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Composition of coarse-grained magnetite from pegmatite dikes related to plutons of quartz monzonite in the Jabal Lababa area, Kingdom of Saudi Arabia

by

W. C. Overstreet[1/], Hassan Mousa and J. J. Matzko[2/]

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1/ U.S. Geological Survey, Denver, CO 80225
2/ U.S. Geological Survey, Reston, VA 22092

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COMPOSITION OF COARSE-GRAINED MAGNETITE FROM PEGMATITE DIKES RELATED TO PLUTONS OF QUARTZ MONZONITE IN THE JABAL LABABA AREA, KINGDOM OF SAUDI ARABIA

by

William C. Overstreet[1/], Hassan Mousa,

and John J. Matzko[2/]

ABSTRACT

Crystals of magnetite as large as 30 mm long and 7 mm thick are locally present in quartz-rich zones of interior and exterior pegmatite dikes related to plutons of quartz monzonite in the Jabal Lababa area. Niobium, tin, and yttrium are strongly enriched in six specimens of magnetite from interior pegmatite dikes in a small pluton where these elements form geochemical anomalies in nonmagnetic heavy-mineral concentrates from wadi sediment. Less abundant anomalous elements in the magnetite are molybdenum, lead, and zirconium, which also tend to be present in anomalous amounts in the nonmagnetic concentrates from the niobium-bearing pluton. The most anomalous trace element in the magnetite is zinc, which is at least 10 times as abundant as it is in the quartz monzonite plutons or in the nonmagnetic concentrates. The capacity of magnetite to scavenge molybdenum, zinc, niobium, lead, tin, yttrium, and zirconium suggests the possible utility of magnetite as a geochemical sample medium.

1/ U.S. Geological Survey, Denver, Colorado 80225
2/ U.S. Geological Survey, Reston, Virginia 22092

INTRODUCTION

Detrital magnetite was used sparingly as a geochemical sample medium in Saudi Arabia in the 1960's, but the only elements determined therein were copper, molybdenum, and zinc (Overstreet and Rossman, 1970, fig. 3; Kahr and others, 1972, p. 44-47; Overstreet, 1978, fig. 4). Elsewhere, magnetite has been shown to reflect primary anomalies for a number of metals, particularly silver, beryllium, cobalt, chromium, copper, molybdenum, niobium, nickel, lead, tin, and zinc (Overstreet and others, 1978, p. 314-484). The presence of these elements in magnetite from other areas, and anomalous values for some of these elements, particularly niobium, tin, yttrium, and zirconium, in rocks, stream sediments, and non-magnetic concentrates from the Jabal Lababa area led to a decision to analyse a few of these easily collected specimens of coarse-grained magnetite to determine if niobium and its pathfinder elements were present. The samples were obtained and analyzed in 1980 during reconnaissance geochemical exploration of the Jabal Lababa area (Overstreet and others, Unpub. data, 1983).

The work on which this report was based was performed in accordance with a cooperative agreement between the U.S. Geological Survey and the Ministry of Petroleum and Mineral Resources. Cooperation of officials of the Deputy Ministry for Mineral Resources, Kingdom of Saudi Arabia, and of personnel of the Saudi Arabian Mission, U.S. Geological Survey is appreciated.

SOURCE OF MAGNETITE

The location of the Jabal Lababa area is shown on figure 1 and the sources of the magnetite used for analysis are indicated on figure 2, which is adapted from reconnaissance geologic maps (Ratte and Andreasen, 1973; Overstreet and others, unpub. data, 1983). The reader is referred to the original reports for a discussion of the regional geology; but in outline, three small plutons of Precambrian postorogenic quartz monzonite intruded layered metasedimentary rocks consisting of chlorite schist, biotite schist and gneiss, quartzite, and marble. Unconformably overlying the quartz monzonite and metasediments are small relicts of the Wajid Sandstone of Cambrian-Ordovician age. Small cones and flows of Quaternary basalt are present. Quartz-rich pegmatite dikes inside the plutons and in the wall rocks locally contain coarse-grained crystals of magnetite up to 30 mm across and 7 mm thick. The magnetite is an accessory mineral in the core and wall zones of the pegmatite dikes, particularly where the pegmatite is rich in quartz and grades into feldspathic quartz veins.

Six samples of the coarse-grained magnetite were selected from gruss and eluvium derived from pegmatite dikes at five sites (fig. 2). Three sites are interior dikes and two sites are exterior dikes.

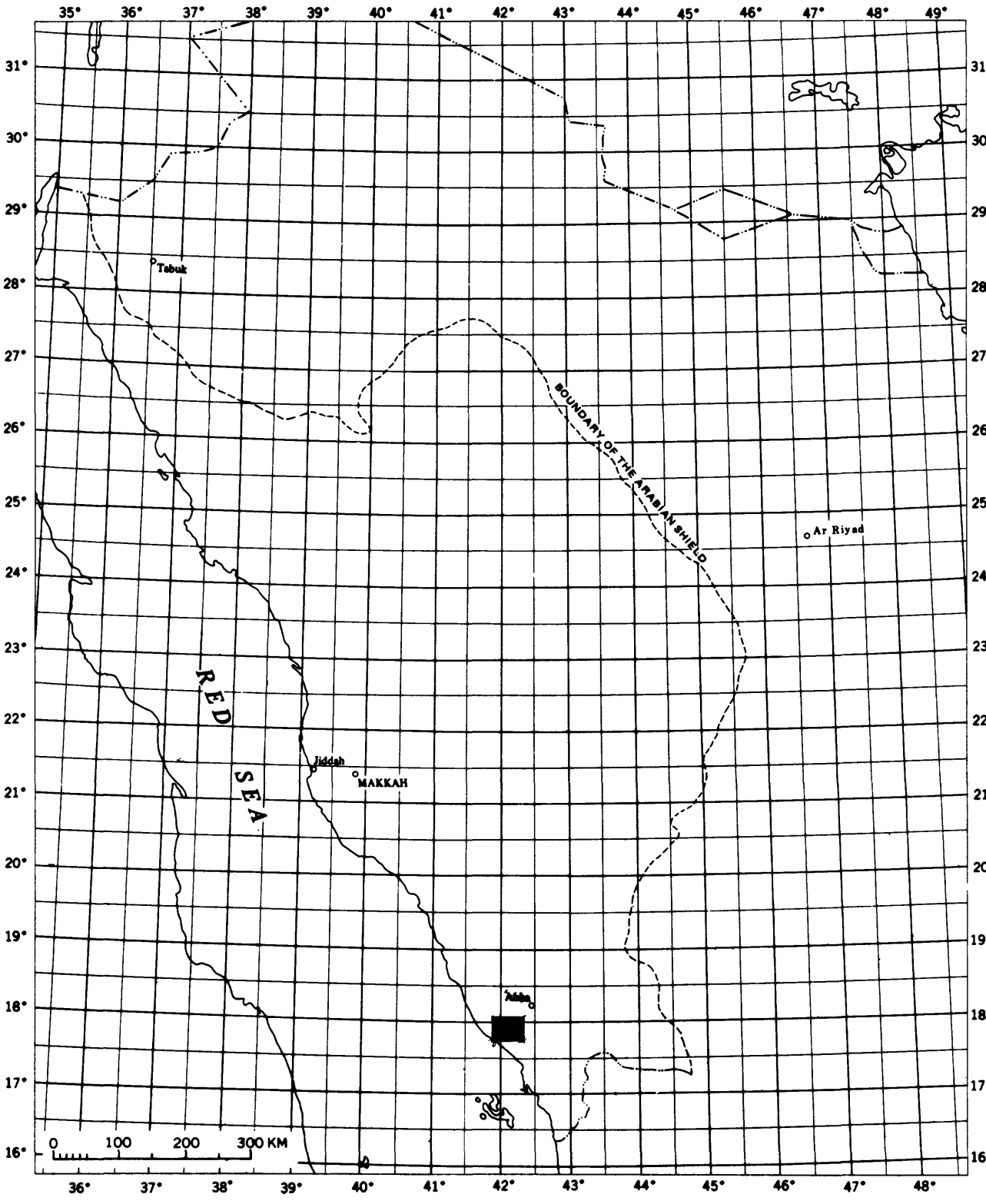

Figure 1.--Index map showing the location of the Jabal Lababa area, Kingdom of Saudi Arabia.

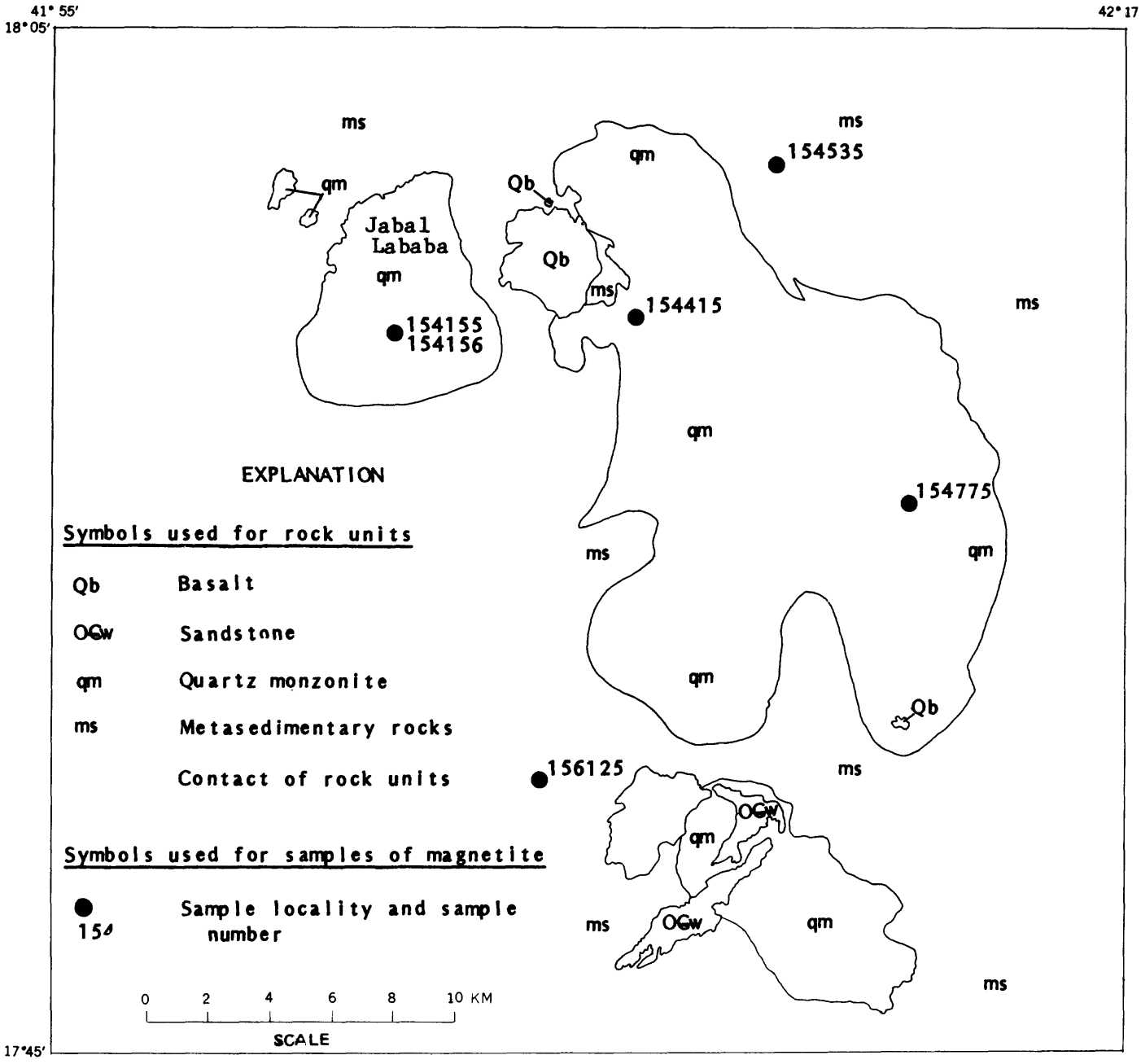

Figure 2.--Map showing outlines of plutons of quartz monzonite in the Jabal Lababa area, Kingdom of Saudi Arabia, and sources of coarse-grained magnetite from pegmatite dikes.

COMPOSITION

Mineralogy

X-ray diffraction studies of magnetite (sample 154415) from an interior pegmatite dike in the eastern pluton of quartz monzonite (fig. 2) showed that the mineral contained lamellar intergrowths of hematite and ilmenite, and inclusions of mica and chromite. Lamellae of hematite and ilmenite can be seen with the aid of a hand lens in most large crystals of magnetite from the five localities. The magnetite (sample 156125, fig. 2) from the exterior pegmatite dike in the southern part of the Jabal Lababa area contains lamellae of hematite and ilmenite and is intergrown with tourmaline and hornblende. The ilmenite is much less abundant than at the other sites.

Chemistry

The results of the spectrographic analyses show that the elements arsenic, gold, beryllium, bismuth, cadmium, lanthanum, antimony, and tungsten are below their respective limits of determination in all samples (table 1). Calcium, silver, boron, barium, and lead are rare. Some samples are notably enriched in niobium, tin, yttrium, and zinc as well as being slightly enriched in molybdenum, lead, and zirconium. For most of the elements shown in table 1, comparable chemical data are lacking in Saudi Arabia. Thus, the table introduces data that were new at the time the analyses were made. To aid in interpreting the trace-element chemistry of these six samples of magnetite, comparisons are made with the results of analyses of 680 samples of detrital magnetite from Alaska, U.S.A. (Overstreet and others, 1978).

Niobium, tin, yttrium, and zirconium

The coarse-grained magnetite from the Jabal Lababa area is enriched in niobium, tin, yttrium, and zirconium where its sources are interior dikes in the western pluton of quartz monzonite (sample 154155 and 154156, fig. 2; table 1). Magnetite from interior dikes in the eastern pluton (samples 154415 and 154775) lacks detectable niobium, yttrium, and zirconium, but contains tin. Magnetite from the exterior dikes varies in its content of these elements accordingly as the dikes are near the northern or southern parts of the eastern pluton. Magnetite from the dike off the northern shoulder of the eastern pluton (sample 154535, fig. 2; table 1) contains niobium and tin, but lacks yttrium and zirconium. Magnetite from an exterior dike off the southwestern lobe of the eastern pluton (sample 156125, fig. 2; table 1) lacks

Table 1.--Results of spectrographic analyses of crystals of magnetite from pegmatite dikes in the Jabal Lababa area, Kingdom of Saudi Arabia

[G, greater than value shown; N, not detected at value shown; L, detected but below the value shown]

Element	154155	154156	154415	154535	154775	156125
			In percent			
Fe	G(20)	G(20)	G(20)	20	G(20)	15
Mg	0.03	0.03	0.07	0.07	0.07	3
Ca	0.07	L(0.05)	L(0.05)	L(0.05)	L(0.05)	0.7
Ti	0.7	G(1)	G(1)	G(1)	G(1)	0.3
			In parts per million			
Mn	5,000	3,000	1,500	2,000	1,500	G(5,000)
Ag	0.7	1	L(0.5)	L(0.5)	L(0.5)	7
As	N(200)	N(200)	N(200)	N(200)	N(200)	N(200)
Au	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)
B	N(10)	N(10)	N(10)	N(10)	N(10)	G(2,000)
Ba	N(20)	N(20)	N(20)	N(20)	N(20)	300
Be	N(1)	N(1)	N(1)	N(1)	N(1)	N(1)
Bi	N(10)	N(10)	N(10)	N(10)	N(10)	N(10)
Cd	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)
Co	20	15	15	30	15	30
Cr	150	150	500	150	200	500
Cu	15	15	70	70	70	150
La	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)
Mo	50	50	30	30	30	10
Nb	200	70	N(20)	70	N(20)	N(20)
Ni	10	15	20	N(5)	7	70
Pb	30	N(10)	N(10)	N(10)	N(10)	100
Sb	N(100)	N(100)	N(100)	N(100)	N(100)	N(100)
Sc	30	15	15	30	15	30
Sn	150	150	30	50	30	L(10)
Sr	300	300	300	300	300	150
V	500	300	500	200	300	500
W	N(50)	N(50)	N(50)	N(50)	N(50)	N(50)
Y	700	70	N(10)	N(10)	N(10)	30
Zn	2,000	1,500	N(200)	N(200)	N(200)	N(200)
Zr	70	30	N(10)	N(10)	N(10)	50

niobium and measurable tin but contains a little yttrium and zirconium. The distributions of these four elements in the magnetite conforms remarkably well with the patterns determined through analyses of rocks, stream sediments, and panned concentrates (Overstreet and others, unpub. data, 1973). That is, the western pluton of quartz monzonite at Jabal Lababa is the only source for samples combining high values for niobium, tin, yttrium, and zirconium.

A strong tendency for beryllium, lanthanum, niobium, tin, yttrium, and zirconium to be associated was observed in magnetite from Alaska, particularly in magnetite from syenite and other potassium-rich alkalic rocks (Overstreet and others, 1978, p. 328-329). With the possible exceptions of beryllium and tin, none of these elements can substitute for Fe^{+2} or Fe^{+3} in magnetite; hence, their presence has been attriubted to other minerals held as inclusions in the magnetite. The role of adsorption of these elements in hematite lamellae in the magnetite is not known. Inclusions may be the source of the niobium, yttrium, and zirconium in the magnetite from the Jabal Lababa area, but beryllium and tin may be either in substitution or in inclusions.

Median and anomalous abundances of these elements in magnetite from Alaska (Overstreet and others, 1978, table 15, p. 151-153, and table 21, p. 264) are compared below with median values for magnetite from pegmatite dikes at Jabal Lababa. The threshold anomalous value for beryllium in the Alaskan magnetite was taken as the lower limit of determination (1 ppm), and the threshold anomalous values for lanthanum, niobium, tin, yttrium, and zirconium were derived from breaks in the observed frequency plots of the reported values for 680 samples (Overstreet and others, 1978, p. 257-259).

	Abundance (in parts per million)		
Element	Median (Jabal Lababa)	Median (Alaska)	Threshold anomalous value (Alaska)
Be	N(1)	L(1)	1
La	N(20)	30	700
Nb	30	10	50
Sn	30	30	700
Y	30	15	150
Zr	10	100	1,500

The magnetite from the Jabal Lababa area thus displays strong positive anomalies for niobium and yttrium in the western pluton (table 1), is generally at or above the median

content of tin, and is deficient in beryllium, lanthanum, and zirconium (table 1) compared with the Alaska magnetite.

The sparsity of lanthanum in the magnetite confirms observations from rocks, wadi sediment, and concentrates that lanthanum is not a pathfinder element for niobium in the Jabal Lababa area (Overstreet and others, unpub. data, 1983). Beryllium, which was a weak pathfinder element for niobium in the other geochemical sample media, and zirconium, which was a strong pathfinder element for niobium, do not play that role in magnetite.

Molybdenum

The amounts of molybdenum from the Jabal Lababa area are similar to the quantities reported for magnetite from other parts of Saudi Arabia:

Source and number of samples	Mo (ppm)
Southern Shield	
Jabal Lababa rocks (155) 1/	N(5)-10
Jabal Lababa magnetite (6)	10-50
Wadi Wassat magnetite (126) 2/	N(5)-100
Tathlith magnetite (554) 3/	N(5)-100
Eastern Shield	
Jabal Bitran magnetite (55) 4/	N(5)-20

1/ Overstreet and others, unpub. data, 1983.
2/ Overstreet and Rossman, 1970, fig. 3
3/ Overstreet, 1978, fig. 4
4/ Kahr and others, 1972, fig. 3.
[N, not detected at value shown]

In the magnetite from Alaska, molybdenum has a highly truncated distribution with most samples containing N(5) ppm molybdenum (Overstreet and others, 1978, table 15). By contrast, magnetite from the Jabal Lababa area and other parts of the southern Shield in Arabia is enriched in molybdenum. The high values for molybdenum in magnetite extend far beyond known niobium-bearing areas; hence, molybdenum cannot fulfill the role in magnetite of a pathfinder element for niobium, which it weakly displays in samples of rock (Overstreet and others, unpub. data, 1983).

None of the samples of magnetite from the Jabal Lababa area is from a locality where the rock contained detectable molybdenum; hence, the magnetite from pegmatite dikes serves

as a scavenger for molybdenum in late stages of magmatic crystallization. The capacity of magnetite to scavenge molybdenum was clearly shown in the samples from Alaska despite their low mean abundance of molybdenum (Overstreet and others, 1978, p. 470-471). The molybdenum content of the magnetite from the Jabal Lababa area is interpreted to be typical background for magnetite from felsic intrusive rocks in the southern part of the Arabian Shield.

Copper, lead, and zinc

The ranges in abundances of copper and lead in the magnetite from the Jabal Lababa area (table 1) are essentially the same as those found for the rocks (Overstreet and others, unpub. data, 1983) but a large difference in the tenors of zinc exist between the samples of magnetite from the western pluton (table 1; fig. 2) and other geochemical sample media, where zinc was below the limit of determination. Elsewhere in the Arabian Shield, magnetite contains similar amounts of copper, but magnetite from the eastern Shield has far less zinc than magnetite from the southern Shield. Magnetite from Alaska resembles that from the southern Shield in its contents of copper, lead, and zinc:

Source and number of samples	Abundances of the elements (in ppm)		
	Cu	Pb	Zn
Saudi Arabia			
Southern Shield			
Jabal Lababa rocks (155) 1/	L(5)-150	N(10)-150	N(200)
Jabal Lababa magnetite (6)	15-150	N(10)-100	N(200)-2,000
W. Wassat magnetite (126) 2/	N(10)-150	No data	50-1,500
Tathlith magnetite (554) 3/	N(10)-200	No data	20-2,000
Eastern Shield			
J. Bitran magnetite (55)	N(10)-100	No data	N(25)-125
Alaska (680) 5/			
Median	50	20	300
Threshold anomalous value	150	200	1,500

1/ Overstreet and others, unpub. data, 1983.
2/ Overstreet and Rossman, 1970, fig. 3
3/ Overstreet, 1978, fig. 4
4/ Kahr and others, 1972, fig. 3
5/ Overstreet and others, 1978, table 21, p. 241-250.
[L, detected but below the value shown; N, not detected at the value shown]

In the Wadi Wassat, Tathlith, and Jabal Bitran quadrangles the highest values for copper were found in magnetite from mafic igneous and metamorphic rocks, and the highest values for zinc were in magnetite from older rocks than the unit of peralkalic granite. The data for the magnetite from pegmatite dikes in the Jabal Lababa area show that copper contents as high as 150 ppm are not restricted to magnetite from mafic rocks. Although copper is enriched in early magmatic differentiates and may enter magnetite in early mafic and ultramafic differentiates, the Cu^{+2} ion, which is slightly smaller than the Fe^{+2} ion but has a higher electronegativity value than Fe^{+2}, does not form a strong bond with oxygen, but has an affinity for sulfur and tends to enter sulfide minerals formed by magmatic segregation (Frietsch, 1970, p. 77-79). Following crystallization of the mafic rocks, copper tends to concentrate in residual hydrothermal fluids (Rankama and Sahama, 1950, p. 695-698) and appears to enter the magnetite of late felsic igneous rocks only to a limited extent. The consistency with which copper in abundances up to 200 ppm appears in magnetite from igneous rocks has been interpreted to show that 200 ppm copper may be about the upper limit of substitution, and that in abundances greater than 200 ppm up to 5,000 to 30,000 ppm copper, the source consists of sulfide minerals included in the magnetite (Overstreet and others, 1978, p. 246-247; Pan and others, 1980, p. 20-23). In the samples of magnetite from Alaska, only 5 percent contained more than 200 ppm copper, and those with the highest tenors in copper were genetically associated with base-metal sulfide deposits (Overstreet and others, 1978, p. 247).

These observations are interpreted to show that the copper contents of magnetite from the Jabal Lababa area are within ranges of concentration to be expected from ionic substitution. The amounts of copper in the magnetite suggest that copper ores associated with late-stage magmatic processes are absent. This agrees with the interpretation made from the amounts of copper in other geochemical sample media from the area (Overstreet and others, unpub. data, 1983). The similarity in the ranges of concentration of copper in magnetite and in rocks is further evidence that magnetite is not a strong scavenger of copper during magmatic crystallization.

The erratic distribution of lead in magnetite from pegmatite dikes in the Jabal Lababa area, and the similarity in the tenors of lead in magnetite and in the rocks shows that magnetite also is not a scavenger of lead during magmatic crystallization. The ionic radius of Pb^{+2} is too large to permit it to substitute for Fe^{+2} or Fe^{+3} in magnetite. Where concentrations of lead as great as 500 ppm are reported in magnetite, as from contact pneumatolitic iron deposits (Frietsch, 1970, p. 88), the source of the lead is not in the structure of the magnetite but is inclusions of apatite or

feldspar, in both of which lead can be accommodated ionically. Sulfide minerals included in magnetite may also be a source for lead. The sparsity of lead in the magnetite from the Jabal Lababa area conforms with the low values of lead in the other sample media (Overstreet and others, unpub. data, 1983) and is interpreted to indicate that lead deposits of magmatic or hydrothermal origin are not associated with the plutons of quartz monzonite. Lead in magnetite does not fulfill the role of weak pathfinder for niobium observed in the other geochemical sample media.

Zinc tends to become enriched in late magmatic differentiates. Because the ionic radius of Zn^{+2} is similar to that of Fe^{+2}, and because Zn^{+2} has a slightly lower electronegativity than Fe^{+2}, Zn^{+2} substitutes easily for Fe^{+2}. Magnetite, therefore, is a notable scavenger of zinc, although in felsic igneous rocks biotite and hornblende have been reported to be preferentially enriched in zinc over magnetite (Frietsch, 1970, p. 55, 79). The great enrichment of zinc in magnetite from pegmatite in the western pluton (fig. 2, table 1), as well as similar enrichment of zinc in magnetite from other parts of the southern Shield, is interpreted to be a geochemical characteristic instead of an indicator of the presence of zinc mineralization related to felsic intrusive rocks despite the fact that in the Jabal Lababa area only the magnetite from the western pluton was so enriched. In other areas, however, zinc contents exceeding 300 ppm have been reported to characterize magnetite from quartz monzonite stocks genetically associated with large deposits of zinc and lead (Hamil and Nackowski, 1971).

Silver and boron

Lower values for silver combine with undetectable boron in all samples of magnetite from the Jabal Lababa area except for the highly anomalous sample 156125 (fig. 2; table 1). This magnetite, also the most lead-rich of the set, contains the anomalously large amount of 7 ppm silver, whereas the rocks themselves lack silver at a lower limit of determination of 0.5 ppm (Overstreet and others, unpub. data, 1983) Boron is anomalously abundant at a tenor of G(2,000 ppm). The low value for iron (15 percent) combined with the large amount of boron (truncated by the upper limit of determination) reflect the tourmaline identified optically in this specimen. Tourmaline is unlikely to be a source for the silver, because the element is not common in that mineral. For example, of 61 samples of tourmaline from igneous and metamorphic rocks in North and South Carolina, U.S.A., only two contained detectable silver, and in each the tenor was 0.3 ppm silver (A. L. Sutton, Jr., written commun., 1971). A more probable source for the silver appears to be inclusions of galena in

the magnetite. Ionic substitution in the structure of the magnetite is not likely, because the ionic radius of Ag^{+} is too great to permit it to substitute for either Fe^{+2} or Fe^{+3} (Pan and others, 1980, table 7).

Silver may also be present in inclusions of galena in sample 154155 where the magnetite contains both silver and lead (table 1), but inclusions of other sulfide minerals, probably pyrite, are the most likely sources where silver is not accompanied by lead (sample 154156). Small amounts of silver have been reported in pyrite of magmatic and hydrothermal origin (Hawley and Nichol, 1961, p. 476).

Manganese, cobalt, chromium, nickel, and vanadium

Ready ionic replacement of Fe^{+2} by Mn^{+2}, Co^{+2}, and V^{+3} and of Fe^{+3} by Cr^{+3} permits these elements to be camouflaged in the structure of magnetite. The Ni^{+2} ion has a limited capability of replacing Fe^{+2} in magnetite (Overstreet and others, 1978, p. 238-245). The values reported for these elements in table 1 follow closely the relative ease of substitution, with manganese, chromium, and vanadium exceeding the abundances of cobalt and nickel. Nickel, which has limited substitution for Fe^{+2} was not detected in one sample.

Magnetite from the Jabal Lababa area is somewhat richer in manganese than magnetite from Alaska (Overstreet and others, 1978, table 15, p. 151-153, and table 21, p. 264), but the Arabian magnetite is notably poorer in the amounts of cobalt, chromium, nickel, and vanadium (table 1):

	Abundance (in parts per million)		
Element	Median (Jabal Lababa)	Median (Alaska)	Threshold anomalous value (Alaska)
Mn	3,000	2,000	3,000
Co	20	50	150
Cr	200	1,000	7,000
Ni	10	70	1,500
V	300	1,500	3,000

These differences in tenors result from the fact that the magnetite from the Jabal Lababa area is from late-stage magmatic products whereas a component in the sources for the magnetite from Alaska is early magmatic mafic and ultramafic rocks. Divalent manganese substitutes for Fe^{+2} in

magnetite of magmatic origin, particularly in late hydrous silica-rich fluids where Mn^{+2} concentrates in Fe^{+2} minerals in pneumatolitic deposits, pegmatite, and hydrothermal veins. There it is chiefly concentrated in hydrous silicate minerals such as biotite and amphibole, and to a lesser extent in magnetite (Overstreet and others, 1978, p. 238-239; Pan and others, 1980, p. 21-22). These relations clearly apply to the manganese content of the magnetite from pegmatite dikes at Jabal Lababa, where a value for manganese as great as G(5,000) ppm may not constitute a significant anomaly.

Magnetite of hydrothermal origin is characteristically depleted in both cobalt and nickel with the nickel being slightly more abundant than cobalt (James and Dennen, 1962). Hydrothermal magnetite typically contains less than 50 ppm nickel (Hegemann and Albrecht, 1955, p. 92). The chromium content of hydrothermal magnetite is also very low, rarely exceeding 100 ppm (Hegemann and Albrecht, 1955, p. 92). The amount of vanadium in magnetite decreases from sources in mafic rocks to sources in felsic rocks (Sen and others, 1959, p. 71). Magnetite from mafic rocks tends to contain more than 500 ppm vanadium, whereas magnetite from felsic rocks has less than 500 ppm vanadium. These observations from the literature are generally in good agreement with the composition of magnetite from pegmatite in the Jabal Lababa area.

Calcium, barium, strontium, and magnesium

The amounts of calcium, barium, strontium, and magnesium in magnetite from the Jabal Lababa area (table 1) are similar to the quantities reported for magnetite from Alaska (Overstreet and others, 1978, p. 236-244, 490):

	Range in concentration of elements			
	In percent		In parts per million	
Source of magnetite	Ca	Mg	Ba	Sr
Jabal Lababa	L(0.05)-0.7	0.03-3	N(20)-300	150-300
Alaska, U.S.A.				
Range	0.02-G(5)	0.03-G(10)	L(50)-G(1,000)	N(100)-500
Median	0.5	0.7	100	70

The Ca^{+2} ion cannot substitute for Fe^{+2} in the magnetite lattice to any marked extent because it is considerably larger than Fe^{+2} and differs from Fe^{+2} in other physical

properties (Frietsch, 1970). Calcium in magnetite is therefore generally attributed to inclusions of calcium-bearing minerals. These observations are borne out by the results of the analyses of the magnetite from Jabal Lababa (table 1). The most calcium-rich sample, specimen 156125 with 0.7 percent calcium, contains inclusions of tourmaline and other minerals. Values for calcium in 61 samples of tourmaline from North and South Carolina, U.S.A., reach as much as 3 percent and have an average of 0.5 percent (A. L. Sutton, Jr., written commun., 1971). Evidently, inclusions of other calcium-beraing minerals than tourmaline alone are needed to account for the presence of 0.7 percent calcium in this magnetite. The tenor in magnesium of this sample also indicates that the source of the calcium is in inclusions. The low values for calcium in the samples of magnetite lacking other chemical indications of inclusions further tends to confirm that the magnetite acquires calcium from inclusions.

Barium is also present in the calcium-rich sample 156125 (table 1). Although the quantity of barium, 300 ppm, is not large, it is probably attributable to inclusions in the magnetite. The Ba^{+2} ion is too large to substitute for Fe^{+2} or Fe^{+3} in the lattice of magnetite; therefore, where barium has been detected in magnetite its presence has been attributed to inclusions of barite or of feldspar in which barium is camouflaged (Frietsch, 1970, p. 84; Overstreet and others, 1978, p. 244).

The amount of strontium in magnetite from the Jabal Lababa area is consistently 300 ppm except for sample 156125, which contains only 150 ppm strontium (table 1). These tenors for strontium are the reverse of what might be expected for sample 156125, which contains the largest amounts of calcium, barium, and magnesium of any of the analyzed magnetite from the Jabal Lababa area. Inasmuch as the calcium, barium, and magnesium are attributed to the presence of inclusions, sample 156125 might contain more strontium than the other magnetite, because strontium is strongly correlated with inclusions and particles of rock intergrown with magnetite (Overstreet and others, 1978, p. 490-491). Although the difference of two reporting intervals in the abundance of strontium in these samples is within the limits of spectrographic confidence, the probability exists that the difference in abundance of strontium is real, but the cause is unknown.

Magnesium can substitute ionically for Fe^{+2} in magnetite, because the Mg^{+2} ion has a slightly smaller radius than the Fe^{+2} ion, and Mg^{+2} forms a stronger bond with oxygen. Magnesium is said to be enriched in magnetite of hydrothermal origin (Hagemann and Albrecht, 1955; Fleischer, 1965), but high values for magnesium in magnetite are also

related to inclusions of other spinels and of magnesium-bearing minerals such as pyroxene, amphibole, and olivine (Overstreet and others, 1978, p. 237). The greatest percentage of magnesium is in the specimen of magnetite (sample 156125, table 1) containing the greatest array of inclusions. Inclusions, instead of ionic substitution, probably account for the 3 percent of magnesium in this sample, whereas the low percentages of 0.03 ot 0.07 magnesium in the other samples may indeed represent ionic substitution for Fe^{+2}. Tenors of magnesium as great as 5 to 7 percent are common on tourmaline from North and South Carolina, U.S.A. (A. L. Sutton, Jr., written commun., 1971). It is possible that most of the magnesium in sample 156125 is in the tourmaline intergrown with the magnetite.

The amounts of calcium, barium, strontium, and magnesium in the magnetite from pegmatite dikes in the Jabal Lababa area are consistent with the conditions of crystallization and the presence or absence of inclusions.

Iron, titanium, and scandium

The tenors of iron, titanium, and scandium in magnetite from the Jabal Lababa area (table 1) are well within the ranges in concentration of these elements in 680 samples of magnetite from Alaska, U.S.A. (Overstreet and others, 1978, table 13, p. 235-251), except that the frequency of values for iron below G(20) percent is higher in the material from Arabia than from Alaska:

	Range in concentration of elements		
	In percent		In parts per million
Source of magnetite	Fe	Ti	Sc
Jabal Lababa	15-G(20)	0.3-G(1)	15-30
Alaska, U.S.A.			
Median	G(20)	1	14
Range	10-G(20)	0.5-G(1)	N(5)-150

Because pure magnetite contains 72.4 percent iron, the expected results of semiquantitative spectrographic analyses of crystals of magnetite would be values for iron that do not fall below the reporting interval of G(20) percent. Results of spectrographic analyses of the Alaskan samples fit this perceived pattern, but the results for the crystals of magnetite from the Jabal Lababa area do not, probably because of difficulty in reading the spectra for iron:

Fe (in percent)	Percentage of results of analyses falling in given interval	
	Alaska, U.S.A.	Jabal Lababa area
10	0.3	0
15	.9	16.8
20	4.4	16.7
G(20)	94.4	66.6
	100.0	100.0

Titanium can substitute readily for iron in magnetite, because the Ti^{+4} ion is intermediate in radius between Fe^{+2} and Fe^{+3} ions, and the Ti^{+4} ion forms a stronger bond with oxygen than either Fe^{+2} or Fe^{+3} (Overstreet and others, 1978, p. 235). The extent for which Ti^{+4} substitutes for Fe^{+2} or Fe^{+3} in magnetite is governed by the titanium content of the material in which the magnetite crystallizes. Silica-rich, late-magmatic, intrusive rocks yield magnetite with less titanium than magnetite from silica-deficient early mafic and ultramafic rocks. These relations are obscured, however, where ilmenite and other titanium-bearing minerals are intergrown with the magnetite, and where the upper values for the titanium content are truncated by the upper limit of analytical detection. Both effects apply to the magnetite from the Jabal Lababa area, where ilmenite is present in the magnetite crystals, where lamellae of ilmenite are present in the magnetite, and where the upper limit of determination is G(1) percent (table 1).

Magnetite in the Jabal Lababa area has scavenged titanium and is richer in the element than the intrusive rocks, which have a mean tenor of 0.15 percent titanium (Overstreet and others, unpub. data, 1983). Comparison of the titanium contents of the magnetite from the Jabal Lababa area and that from Alaska, U.S.A., shows clear similarities, but the censored values above 1 percent constitute a potentially wide field of difference. Owing to these truncated data, the reported values for titantium cannot be evaluated in the context of a pathfinder element for niobium.

Scandium is slightly enriched in magnetite from the Jabal Lababa area over its tenor in local plutonic rocks where the average value is L(5) (Overstreet and others, unpub. data, 1983). The scandium content of ferromagnesian minerals in silicic rocks is between 5 and 30 ppm (Rankama and Sahama, 1950, p. 512). The values for scandium in table 1 are also within the range in concentration found for scandium in magnetite from Alaska. In the material from Jabal Lababa no evidence was noted for a pathfinder role of scandium for tin or tungsten.

IMPLICATIONS FOR USE OF MAGNETITE AS A SAMPLE MEDIUM IN GEOCHEMICAL EXPLORATION

The results of the analyses of only six samples of magnetite from the Jabal Lababa area are insufficient to serve as a basis for the evaluation of magnetite as a geochemical sample medium. The results of these analyses do show that niobium, tin, and yttrium are enriched in magnetite from the only part of the Jabal Lababa area where positive anomalies for these elements are present in other media. These results also show a remarkable continuity in values for copper, molybdenum, and zinc between this new work and the results of early investigations of the trace-element composition of detrital magnetite in Arabia (Overstreet and Rossman, 1970; Kahr and others, 1972; Overstreet, 1978).

Work done elsewhere after those early investigations in Arabia clearly indicates that the trace-element contents of magnetite can be used to discriminate intrusive rocks of different ages; to identify igneous rocks that are potential sources for deposits of silver, beryllium, cobalt, chromium, copper, molybdenum, niobium, nickel, lead, tin, tungsten, zinc, and the P+-group metals; and to identify the presence of these metals in other types of rock (Theobald and others, 1967; de Grys, 1970; Hamil and Nackowski, 1971; Overstreet and others, 1978; Pan and others, 1980).

The ease with which detrital magnetite can be recovered from wadi sediments by the use of a hand magnet on the floor of the wadi, combined with the scavenging capacity of magnetite for many trace elements sought in geochemical exploration and the high density of the mineral result in a medium possessing advantages for use where aeolian contamination is a factor and time required to prepare heavy-mineral concentrates is not available. A great disadvantage is intense iron radiation in emission spectrographic analysis which makes the reading of the spectrogram difficult for other elements. Atomic absorption methods are available for use with magnetite that permit the ready determination of silver, bismuth, cadmium, cobalt, copper, nickel, lead, and zinc in a single solution (Nakagawa, 1975). Platinum-group metals, exclusive of iridium, can be determined in magnetite by a combination of fire-assay and emission-spectrographic methods (Cooley and others, 1976), which opens the possibility for detecting micron-sized particles of Pt-group elements in sources not previously identified as Pt-bearing, but the method is tedious. Direct methods for determining the Pt-group metals by induction-coupled plasma spectrometry (ICP) afford a feasible analytical procedure for the production-line analyses needed for geochemical exploration. The full potential of magnetite as a geochemical sample medium is inadequately known in Saudi Arabia.

DATA STORAGE

Data file USGS-DF-04-20 (Overstreet and others, 1984) has been established for the storage of data used in this report.

No entries or updates have been made to the Mineral Occurrence Documentation System (MODS) data bank.

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