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GEOCHEMISTRY AND ORIGIN OF THE TITANIFEROUS MAGNETITE DEPOSIT, IRON MOUNTAIN, WYOMING

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ABSTRACT

Geochemical evidence indicates that the Iron Mountain, Wyoming titaniferous magnetite deposit did not form from an immiscible magmatic fluid, from fluids residual to the crystallization of a normal basic melt, or from material derived from the mafic silicates of the host rock. Differentiation from some type of anorthositic magma, and remobilization of a preexisting ore body are shown to be unlikely sources of the iron and titanium.

The geochemistry of the deposit was studied in an effort to determine the source of the material forming this ore body. Mineral fractions from the ore and anorthosite country rock were analyzed for their ferride element content.

The data show that the ore materials could have been derived from oxide inclusions in the plagioclase of the anorthosite host rock. Chemical analyses reveal that sufficient iron and titanium have been removed from the surrounding anorthosite during recrystallization to account for the ore. It is suggested that during metamorphism and recrystallization of the anorthosite, iron and titanium, originally present in the plagioclase as exsolved needles, diffused out of the feldspar. Released material plus intergranular fluids migrated toward areas of low pressure along the crest of the Laramie Range antiform, and at favorable locations replaced the anorthosite.

INTRODUCTION

The origin of titaniferous magnetite ore bodies such as the one at Iron Mountain, Wyoming, is generally ascribed to some form of magmatic segregation. This process is believed to have produced late-stage iron-rich fluids which intruded the anorthosite host rocks, or, the ores are considered to be the result of *in situ* concentration of residual magmatic fluids. It is significant that all the early workers at Iron Mountain recognized that the ore bodies formed later than the anorthositic rocks and, therefore, could not represent early crystal differentiates. A brief review of the early literature on the Iron Mountain deposit has been given by Hagner (1968).

Newhouse and Hagner (1950) and Hagner (1968) present evidence supporting a replacement origin of the Iron Mountain deposit. It is pointed out that the mineralogy of the ore bodies changes markedly along strike, dip, and plunge, and that massive ore is concentrated along the fold axes whereas olivine-rich ore occurs on the limbs of folds. In places the halo of mineralized rock surrounding the ore bodies transects the foliation of the anorthosite. In addition, replacement features are noted in thin sections and polished surfaces of the ore. The most convincing evidence for replacement is the fact that the strike of the layering in the largest ore body is more easterly than the trend of the body itself (Fig. 1). The ore is believed by Newhouse and Hagner to have formed during granulation, fracturing, and recrystallization of the host anorthosite and to have been emplaced by replacement of the anorthosite.

Accepting the replacement origin of the ore, the possible sources of the ore-forming material include: (1) late-stage magmatic fluids, (2) an early liquid segregation, (3) a pre-existing ore, remobilized by metamorphism, and (4) material originally dispersed in the anorthosite and mobilized during metamorphism.

In the present study the geochemical character of the ore at Iron Mountain, Wyoming is investigated in an effort to determine the source and origin of the ore-forming material. It is believed that the geochemical data provide evidence of the conditions of formation of the ore deposit.

GEOLOGY AND MINERALOGY

The Iron Mountain deposit, in Sec. 22, T. 19 N., R. 71 W., is 47 miles northeast of Laramie by road and is located in the east-central part of the Laramie anorthosite complex. It contains the greatest concentration of titaniferous magnetite ore in the Laramie Range. Here the largest ore body is approximately 1200 feet long, and over 100 feet thick at the widest part; it is located near the southern end of the deposit. Another large ore body, about 375 feet long ~~and~~ and 70 feet thick, occurs in the northern part; much of this ore body has been removed by mining. Both of these bodies are arcuate in form and plunge to the southeast (Fig. 1). Individual ore bodies are lenses or tabular masses commonly arranged in discontinuous and overlapping or en echelon manner conformable to the foliation of the anorthosite; an occasional body transects the foliation. The en echelon arrangement is believed by Hagner (1968) to be due to introduction of ore along zones of shear fracturing that deviate from the compositional layering of the ore and the foliation of the anorthosite.

The Iron Mountain deposit, as well as most of the other titaniferous magnetite deposits of the Laramie Range, is aligned roughly north-south near the eastern margin of a large Precambrian anorthosite mass (Newhouse and Hagner, 1957) All but a few small ore bodies occur along or near the crest of the antiform in the anorthosite mass, where the rock has undergone extensive shearing, granulation, and recrystallization (Fig. 2). The major ore bodies are found where the trend of the antiform changes direction and becomes convex to the east. Such locations

in the granulated and recrystallized anorthosite were apparently favorable structural sites for the accumulation of ore at Iron Mountain (Hagner, 1968).

The mineralogy of the Iron Mountain ore is relatively simple, the ore minerals being magnetite, ilmenite, and spinel. Olivine formed with the ore minerals, but somewhat earlier. Small amounts of biotite, with or without amphibole, occasionally form rims on oxide grains and on olivine. Plagioclase is present in all but the massive ore, and represents recrystallized anorthosite; orthopyroxene is found with the ore where minor amounts of disseminated magnetite-ilmenite occur in layers of noritic anorthosite. Alteration of magnetite to hematite occurs on a limited scale. Layering, largely as variations in olivine percentage, is a common feature of the ore.

Newhouse and Hagner (1950) recognized two types of ore at Iron Mountain; (1) massive magnetite-ilmentite with minor spinel, and (2) magnetite-ilmenite, spinel, and olivine with or without plagioclase. A third type, not found at Iron Mountain consists of magnetite-ilmenite, spinel, apatite, and, in places, olivine.

The ore at Iron Mountain has been divided into 3 grades. Grade 1 consists of massive magnetite-ilmentite with 0 to 35% olivine and minor spinel; TiO_2% ranges from 16 to 23. Grade 2 contains magnetite-ilmenite and 35 to 65% silicates, chiefly olivine, and minor spinel, plagioclase, and orthopyroxene; TiO_2% ranges from 10 to 16. Grade 3 contains magnetite-ilmenite and 65 to 85% silicates, largely plagioclase with minor olivine and orthopyroxene; TiO_2% ranges from 5 to 10. Grades 2 and 3 do not form outcrops but are shown on geologic sections (Fig. 3). The anorthite content of plagioclase adjacent to massive ore is about 5% higher than that some distance away. It is also 4 to 5% higher than that adjoining ore of grades 1 and 2 and mineralized anorthosite (Table 1). The possible

significance of this is discussed in the section on Amount of Material Removed from Plagioclase.

The ore bodies at Iron Mountain are surrounded on both the hanging wall and footwall by zones of non-commercial mineralized anorthosite. Two types of mineralized anorthosite are recognized based on the percentage of minerals present (Fig. 1). Mapped as Type 1 are areas where from 5 to 15 percent of the anorthosite consists of masses of grades 2 and 3 ore; in Type 2 about 75% of the anorthosite contains from 2 to 7% magnetite-ilmenite and 5 to 15% olivine; the remainder is anorthosite. One type may pass into the other, or into ore along strike or down dip (Fig. 3). This halo of low-grade mineralization is developed principally along the hanging wall of the ore zone, and in places it transects and replaces the host anorthosite.

The mineragraphy of the ore has been described by Turner (1947) and Hagner (1968). Magnetite, ilmentite, and spinel occur as discrete grains and as various kinds of intergrowths and overgrowths. The plagioclase of the anorthosite commonly contains minute needles and fine particles believed to be exsolved titanohematite (DeVore, 1955). Examination of some of the larger needles supports this identification. Needles are rare or absent in the recrystallized borders of plagioclase grains (Fig. 4). Their abundance is greatly diminished in the recrystallized plagioclase associated with the ore. In apatite-bearing ore, plagioclase contains very few needles, but opaque dust is fairly common in the apatite itself.

SAMPLE PREPARATION AND ANALYTICAL PROCEDURE

Thirty-four rock and ore samples were separated into plagiocalse, magnetite, ilmentite and olivine fractions. Other minerals present were not analyzed because of limited amounts, or because their extremely small size made purification impossible.

In all, 88 mineral fractions were analyzed for up to seven different elements (Fe, Ti, Cr, Ni, Mn, Mg, V), by X-ray emission; vanadium analyses were performed by Technical Service Laboratories using optical emission spectrography.

The samples were crushed and separated with a Franz Isodynamic Separator. Magnetite and ilmenite fractions were purified with Clereci's solution, but because of the intimate intergrowths entirely pure material was unobtainable. Final purification of mineral fractions was by hand picking under a binocular microscope. In the case of olivine and plagioclase, foreign grains and grains containing abundant oxide blebs were removed. Any spinel that remained in the magnetite and ilmenite at this stage could seldom be removed due to its minute size.

Estimates of average sample purity based on grain counts and disregarding exsolved material are as follows: plagioclase 99%, olivine 98%, ilmenite 85-90%, magnetite 80-85%. The values for magnetite and ilmenite make allowance for the estimated percentage of spinel that is present.

The purified minerals were ground to minus 200 mesh, dried, and mixed with lithium tetraborate in the proportion 0.1500 grams mineral (0.2000 grams for plagioclase) per 1.0500 grams lithium tetraborate. The mixtures were then fused for 15 minutes at 1000°C. in a graphite crucible, cooled, weighed, and brought up to weight (1.2000) by addition of spectrographic grade graphite. The fusion and graphite were then reduced to minus 300 mesh and pressed onto a polyvinyl acetate backing at 23,000 lbs. pressure for 3 minutes. Randomly selected samples of each mineral were prepared in triplicate for checks of reproducibility. Analysis of the samples was by X-ray emission spectorgraphy using standard methods. The instrument used was a Norelco Universal Vacuum X-ray Spectrography equipped for pulse height analysis.

Each set of samples was analyzed for one element at a time to avoid errors resulting from resetting the instrument. In addition, one sample was left in position in the instrument as a standard throughout the course of each run. The radiation intensity of this standard (as counts per second) was measured before and after each of the other samples was run. The intensity ratio for each sample was then calculated and used in order to eliminate the effect of instrumental fluctuations. To reduce error resulting from "matrix" effects, separate standards were prepared for each mineral.

Precision of the analyses was determined empirically from replicate analyses. For all analyses except those of magnetite, the standard deviation was 4% of the amount present, or less. The standard deviation of the analyses of magnetite for Fe and Ti was less than 4%, but that for Mn, and Ni was respectively, 9, and 19% of the amount present. The V analyses have an accuracy of 5-10% of the amount present.

ANALYTICAL RESULTS

Estimates of the mineral composition of the analyzed samples are given in Table 2. The Iron Mountain material was selected from drill core of different grades of ore, and at various distances from massive ore. Where possible, samples were taken from a single core representing the transition from lower to higher grades of ore. Some core samples are from layers or blocks of anorthosite with ore on either side.

Material was also selected from other titaniferous magnetite occurrences in the anorthosite complex for comparison with the Iron Mountain ore. Thus the samples preceded by Il, and Tr are surface materials from magnetite-ilmenite ore bodies and country rock,and Ga-1 and Ga-2 are surface samples of mineralized gabbro. The results of these chemical analyses are given in Table 3.

In evaluating the Wyoming geochemical data, comparison was made with similar data from the Skaergaard intrusion, East Greenland, The geochemistry of the Skaergaard intrusion has been discussed by Wager and Mitchell (1951), Vincent and Phillips (1954), and more recently by Wager and Brown (1967). From their chemical analyses, the composition of the magma and the crystallizing phases at all stages of differentiation has been determined. This permits a comparison of data with analyses of minerals that formed at different stages during the differentiation of a basic magma. Since the geologic situation at Iron Mountain is not the same as at the Skaergaard, the results may not be strictly analogous. However, one possible origin of the Wyoming ores is by differentiation of a basic magma. If this origin obtains, geochemical similarities should exist with the Skaergaard rocks.

Magnetite

The Iron Mountain magnetite contains between 5 and 19% TiO_2. From microscopic study it appears that the TiO_2 is present as exsolved ilmenite with differences in analyses being attributable to differences in the amounts of exsolved ilmenite present. No systematic variation in the amount of Ti versus grade of ore was found. However, in ore containing more than 40% opaque minerals TiO_2 values generally exceeded 12%; ore with less than 40% opaque minerals, the magnetite contains 5 to 7% TiO_2.

Magnetite from Iron Mountain contains concentrations of Mn (1000-4000ppm) and Ni (200-400ppm) which are similar to the concentrations reported by Wager and Mitchell (1951) for Skaergaard material. Significantly, the 2000 ppm V common to the Wyoming magnetite is much higher than was found at the Skaergaard where V occurs only in the early crystallizing magnetite.

Because the Mn and Ti content of the magnetite samples showed a close and direct relationship, it is concluded that the Mn indicated is actually contained in the included ilmenite rather than in the magnetite itself. Conversely Ni and

V are actually in the magnetite, a conclusion supported by the fact that ilmenite fractions consistently contain less of these elements that the magnetite fraction from the same sample.

Chromium was present in qualitatively detectable amounts.

Ilmenite

The ilmenite fractions of the Iron Mountain ores contained detectable amounts of Mn, V, Ni, Cr, but only Mn and V could be measured quantitatively by the methods used. The Mn concentrations of from 2000 to 3000 ppm are close to those found at the Skaergaard. The V content at Iron Mountain is generally less than 400 ppm though values up to 1000 ppm were found.

Spinel

The presence of spinel was noted in most of the samples but only in small, widely dispersed amounts. This made recovery and analysis impossible by the methods used.

Olivine

With one exception (Tr6-14) all of the olivine analysed is associated with the ore. The mole percentage of forsterite in ore olivine was found, by non-chemical means, to range between Fo_{60} and Fo_{45}, with no pattern of variation between high and low grade ore. Non-ore olivine is only slightly more magnesic.

Minor elements detected in the Wyoming olivine included Ti, Cr, Mn and Ni. The few hundred parts per million Ti found are probably present as oxide inclusions. Mn (3000-4000 ppm) and Ni (400-600 ppm) are both present in the olivine itself. The Ni concentration is greater in the more magnesic olivine, whereas Mn is more abundant in the less magnesic varieties. These relationships are to be expected by analogy with the Skaergaard, where Wager and Mitchell (1950) found Ni to be concentrated in the early crystallized olivine and Mn to increase in late stage olivine.

Plagioclase

It has been noted that most of the plagioclase in the Laramie Range anorthosite mass is somewhat clouded by opaque, microscopic needles thought to consist of titanohematite. Where the anorthosite has undergone granulation and recrystallization, these needles are absent.

The phenomenon of clouding of plagioclase has been discussed in detail by MacGregor (1931) who concluded it was the result of exsolution during thermal metamorphism. The Fe was considered to have originally been present in the plagioclase structure. Poldervaart and Gilkey (1954) suggested that clouding may also result from diffusion of Fe and Ti into the crystal from areas of higher concentration outside the grain. This means of producing clouding would be most effective near ore bodies, but might also occur in rocks containing abundant mafic minerals.

In the Laramie Range anorthosite, clouding is pronounced several miles from the ore as well as adjacent to it. This suggests that the needles are the result of exsolution rather than diffusion into the crystal, and indicates that the Fe and Ti were present in the plagioclase at the time it formed, either within the structure or absorbed on intracrystal planes. Furthermore, needles are rare or absent in granulated and recrystallized grains and grain borders but remain in non-crystallized grain cores. It is therefore concluded that the Fe and Ti which first formed the needles were later remobilized and dispersed during recrystallization.

In the present study all grain fragments containing visible needles were removed by hand picking under a binocular microscope. Thus the analyses presented represent needle-free, recrystallized material. Of the elements studied in this investigation, only Fe and Ti occur in plagioclase in amounts sufficient for quantitative analysis. Ni, Mn, and Cr were detected qualitatively but not in determinable amounts.

The recrystallized plagioclase generally contains 2000 - 3000 ppm Fe and 300 - 600 ppm Ti. DeVore (1955), presented additional analyses of plagioclase from the Laramie Range. His work included analyses of both the non-recrystallized cores and the recrystallized borders of plagioclase grains. He found, in general, that grain borders contain more Fe and less Ti than the cores. Averages of his analyses are Fe 2900 ppm core versus 3200 ppm border; TiO_2 0.08% border versus 0.13% core. It is noted, however, that for more than 1/3 of the core-border pairs the relationship of more Fe in the recrystallized border than in the core does not hold. Where the analyses were of totally recrystallized and totally non-recrystallized grains, DeVore found that the recrystallized material contained less Ti and Fe.

Table 4 summarizes the averages of plagioclase analyses presented by DeVore (1955) and Reinking (1967). In column 1 the analyses of recrystallized border material by both writers are averaged together. As is clearly indicated by the table, recrystallization of the plagioclase has resulted in a net loss of both Ti and Fe.

ORE GENESIS

Because the replacement origin of the Iron Mountain ore rules out formation by the accumulation of early formed crystals, three sources for the ore material are possible. The ore may represent an early or late magmatic differentiate, a metamorphically remobilized primary ore, or it may have been derived from the host rock itself during metamorphism.

Magmatic Origin

If we assume the ore is magmatic in origin, then it represents either an early liquid segregation, e.g., an immiscible oxide phase, or a later stage residual fluid. At the Skaergaard, Wager and Mitchell (1951) have shown that both Ni, and V are all but removed by midway through the crystallization of a basic magma.

The question exists whether the Skaergaard magma and a magma which might have formed the Laramie Range anorthosite would be sufficiently similar to yield the same fractionation trends. However, when the entire anorthosite complex including the noritic material is considered any such magma would have had to be at least gabbroic-anorthositic. In view of this, it is believed that the Laramie Range complex contains sufficient mafic constituents to have removed the Ni and V from the mobile phase before any residual fluid formed. It is concluded therefore, that the Iron Mountain ores are not the product of residual magmatic fluids.

It might be suggested that an immiscible Fe-Ti oxide-rich liquid separated early during the crystallization of magma, and later reinvaded the anorthosite to produce these replacement-type ores. However, the very high crystallization range of iron oxide liquids makes it doubtful that such a liquid could have remained fluid long enough to replace the solid anorthosite. Therefore, this idea does not provide an acceptable explanation for the Iron Mountain ores.

Remobilized Pre-existing Ore

Another conceivable source of ore-forming material at Iron Mountain is a pre-existing ore body which was remobilized during metamorphism and then replaced the anorthosite. If such earlier ores existed, the reasoning applied to late stage and immiscible fluids is applicable here. Moreover, there is no positive evidence to suggest that such ores ever existed and no one who has worked in the area has suggested this as a likely origin.

Host Rock Source

The final suggested source for the ore forming material is metamorphic mobilization of Fe and Ti dispersed in the host rock anorthosite. If this is to be accepted, it must be shown that (1) the ore material was originally present in the anorthosite and has been released, and (2) conditions existed to cause this release and subsequent concentration.

As previously stated, the margins of many plagioclase grains at Iron Mountain, and in some cases entire grains, have been recrystallized. In such material, oxide needles are not present, suggesting dispersal of the Fe in this needle-free material during recrystallization.

In the present study, only material from recrystallized grain borders was analyzed. These samples contain up to 0.3% Fe and about 0.05% Ti. DeVore (1955) analyzed granulated and non-granulated plagioclase, and grains with granulated borders and non-granulated centers were analyzed separately. Our samples are grouped with DeVore's "granulated plagioclases".

Incidental to another problem, DeVore briefly considered the implications of his analyses with regard to the origin of the Iron Mountain titaniferous magnetites. Ti decreases in the inclusion-free recrystallized borders and there is less Ti in granulated than in nongranulated bulk plagioclase samples. Based on this, he concluded that Ti had been released from the plagioclase during recrystallization. Sen (1960) verified the fact that Fe and Ti do indeed migrate out of plagioclase crystals. DeVore states, however, that Fe increases in the recrystallized plagioclase and concludes that recrystallization took place in an Fe-rich environment. He believes the Fe was already present in the dispersed phase and was joined by the released Ti. This conclusion is evidently based on the apparent Fe concentration gradient decreasing toward the centers of plagioclase grains.

Several problems are raised by this interpretation. First, for 9 of his 23 core-border pairs, the trend described by DeVore does not obtain. Instead, the cores contain more total Fe than the borders. More importantly, as Table 4 shows, comparison of totally recrystallized grains versus totally non-recrystallized grains shows less iron in the recrystallized material. When all available analyses are averaged (Table 4) it is clear that recrystallization of the Laramie Range anorthosite did in fact release Fe (approximately 0.05%) as well as Ti (0.4% TiO_2). It is our conclusion that this released material was the source of Fe and Ti in the Iron Mountain ores.

Concerning the latter, the anorthosite has been strongly fractured, granulated, recrystallized, and folded into an antiform. During the recrystallization, Fe and Ti were definitely dispersed as is shown by the absence of oxide needles in recrystallized portions of the grains.

It must also be demonstrated the Fe and Ti were available in the host rock and did, in fact, move. Three possibilities exist: the Fe and Ti could have been released from mafic silicates, from the plagioclase, or from discrete grains of accessory magnetite.

Accessory magnetite-ilmentite is present in the anorthosite in amounts up to several percent. Near the ore, and extending up to 2000 feet from it, is a halo of mineralized anorthosite containing up to 10% magnetite-ilmenite. It is from this first few thousand feet that metamorphically produced ore would probably be derived. Thus, this increase rather than decrease in the amount of magnetite-ilmenite near the ore indicates that simple mobilization of accessory oxides was not the source of the Fe in the ore.

Study of the mafic minerals in the Laramie Range anorthosite has failed to show any consistent loss of Fe by these minerals as the ore zone is approached. Moreover, the major ore bodies in the Laramie Range lie within the lowermost anorthosite layer which generally contains less than 5% mafic minerals. Therefore, it is concluded that the Fe in the ore was not derived from mafic silicates in the anorthosite.

Because the plagioclase in the Laramie Range anorthosite is "clouded" by Fe-Ti bearing needles and dust, plagioclase must be considered as a possible source for the ore-forming material. MacGregor (1931), and Poldervaart and Gilkey (1954), indicate that a post-crystallization increase in temperature rather than a temperature decrease may be required to produce "clouding". Such an increase did occur during metamorphism of the anorthosite mass. It is probable, therefore, that exsolution of Fe and Ti and the resulting clouding of the plagioclase took place during the early stages of metamorphism of the anorthosite.

It is noted that in these averages, values over 0.55% Fe have been disregarded as this is about the maximum the plagioclase structure is thought capable of containing (Deer, Howie, and Zussman, V. 4, 1963, and Sen 1960). This limit must be applied because Fe is present in the plagioclase as needles of material originally exsolved in the structure.

AMOUNT OF MATERIAL REMOVED FROM PLAGIOCLASE

It must now be demonstrated that sufficient Fe and Ti could have been released from the granulated plagioclase to form the Iron Mountain ore. Newhouse and Hagner (1950) estimated that the Iron Mountain deposit contained 9,150,000 tons of grades 1, 2, and 3 ore, the mean Fe content of which was about 34%. Recent estimates suggest a figure of 23 million tons of "ore", but this value includes a large amount of low grade "mineralized anorthosite" which was not included inthe earlier estimate. For purposes of calculation, it is assumed here that this 23 million tons of ore plus anorthosite might average as high as 17% Fe.

Based on the differences in the average analyses of recrystallized and non-recrystallized plagiocalse summarized in Table 4, it is estimated that 0.05 weight percent Fe was released by the granulated plagioclase. Calculations using these figures indicate that the granulation of 2.6 kilometers would have supplied enough Fe for just over 23 million tons of ore. This 2.6 kilometers is actually more than is necessary since the Fe present in the replaced rock has not been included in the calculations.

DeVore's calculations showed that enough Ti would be released from 2 cubic kilometers of granulated material to form 30 million tons of titaniferous magnetite containing 15% TiO_2. The present writers agree that this was the source of the Ti ar Iron Mountain.

Because the ore at Iron Mountain is located near the crest of the antiform, migration of material is believed to have been toward the crest, and the source rocks should be down the flank and plunge from the ore bodies. The ore bodies

extend as discontinuous bodies for approximately 4000 ft. along strike. Granulation of the anorthosite down dip and plunge for a distance of 3000 feet, and to a depth of 3000 feet, would provide the required 2.6 cubic kilometers of anorthosite. Analyses by the writers and by DeVore show the plagioclase in this area to be Fe deficient. It is therefore concluded that the Fe and Ti in the ore were derived metamorphically from the anorthosite adjoining the ore zone.

MINERALIZED NORITE

Mineral fractions from two samples of mineralized norite were analyzed to determine if they were chemically similar to the Iron Mountain ores. These samples, Ga-1 and Ga-2, were collected from small bodies 10 miles northwest of Iron Mountain.

Like the Iron Mountain material, the norite samples show evidence in thin section of replacement by magnetite. However, massive ore, representing almost totally replaced host rock, is lacking. The location of these bodies several miles from the antiformal crest in the anorthosite, suggests there was little or no structural control of mineralization exerted by the antiform. The norite bodies have been intruded into the anorthosite and are younger than the anorthosite mass.

Chemically, the magnetite and ilmenite from samples Ga-1 and Ga-2 are unlike the ores at Iron Mountain. Magnetite from the mineralized norite contains less Ni, and V than ores elsewhere in the anorthosite mass, and the ilmenite in the norite ores has less V. The V content of the magnetite, one tenth that found at Iron Mountain, is most significant.

From these trace element variations, and the difference in geologic environment of the ore in norite, it is concluded that the origin of this ore differs from that of the ore at Iron Mountain. Additional work will be required to determine the genesis of the mineralized norite bodies.

CONCLUSIONS

The geochemical data suggest that the Iron Mountain titaniferous magnetite deposits do not represent a residual concentration from a basic magma, nor an early liquid magmatic segregation. That the ore is a residual concentration from crystallization of an anorthosite magma, or represents remobilized pre-existing ore is also considered unlikely. An early crystal accumulation is disproved by both field and geochemical evidence. Mafic silicates in the anorthosite show little or no loss of Fe during metamorphism, and thus could not have supplied a significant amount of material to the ore bodies. The source, origin, and mechanism of release and concentration of material postulated, appear to be the most satisfactory explanation of the formation of the ore at Iron Mountain.

The most likely source of the Fe and Ti appears to have been exsolved oxide needles in the plagioclase. During granulation and recrystallization of the anorthosite mass, Fe and Ti present in these needles was mobilized. The released material migrated down a concentration-potential gradient toward areas of low pressure along the fractured crest of the Laramie Range antiform. At favorable locations, particularly at points of change of axial trend, magnetite and ilmenite replaced the host anorthosite. Calculations indicate that sufficient Fe and Ti were removed from the anorthosite adjoining the deposit to account for all known ore.

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Table 1

Anorthite Content[1] of Plagioclase in Different Environments
Iron Mountain, Wyoming

Environment of Specimens	Average Anorthite %	Number of Specimens	Range
Anorthosite not adjoining ore	48.9	20	40-56
Mineralized anorthosite, Types 1 and 2	50.0	26	45-55
Anorthosite in and adjoining (within 2 ft.) grades 2 and 3 ore	49.1	23	38-56
Anorthosite adjoining (within 15.5 ft. or less) grade 1 ore	54.1	6	51-56

1 Determined petrographically using universal stage

TABLE 2

MINERAL COMPOSITION OF SAMPLES
(as volume percent)[1]

Sample Number	Magnetite-Ilmenite	Spinel	Olivine	Pyroxene	Biotite	Plagioclase	Apatite	Needles in plagioclase cores[2]	Comments
3-110	3	1	15		5	76		Moderate	Plag slightly altered
9-31	1				1	98		Abundant	
9-89	75	10	15					-	
9-111	65	8	20		7			-	
9-169	85	10	Tr		5			-	
9-178	2		20		3	75		Moderate	Plag, olivine, moderately altered
9-227	80	10	8			2		-	
14-106	1				5	94		Abundant	Plag moderately altered
14-150	45	5	3		2	45		Sparse	
14-176	25	Tr	40			35		Abundant	
14-223	10	Tr	15		2	75		Moderate	
14-289	10	Tr	Tr		2	88		Abundant	Plag moderately altered
15-81			2			98		Abundant	Plag moderately altered
15-97			15		3	75		Abundant	Plag moderately to highly altered
15-135	10		10		10	70		Sparse	
15-171	1		8		1	90		Moderate	
16-214	Tr			3		97		Very sparse	
16-242	2			28		70		Moderate	Hypersthene altered
17-203	20	2	60		3	15		Sparse	
17-222	15	Tr	10		3	70		Very sparse	
17-227	20	2	50		3	25		Sparse	
Il-1	100							-	Massive ilmenite
Ga-1	20			65	5	10		Absent	Mineralized norite
Ga-2	25			45		30		Absent	Mineralized norite
Tr 6-4	2		15		3	80		Abundant	Plag moderately altered
Tr 7-18a	3				7	90		Abundant	Plag moderately altered
Tr 15-6	Tr					99		Moderate	Plag highly altered

[1] Estimated from thin section examination.
[2] Abundance in cores of large, nongranulated grains.

TABLE 4

Average Fe and Ti Content of Recrystallized and Non-recrystallized

Plagioclase[1]

Laramie Range, Wyoming

	Partially Recrystallized Grains[2]		Whole Grains[3]		All Analyses	
	Recrystallized Borders	Non-recrystallized Cores	Recrystallized	Non-recrystallized	Recrystallized	Non-recrystallized
Ti	0.08%	0.13%	0.06%	0.11%	0.08%	0.12%
Fe	0.27%	0.29%	0.28%	0.35%	0.27%	0.32%

1. Values over 0.55% Fe omitted. See text
2. DeVore (1955) plus Reinking (1967)
3. DeVore (1955)

TABLE 3
PARTIAL CHEMICAL ANALYSES

Sample Number	MAGNETITE Fe	Ti	V	Mn	Ni	ILMENITE Fe	Ti	V	Mn	Ni	OLIVINE Fe	Ti	Mg	Mn	Ni	PLAGIOCLASE Fe	Ti	Mn	Ni
	(As Weight Percent)					(As Weight Percent)					(As Weight Percent)					(As Weight Percent)			
3-110	-	-	-	-	-	-	-	-	-	-	31.85	0.0959	15.02	0.389	0.0460	0.225	0.0525	*	*
9-31	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.216	0.0335	*	*
9-89	44.50	8.69	0.15	0.279	0.0280	30.95	25.10	0.012	0.358	*	27.20	0.0397	17.69	0.326	0.0493	0.192	0.0600	*	*
9-111	49.00	9.95	0.20	0.288	0.0333	30.75	25.10	0.011	0.305	*	24.60	0.0485	19.59	0.297	0.0550	-	-	-	-
9-169	52.20	10.46	0.24	0.265	0.0265	29.80	25.45	0.011	0.267	*	-	-	-	-	-	-	-	-	-
9-178	47.20	3.42	0.18	0.153	0.0280	-	-	-	-	-	-	-	-	-	-	0.201	0.0585	*	*
9-227	44.60	10.44	0.17	0.260	0.0240	28.60	25.00	0.011	0.310	*	-	-	-	-	-	-	-	-	-
14-106	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.240	0.0400	*	*
14-150	52.00	4.28	0.20	0.129	0.0330	33.45	24.50	0.025	0.422	*	31.85	0.0292	13.40	0.420	0.0428	0.198	0.0420	*	*
14-176	52.70	3.57	0.29	0.140	0.0270	32.81	24.53	0.034	0.316	*	-	-	-	-	-	0.257	0.0450	*	*
14-223	57.70	4.20	0.14	0.121	0.0355	32.80	25.00	0.020	0.392	*	31.25	0.0416	15.28	0.386	0.0409	0.199	0.0355	*	*
14-289	57.40	3.46	0.26	0.121	0.0293	32.60	25.10	0.026	0.376	*	-	-	-	-	-	0.221	0.0320	*	*
15-81	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.224	0.0325	*	*
15-97	48.70	3.30	0.18	0.113	0.0320	33.20	25.30	0.054	0.294	*	-	-	-	-	-	0.284	0.0310	*	*
15-135	52.80	2.25	0.17	0.138	0.0535	31.60	24.85	0.110	0.252	*	-	-	-	-	-	0.340	0.0320	*	*
15-171	-	-	0.55	-	-	32.20	24.85	0.030	0.319	-	-	-	-	-	-	0.272	0.0355	*	*
16-214	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.235	0.0285	*	*
16-242	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.226	0.0305	*	*
17-203	-	-	0.54	-	-	34.70	25.20	0.020	0.419	*	33.60	0.0344	15.78	0.393	0.0400	0.159	0.0445	*	*
17-222	52.70	3.73	0.22	0.121	0.0405	32.20	24.55	0.023	0.443	*	32.65	0.0626	14.28	0.397	0.0426	0.182	0.0698	*	*
17-227	53.70	4.02	0.18	0.125	0.0295	32.00	25.45	0.024	0.448	*	32.70	0.0446	13.46	0.392	0.0420	0.165	0.0710	*	*
Il-1	52.00	3.60	0.19	0.060	0.0260	33.85	25.15	0.009	0.280	*	-	-	-	-	-	-	-	-	-
Ga-1	38.10	11.45	0.015	0.448	0.0175	33.40	24.75	0.006	0.469	*	-	-	-	-	-	0.212	0.0620	*	*
Ga-2	42.25	8.19	0.023	0.298	0.0125	32.00	24.90	0.005	0.464	*	-	-	-	-	-	0.158	0.0490	*	*
Tr6-4	-	-	-	-	-	33.40	24.25	-	1.220	*	27.30	0.0414	-	0.307	0.1238	0.182	0.0480	*	*
Tr7-18a	-	-	-	-	-	-	-	0.005	-	-	-	-	-	-	-	0.175	0.0350	*	*
Tr15-6	-	-	-	-	-	-	-	0.036	-	-	-	-	-	-	-	0.195	0.0475	*	*

* Insufficient to be determined
\- No analysis