are jointed, moderately rounded and fresh within an inch of the surface. Field relations such as size, shape and structure are described in the next section (IV - Structure).

The Iron Mountain intrusive deforms the Eocene Claron formation, and other intrusives presumably of the same age as the Iron Mountain intrusive intrude the oldest volcanic rocks. The volcanic rocks are post-Claron in age. The Iron Mountain intrusive is therefore considered Tertiary in age; probably post-Eocene.

Most of the quartz monzonite is altered but, because the alteration will be described in part VI (Alteration), the petrographic description which follows is of unaltered quartz monzonite porphyry.

Mineral composition

Phenocrysts

Plagioclase - The plagioclase ranges in composition from calcic andesine to sodic labradorite (An_{45} - An_{55}). Crystals are moderately zoned and contain inclusions of apatite. Some contain a little biotite and/or magnetite. The maximum length of the euhedral, lath-like plagioclase crystals ranges from $2\frac{1}{2}$ to 6 mm.

Biotite - The biotite is euhedral, strongly pleochroic, dark brown to pale straw yellow, and some contains inclusions of plagioclase, apatite and magnetite. $N_y = N_z = 1.63$.

Augite - The augite is euhedral, very pale green in thin-section and contains inclusions of magnetite, apatite and biotite. The extinction angle is between 47 and 50 degrees.

Hornblende - The hornblende is euhedral, pleochroic, green to pale straw yellow, and contains inclusions of apatite, magnetite, biotite and plagioclase. The extinction angle is approximately 22 degrees.

Groundmass

The groundmass is composed of anhedral equigranular quartz and orthoclase in approximately eutectic proportions (30% quartz and 70%

orthoclase). The grains range in size within the Iron Mountain intrusive from about 0.02 mm to 0.1 mm. Pseudomorphs of alpha-quartz after beta-quartz are common in the groundmass and are recognized by their euhedral bipyramidal form. They are less than 0.1 mm long, but most are larger than an average groundmass grain in any given thin-section. Beta-quartz pseudomorphs are minor constituents of the groundmass and are not present in all sections.

Accessory Minerals

Small apatite and magnetite crystals are scattered in the groundmass and included in phenocrysts.

Summary

A summary of the proportion of minerals and their approximate range in the unaltered quartz monzonite porphyry follows:

Phenocrysts	% of rock
plagioclase	34%
biotite	5% (3 - 8%)
augite	4% (2 - 6%)
hornblende	2% (0 - 4%)
Total phenocrysts	45%
Groundmass	
orthoclase	38%
quartz	17%
Total groundmass	55%
Accessory minerals	
magnetite and apatite	1 - 2%

Texture

The Iron Mountain intrusive is a quartz monzonite porphyry composed of medium grained, subhedral to euhedral phenocrysts of plagioclase, biotite, augite and hornblende in a microcrystalline groundmass of quartz and orthoclase (figure 2).

There is no preferred orientation of phenocrysts except in a band not more than several feet thick along some contacts. The contacts are very poorly exposed except in drill holes, but in some holes the quartz monzonite shows a planar orientation of phenocrysts parallel to the contact. In some places phenocrysts have been broken and the fragments strung out parallel to the contact. The result is a narrow band of mylonitized quartz monzonite along the contact with the same composition and texture as the dike rock shown in figure 5. In hand specimen this mylonitized quartz monzonite is very difficult to distinguish from the Sandy member of the Carmel formation with which it is in contact.

An outcrop of vesicular quartz monzonite porphyry was found about 1,000 feet south-southwest of the summit of Iron Mountain.

Border facies of quartz monzonite

The quartz monzonite at the borders of the Iron Mountain intrusive differs slightly from most of the quartz monzonite away from the borders. A border facies (figure 3) of the quartz monzonite is distinguished from the normal quartz monzonite by:

1) a finer grained groundmass

2) an abundance of hornblende phenocrysts.

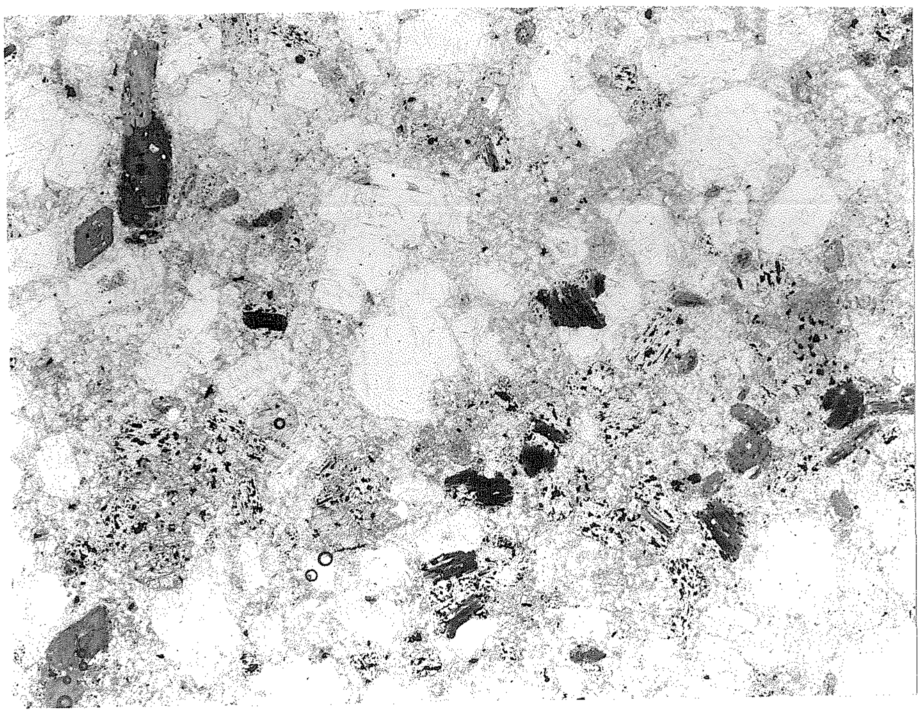
Where the groundmass is finer-grained than normal, the phenocrysts tend to be slightly smaller in average size. The apparent decrease in the abundance of hornblende away from the contacts is due, at least in part, to the alteration of hornblende and the difficulty in distinguishing altered hornblende from altered biotite. Because the present erosion surface is probably not far from what was the roof of the intrusive and because there

Figure 2a - Photomicrograph, plain light ($7\frac{1}{2}$X)

Quartz monzonite porphyry with typical groundmass (average 0.05 mm). Biotite is altered to magnetite and orthoclase.

Figure 2b - Photomicrograph, crossed nicols ($7\frac{1}{2}$X)

same as above



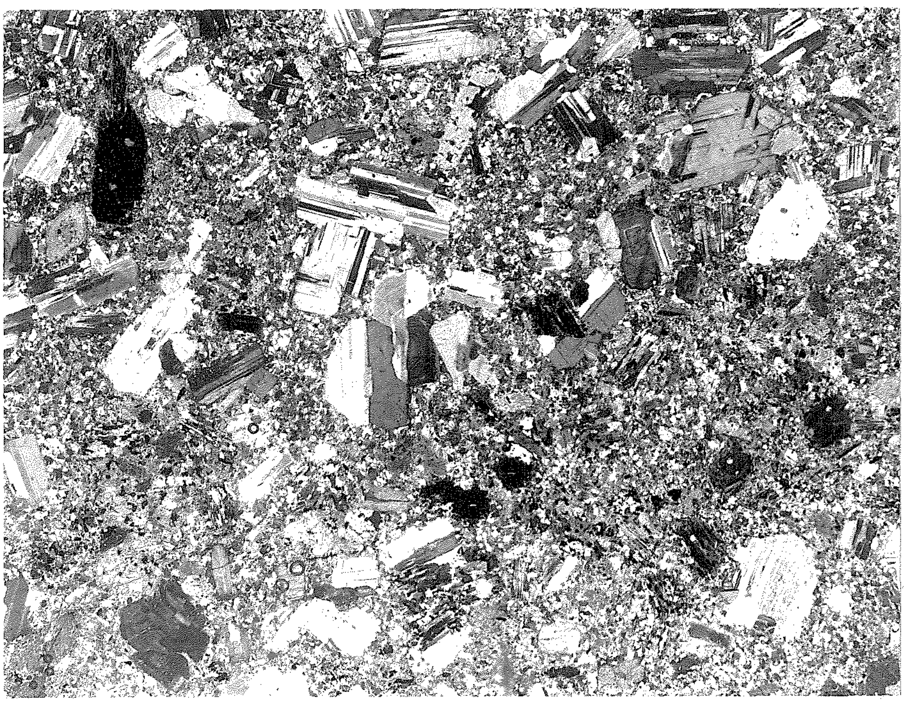
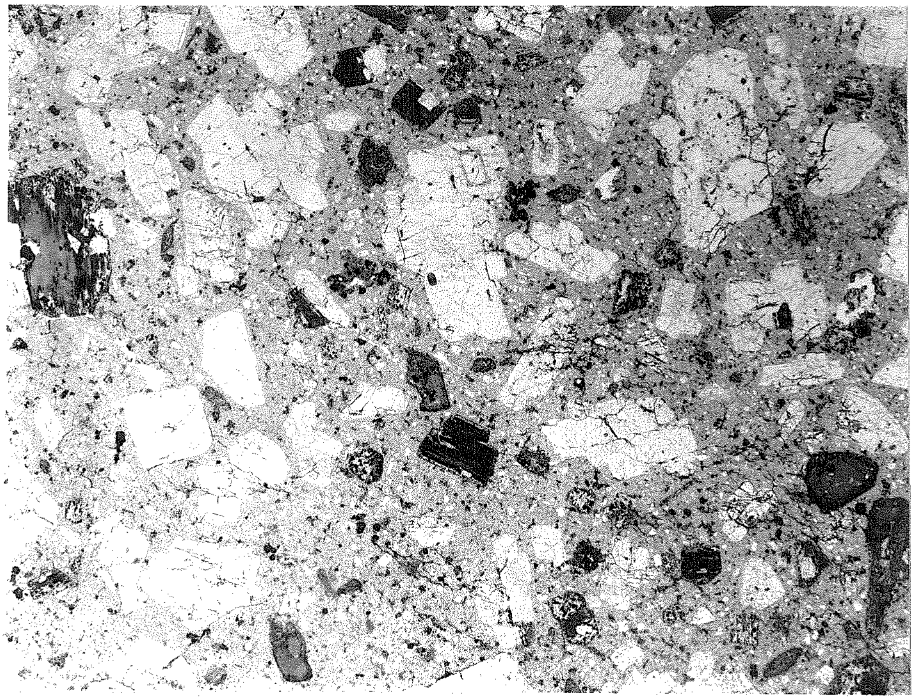


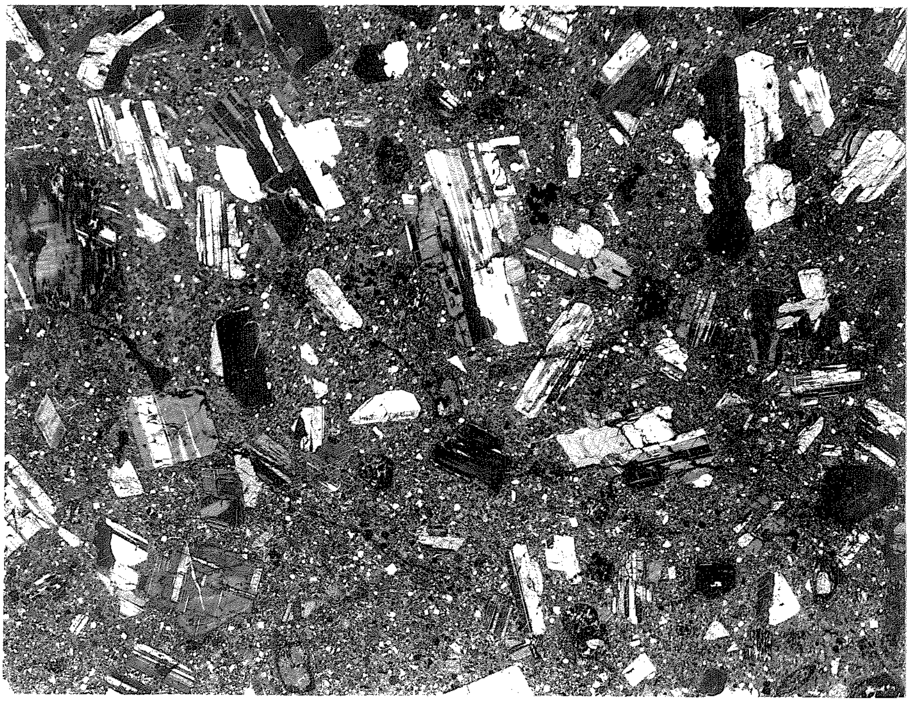
Figure 3a - Photomicrograph, plain light ($7\frac{1}{2}$X)

Border facies of quartz monzonite porphyry with finer grained groundmass (average grain size 0.02 mm).

Figure 3b - Photomicrograph, crossed nicols ($7\frac{1}{2}$X)

same as above





is reason to believe that the intrusive might be the result of multiple intrusion (see part IV, Structure), it is not surprising that the border facies of the quartz monzonite is commonly found away from the edges of the Iron Mountain intrusive. Unless both the structure of the intrusive and the third dimension are considered, the relation of the border facies to normal quartz monzonite is not apparent. The thickness of the border facies is perhaps of the order of 1,000 feet.

Quartz monzonite porphyry dikes

Mineral composition

The mineral content of the dikes is the same as that of the quartz monzonite porphyry.

Texture

There is a gradation in texture in the quartz monzonite porphyry dikes, from foliated quartz monzonite porphyry showing only minor brecciation of phenocrysts (figure 4) to fine grained quartz monzonite with a mylonitic texture (figure 5). The thickness of the dikes ranges from about 6 inches to several feet. Thin dikes and the borders of the thicker dikes tend to be mylonitic or finer grained and more strongly foliated than the interior parts of the thicker dikes. Unless the field relations are known the dike rock cannot be distinguished from the foliated and mylonitized quartz monzonite porphyry along some contacts. I interpret all of the mylonitized rock as being broken during intrusion.

Distribution of dikes and relation to other rocks

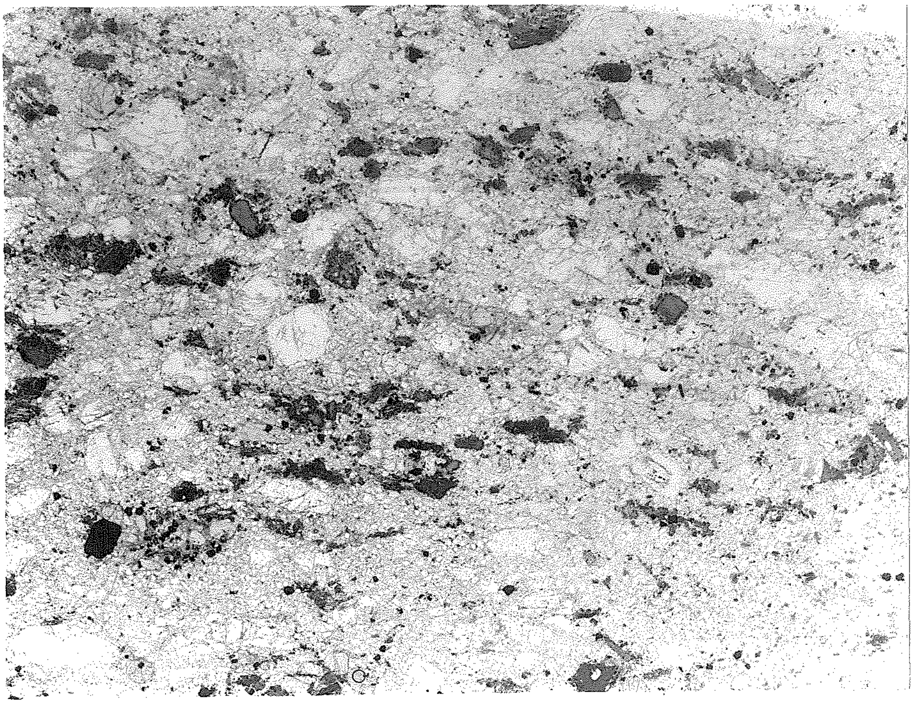
Dikes and sills are rare in the Iron Mountain area and, with one known exception, are restricted in area of occurrence to the quartz monzonite porphyry. The exception is a thin sill intruded into the upper part of the Homestake limestone on the southwest flank of the Iron Mountain

Figure 4a - Photomicrograph, plain light ($7\frac{1}{2}$X)

Quartz monzonite dike - This dike cuts quartz monzonite porphyry. Note planar arrangement of phenocrysts.

Figure 4b - Photomicrograph, crossed nicols ($7\frac{1}{2}$X)

same as above



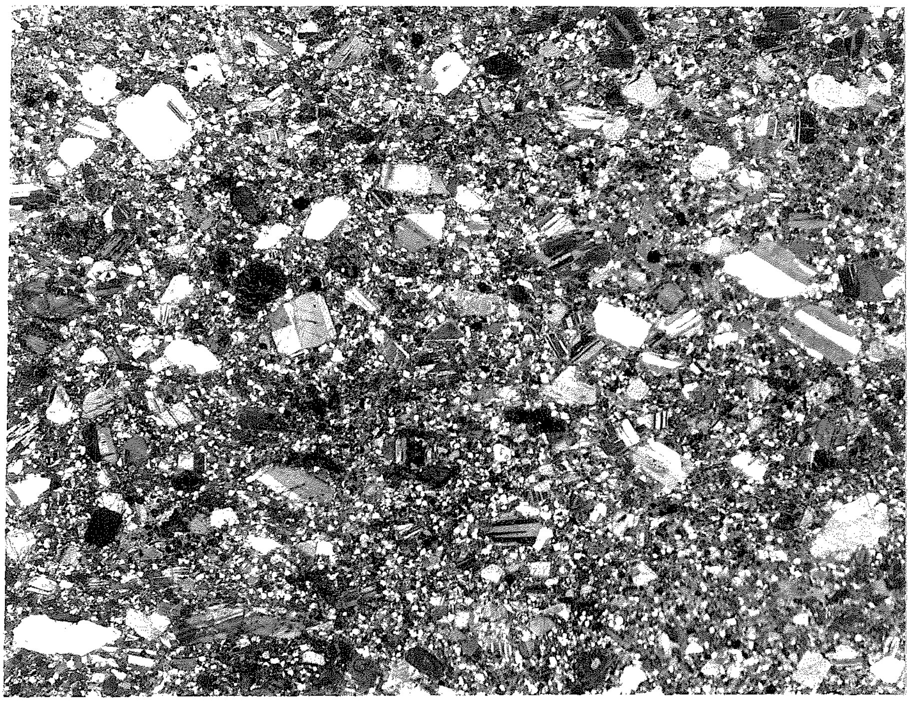
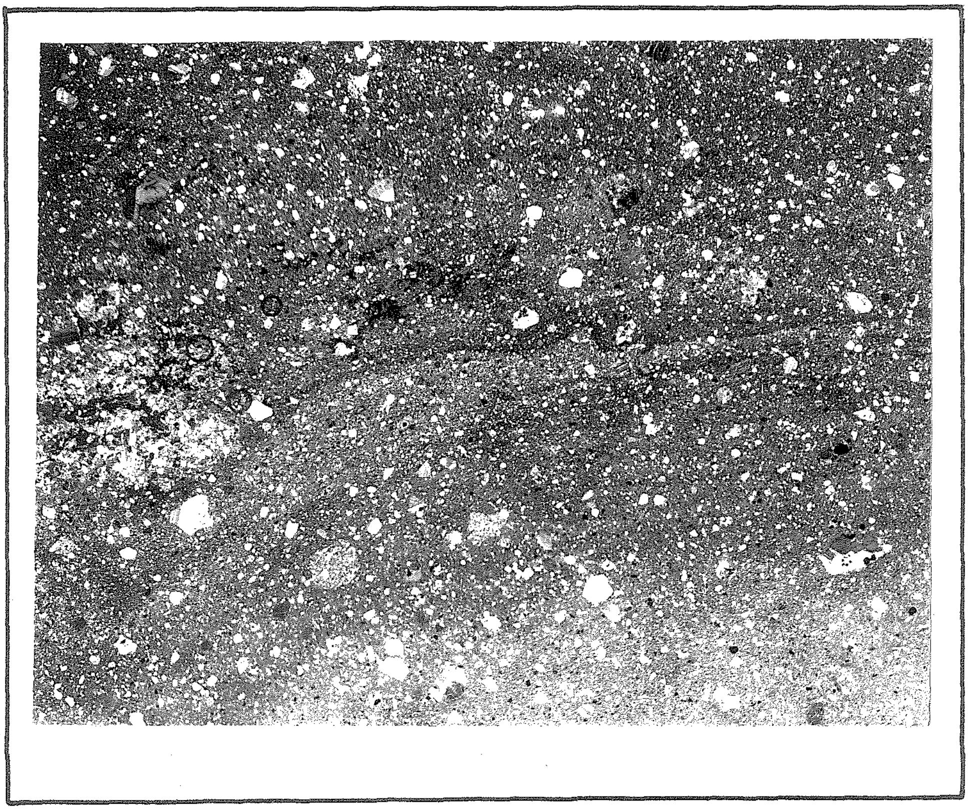


Figure 5a - Photomicrograph, plain light ($7\frac{1}{2}$X)

Quartz monzonite dike - This dike is approximately one foot thick and cuts quartz monzonite porphyry. Note mylonitic texture and xenolith of quartz monzonite porphyry (left center) with flow banding curving around it.

Figure 5b - Photomicrograph, crossed nicols ($7\frac{1}{2}$X)

same as above



intrusive. The contacts between the dikes and the porphyry are sharp. The dikes probably represent the injection of a later stage of quartz monzonite magma into a fractured and solidified earlier stage of the intrusive.

IV STRUCTURE

Introduction

Iron Mountain (see geologic map, plate 1, and sections, plates 2 and 3) is one of three intrusives in the Iron Springs district. The present form of the Iron Mountain intrusion is the result of intrusive deformation of a pre-intrusive structure. The pre-intrusive structure, a northeast trending fault and asymmetrical fold, probably controlled not only the Iron Mountain intrusive but also the other two intrusives in the district (figure 1).

The Iron Mountain intrusive as presently exposed is roughly oval in plan. It is approximately 4 miles long and 2 miles wide with its long diameter oriented northeast. Sedimentary rocks on all sides either dip away from the intrusive or are overturned and dip toward the intrusive. Remnants of the sedimentary rocks on the roof of the intrusive remain and have proved very useful in working out the structural history of the Iron Mountain intrusive. The form of the intrusive is composite: the northwestern boundary cuts across the sediments and is stocklike; the balance of the intrusive is remarkably conformable with a single sedimentary horizon. The Iron Mountain intrusive was thus forcibly emplaced by breaking the sedimentary cover along the northwest contact of the intrusive and pushing the cover aside as if it were a trap-door hinged on the southeast.

The minerals in the quartz monzonite are randomly oriented except for a very narrow strip along some contacts. Because of the restricted occurrence of primary foliation, the foliation can not be used to map the igneous structure. Joints can not be used for this purpose unless it can be proved that they are related to a primary feature. This can not be done at Iron Mountain. Joints were mapped over part of the area in the hope that they might be used as permissive though not compelling evidence of a structural pattern due to intrusion. No pattern is evident from the joints mapped except perhaps some parallelism between some of the joints and faults of late- or post-intrusive age.

Pre-Intrusive deformation

Post-Entrada - pre-Iron Springs disturbance

The disturbance which resulted in local erosion of the Entrada formation and part of the Homestake limestone, deposition of the Marshall Creek breccia, and non-deposition of part of the Iron Springs formation, is important only because of the part it might have played in determining the orientation of later deformation. According to Mackin (1947a, p. 11) the trend of this disturbance was north-northeast. Spieker (1946, p. 150 - 152) places the eastern boundary of an orogenic belt, contemporaneous with the post-Entrada - pre-Iron Springs deformation, through the Iron Springs district. The trend of this boundary is approximately northeast.

Post-Iron Springs - pre-Claron deformation

The pre-intrusive structural relations in the Iron Mountain area are difficult to decipher because pre-Claron rocks do not crop out in the Iron Springs district except around the three intrusives, and there the pre-intrusive structure is obscured by intrusive deformation. In order to make a reasonable interpretation of the structure at Iron Mountain it is necessary to consider:

1) The structural relations incompatible with intrusive deformation.

2) The structural history of the surrounding region.

An example of a structure incompatible with intrusive deformation is the Calumet fault, extending from a point near the southwestern corner of the map to a point near the northeastern corner of the map. The south dip of this fault south of the Duncan pit and the direction and amount of displacement are not easily explained by deformation due to intrusion.

The Calumet fault borders the south and east margins of the intrusive. Its trace is approximately located from outcrops south of the Duncan pit and south of Oak Springs. Its trace elsewhere is inferred and approximates the southern and eastern boundaries of the intrusive from a point south of the Pinto pit to the place south of Oak Springs where it can again be traced in the sedimentary rocks. According to my interpretation, the trace of the fault swings northward east of Oak Springs and is cut off by the tongue of quartz monzonite protruding northeast of Oak Springs.

A second structure incompatible with intrusive deformation is a fold (figure 7) inferred to have been present before intrusion on the north end of Iron Mountain. This fold probably correlates with the Calumet fault (figure 6). The most likely place from which to derive the sedimentary rocks in the thrust plate in Oak Springs Flat is from an area above the intrusive rock on the north end of Iron Mountain. A reconstruction of the lateral extent of those sedimentary rocks and the sedimentary rocks in the Mountain Lion area suggests that they could not have been flat-lying at the beginning of intrusion, otherwise there would not have been room for them on the roof of the intrusive. The fold (figure 6 and 7) accounts for the excess section and is a reasonable extension of the Calumet fault.

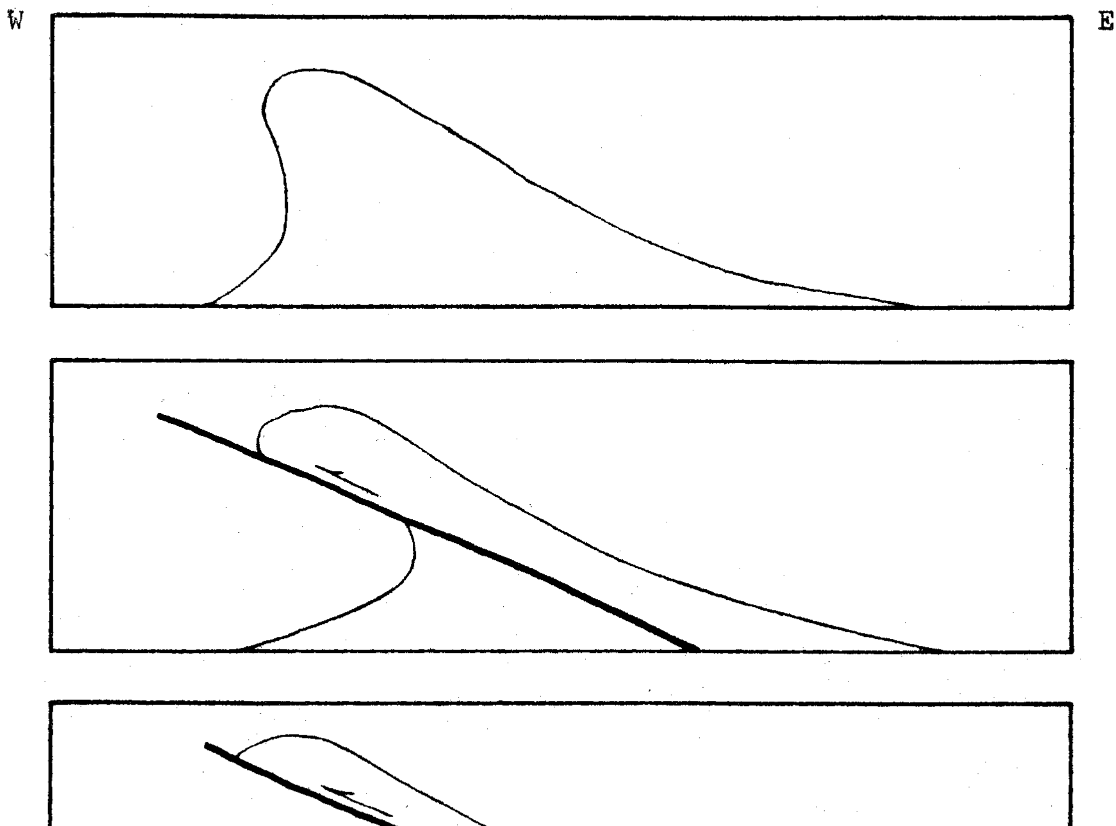


Figure 6. Diagrammatic sections through post-Iron Springs - pre-Claron structure at Iron Mountain before deformation by intrusion. From top to bottom - Transition from fold to thrust fault (Calumet fault) between area east of the Mountain Lion pit and area northeast of Oak Springs. This is a lateral sequence in space, not a time sequence.

Evidence of post-Iron Springs - pre-Claron folding with axes trending north-northeast and northeast is abundant in the surrounding region (Gregory, 1950, p. 115 - 117, Gardner, 1952, p. 19, and Cook, E. F., 1954, p. 14 and 43). In Parowan Gap (figure 1) the Claron formation lies with angular unconformity on folded Jurassic and Cretaceous sedimentary rocks. The axial plane of the fold strikes approximately northeast or north-northeast and probably dips steeply northwest. At Iron Mountain the axial plane apparently dipped southeast. Because the folding took place at a very shallow depth this divergence in the dip of the axial planes might be expected.

Any post-Iron Springs - pre-Claron structure must have resulted in an angular unconformity between the Iron Springs and Claron formations. The contact above the intrusive has been destroyed by erosion but is interpreted as having been unconformable (figure 7). The depositional contacts exposed around Iron Mountain are conformable because presumably they lie beyond the limits of the post-Iron Springs - pre-Claron deformation.

In summary, to satisfactorily explain the structural relations at Iron Mountain it is necessary to postulate a pre-intrusive structure. A northeast-striking, southeast-dipping thrust fault and fold (figure 6) of post-Iron Springs - pre-Claron age is compatible with the regional geology and satisfactorily explains the structural relations at Iron Mountain that cannot be explained by intrusive deformation alone. The folding and faulting of the sedimentary rocks now exposed occurred within a mile of the surface, as the Iron Springs formation was the youngest formation present. This pre-intrusive thrust fault (Calumet fault) makes it possible to explain the Blowout, A, and B ore bodies as mineralization of Homestake limestone (plate 2, section D-D' and plate 3, section E-E'). These ore bodies have been interpreted by others as mineralization of quartz monzonite. Inasmuch as widespread replacement of quartz monzonite by iron mineralization would be extraordinary in the Iron Springs district, the Blowout, A, and B ore bodies are more reasonably explained as replacement bodies in Homestake limestone.

Intrusion

Intrusive contacts

There are two kinds of contacts between quartz monzonite and sedimentary rocks:

1) Quartz monzonite conformable with the lower part of the Carmel formation.

2) Quartz monzonite cross-cutting Jurassic and Cretaceous sedimentary rocks.

With the exception of relations on the northwest side of Iron Mountain the intrusive is conformable with the lower part of the Carmel formation, almost everywhere with the comparatively thin Sandy member. Although the Sandy member is not well exposed, its relationship to the intrusive contact is well established by drilling. In only a few places is the Sandy member absent between the Homestake limestone and the intrusive, and in those places the Homestake limestone is strongly mineralized. Near Shurtz Creek, 6 miles south of Cedar City, the Carmel formation is underlain by the massive sandstone of the Jurassic Navajo formation. Several beds of gypsum, present between the two formations near Shurtz Creek, might have been present at Iron Mountain prior to intrusion and may have controlled the intrusion along this horizon.

The cross-cutting contacts are interpreted as intrusive contacts. Faults were caused by intrusive forces and later controlled the intrusive contact. Further displacement along these contacts continued during the emplacement of the intrusive, although the quartz monzonite at the contact had solidified before movement ceased. The separation of cross-cutting intrusive contacts from fault contacts between intrusive and sedimentary rocks is thus largely a matter of interpretation.

Intrusive deformation

The relations between intrusive and sedimentary rocks in the Mountain Lion and Oak Springs Flat areas call for a complex sequence of pre-intrusive and intrusive events. Minor modification of this sequence of events will explain the less complex structure of the southwestern part of the area.

Before the intrusion of quartz monzonite, the Claron formation rested on the Iron Springs formation, with approximate conformity on the flat-lying flanks of the pre-Claron structure and probably with angular unconformity along the eroded apex. The first effect of the intrusion of quartz monzonite was the development of a gentle fold on the older structure (figure 7). As this fold steepened, faults developed and a wedge of sedimentary rocks was forced upward and eastward by the intrusive (figure 8). Henceforth, this thrust fault caused by intrusive forces early in the intrusion of the quartz monzonite will be referred to as the early intrusive thrust fault. The displacement along the early intrusive thrust fault was approximately 5,000 feet. As there were probably not more than a few hundred feet of volcanic rocks overlying the Claron formation, the early intrusive fault must have intersected the surface just east of the map area (see "east" side of figure 8). According to my interpretation the early intrusive faulting was initiated by intrusive forces before the arrival of quartz monzonite, and the faults themselves controlled the boundaries of the early stage of intrusion (figure 8). The fault boundary on the east was temporary, however, and as intrusion continued the intru-

RECONSTRUCTION OF GEOLOGY SHOWN BY SECTION A-A', PLATE 2.

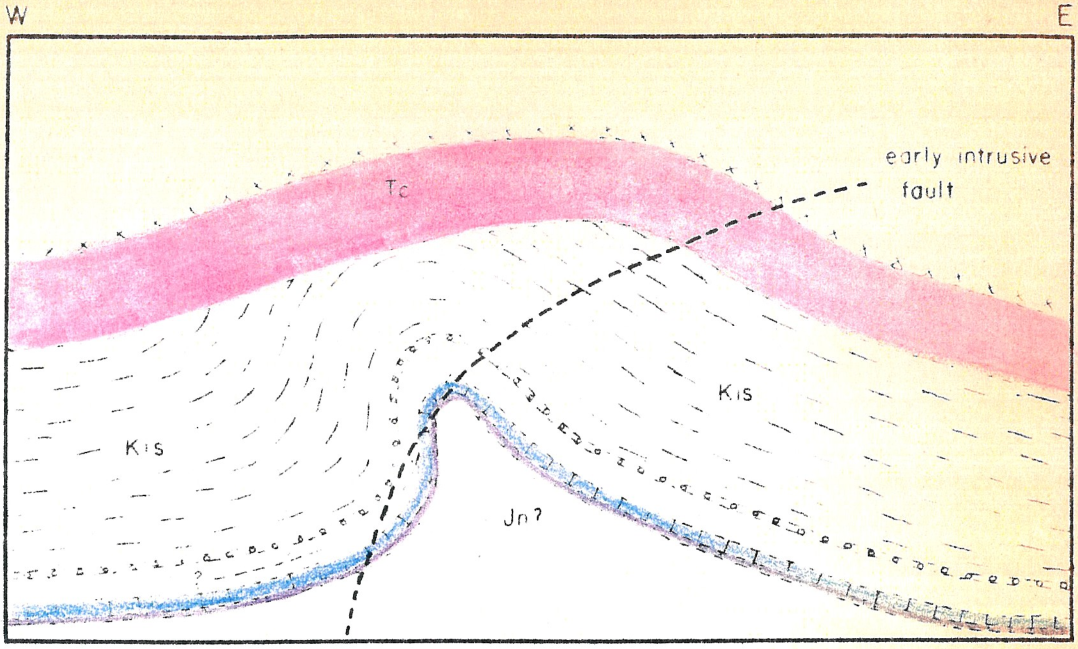


Figure 7. Early intrusive fold developed on crest of post-Iron Springs - pre-Claron fold. Relation of post-Iron Springs - pre-Claron fold to Calumet fault is shown in figure 6.

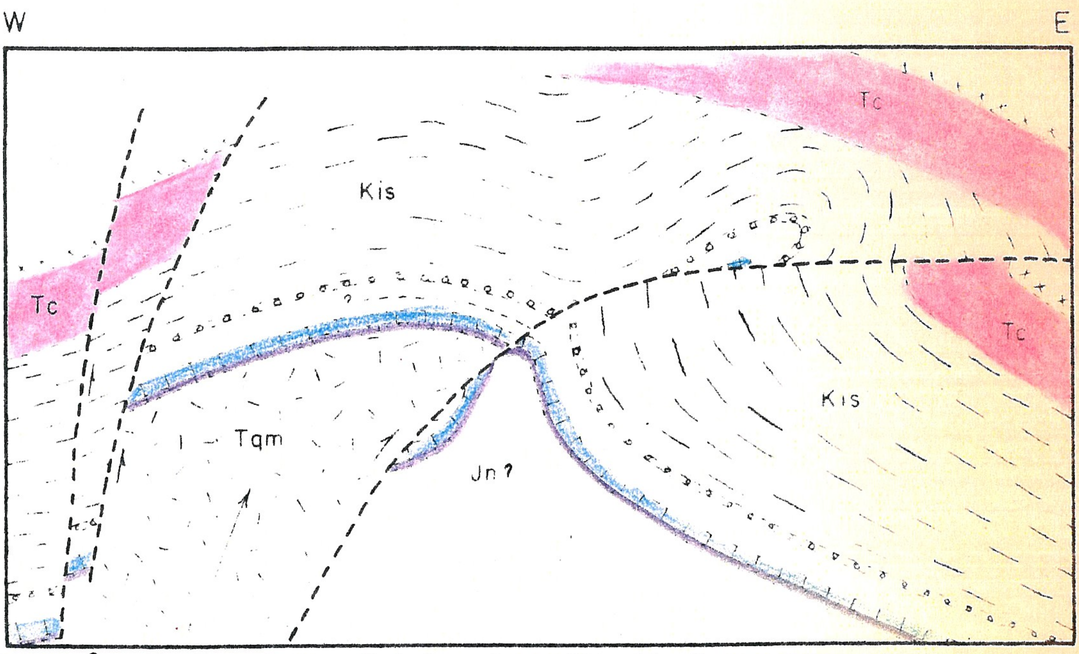


Figure 8. Early stage of intrusion with displacement on boundary faults.

SCALE 1" = 4,000 '

Formations: Tqm=intrusive, Tc=Claron, Kis=IronSprings, Jn=Navajo

RECONSTRUCTION OF GEOLOGY SHOWN BY SECTION A-A', PLATE 2

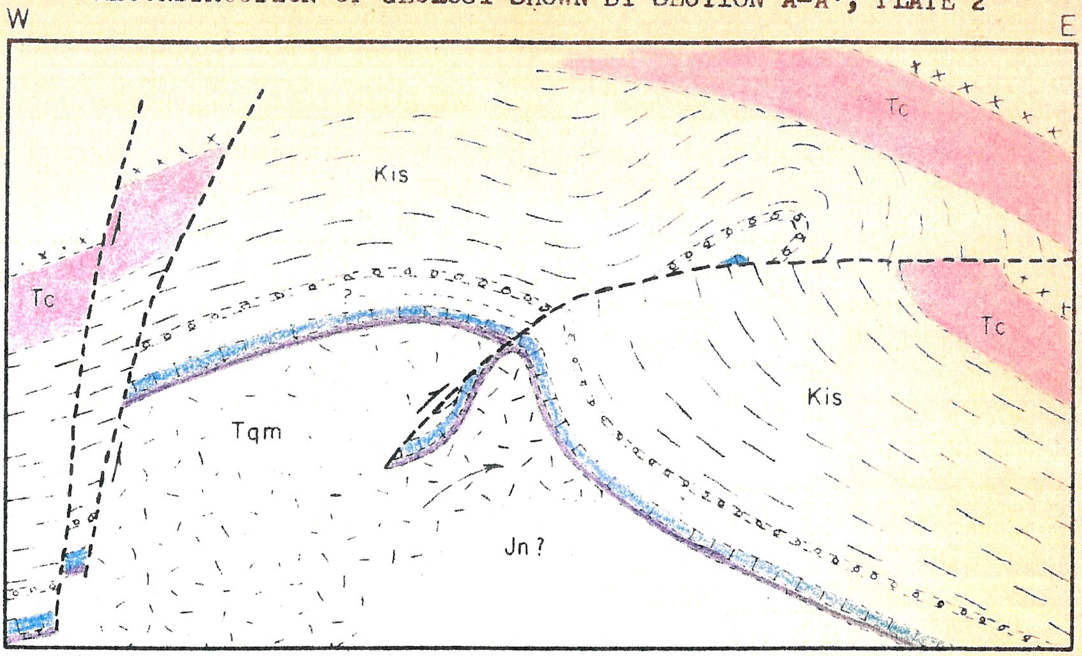


Figure 9. Later stage of intrusion.

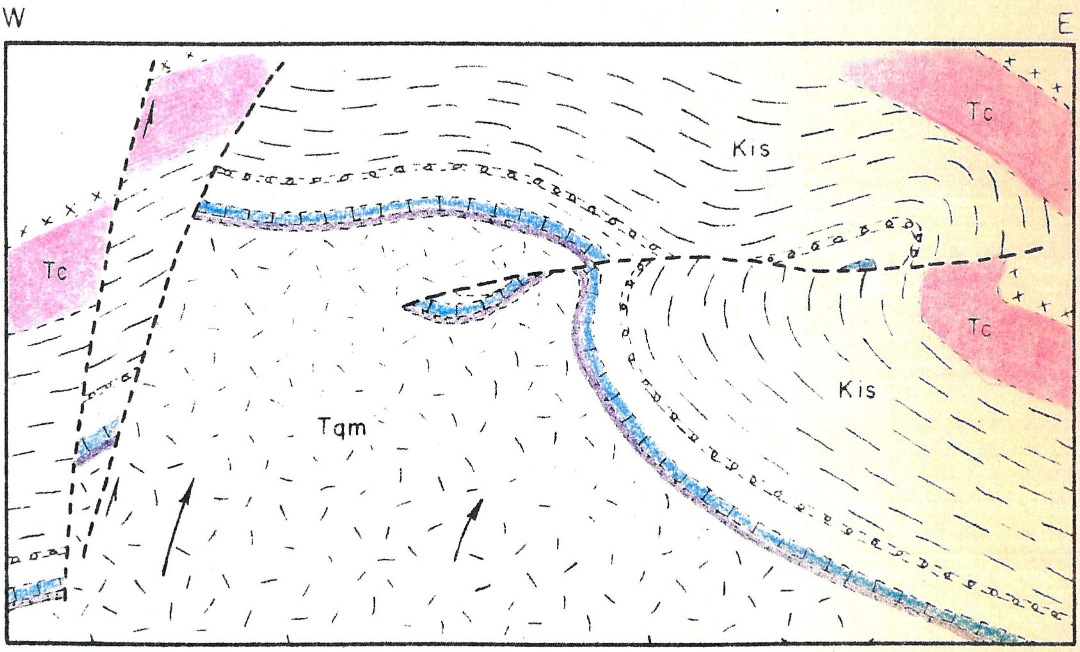


Figure 10. Continuing intrusion, movement on west boundary faults and deformation of sediments and early intrusive fault.

SCALE 1" = 4,000'

Formations: Tqm=intrusive, Tc=Claron, Kis=Iron Springs, Jn=Navajo

RECONSTRUCTION OF GEOLOGY SHOWN BY SECTION A-A', PLATE 2

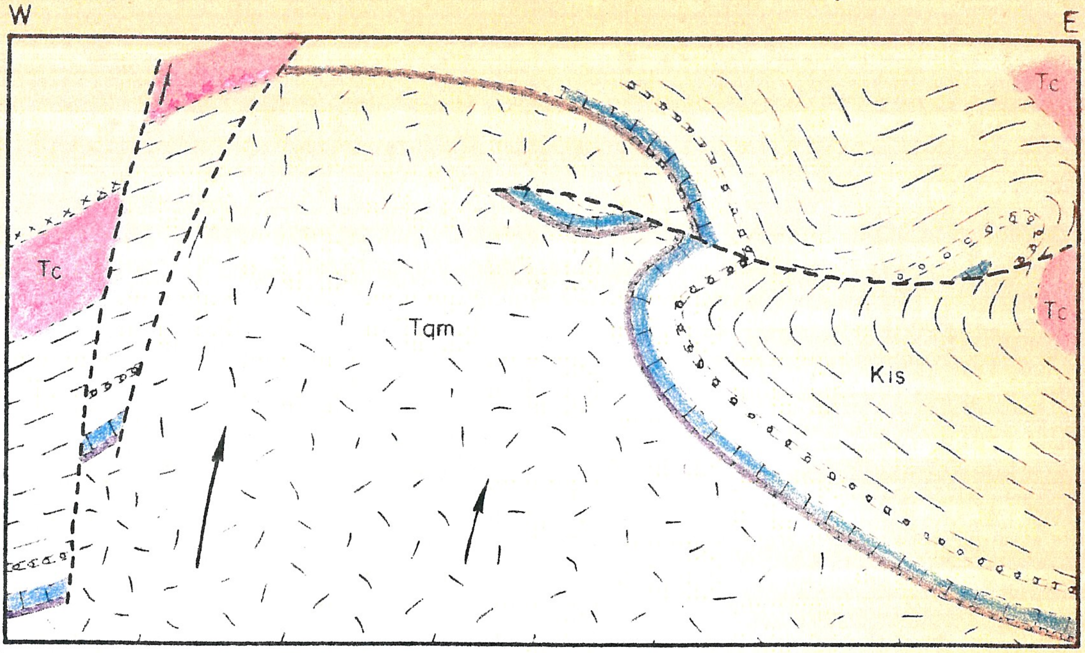


Figure 11. Continuing intrusion and deformation.

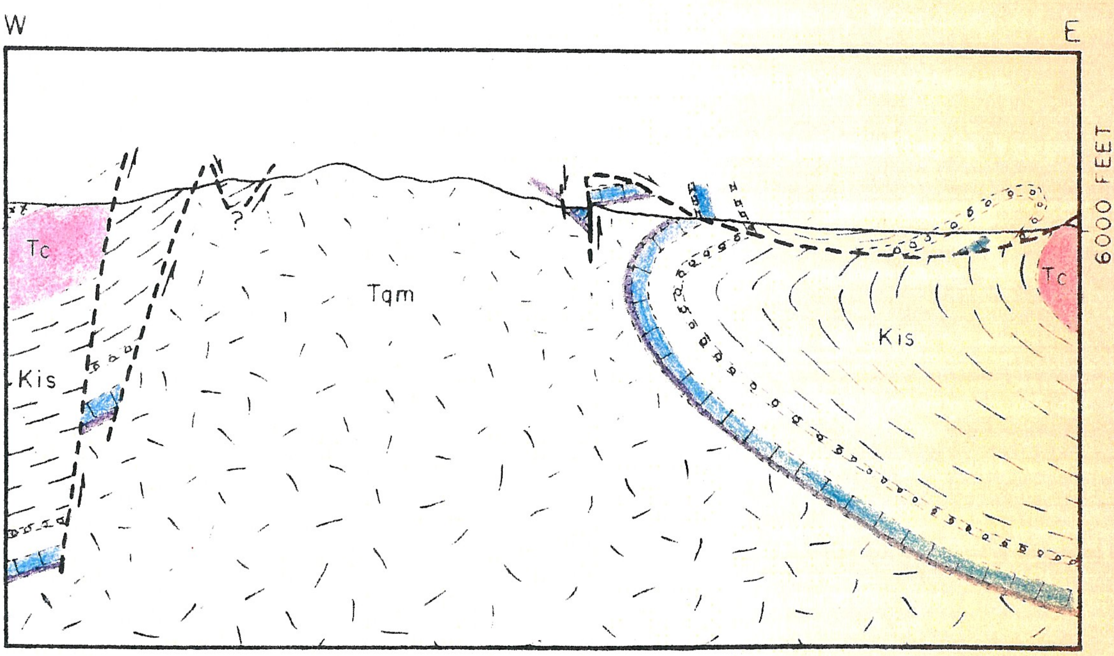


Figure 12. Section A-A', plate 2. Minor faults superimposed on structure shown in figure 11.

SCALE 1" = 4,000'
Formations: Tqm=intrusive, Tc=Claron, Kis=Iron Springs, Jn=Navajo

sive was forced across the fault and along the base of the Sandy member of the Carmel formation (figure 9). Continued intrusion further deformed the sedimentary rocks and the early intrusive fault plane (figures 10 and 11).

The displacement on the early intrusive thrust fault (figure 8) decreases rapidly along its southwestward extension. The present trace of the early intrusive thrust fault probably extends southwestward from the western edge of the Mountain Lion pit; west of the sedimentary rocks remaining as pendants or screens in the intrusive; and into the Burke-Pinto area. Displacement along this fault in the Burke-Pinto area is minor or absent. If the thrust sheet extended very far south from Oak Springs flat it has been removed by erosion. The change in the nature of the pre-intrusive structure southeast of the Mountain Lion area (figure 6) may have influenced the deformation due to the intrusive. Displacement along the faulted intrusive contacts forming the northwest boundary of the intrusive also probably decreases southwestward. Thus the northeast portion of the intrusive structure at Iron Mountain approximates a trap-door hinged on the southeast side, but southwestward as the opening becomes smaller the structure more closely resembles a concordant pluton.

Alternate interpretation of structural relations in Oak Springs flat

The structure in Oak Springs flat (figure 6) might be interpreted as a slide, instead of an early intrusive thrust deformed by subsequent intrusion. If this block of folded sedimentary rocks was moved into its present position by sliding, the sliding probably occurred in recent times inasmuch as the base of the "slide" is close to the present erosion surface. The material in the "slide block" was derived from the roof of the intrusive and includes material which, in part, must have rested above the Mountain Lion area, as the source area available on the roof of the intrusive west of the Mountain Lion is inadequate by itself. Mineralization in the limestone in the Mountain Lion area is strong, and yet there is no mineralization in the "slide block" except where limestone is near the intrusive. This would suggest very strongly that the mineralization is later than the "slide". The mineralization, however, is almost certainly closely related to the intrusive and took place during or soon after the late stages of intrusion.

The limestone in the block is brecciated, particularly in the east end, but attitudes are generally valid and the formations are in place relative to each other. It is difficult or impossible to distinguish brecciation due to sliding or thrusting from brecciation due to post-Entrada - pre-Iron Springs deformation. The time of origin of any of the brecciation is a matter of interpretation and must be based on evidence such as the distribution of the breccia relative to the location of faults and outcrops of Marshall Creek breccia. The brecciation in the limestone is tectonic and could be the result of deformation of any age, although the fact that it is very well cemented might be difficult to reconcile with a recent origin.

Post-intrusive - pre-mineralization deformation

A number of faults with steep dip offset the contact between the sedimentary and the intrusive rocks. Those with a north or northwest trend are perhaps related to a regional fault pattern, but others are probably due to late intrusive movements or to shrinkage of the intrusive as it cooled. They are therefore not strictly post-intrusive faults but late intrusive faults. A fine grained sill, cropping out in the Duncan pit, is offset by a northwest trending fault, proving that at least some displacement occurred on this fault after the intrusion of the sill. The dikes and sills are later than the solidification of the outer shell of the quartz monzonite. It is probable that the post-intrusive or late intrusive faulting and the intrusion of the dikes and sills were almost contemporaneous. As mineralization in some places occurs only on one side of a post-intrusive fault even though there is limestone on the unmineralized side, the mineralization must be later than the post-intrusive or late intrusive faults. The displacement in many places is too small to have removed from observation any mineralization across the faults. The mineralization is also definitely later than a sill intruded into Homestake limestone in the Burke pit. (The exposure observed has since been destroyed in the mining operation.)

Movement on faults during and after mineralization

Mineralization in fissure veins in the quartz monzonite intrusive and in the sedimentary rocks is a filling of open spaces. Thick fissure veins are composite veins formed by recurrent opening during mineralization. Slickensides and deformed minerals are common in the replacement bodies. There is also evidence of comparatively recent displacement on some faults. At Desert Mound on the southwest end of Granite Mountain, a fault of recent age offsets Quarternary gravel. Faults probably have been active with little if any interruption from the time of intrusion to the present.

V MINERALIZATION AND CONTACT METAMORPHISM

Introduction

Mineralization in the Iron Springs district formed massive replacement bodies in the Homestake limestone member of the Carmel formation and to a lesser extent fracture and breccia filling in quartz monzonite, the Sandy member of the Carmel formation, the Entrada and the Iron Springs formations. The most abundant minerals in the replacement bodies are magnetite, specularite, phlogopite, and carbonates; in the fracture and breccia filling, diopside, calcite, apatite, phlogopite and magnetite.

Contact metamorphism is almost entirely restricted to the Sandy member of the Carmel formation. This member is now a very fine-grained diopside-feldspar rock, containing beds of quartz sandstone in which rounded detrital grains of quartz are unaffected by metamorphism. On the north and west borders of the intrusive where the Iron Springs formation is in contact with quartz monzonite, the only visible effects of metamorphism are the local development of light spots in shales and siltstone, and the transformation of quartz sandstones to quartzites by silica cementation.

The McCahill ore body, located on the southwest flank of Iron Mountain, was selected for a detailed study of the mineralization and metamorphism in the Carmel formation because of its relatively simple structure and the availability of diamond drill core and chemical analyses. Geologic sections of this ore body are shown on plates 4 and 5.

Contact metamorphism

Sandy member of Carmel formation

The origin, whether sedimentary or metamorphic, of the lowermost member of the Carmel formation exposed in the Iron Springs district has been subject to controversy. Leith and Harder (1908, pp. 25 and 36) described the Sandy member as an altered contact phase of the Homestake limestone, containing a sandstone.

> "The limestone adjacent to the andesite has been locally replaced by iron ore and has been generally vitrified, silicated, and kaolinized..... The altered limestone is a grayish, yellow, or greenish, fine-grained, argillaceous-looking rock....."

> "The altered contact phases of limestone are often hard to distinguish from a much-fractured quartzite or clayey sandstone which is locally exposed below the limestone and constitutes a part of the same formation."

Mackin (1954) said:

> "Microscopic study indicates, however, that nearly all of the rock mapped (by Leith and Harder) as altered limestone is a siliceous siltstone that has been moderately hornfelsed;....."

For an understanding of the structure and the mineralization it is important to know whether the contact between the Homestake limestone member and the Sandy member of the Carmel formation represents a stratigraphic horizon or the limit of alteration in sedimentary rocks adjacent to the intrusive. The lines of evidence available are: the present mineralogy and composition; preserved sedimentary horizons; and comparison with sections of the Carmel formation not intruded by igneous rocks.

The Sandy member consists of a greenish- and brownish-gray argillaceous-looking rock, interbedded with fine-grained impure quartz sandstones. The argillaceous-looking rock is extremely fine-grained, and identification of the minerals is difficult with a microscope. The major minerals are feldspar, diopside, and carbonate (not calcite because both indices are greater than 1.54). Minor minerals are phlogopite or iron-poor biotite, kaolin(?), magnetite, chlorite (penninite ?), calcite, amphibole (tremolite-actinolite ?), sphene and tourmaline. Part of the feldspar is sanidine, identified by its negative relief, low birefringence and low 2V(-); part is albite, identified by its negative relief, low birefringence and albite twinning. Unfortunately most of the grains are too small to yield an optic figure and do not show twinning. The analyses for Na and K shown in table 1 are of diopside-feldspar rock from the Sandy member. These samples contained

Sample No.	(wt. percent) Na_2O	K_2O
11M902	2.30	0.86
43M1015	4.17	0.38
5M853	2.38	3.54
34M840	4.59	0.90
34M795	0.72	10.32

Table 1 - Results of analyses (flame photometer)*

negligible amounts of Na and K bearing minerals other than feldspar. Evidently, important amounts of both sanidine and albite are present in the Sandy member of the Carmel formation. The presence of sanidine, not another K-feldspar, was confirmed by X-ray powder diffraction.

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* The samples were prepared under the direction of C. Engel and analyzed under the direction of A. Chodos, California Institute of Technology.

The sandstone consists of rounded detrital grains of quartz in a matrix that resembles the non-sandy units of the Sandy member. Most of the quartz grains have been unaffected by metamorphism or mineralization, but locally some have been replaced by carbonate. Partial chemical analyses of units of the Sandy member are summarized in table 2.

	Fe	SiO_2	Al_2O_3	CaO	MgO	CO_2
A.	10.5	37.3	11.0	11.2	8.2	
B.	2.8	49.8	9.5	12.0	6.0	
C.	2.3	60.0	11.2	5.8	7.3	2.1*

A. Average of 8 analyses, weakly mineralized diopside-feldspar rock between ore and uppermost sandstone unit.

B. Average of 4 analyses, diopside-feldspar rock between two sandstone units.

C. Average of 15 analyses, quartz sandstone

(*average of 8 analyses)

Table 2 - Composition of units of the Sandy member of the Carmel formation. (Analyses by Columbia Iron Mining Company)

The present composition, particularly the Na content (table 1), is unusual for sedimentary rocks in a limestone environment, indicating that the composition has changed during metamorphism. On the basis of the present mineralogy and composition, one can only speculate about the nature of the diopside-feldspar rock before metamorphism.

Locally, a foot or two of the impure limestone at the base of the Homestake limestone is metamorphosed to medium-grained calcite-diopside-garnet rock. The contact between this rock andthe diopside-feldspar rock underlying it is sharp. The marked difference between these two rock types after metamorphism suggests that they were different before metamorphism. Both these rock types are veined by minerals common to the mineralization, chiefly phlogopite, calcite and magnetite.

Gregory has described sections of the Carmel formation cropping out on the Colorado Plateau not far from Cedar City (Gregory, 1950, p. 81, 83, 89 and 93). Two of the three complete sections described contain sandy and shaly beds, but the distribution of these beds within the formation does not permit positive correlation with the two members of the Carmel formation as described in the Iron Springs district. On the basis of the sections in the Colorado Plateau and the sandstone beds preserved in the Iron Springs district, the most reasonable guess as to the original character of the Sandy member is that it consisted of impure limy sandstones interbedded with silty limestone or limy siltstone. The fine-grained material has been metamorphosed; the quartz grains in the sandstone have been preserved.

Contact metamorphism associated with sill

On the southwest flank of Iron Mountain a sill, probably related to the dikes that intrude the quartz monzonite, intrudes the Homestake limestone approximately 60 feet below the top. The sill, about one foot thick, is very fine-grained but not glassy. Tiny biotite phenocrysts are oriented parallel to the plane of the sill. A partial analysis of the sill shows: Fe- 1.7, SiO_2- 55.2, Al_2O_3- 20.0, CaO- 2.28, MgO- 5.34, P- 0.06, S- 0.006 and CO_2- 1.8. Because the sill is thin and has reacted strongly with the limestone this analysis probably does not accurately represent the composition of the sill at the time of intrusion. Contact metamorphism associated with the sill is asymmetric. The chief minerals in the contact rock below the sill are pale green garnet and olivine (forsterite); above the sill, prehnite and garnet. The prehnite occurs in radial masses, and in hand specimen has been mistaken for chert. Both contact zones are about the same thickness as the sill and are veined by small amounts of calcite, chlorite, chalcedony, pyrite, apatite, analcite(?), zeolite(?), topaz(?) and hibschite(?). The 60 feet of limestone above the sill contains small, pale green garnets sparsely disseminated or concentrated along tiny channelways but otherwise appears unaffected.

Mineralization

Replacement

Replacement bodies are restricted to the Homestake limestone member of the Carmel formation. Replacement evidently started wherever mineralizing fluids entered the limestone, and continued for greater or less distances into the limestone. All the ore bodies are in contact with quartz monzonite or separated from it only by the Sandy member of the Carmel formation. Where the total thickness of the limestone is not replaced, the ore bodies are restricted to the bottom part. Contacts between ore and limestone are very sharp. Gougy-looking limonitic material, commonly only a few inches thick, separates ore from fresh limestone. No gradation between ore and limestone is found.

Two types of mineralization may be distinguished within the McCahill ore body. One type, which I will call iron mineralization, is composed chiefly of iron oxides (magnetite and specularite). Either magnetite or specularite may be the predominant iron oxide. The most abundant gangue minerals are phlogopite and carbonates. Most of the phlogopite is pale green, but some of the larger grains are pale brown in the center with pale green rims. The carbonates are calcite, ankerite(?) and siderite. Relatively minor amounts of apatite, sanidine, quartz, chalcedony and pyrite, and rare chalcopyrite, bornite and galena, are found in the iron mineralization.

The other type of mineralization, which I will call phlogopite mineralization, contains phlogopite, calcite, apatite, sanidine, iron oxides (magnetite and specularite), and quartz in about that order of abundance. The properties of the minerals are the same as those in the iron mineralization but the abundance of phlogopite and calcite, and the scarcity of the iron oxides, distinguish this rock from the iron mineralization. Locally, phlogopite is so abundant that the rock is micaceous. The phlogopite mineralization can generally be separated from iron mineralization on the basis of chemical composition. The phlogopite mineralization usually contains a high magnesium content (more than 10 percent MgO), a high phosphorus content (about 1 percent or more P), and a low iron content (commonly less than 10 percent Fe).

The paragenesis in both types of mineralization is the same:

```
          apatite
sanidine -  phlogopite - sulfides - calcite - quartz - (Fe, Mg) carbonates.
            magnetite
```

Specularite replaces magnetite along crystal directions, fractures and grain boundaries but cannot otherwise be placed in the above sequence. The ore bodies have a high porosity, and the late minerals commonly occur in vugs. The sulfides are rare and are found chiefly in the top part of the iron mineralization.

The phlogopite mineralization is less common than the iron mineralization. In the McCahill ore body, phlogopite mineralization is always found adjacent to quartz monzonite where the intrusive cuts through the Sandy member into the Homestake limestone member of the Carmel formation (section J-J', plate 4). Most of the phlogopite mineralization is coarse-grained and easily recognizable in hand specimen, but locally it is so fine-grained that microscopic examination is necessary to distinguish it from the non-sandy units in the Sandy member of the Carmel formation. Phlogopite mineralization, apparently separated from quartz monzonite by the Sandy member of the Carmel formation, is presumably connected, off the section, with phlogopite mineralization in contact with quartz monzonite or unusually close to quartz monzonite.

Volume for volume replacement - The sections of the McCahill ore body (plates 4 and 5) show that limestone has been replaced with no marked reduction in volume. There is no evidence of collapse in the rocks above the ore body. Some variation in apparent thickness of the Homestake limestone is the result of changes in the component of dip normal to the plane of the sections. Variations in true thickness are probably the result of original variations in the thickness of the limestone and local erosion and channeling of the limestone before deposition of the Entrada formation.

Replacement of Ca and CO_2 by Fe, Si, Al, Mg, K, P and S - In order to determine what has been added and what has been removed in the replacement process, it is important to know the original composition of the limestone and the composition of the ore that has replaced it. Tables 3 and 4 show the composition of unmineralized limestone in holes MC27 and IC1 (section K-K', plate 4). The specific gravity of 11 samples distributed through the section was measured by weighing in water and in air. The mean specific gravity of the limestone is 2.70: maximum deviation is 0.03. The amount of each constituent for each hole is determined by the equation:

$$\text{amount} = \frac{\text{units}}{K} = \sum(\text{sp. gr.})(\text{wt. percent})(\text{footage})$$

The constant (K) is dependent on the units selected. Because only the relative amounts of each constituent are required in comparing the replaced and unreplaced limestone, the amounts are computed in terms of $\frac{\text{units}}{K}$.

Before computing the amount per hole of the various constituents in the ore body it was necessary to have some measure of the specific gravity. One hundred samples of ore were selected and their specific gravities measured. Each sample represented 10 feet of drill core which had been split and analyzed. The relation between specific gravity and Fe content in the ore body is shown in figure 13. The more extreme deviations from the empirical curve probably result from the marked inhomogeneity of the ore on a hand specimen scale. Thus a specific gravity measurement not representative of the 10 feet of core is plotted against an Fe analysis which is representative. I have assumed that the curve drawn in figure 13 averages out this source of error. Empirically, the specific gravity is a function of the Fe content for this ore body. This might reasonably be expected because the most abundant gangue minerals, phlogopite and carbonate, have approximately the same specific gravity, both being significantly lower than magnetite and specularite. The specific gravity values used in the calculation of the amounts of the various constituents in the ore body were determined from the Fe content using the curve in figure 13.

The amounts of SiO_2, Al_2O_3 and MgO in the ore body and in unreplaced limestone are compared graphically for section K-K' (plate 4) and section M-M' (plate 5). These amounts are the total amounts for each hole. For holes in which replacement of the limestone is incomplete, amounts of the various constituents in the unreplaced limestone are interpolated from the two limestone holes which have been analyzed. Important amounts of Si, Mg and Al have been added in the replacement process. The amounts $(\frac{\text{units}}{K})$ of

Table 3 - Partial chemical analyses of unmineralized Homestake limestone, hole MC27, (Analyses by Columbia Iron Mining Company)

Footage	Fe	SiO_2	Al_2O_3	CaO	MgO	P	S	CO_2	Total
820-827	0.8	25.8	6.0	34.1	6.6	0.07	0.09	23.4	97.2
-837	0.6	14.6	4.2	43.3	4.6	0.04	0.06	31.6	99.3
-847	1.1	16.6	4.7	43.4	3.0	0.05	0.22	30.5	99.9
-857	0.6	10.6	3.7	46.9	2.7	0.02	0.29	34.3	99.2
-867	0.8	14.5	3.9	44.2	3.5	0.05	0.24	31.2	98.5
-877	0.4	7.6	2.1	49.2	3.3	0.05	0.22	37.1	100.0
-887	0.6	7.4	2.1	48.6	3.0	0.02	0.25	37.2	99.2
-897	0.5	9.1	2.5	47.4	2.9	0.03	0.26	35.6	98.3
-907	0.6	8.0	3.7	47.2	3.5	0.02	0.29	36.6	99.9
-917	0.7	11.6	3.4	44.1	4.8	0.04	0.29	33.0	97.9
-927	0.6	5.9	1.9	49.1	3.0	0.03	0.22	38.0	98.8
-937	0.5	4.0	1.4	51.1	1.9	0.03	0.16	40.1	99.3
-947	0.5	4.0	1.4	50.8	1.7	0.02	0.20	40.1	98.8
-955	0.5	3.4	1.3	50.1	2.1	0.02	0.22	40.4	98.1
-963	0.5	4.1	1.0	50.6	2.2	0.02	0.18	39.7	98.4
-974	0.5	11.4	2.6	44.8	2.8	0.02	0.15	39.6	100.0
-984	0.8	4.0	1.6	50.4	1.8	0.02	0.04	40.6	99.6
-993	0.6	4.3	1.6	51.6	1.7	0.03	0.14	39.6	99.8
-1001	0.6	4.6	1.6	51.1	1.7	0.02	0.18	39.4	99.8
-1011	0.8	5.2	1.7	51.0	1.9	0.03	0.19	38.8	99.8
-1021	0.8	7.1	2.4	49.0	2.1	0.01	0.22	37.1	98.9
-1031	0.8	4.7	1.6	50.0	2.0	0.03	0.36	33.0	98.5
-1037	1.3	14.4	5.1	41.4	3.0	0.04	0.41	30.5	96.3

Table 4 - Partial chemical analyses of unmineralized Homestake limestone, hole IC1, (Analyses by Columbia Iron Mining Company)

Footage	Fe	SiO_2	Al_2O_3	CaO	MgO	P	S	CO_2	Total
351-358	1.7	32.2	7.8	29.9	9.4	0.06	0.05	15.8	97.7
-364	0.8	12.6	3.8	44.1	3.8	0.06	0.04	32.3	97.9
-374	1.4	16.8	4.6	39.9	5.2	0.06	0.75	28.0	96.7
-384	1.1	11.2	4.0	42.9	3.2	0.04	0.04	35.0	97.9
-394	2.2	12.8	4.9	41.0	3.5	0.04	0.02	33.9	99.3
-404	1.0	11.2	3.7	45.1	2.6	0.05	0.02	34.8	99.0
-414	1.0	11.0	3.6	44.9	2.8	0.04	0.22	34.7	98.6
-424	0.8	16.0	4.4	42.1	3.4	0.04	0.19	30.5	97.6
-430	0.7	17.3	5.3	39.2	4.4	0.03	0.15	29.4	96.6
-444	0.7	9.6	2.3	48.7	2.9	0.04	0.18	35.3	98.9
-454	0.5	5.8	2.0	49.5	2.5	0.03	0.11	38.4	98.9
-464	0.9	8.3	2.2	47.9	2.8	0.03	0.25	35.6	98.2
-474	0.6	6.5	2.0	50.8	2.2	0.03	0.21	37.7	100.1
-484	0.7	10.5	3.1	45.9	3.9	0.03	0.30	34.0	98.5
-494	0.8	7.1	2.3	47.9	2.2	0.02	0.06	36.8	97.6
-504	0.6	4.4	1.7	51.2	1.9	0.03	0.22	38.8	99.0
-514	0.4	3.6	1.5	51.4	2.2	0.03	0.20	39.7	99.1
-524	0.4	4.2	1.7	50.2	2.0	0.03	0.16	40.0	98.7
-534	0.6	5.2	2.0	49.4	1.9	0.03	0.24	39.1	98.5
-544	0.8	8.5	3.2	47.6	2.2	0.04	0.31	35.8	98.5
-547	1.0	14.2	5.2	41.6	3.0	0.03	0.40	30.2	95.7

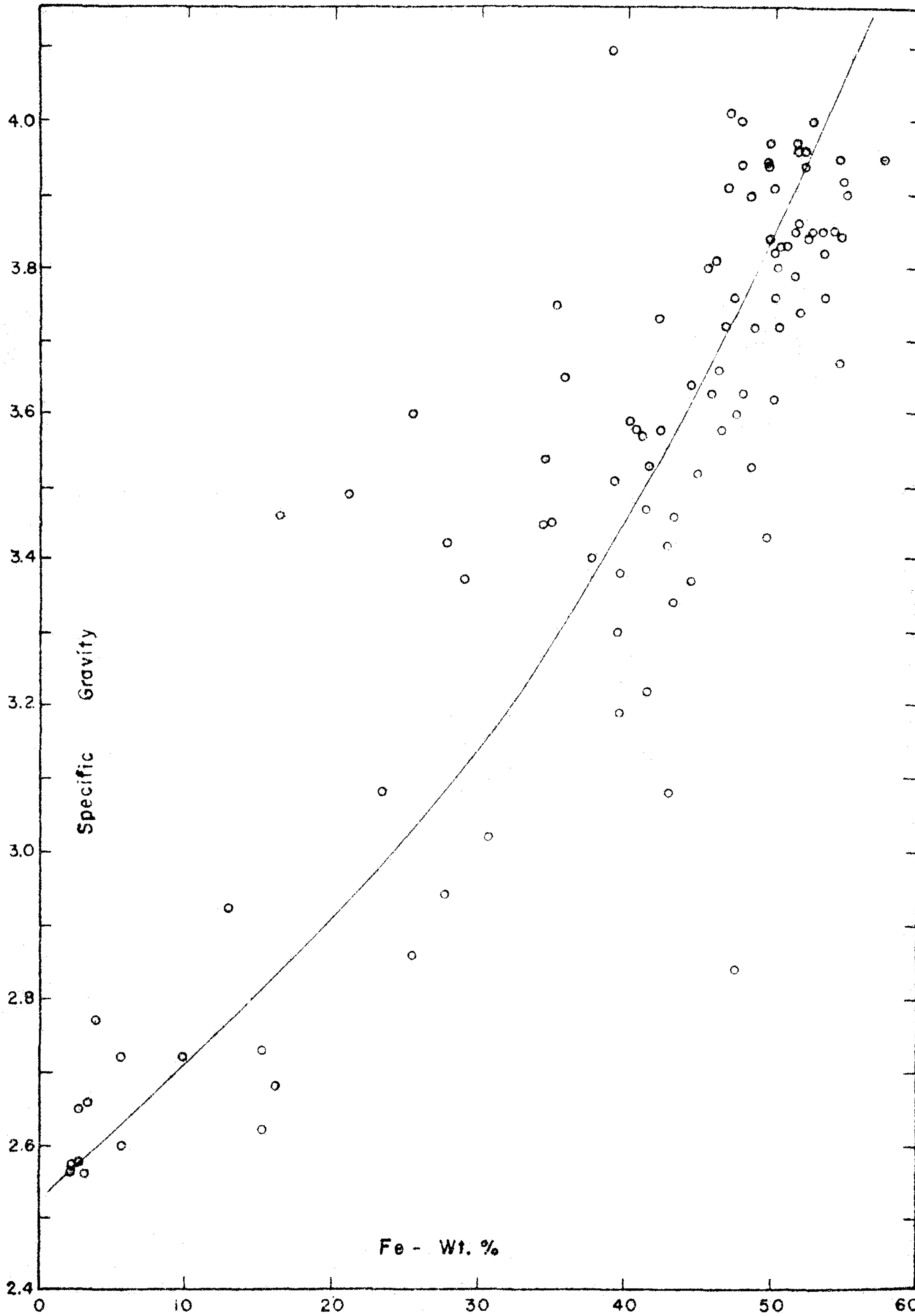

Figure 13 - Relation of sp. gr. to Fe content in ore body.

Fe added range from 12,000 to 38,000 in completely replaced sections of limestone and are too large to plot on plates 4 and 5. The amount of Fe in unreplaced limestone is negligible (in hole MC27, 407 and in hole IC1, 402). The amount of P and S are not shown on plates 4 and 5, but inasmuch as the weight percent of these constituents is higher in the ore than in the limestone, and the density of the ore is appreciably higher than the density of the limestone, it is apparent that P and S have also been added.

The abundance of the K-bearing minerals, phlogopite and sanidine, in the ore bodies, particularly in the phlogopite type of mineralization, suggests strongly that K is more abundant in the ore than in the limestone. The Homestake limestone was not analyzed for potassium but the totals suggest that there is not much room for potassium. One sample from the ore body was analyzed and contained 4.79% K_2O and 0.16% Na_2O. The chief minerals in this sample were sanidine and phlogopite. Large amounts of CaO and CO_2 have been removed in the replacement process. Any hypothesis presented to explain the origin of the ore must explain not only the addition of large amounts of Fe and the loss of Ca and CO_2, but also the addition of important amounts of Si, Mg, Al, K, P and S.

The top, and to a lesser extent the bottom of the Homestake limestone are less pure than the middle (tables 3 and 4). This unequal distribution of impurities in the limestone persists in the ore bodies. Ore that has replaced more impure limestone tends to be of lower grade than ore that has replaced more pure limestone.

Open space filling

Most mineralization in the quartz monzonite, the Sandy member of the Carmel formation, the Entrada formation and the Iron Springs formation occurs as open space filling in joints or fractures and between breccia fragments. The most abundant minerals are magnetite, apatite, quartz, calcite, diopside and phlogopite. Composite joint fillings as much as 12 feet thick occur in the quartz monzonite and consist largely of magnetite, with minor amounts of apatite, diopside and quartz. The individual fillings are seldom more than a foot thick, and apatite crystals oriented perpendicular to the joint walls apparently grew inward from the walls of the joint. One filled joint, cropping out at the south end of the Mountain Lion Pit, consists predominantly of diopside, with magnetite, apatite and calcite subordinate. Some of the diopside crystals are as much as 15 inches long. I interpret the large composite joint fillings in the intrusive to be the result of continued reopening of the joints during mineralization.

Mineralization in the Entrada and Iron Springs formations is not common. Fractures and interstices between breccia fragments, above completely replaced sections of Homestake limestone in the Rex Ore Body, are filled with magnetite, calcite, apatite, diopside, phlogopite and quartz. Where mineralization is intense a little replacement of the borders of breccia fragments by magnetite occurs. This kind of mineralization is generally low in grade but, because it is coarser and has a higher magnetite/specularite ratio than the replacement mineralization, it should prove more amenable to concentration than low grade replacement bodies.

Open space filling in the Sandy member of the Carmel formation is similar to that in the Entrada and Iron Springs formations and is always found where the Sandy member underlies replaced limestone. Few holes have been drilled away from ore bodies, but in holes drilled through unreplaced Homestake limestone on the edge of the McCahill Ore Body, the Sandy member is unmineralized or only slightly mineralized. It is likely that small fractures in the Sandy member gave the ore fluids access to the limestone.

A number of minerals, unimportant because of their rarity in the Iron Springs district, occur in the Sandy member of the Carmel formation, especially near the contact with the intrusive. These minerals occur isolated and in veins and fractures, and include analcite, gypsum, barite, scolecite, epidote, red-brown garnet, scapolite, tourmaline, pyrite and chlorite. In the Desert Mound Pit on the southwest end of Granite Mountain, a vein or fracture filling, younger than ore, contains gypsum, cinnabar, jarosite, limonite, and red-brown garnet.

The paragenesis for open space filling is the same as that for replacement:

apatite
diopside - phlogopite - calcite - quartz
magnetite

Diopside is common in the open space filling type of mineralization but absent in the replacement type. Sanidine is much less abundant in open space mineralization than in replacement mineralization. Phlogopite, pale brown in open space mineralization, is generally pale green in replacement mineralization. Partial chemical analyses of diopside, phlogopite and apatite, all from open space mineralization, are given in table 5.

Replacement and open space mineralization, although described separately, are very similar. Minerals from each differ only in relative abundance. The paragenesis is the same for each and they probably were precipitated from the same fluids during a single period of mineralization. Non-limy rocks were evidently inert to the ore-bearing fluid, permitting mineralization only in open spaces, while the Homestake limestone reacted strongly with the ore-bearing fluids, yielding extensive replacement bodies.

Mineral and approx. formula	Fe	SiO_2	Al_2O_3	MgO	CaO	F	Cl	P_2O_5
diopside $Ca_2Mg_2FeSi_5O_{15}$	8.4	53.8	0.8	13.3	18.9	n.d.	n.d.	n.d.
phlogopite $K_4Fe_3Mg_9(OH,F)_8Si_{12}Al_4O_{40}$	5.9	43.3	11.6	12.3	0.9	2.2	n.d.	n.d.
apatite $Ca_{15}F_2ClP_9O_{36}$	n.d.	n.d.	n.d.	n.d.	52.7	2.3	2.2	40.1

Table 5. Partial analyses of diopside, phlogopite and apatite. (F analyses by A. Chodos, California Institute of Technology, other constituents by Columbia Iron Mining Company)

Distinction between metamorphism and mineralization

Metamorphism may be distinguished from mineralization in the Iron Springs district on the basis of mineralogy, distribution and relative age. Many of the minerals are common to both metamorphism and mineralization, but the abundance of the minerals is markedly different. Metamorphic rocks contain chiefly diopside, carbonates, albite and sanidine. Albite seems to be restricted to the metamorphic rocks. Iron oxide and phlogopite are much more abundant in the mineralization than diopside and sanidine.

It might be argued that this difference in mineralogy is a difference only in the effect of a single process on two different rock types. There are, however, differences in the distribution and age relationships. Metamorphism in the Sandy member of the Carmel formation occurs everywhere along its contact with the intrusive and there is no evidence, even on a small scale, that this reaction occurs along veins or fractures. Mineralization, in contrast, occurs only locally and is commonly found in fractures. Fractures in the metamorphic rock are filled with mineralization, indicating that the mineralization is younger than metamorphism. Although both processes are associated with the intrusive they are different in mineralogy, distribution and age. The age difference is probably small but significant.

Oxygen isotopes in calcite, magnetite and quartz *

The variation in the ratio of O^{18}/O^{16} between two oxygen-containing compounds in isotopic equilibrium with each other is probably dependent primarily on temperature. The equilibrium fractionation of oxygen isotopes between two oxygen-containing compounds is most pronounced at low temperature and decreases with increasing temperature. If it can be established that two minerals were formed in isotopic equilibrium, the temperature of formation may be determined if the equilibrium relationship between the two minerals is known. Until equilibrium relationships between mineral pairs for various temperatures have been experimentally determined this temperature scale is qualitative.

If a mineral already formed is subjected to a new environment, fractionation may take place. If equilibrium is attained, the isotopic composition of the mineral will reflect the new environment; if equilibrium is not attained it will reflect only the direction of change.

Oxygen in samples of magnetite, calcite and quartz from the Iron Springs district was analysed. The analyses were done by, or under the supervision of R. N. Clayton and S. Epstein.

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* For a more complete description of the principles and techniques involved and the results of analyses of samples from various geologic environments see: Clayton, (1955), and Clayton and Epstein, (in press).

The results are reported in terms of δ. δ is defined by the expression:

$$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1 \right) \times 1000$$

where R_{sample} is the ratio of O^{18}/O^{16} in the sample and $R_{standard}$ is the ratio of O^{18}/O^{16} in mean sea water. Then for mean sea water $\delta = 0$. In the systems $CaCO_3$-H_2O and SiO_2-H_2O, the fractionation is large and positive for both $CaCO_3$ and SiO_2 relative to water at low temperatures and small and positive for high temperatures. The fractionation between magnetite and water has been observed to be small and therefore the δ for magnetite approximates the δ for water from which it formed (Clayton, 1955, p. 58).

The results of some of the analyses are plotted in figure 14. The composition of oxygen in the limestone is in the range expected for a Mesozoic limestone subject to isotopic exchange with ground water. The sill is the one described under Metamorphism. $CaCO_3$ from the contact rock of the sill and the limestone above it has an isotopic composition that differs from that of the rest of the limestone. The lower δ numbers for samples of $CaCO_3$ from the contact rock of the sill and the limestone above it probably mean that these rocks have exchanged oxygen isotopes with water of higher temperature or different isotopic composition or both. The mineralogy of the contact rock and the limestone above the sill indicates independently that hot fluids have acted upon this rock.

The δ numbers for calcite in open space mineralization (δ = 4.7 and 6.4) are among the lowest obtained for calcite by Clayton, suggesting a very unusual isotopic composition for the ore fluids or a high temperature. The isotopic composition of magnetite and quartz occurring together in an ore body was determined ($\delta_{magnetite} = 3.5$, $\delta_{quartz} = 6.8$). If these

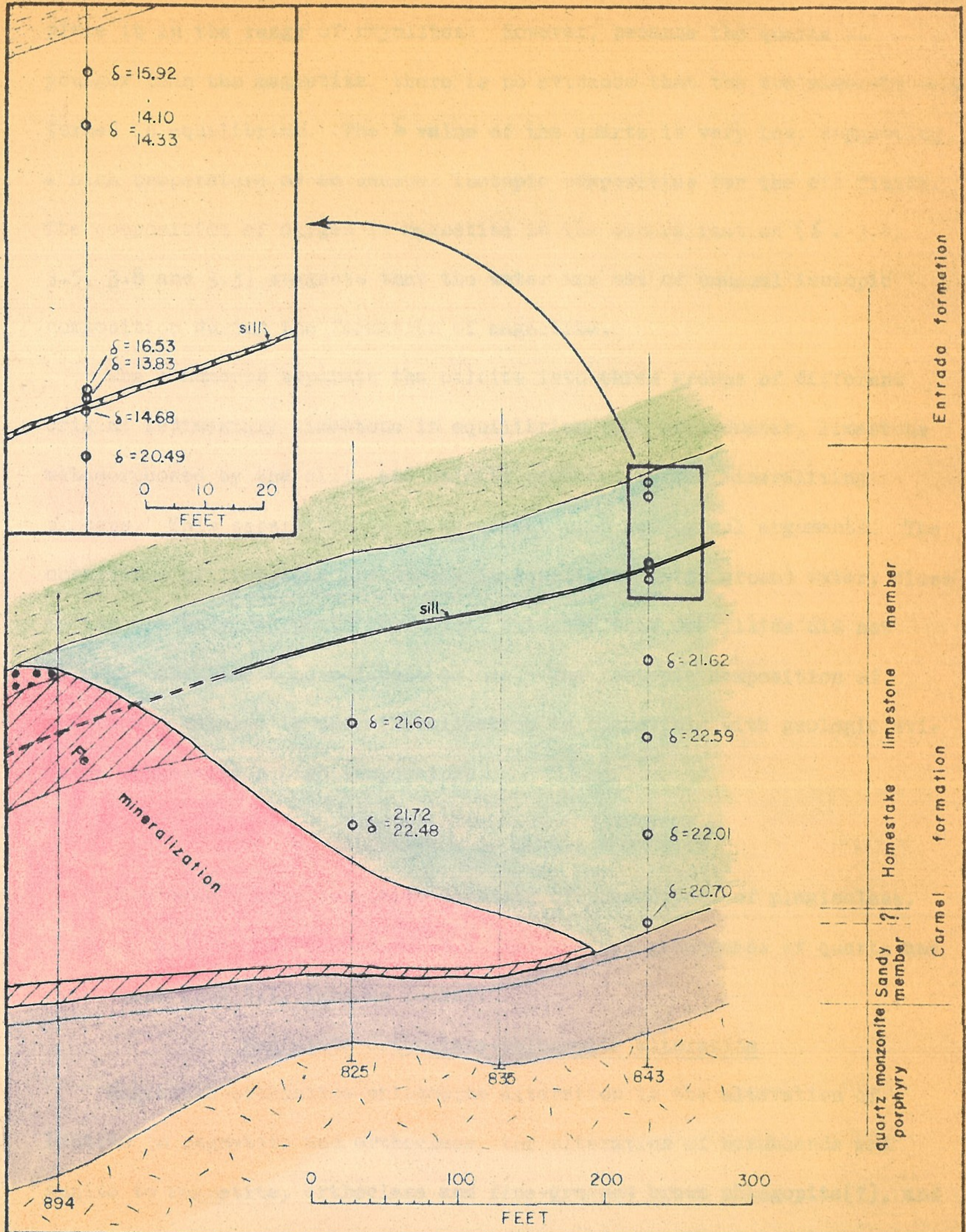


Figure 14 - Location of $CaCO_3$ samples analyzed for oxygen isotopes.

minerals had been formed in equilibrium, a guess of the temperature would place it in the range of rhyolites. However, because the quartz is younger than the magnetite, there is no evidence that the two minerals were formed in equilibrium. The δ value of the quartz is very low, suggesting a high temperature or an unusual isotopic composition for the ore fluids. The composition of oxygen in magnetite in the mineralization ($\delta = 3.4$, 3.5, 3.8 and 3.3) suggests that the water was not of unusual isotopic composition during the formation of magnetite.

The δ numbers separate the calcite into three groups of different origin; sedimentary limestone in equilibrium with groundwater, limestone metamorphosed by the sill, and calcite produced by the mineralizing process. This separation is in agreement with geological arguments. The occurrence of limestone presumably in equilibrium with ground water, close to the ore body, supports geological evidence that ore fluids did not permeate the limestone adjacent to ore. The isotopic composition of quartz and calcite in the mineralization is compatible with geologic evidence suggesting a high temperature.

VI ALTERATION OF QUARTZ MONZONITE

Unaltered quartz monzonite consists of phenocrysts of plagioclase, biotite, augite and hornblende in a fine-grained groundmass of quartz and orthoclase (see III, Igneous rocks).

Magnetite-orthoclase-phlogopite alteration

Magnetite-orthoclase-phlogopite alteration is the alteration of biotite to magnetite and orthoclase, the alteration of hornblende and augite to magnetite, orthoclase and fine-grained brown phlogopite(?), and the veining or dissemination of phlogopite and magnetite in the groundmass. The alteration of biotite is strong and proceeds inward preferentially along the biotite cleavage. Pseudomorphs after biotite, now consisting of magnetite and orthoclase, can be recognized by the preserved crystal form and the orientation of magnetite and orthoclase along the cleavage directions of biotite (figure 15). Hornblende and augite are much less affected by this alteration than is biotite. They are altered to a fine mixture of magnetite, orthoclase and brown phlogopite(?). Commonly biotite is 50 to 100 percent altered, hornblende if present is slightly altered around its edges, and augite is relatively fresh. Most samples contain magnetite and phlogopite in veinlets or disseminated in the groundmass.

The indices ($N_Y = N_Z = 1.63$) of the biotite in the quartz monzonite indicate that its composition is probably near $H_{10}K_5Fe_6Mg_9Al_5(SiO_4)_{15}$ (Winchell, 1951, p. 374). A point count of the magnetite-orthoclase pseudomorphs after biotite indicates that all the iron can be accounted for as magnetite in the pseudomorphs if some such equivalence as the following exists between biotite and its alteration products:

$$\underset{\text{biotite}}{H_{10}K_5Fe_6Mg_9Al_5(SiO_4)_{15}} \approx \underset{\text{orthoclase}}{5\ KAlSi_3O_8} + \underset{\text{magnetite}}{2\ Fe_3O_4} + 9\ Mg^{++} + 10\ OH^- + 2O^{--} + 8e$$

Mg, OH^- and O^{--} can not be accounted for in the alteration products of the biotite but may be present in other minerals in the rock. An extensive sampling program and a number of chemical analyses would be necessary to establish any relationship between alteration and composition of quartz monzonite.

Magnetite-orthoclase-phlogopite alteration occurs throughout the Iron Mountain intrusive as presently exposed but seems to be weaker near the roof and margins of the intrusive. The distribution of this alteration suggests that it is deuteric.

Development of cavities and micrographic texture in groundmass

Locally within the intrusive the groundmass of the quartz monzonite contains cavities, and quartz and orthoclase have a spherulitic or micro-

Figure 15a - Photomicrograph, plain light (115X)

Alteration of biotite to magnetite and orthoclase. Note the two rounded residuals of biotite in the crystal on the left.

Figure 15b - Photomicrograph, crossed nicols (115X)

same as above

graphic texture. The cavities and the micrographic texture generally occur together. The cavities (figure 16) are irregular in shape and are filled with secondary minerals; quartz, calcite, chlorite, montmorillonite(?), phlogopite, diopside, magnetite and pyrite. The micrographic texture of the quartz and orthoclase groundmass is commonly developed radially from the edges of phenocrysts. An example of micrographic texture in the groundmass is shown in figure 17. The radial pattern is progressively less pronounced as the coarseness of micrographic texture increases. A few samples show only a spherulitic texture, presumably because the micrographic texture is too fine to be observed.

The distribution of cavities and micrographic texture in the groundmass is apparently random. It seems to be unrelated either to magnetite-orthoclase-phlogopite alteration or to mineralization. This type of alteration may be either deuteric or primary. The radial pattern of the micrographic intergrowth away from the edges of phenocrysts suggests that the texture is primary. The excellent correlation of the micrographic texture and cavities suggests that a fluid had a part in the origin of the micrographic texture, inasmuch as the cavities are probably either solution cavities or cavities resulting from the release of volatiles in the cooling magma.

Calcite alteration

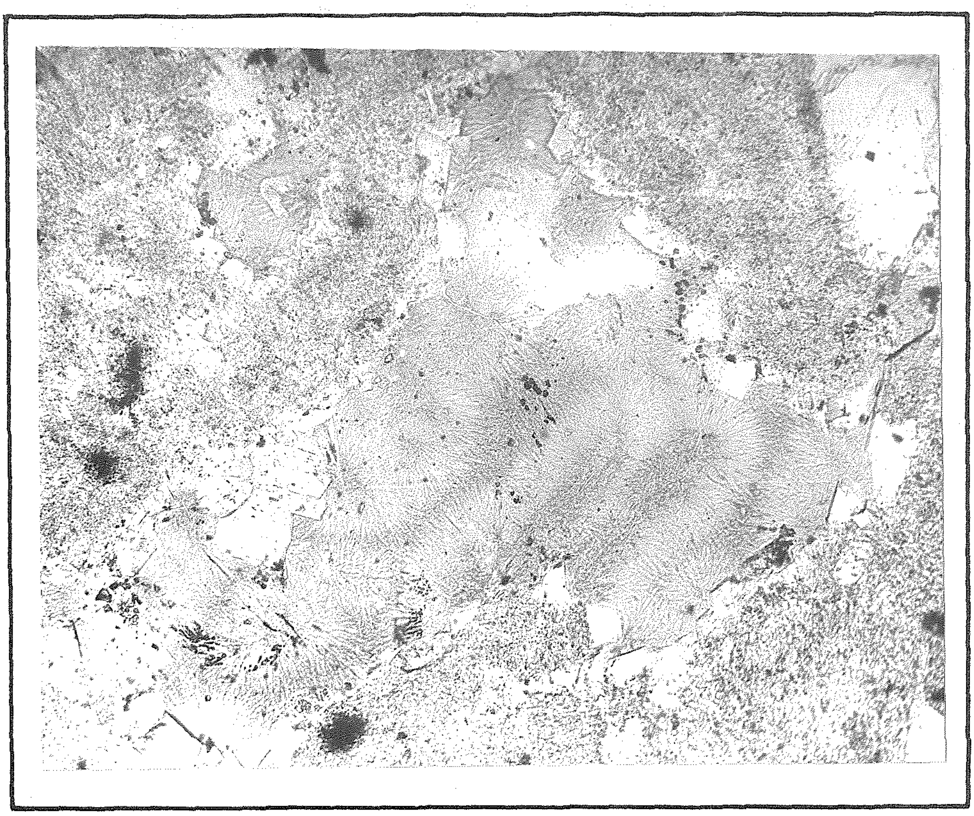
The most distinctive features of calcite alteration are the preferential replacement of augite and to a lesser extent plagioclase, and the veining of the rock by calcite. Calcite may replace part or all of the augite. Veins of calcite cut through the rock irrespective of mineralogy, suggesting that the veining may be fracture controlled. Locally, where calcite alteration is intense, minor amounts of apatite and diopside are

Figure 16a - Photomicrograph, plain light (115X)

Cavities in groundmass of quartz monzonite filled with quartz and chlorite.

Figure 16b - Photomicrograph, crossed nicols (115X)

same as above



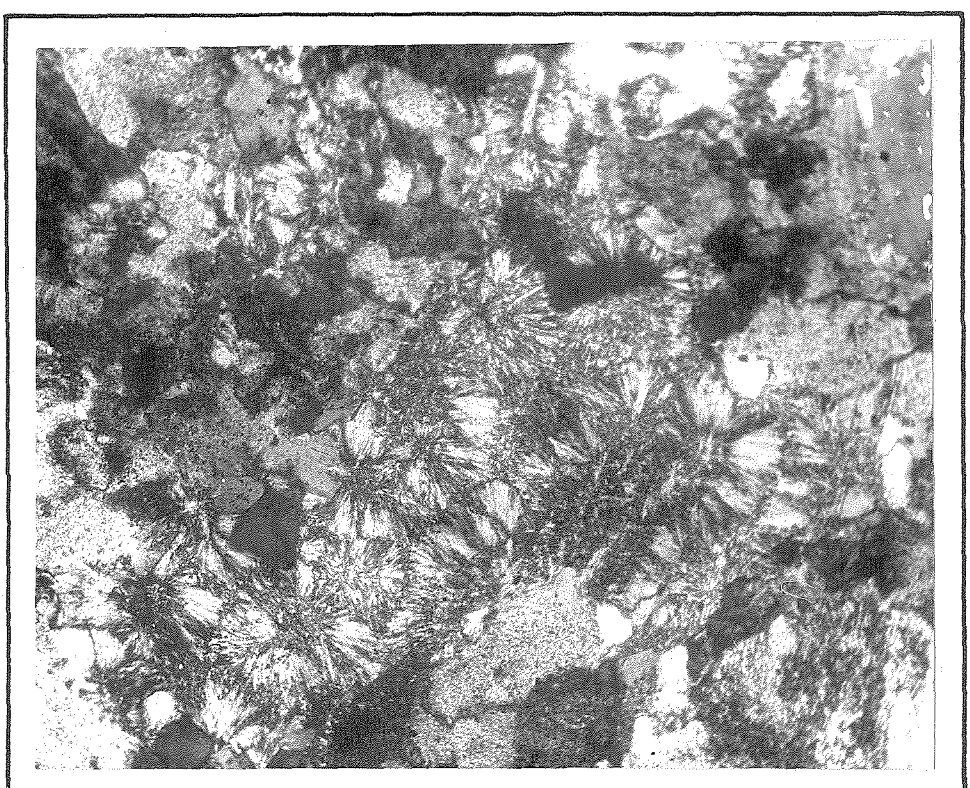
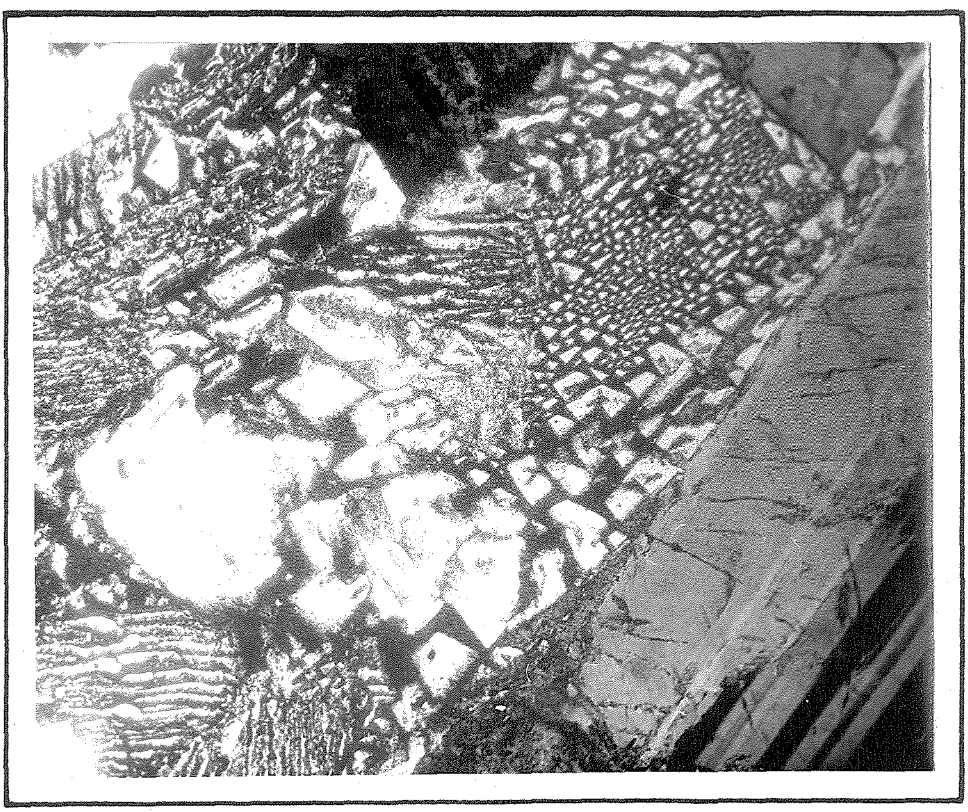


Figure 17a - Photomicrograph, plain light (115X)

Micrographic texture of quartz and orthoclase in groundmass of quartz monzonite.

Figure 17b - Photomicrograph, crossed nicols (115X)

same as above



found in the veins with calcite. Calcite alteration is almost always found near mineralization, but mineralization is not always found near calcite alteration. Calcite alteration may be closely related to mineralization at Iron Mountain.

Sericitization

Sericitization is rare at Iron Mountain and probably is the result of late hydrothermal fluids escaping along fractures and joints. Plagioclase is altered to brown-stained sericite, the mafic minerals are altered to a dark brown fine-grained unidentified aggregate, and the groundmass is weakly or moderately sericitized. The sericitized rock is bleached and crumbly and is veined locally by stilbite.

Other types of alteration

Several other types of alteration are found in the quartz monzonite but do not fit under any of the above headings. Sphene is common locally in the groundmass and in fractures and is not primary. Apatite is a common accessory mineral in fresh quartz monzonite but may also have been introduced or redistributed along veinlets and is evidently associated with phlogopite. In a few thin-sections from the edge of the intrusive near ore, hornblende is moderately altered to montmorillonite. A few radiating crystals of tourmaline are found in the graphic groundmass of some thin-sections, and orthoclase is commonly weakly or moderately altered to very fine kaolin(?).

Discussion

Minerals stable under the conditions of deuteric alteration are the anhydrous minerals plagioclase, augite, quartz and orthoclase. The hydrous minerals, biotite and hornblende are altered to magnetite, orthoclase and phlogopite. Biotite is far more abundant than hornblende and is altered to magnetite and orthoclase. In metamorphic rocks the breakdown of biotite to orthoclase and other minerals occurs with increasing grade of metamorphism, suggesting that the deuteric alteration of biotite to magnetite and orthoclase may take place at a temperature above the stability range of biotite. The temperature of the intrusive might be raised after intrusion by the heat of crystallization released when the groundmass crystallized as a result of a sudden loss of volatiles, or the biotite may become unstable by the reduction in pressure alone.

Calcite alteration and sericitization are superimposed on deuteric alteration and probably belong to the period of mineralization and post-mineralization respectively.

VII ORIGIN OF MINERALIZATION

Mineralization at Iron Mountain is a strong preferential replacement of limestone by magnetite, specularite, phlogopite, carbonates, apatite, and sanidine and some filling of open spaces by magnetite, apatite, diopside, phlogopite and carbonates. Any hypothesis presented to explain the mineralization must account for the removal of Ca and CO_2 from the limestone and the addition of Fe, Si, Al, Mg and K.

Environment of mineralization at Iron Mountain

Temperature

The occurrence of minerals such as diopside, sanidine, phlogopite, magnetite and specularite in the mineralization suggests a high temperature relative to most hydrothermal fluids. The transformation of a low temperature K-feldspar such as orthoclase to sanidine results from the disordering of Si and Al atoms in the feldspar structure above a particular temperature. In a hydrothermal environment, however, sanidine might form in a disordered state at a lower temperature because of disequilibrium and insufficient time for the ordering of the feldspar molecule. Sanidine at Iron Mountain probably formed directly from hydrothermal fluids and can not be used to quantitatively fix a minimum temperature.

Isotopic evidence suggests that the temperature was in the upper range of hydrothermal deposits.

Pressure

Vesicles and cavities in the quartz monzonite show that the confining pressure on the rock was less than the internal pressure of volatiles while the rock was in a mobile state. If the cavities were formed by solution of material after the crystallization of the quartz monzonite their presence does not indicate low pressure. Vesicles are commonly found in extrusive rocks, and their presence in intrusive igneous rocks is suggestive of near surface intrusion. If my interpretation of the structure and stratigraphy at Iron Mountain is correct, the parts of the intrusion that contain vesicles might have been within 1,000 feet of the surface (see figure 11). A reasonable estimate for the depth of mineralization would be between 3,000 and 5,000 feet. If channelways were open to the surface and filled with water, the hydrostatic pressure was somewhere between 90 and 150 atmospheres. The pressure of water at its critical temperature (374°C.) is 218 atmospheres. If the temperature of the ore fluids was somewhere between 400° and 700°C. a gas phase would form and probably displace the water from the channelways. In this event (high temperature, low pressure and open channelways to the surface) the ore fluid would have been a mixture of gases forming fumaroles at the surface.

Rate

No structural or compositional reason is apparent for the sharp contact between ore and unrecrystallized limestone or for the marked discontinuity in the isotopic composition of oxygen between ore and limestone. My interpretation of the sharp contact is that the mineralizing process was rapid and that the ore fluid reacted with limestone and passed upward toward the surface along fractures or other channelways without permeating or affecting the limestone that is unmineralized.

Chemical and structural control

The mineralization at Iron Mountain shows a strong preference for limestone. The occurrence of mineralization in fractures in non-limy rocks indicates that there is also some structural control. The ore fluids evidently traveled upward along fractures but formed replacement bodies only where they encountered limestone.

Source of ore fluids

The ore fluids were associated with the quartz monzonite but may or may not have been derived from the quartz monzonite at depth or the quartz monzonite now exposed. Leith and Harder (1908, p. 79) first suggested that the mineralization might be associated with the alteration of biotite and hornblende in the quartz monzonite but stated that they knew of no way to prove it. Mackin (1947a, p. 43-47; and 1954) suggested that the iron in the ore deposits was derived from mafic minerals in the quartz monzonite by a process of deuteric alteration and released locally where fractures cut the partially consolidated rock. The rock adjacent to these fractures or joints contains 30% less iron than the rest of the rock (Mackin 1954). This hypothesis was derived in large part from Mackin's study of the Three Peaks intrusive. A study of a few thin sections taken from the Three Peaks intrusive shows that the quartz monzonite adjacent to joints which cut deuterically altered rock differs from the quartz monzonite farther away from the joints. The rock adjacent to the joints contains less magnetite and phlogopite in the groundmass and a little more clay dusting of the orthoclase. It is very likely that the groundmass of the quartz monzonite along these joints was a source of iron, but not necessarily that the iron in the groundmass was derived from the mafic minerals. Pyroxene is fresh, and hornblende is rare. A point count suggests that magnetite-orthoclase pseudomorphs after biotite contain enough magnetite to account for the iron in a biotite with an iron content suggested by the optic properties ($N_Y = N_Z = 1.63$).

At Iron Mountain joints are much less evident than they are at Three Peaks, and there is little if any difference between quartz monzonite adjacent to joints and quartz monzonite away from joints.

The source of the ore fluids may be related to the deuteric alteration of the quartz monzonite, but at Iron Mountain a relationship has not been proved. Other intrusives such as the Mt. Stoddard intrusive are deuterically altered in the same way but are associated with no known mineralization. If the quartz monzonite was the source of the ore fluids it must be proved that not only Fe but also Si, Mg, Al and K were derived from it.

Transportation and deposition of material

Small fractures in the Sandy member of the Carmel formation and to a lesser extent in the quartz monzonite below the ore bodies are filled with minerals common to the mineralization. This may be evidence that the ore fluids gained access to the limestone through these channelways. Some weak mineralization may be found in fractures in sedimentary rocks above the ore bodies. Calcite veins and fracture fillings are more common than other types of mineralization above the ore bodies but are far too rare to account for the Ca and CO_2 that were removed from the limestone during replacement. At a distance of 500 to 600 feet above the replaced limestone the sedimentary rocks contain no mineralization and give no other evidence that there is mineralization in the limestone below. The ore fluids entered the limestone through numerous fractures in the Sandy member of the Carmel formation and the periphery of the intrusive, replaced the limestone and escaped upward, leaving little or no trace in the sedimentary rocks above the ore bodies.

Zies (1929) has described fumaroles in the Valley of Ten Thousand Smokes from which magnetite was deposited. Reporting on the expedition of 1919 he said (1929, p. 6):

> "In 1919 Allen and Zies recorded a temperature of 239° at fumarole No. 148 and concluded from the hard siliceous material partly covering the vents that the temperature had been much higher. Magnetite was also found in several other areas in which the temperatures then recorded (1919) were as high as 500°. The incrustations found at the surface of No. 148, in common with practically all of the other areas, contained chlorides and fluorides; ammonium chloride in particular was observed. The various gases in the steam, and the halides in the surface incrustations suggest the mechanism by which the iron and extraneous metals found in the magnetite were transported."

The gases in the steam consisted of small amounts (less than one percent) of HCl, HF and H_2S. Compounds which have an appreciable vapor pressure and do not hydrolyze at a given temperature may be transported by steam in a dynamic system. Ferric chloride probably has a sufficiently large vapor pressure above 300°C. to be transported by moving steam. Stirnemann (1925, p. 355) measured the vapor pressure of ferric chloride and found $p = 0.81$ atm. at 305°C. and $p = 11.7$ atm. at 525°C.

Fumarole No. 148, which contained an estimated 10 tons of magnetite in 1919 was revisited in 1923 by C. N. Fenner (Zies, 1929, p. 18). He found that the temperature of the steam was 97°C. and the magnetite had disappeared. The explanation given by Zies is that when the temperature falls to the point where steam condenses, HCl goes into solution, forming hydrochloric acid which dissolves the magnetite.

The evidence from the Valley of Ten Thousand Smokes suggests that iron may be transported as a chloride and proves that iron in some form can be transported in a vapor phase at high temperature and deposited as magnetite. The magnetite however is attacked by hydrochloric acid when the temperature falls below the condensation point of steam. I found no evidence of any such attack at Iron Mountain.

Wells (1938, p. 499) assumed that, except for a minor amount of soda, only iron had to be added to explain the mineralization in the Iron Springs district. He proposed that the iron was transported as ferric chloride in a vapor phase at a temperature between 500° and 600°C. but could not account for the removal of Ca except as $CaCl_2$ carried away in a liquid water solution. In order for a replacement process to be plausible the addition and removal of material must take place at the same time and therefore at approximately the same temperature and pressure. Water to carry away the $CaCl_2$ can not be present at low pressure and at the temperature suggested. Any proposal that caverns were formed in the Homestake limestone and later filled with magnetite and other ore minerals does not fit the facts in the Iron Springs district.

Any equations written to express the reactions taking place during the replacement of limestone are very speculative. For example one might write:

$$3\ Fe_2Cl_6(g) + 8\ H_2O(g) \rightleftharpoons 2\ Fe_3O_4 + 16\ HCl(g) + Cl_2(g)$$

Assuming that a vapor phase is present during the transportation and deposition of magnetite, the direction and rate of the equation will be very sensitive to the partial pressure of HCl ($K = \frac{p_{HCl}^{16}}{p_{H_2O}^{8}} \frac{p_{Cl_2}}{p_{Fe_2Cl_6}^{3}}$).

I know of no way to estimate what the HCl content of the system was. The situation is further complicated at high temperature by the dissociation of Fe_2Cl_6 and other constituents. Although some magnetite was precipitated away from a known limestone environment, it is almost certain that the limestone played an important part in the formation of magnetite and other ore minerals. If limestone is present in an open system, the reaction above will be driven to the right by the removal of HCl from the system.

$$CaCO_3 + 2\,HCl\ (g) \rightleftharpoons CaCl_2 + H_2O\ (g) + CO_2\ (g)$$

The partial pressures of HCl, H_2O and CO_2 control this reaction ($K = \frac{p_{H_2O} + p_{CO_2}}{p_{HCl}^{2}}$). The method of removal of Ca remains unexplained unless some compound of Ca, perhaps $CaCl_2$, is soluble in steam at high temperature.

If compounds of iron (not necessarily halides) exist which are soluble in steam a general form of the reaction might be written:

$$Fe^{++} + 2\,Fe^{+++} + 4\,OH^{-} \rightleftharpoons Fe_3O_4 + 4\,H^{+}$$

A reduction in the hydrogen ion concentration because of reaction with limestone in an open system would drive this reaction to the right.

It is probable that a vapor phase consisting largely of steam was important in the Iron Springs district during at least part of the mineralization. Because iron chloride has a high vapor pressure it can probably be readily transported in a vapor phase consisting largely of steam at high temperature and low pressure. Most compounds of the other constituents that must be transported, Ca, Si, Mg, Al and K, do not have high vapor pressures. If compounds of these metals and Fe are soluble in steam at high temperatures and low pressures, they may be transported in a vapor phase even though they do not have a high vapor pressure.

VIII ECONOMIC ASPECTS

Most of the economically important ore in the Iron Springs district occurs in the Homestake limestone member of the Carmel formation. Where the structure is simple, positive magnetic anomalies are a very good guide to mineralized limestone. In structurally complex areas within and along the borders of the intrusive the interpretation of magnetic data is limited by the magnetite content of the intrusive. In these areas magnetic data are not sufficient to intelligently predict the location of mineralized limestone. A combination of magnetic data, structural interpretation and perhaps the occurrence of calcite alteration in quartz monzonite covering mineralized limestone may lead to the discovery of ore bodies not presently known.

What appear to me to be the most promising areas for exploration at Iron Mountain are discussed below.

The structural relations near the northeast corner of the Iron Mountain intrusive are very uncertain, particularly the relationship between the deformed early intrusive thrust fault and the fault forming the northern boundary of the intrusive, the amount of displacement on the north-bounding fault, and the depth to limestone north of the intrusive. The east-northeast dip of the Iron Springs formation north of the Mountain Lion pit suggests that there may be a crest in an anticlinal structure somewhere north-northwest of the Mountain Lion pit and therefore a minimal depth to limestone.

The west-dipping Carmel formation exposed east of the Mountain Lion pit trends north-northwest, and its extension beneath the deformed early intrusive thrust sheet may be mineralized. To date exploration has been confined to the thrust sheet. It may be necessary to drill through some quartz monzonite in addition to the sedimentary rocks in the thrust sheet in order to penetrate the limestone in the west-dipping sedimentary rocks.

Because the sedimentary rocks occurring within the borders of the intrusive are very poorly exposed, it is difficult to determine whether they are roof pendants or screens. The location of some of these sedimentary outcrops in topographic lows within the borders of the intrusive and their linear distribution along northeast trending lines suggest that some are screens. The screens probably originate as a result of one or both of the following:

1) remnants along pre-intrusive fault. (Black Hawk, A, B, and Blowout ore bodies)

2) remnants along the early intrusive thrust fault. (Mountain Lion and Comstock areas)

The possibility exists that limestone, covered by quartz monzonite at the present surface, may be found along one or both of these structures.

The displacement on the northeast trending fault bounding the intrusive on the northwest side and the faults parallel to it has not been determined. There is a suggestion that the displacementon these faults decreases southwestward, particularly on the fault forming the contact between the Claron formation and the Iron Springs formation. The displacement on the bounding fault is not great in the Burke pit. There may therefore be limestone at a reasonable depth north and northeast of Milner Hill.

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