DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Minor elements in Magnetic concentrates from the Syenite-Shonkinite Province, Southern Asir, Kingdom of Saudi Arabia

by

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Open-File Report 87-295

Report prepared by the U.S. Geological Survey in cooperation with the Deputy Ministry for Mineral Resources, Saudi Arabia

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

1/ USGS, Retired
2/ USGS, Denver, CO

1987

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MINOR ELEMENTS IN MAGNETIC CONCENTRATES FROM THE SYENITE-SHONKINITE PROVINCE, SOUTHERN ASIR, KINGDOM OF SAUDI ARABIA

by

William C. Overstreet, Gordon W. Day, Theodore Botinelly, and George Van Trump, Jr.

ABSTRACT

Magnetic concentrates from 106 localities in three plutons of syenite and one pluton of shonkinite in the southern Asir were analyzed spectrographically for 31 elements to determine if anomaly-enhancement techniques would identify mineralization not disclosed by conventional geochemical sample media. Positive anomalies are lacking for all elements except vanadium. Vanadium contents as high as 0.7 percent were identified in magnetic concentrates from the syenite pluton to the southeast of Suq al Ithnayn, but magnetite is sparse. This observation indicates a need to reexamine magnetite-rich drill core for possible ore-grade tenors in vanadium from the zoned pluton at Lakathah. Experimental analyses for platinum-group metals in magnetic concentrates from layered mafic plutons at Jabal Sha'i', Jabal al Ashshar, and Hishshat al Hawi should be performed to determine whether micron-size particles of the platinum-group metals are present in mafic rocks of the Arabian Shield.

ACKNOWLEDGMENTS

The work on which this report is based was performed in accordance with a work agreement between the U.S. Geological Survey (USGS) and the Saudi Arabian Ministry of Petroleum and Mineral Resources. Appreciation is expressed to these organizations, and to J. J. Matzko, USGS, and to M. A. Hussain and G. H. Abubakar, USGS, Jeddah, for help received in the preparation of the magnetic concentrates used for spectrographic analyses.

INTRODUCTION

AREAS COVERED AND PREVIOUS WORK

Three areas in the syenite-shonkinite province to the southeast of Abha in the southern Asir were the sources of magnetic concentrates used in the present investigation (fig. 1). All these areas are in the Red Sea escarpment where locality 1 includes about 300 km^2 around the syenite plutons at Jabal Fayfa and Jabal Bani Malik. Locality 2 occupies an area of 100 km^2 around the pluton of syenite between Wadi Rudum and Wadi Bishah, about 25 km to the southeast of Suq al Ithnayn. An area of 70 km^2 at Jabal Atwid includes a shonkinite pluton (locality 3, fig. 1). Altitudes range from 270 m at the base of Jabal Fayfa to 2,300 m at the top of Jabal Atwid. Even the steepest parts of the three main plutons are locally cultivated by means of intricate systems of terraces watered in part from steep wadis.

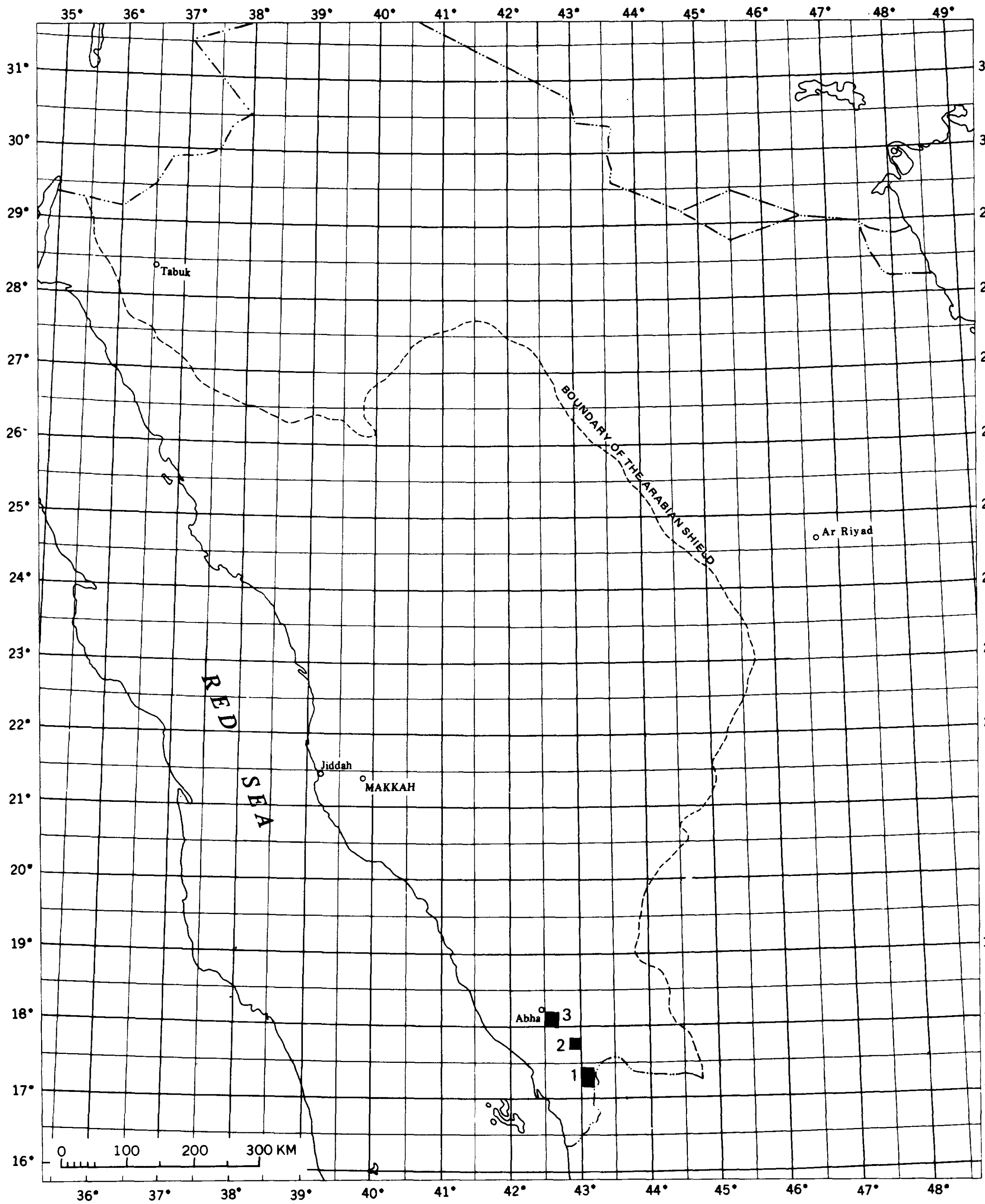


Figure 1.--Index map showing areas covered by magnetic concentrates from areas underlain by syenite plutons at Jabal Fayfa and Jabal Bani Malik (1), syenite pluton between Wadi Rudum and Wadi Bishah (2), and shonkinite pluton at Jabal Atwid (3).

Previous geologic work in the three areas included the 1:500,000-scale geologic map of Brown and Jackson (1959) and the 1:100,000-scale geologic quadrangle maps that include the shonkinite pluton (Coleman, 1973) and the syenite plutons (Fairer, 1981; 1982). A geochemical reconaissance of mineral deposits in the three areas (fig. 1) was conducted by Overstreet and others (1983).

Syenite plutons

Jabal Fayfa and Jabal Bani Malik.--Late Precambrian post-tectonic plutons of syenite intrude metamorphosed Precambrian sedimentary and mafic volcanic rocks of the Sabya and Baish Formations at Jabal Fayfa and Jabal Bani Malik (fig. 2). Fairer (1981, table 3) reports that the ratios of quartz to plagioclase and to orthoclase in the syenite are variable, but that the ratios of hornblende to biotite and to allanite, and of apatite to zircon, are constant. Relative radioactivity of the two plutons is constant and is generally two to four times that of the metamorphic rocks. The plutons are complexly reintruded bodies characterized by an extraordinary number of faults (Fairer, 1981) that are not shown on figure 2. The absence of complex Nb-, Ta-, and Zr-bearing minerals and the presence of common hornblende, biotite, apatite, titanite, zircon, hastingsite, and augite in concentrates prepared from alluvium derived from the plutons is interpreted to indicate that these rocks are common miaskitic syenite.

Pluton southeast of Suq al Ithnayn.--The syenite pluton between Wadi Rudum and Wadi Bishah to the southeast of Suq al Ithnayn (fig. 3) is also of late Precambrian age. It intrudes Precambrian rocks of the Sabya formation and the Khamis Mushayt complex of Fairer (1982). The syenite is composed principally of orthoclase, clinopyroxene, hornblende, biotite, and quartz with accessory apatite, titanite, and zircon. The rock is miaskitic syenite that is only slightly more radioactive than its wall rocks.

Shonkinite pluton at Jabal Atwid.--The Precambrian shonkinite pluton at Jabal Atwid (fig. 4) intrudes a sequence of metamorphosed Precambrian sedimentary and volcanic rocks (Coleman, 1973). The main components of the shonkinite are orthoclase, olivine, diopside, augite, and acmite. Accessory minerals include nepheline, apatite, and titanite with minor amounts of thorite, baddeleyite, and monazite (Overstreet and others, 1984a, table 2). The radioactivity of the shonkinite (fig. 4) is only slightly greater than its wall rocks, which suggests that thorite and monazite are indeed rare minerals.

Mineral potential

On the basis of reconnaissance geologic mapping (Coleman, 1973; Fairer, 1981, 1982) and reconnaissance geochemical exploration (Overstreet and others, 1984a), the potential for economic mineral deposits in the areas covered by figures 2-4 was thought to be low. Geochemical data from the present investigation confirm these appraisals.

PURPOSE OF THE PRESENT INVESTIGATION

Geochemical investigations conducted by the USGS in Saudi Arabia between 1963 and 1966 (Theobold, 1970a; 1970b) showed the distribution of Cu, Mo, and Zn in detrital magnetite from the Precambrian shield. The abundances of other minor elements (some of which were important to geochemical exploration) in the detrital magnetite were not determined at the time because of technical difficulties in the analysis for small amounts of these elements in the presence of

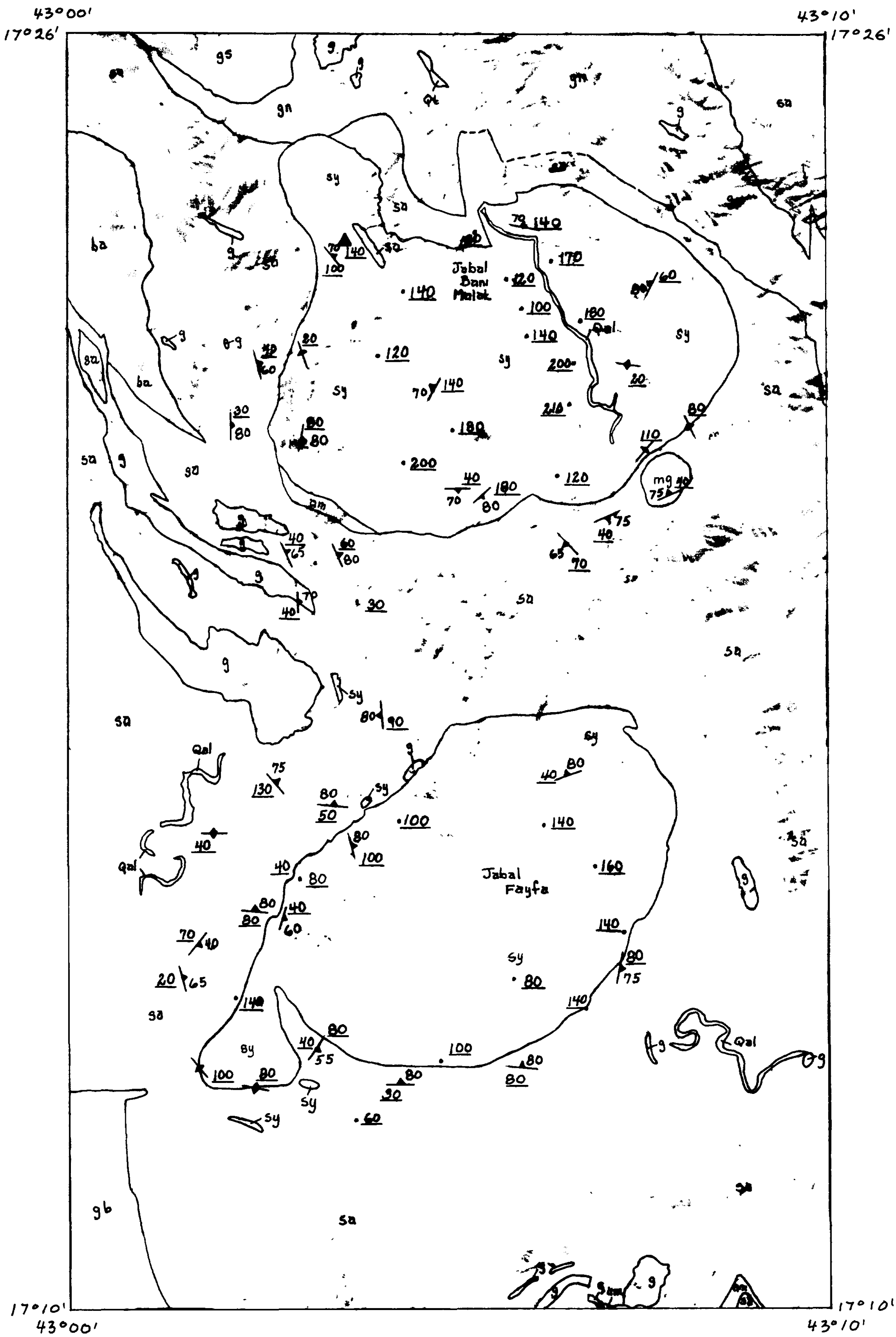
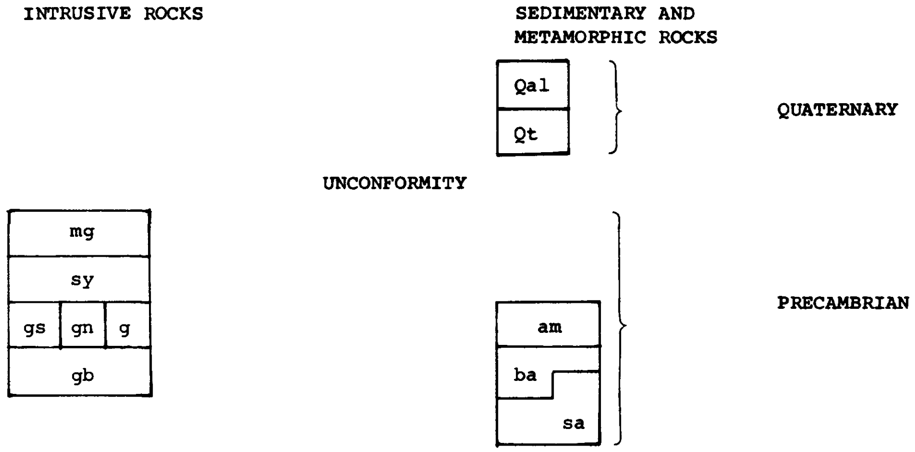


Figure 2.--Reconnaissance geologic map showing the plutons of syenite at Jabal Fayfa and Jabal Bani Malik, and relative radioactivity of rocks. Adapted from Fairer (1981).

EXPLANATION

CORRELATION OF MAP UNITS
(Adapted from Fairer, 1981)



DESCRIPTION OF MAP UNITS

Qal — ALLUVIUM--Unconsolidated, poorly sorted silt, sand, and gravel in beds of wadis

Qt — TERRACE DEPOSIT--Unconsolidated sand and gravel covered in part by loess

mg — BIOTITE-QUARTZ MONZONITE--Light-gray, coarse-grained, posttectonic plugs

sy — SYENITE--Dark- to medium-gray, coarse-grained, posttectonic plutons

gs — SYNTECTONIC GRANITIC ROCKS--Light- to dark-gray, massive to layered

gn — GNEISS--Biotite, quartz, amphibole, plagioclase, and orthoclase gneiss

g — GRANITE--Granitic rocks ranging in composition from quartz diorite to quartz monzonite

gb — METAGABBRO--Hypabyssal sills and pods in Sabya Formation, greenschist facies

am — AMPHIBOLITE--Amphibole-orthoclase-quartz amphibolite in gneiss and schist

ba — BAISH FORMATION--Greenstone and green schist, sparse chert, marble, and metagraywacke

sa — SABYA FORMATION UNDIVIDED--Quartz-biotite schist, quartz-sericite schist, phyllite, black slate, marble; quartzite, and greenschist

SYMBOLS

CONTACT--Dashed where approximately located; fault contacts common

STRIKE AND DIP OF FOLIATION--Vertical or inclined in syenite

•180 RATE OF COUNT ON SCINTILLOMETER--locality shown by dot or by symbol for strike and dip

▲ MAGNETIC CONCENTRATE--Source of sample used for replicate mineralogical and spectrographic analyses

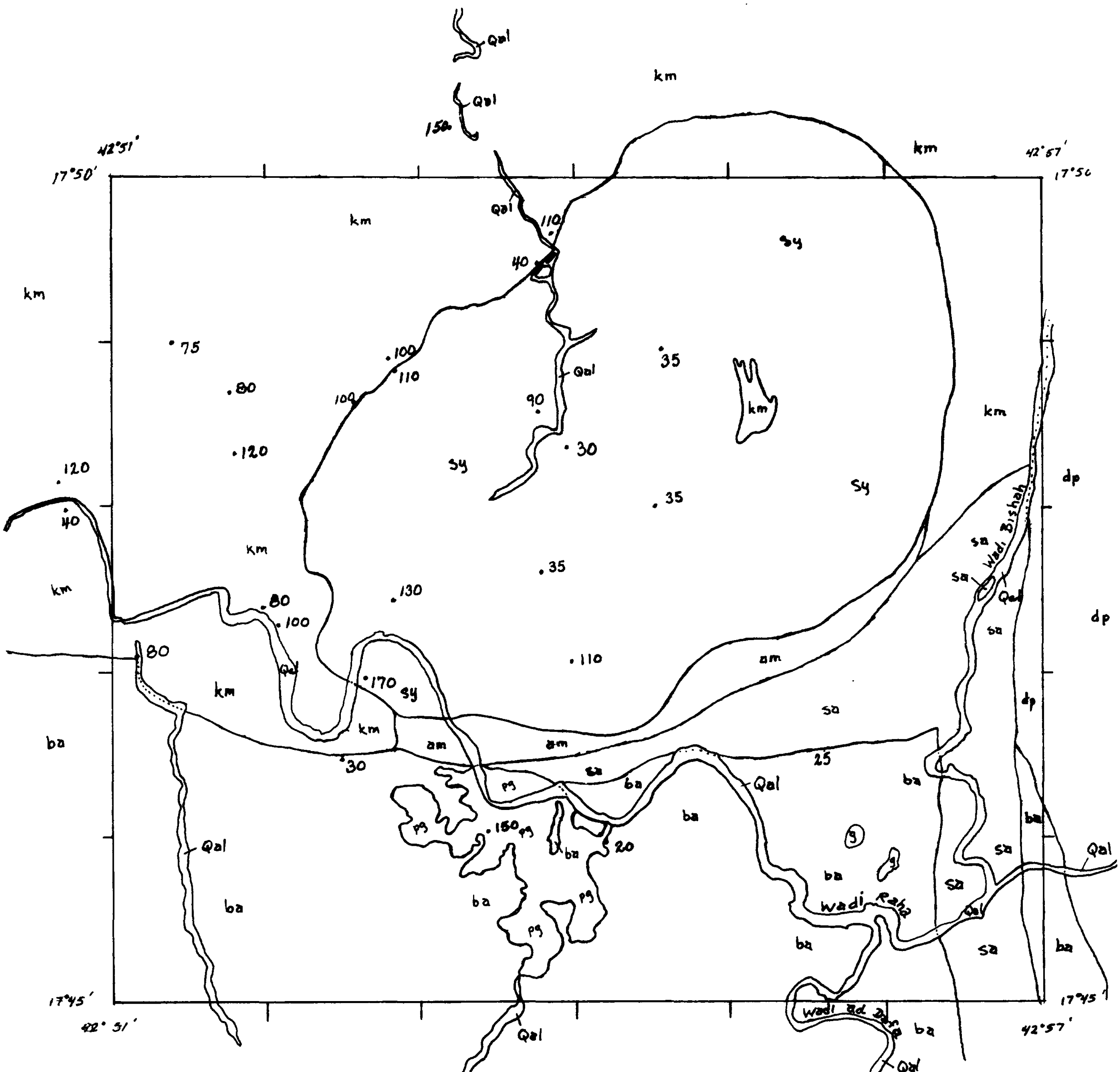
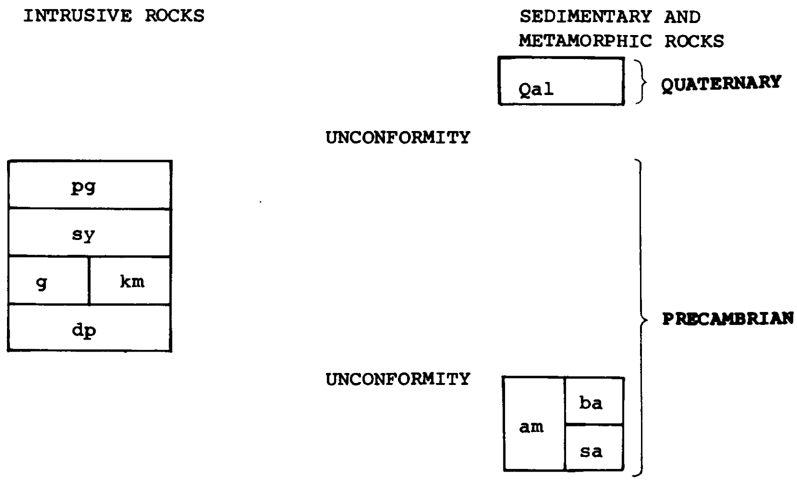


Figure 3.--Reconnaissance geologic map showing the syenite pluton between Wadi Rudum and Wadi Bishah southeast of Suq al Ithnayn, and relative radioactivity of rocks. Adapted from Fairer (1982).

EXPLANATION

CORRELATION OF MAP UNITS
(Adapted from Fairer, 1982)



DESCRIPTION OF MAP UNITS

Qal ALLUVIUM--Unconsolidated, poorly sorted silt, sand, and gravel in beds of wadis

pg PEGMATITE--Coarse-grained, pale-pink to white pegmatite, many septa of wall rocks

sy SYENITE--Medium- to coarse-grained, white, pink, and dark gray; generally sharp contacts

g GRANITE--Medium-grained, light gray, syntectonic to posttectonic

km KHAMIS MUSHAYT COMPLEX--Gneissic to structureless, light-gray to white granitic rock

dp DIORITE--Fine-grained, dark-gray, brown-weathering, pyritiferous diorite

am AMPHIBOLITE--Greenish-black to black amphibolite adjacent to intrusive syenite

ba BAISH GROUP--Baealtic greenstone and greenschist, sparse marble and chert

sa SABYA FORMATION UNDIVIDED--Quartz-sericite schist, biotite-quartz-sericite schist, quartzite

SYMBOLS

——— - - - CONTACT OF GEOLOGIC UNITS--dotted where covered

•110 RATE OF COUNT ON SCINTILLOMETER--locality shown by dot

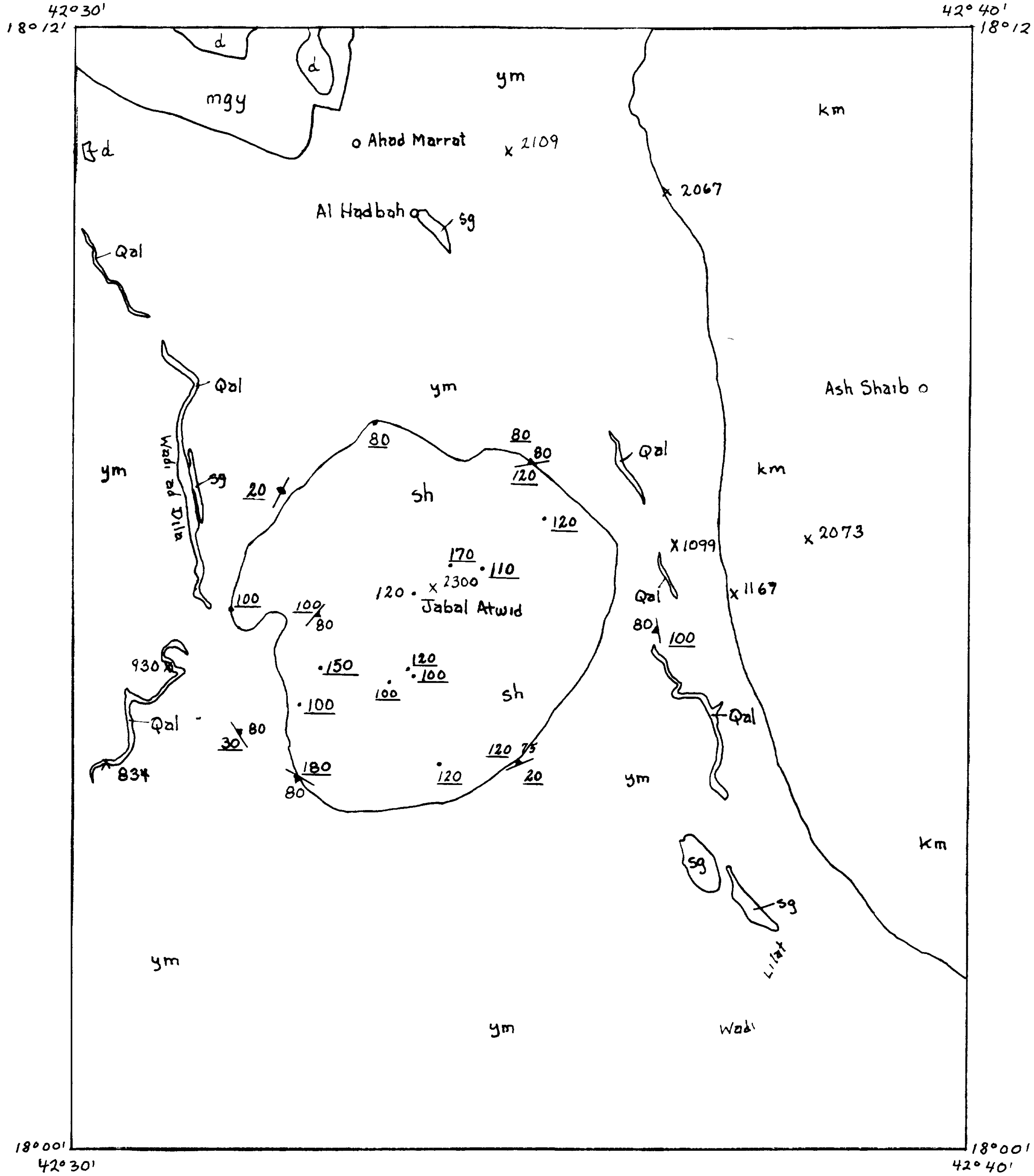


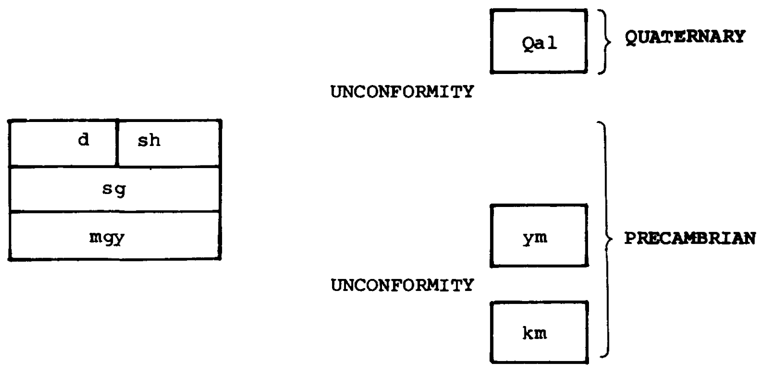
Figure 4.--Reconnaissance geologic map showing the pluton of shonkinite at Jabal Atwid, and relative radioactivity of rocks. Adapted from Coleman (1973).

EXPLANATION

CORRELATION OF MAP UNITS
(Adapted from Coleman, 1973)

INTRUSIVE ROCKS

SEDIMENTARY AND METAMORPHIC ROCKS



DESCRIPTION OF MAP UNITS

Qal	ALLUVIUM--Unconsolidated, poorly sorted silt, sand, and gravel in beds of wadis
d	DIORITE--Fine- to medium-grained, dark greenish gray diorite and quartz diorite
sh	SHONKINITE--Medium- to coarse-grained, dark-gray
sg	QUARTZ MONZONITE--Fine- to medium-grained, light-gray quartz monzonite and granite
ym	YOUNG METAMORPHIC ROCKS--Variably metamorphosed pelitic schist, marble, and matabasalt
mgy	GABBRO AND YOUNG METAMORPHIC ROCKS--Intrusive gabbro; metamorphic rocks dominant
km	KHAMIS MUSHAYT GNEISS--Granitic orthogneiss, paragneiss, migmatite, amphibolite, and pegmatite

SYMBOLS

CONTACT of geologic units

STRIKE AND DIP OF FOLIATION--vertical or inclined

• 110 RADIOACTIVITY--in counts per second; locality shown by dot or by symbol for strike and dip

X 1169 SPOT ELEVATION--in meters

overwhelming quantities of the major elements in the iron-rich sample medium. These technical difficulties have been largely overcome (Nakagawa, 1975; Overstreet and others, 1978; Pan and others, 1980).

The purpose of this report is to examine the use of detrital magnetite as a geochemical sample medium in the Arabian Shield. The magnetic fraction of panned concentrates were used to accomplish this (Overstreet and others, 1984a).

The Deputy Ministry for Mineral Resources requested a review of the technical background on the use of detrital magnetite as a geochemical sample medium. Such a review was perceived to be necessary in the context of the growing interest in applications of geochemistry to mineral exploration in Saudi Arabia. In another report (Overstreet and Day, 1985), the role of magnetic concentrates as a geochemical sample medium is considered in its historic relation to the use of heavy-mineral concentrates in the search for ore deposits.

PROCEDURES

COLLECTION AND PREPARATION OF DETRITAL MAGNETITE

Heavy-mineral concentrates were panned from 10-kg samples of wadi sediment that were sieved to -10-mesh prior to panning. A permanent magnet was passed over the dry concentrate to remove magnetic minerals. The magnetic fraction was further cleaned by a hand-held magnet to separate the strongly magnetic minerals from entrapped weakly magnetic grains. The ferromagnetic material was retained for mineralogical and spectrographic analyses, and the paramagnetic material was retained in case the results of the determinations of niobium in the magnetic and nonmagnetic concentrates indicate a partition of niobium into the paramagnetic fraction. The results of the analyses of both types of concentrates disclose so few niobium-bearing samples and such low tenors of niobium (Overstreet and others, 1984a) that the element, either for itself or as a pathfinder for tantalum, has no economic potential; therefore, the paramagnetic fraction of the concentrate does not require analysis.

Sixty one magnetic concentrates were obtained from syenite plutons at Jabal Fayfa and Jabal Bani Malik, 26 came from syenite plutons to the southeast of Suq al Ithnayn, and 19 came from shonkinite plutons at Jabal Atwid. In addition to the 106 samples for analysis, one magnetic concentrate was split into 15 replicate samples for analysis in a test of laboratory variance.

MINERALOGICAL ANALYSES

All the magnetic concentrates were examined under a binocular microscope for intergrown and attached grains before the samples were ground for analysis. After grinding, the colors of the resulting powders, which are essentially composite streaks of the magnetic concentrates, were classed according to the rock-color chart of the United States National Research Council (Goddard and others, 1948) to determine the influence of the intergrown and attached grains on the colors of the powders.

The 15 splits of the magnetic concentrate used for replicate spectrographic analyses were examined individually by X-ray diffraction to determine the mineralogical variance in the splits.

SEMIQUANTITATIVE SPECTROGRAPHIC ANALYSES

Method

The method of semiquantitative spectrographic analysis used by Gordon W. Day, USGS, Denver, Colorado, on the magnetic concentrates to accommodate iron-rich geologic materials is modified from the procedure used by Grimes and Marranzino (1968) by using a 5 mg sample instead of the usual 10 mg sample. The procedure is been rarely used (at the DMMR Chemistry Laboratory in Jeddah) on magnetite with different limits of determination and without analyzing for thorium (duBray, 1981, table 1; Overstreet and others, 1984a, table 1).

The analytical results were given in the series 1, 0.7, 0.5, 0.3, 0.2, 0.15, 0.1, and so on. Because of the small amount of the magnetite used for analysis, the lower limits of determination are higher than those obtained with the conventional 10-mg sample. When the weight of the sample was less than 5 mg, the lower limits of determination were factored upward (table 1). Values truncated by the limits of determination were identified by letters:

N = Not detected at the lower limit of determination or at value shown

L = Detected, but below the lower limit of determination, or below value shown

G = Greater than upper limit of determination, or greater than value shown

For some statistical operations, values such as those shown in table 1 were substituted for the technically censored data.

Precision

Fifteen replicate splits of one magnetic concentrate (fig. 2) were added to the 106 magnetic concentrates and the full set of 121 samples was arranged in random order using tables of random permutations (Moses and Oakford, 1963). The results of the analyses of the 15 replicate splits show that the amount of iron was reported as greater than 30 percent in all splits, that barium was detected below the limit of determination, and that Ag, As, Au, Be, Bi, Cd, La, Mo, Nb, Sb, Sn, Sr, W, and Th were not detected at their lower limits of determination in all splits (table 2). The range in values for the detected elements is small, one laboratory-reporting interval above the minimum value for Ti, Ba, Cr, Ni, Sc, and V, two laboratory-reporting intervals above the minimum value for Co and Y, three laboratory-reporting intervals above the minimum value for Mg, Ca, Cu, Zn, and Zr, and four laboratory-reporting intervals above the minimum value for lead. Inasmuch as the acceptable precision of the method is three laboratory reporting intervals, the results of the replicate analyses show that the reported values, except those for lead, display acceptable precision. Ranges in reporting intervals shown as zero in table 2 do not imply that there is no difference in the abundance of the element from split to split; they only show that the difference could not be measured.

Among the detected elements, Ti, Mn, Co, Cr, V, and Zn readily substitute for Fe^{+2} or Fe^{+3}, and Mg, Cu, Ni, and Sc show limited substitution. The elements that substitute readily tend to have less variation in laboratory reporting intervals

Table 1.—Upper and lower limits of determination for 31 elements by semiquantitative spectrographic methods.

[Analyses performed by USGS, Denver, Colorado, and values substituted for technically censored data in some statistical operations. Values are for 5 mg of magnetite taken for analysis; where lesser quantities of magnetite were analyzed, high values for the lower limits of determination were reported, but the substitute values were retained.]

Element	Limits of determination		Substitute Values		
	Lower	Upper	N	L	G
		In percent			
Fe	0.1	30	--[1]	--	50
Mg	.05	10	--	--	--
Ca	.1	20	--	--	--
Ti	.005	2	--	--	3
		In parts per million			
Mn	20	10,000	--	--	--
Ag	1	10,000	--	--	--
As	500	20,000	--	--	--
Au	20	1,000	--	--	--
B	20;L(50);L(70)	5,000	--	10	--
Ba	50	10,000	--	--	--
Be	2;N(5);N(7)	2,000	0.7	--	--
Bi	20	2,000	--	--	--
Cd	50	1,000	--	--	--
Co	10	10,000	--	--	--
Cr	20	10,000	--	--	--
Cu	10	50,000	--	--	--
La	50;N(100);N(150)	2,000	50	--	--
Mo	10;N(20);N(30)	5,000	10	--	--
Nb	50;N(100);N(150)	5,000	15	20	--
Ni	10	10,000	--	--	--
Pb	20;N(50);N(70)	50,000	7	10	--
Sb	200;N(700)	20,000	200	--	--
Sc	10;N(30)	200	3	5	--
Sn	20;N(50);N(70)	2,000	20	--	--
Sr	200;N(300); N(500);N(700)	10,000	70	--	--
V	20	20,000	--	--	--
W	100;N(200);N(300)	2,000	100	--	--
Y	20;N(70)	5,000	7	10	--
Zn	500;N(1,000); N(1,500)	20,000	150	200	--
Zr	20:N(70)	2,000	10	--	--
Th	200;N(700)	20,000	100	--	--

[1] Substitute value not needed.

Table 2.—Results of analyses of 15 replicate splits of one sample of detrital magnetite from the area of the syenite pluton at Jabal Bani Malik, showing number of laboratory reporting intervals from the minimum to the maximum value for each element

[Analyses performed by USGS, Denver, Colorado.]

Element	Minimum	Maximum	Mean	Laboratory reporting intervals
In percent				
Fe	G(30)	G(30)	G(30)	0
Mg	0.2	0.7	0.3	3
Ca	.3	1.0	.5	3
Ti	2	G(2)	G(2)	1
In parts per million				
Mn	1,500	1,500	1,500	0
Ag	N(1)	N(1)	N(1)	0
As	N(500)	N(500)	N(500)	0
Au	N(20)	N(20)	N(20)	0
B	L(20)	L(20)	L(20)	0
Ba	100	150	150	1
Be	N(2)	N(2)	N(2)	0
Bi	N(20)	N(20)	N(20)	0
Cd	N(50)	N(50)	N(50)	0
Co	30	70	50	2
Cr	70	100	70	1
Cu	30	100	50	3
La	N(50)	N(50)	N(50)	0
Mo	N(10)	N(10)	N(10)	0
Nb	N(50)	N(50)	N(50)	0
Ni	50	70	50	1
Pb	N(20)	50	L(20)	4
Sb	N(200)	N(200)	N(200)	0
Sc	15	20	15	1
Sn	N(20)	N(20)	N(20)	0
Sr	N(200)	N(200)	N(200)	0
V	1,000	1,500	1,500	1
W	N(100)	N(100)	N(100)	0
Y	L(20)	30	L(20)	2
Zn	N(500)	700	N(500)	3
Zr	300	1,000	500	3
Th	N(200)	N(200)	N(200)	0

than the elements with limited capacity for substitution. The detected elements that do not substitute isomorphically in magnetite (Ca, Ba, Pb, Y, and Zr) are present in inclusions and intergrowths. Their variations in laboratory-reporting intervals between minimum and maximum tend to be greater than the variations of the elements that can substitute for Fe^{+2} and Fe^{+3} (table 2). Mechanical division of the inclusions and intergrowths in the preparation of the splits of the detrital magnetite is thus less perfect than the division of the magnetite itself, and is influenced by the behavior of sparse particles in large amounts of other particles (Clifton and others, 1969; Harris, 1982).

The low variation in the determined elements may not be real but may reflect the general difficulty of reading Fe-rich spectrograms.

MINERALOGY OF THE MAGNETIC CONCENTRATES

WEIGHTS OF DETRITAL MAGNETITE

The weights of the magnetic fractions obtained from the raw concentrates panned from standard 10-kg samples of alluvium derived from the plutons of syenite and shonkinite, and from their wall rocks, are low when compared with the weights of nonmagnetic fractions of the concentrates (Overstreet and others, 1984a; table 3).

Descriptions of the syenite (Fairer, 1981, table 3; 1982, p. 9) and shonkinte (Coleman, 1973, p. 4) do not list magnetite among the accessory minerals. In this study, the average concentration ratios for magnetite from areas underlain by syenite are 1086 and 1064 at Jabal Fayfa and Jabal Bani Malik, but decrease to 125 at the pluton southeast of Suq al Ithnayn. The concentration ratio for the magnetite from the shonkinite is 129.

COMPOSITION DETERMINED BY X-RAY DIFFRACTION

The 15 splits of the sample of detrital magnetite from the Jabal Bani Malik area used for replicate spectrographic analyses (fig. 2) were analyzed by X-ray diffraction and found to consist of magnetite and hematite, with a trace of ilmenite too sparse to be identified (table 4). Much of the hematite and ilmenite is intergrown with the magnetite, as was shown for coarse-grained crystals of magnetite from the Jabal Lababa area (Overstreet and others, 1984c).

The peak heights of the strongest of these component minerals were measured for each mineral. However, peak heights depend on the amount of mineral present, on the amount of sample in the holder, and on the orientation (preferred orientation can enhance peak heights). The raw data can be corrected to reduce the effect of variation in sample preparation by assuming the peak heights should have a constant total of 100 (table 4). Frequency plots of the corrected peak heights show that the splits are very similiar in mineral composition, with one or two variants that may represent aberrant X-ray response (fig. 5).

Comparison of the frequency plots of the major minerals (fig. 5) with the distribution of the detected elements having variance in tenor in the 15 splits (table 5) shows little tendency for the abundances of the elements to be greater in the splits with high-magnetic response accordingly as the elements can substitute readily (fig. 5A), to a limited extent (fig. 5B), or not at all (fig. 5C) in the

Table 3.—Sources and average weights of magnetic and nonmagnetic concentrations

Source of concentrates	Average weight (g) by type of concentrates	
	Magnetic	Nonmagnetic
Jabal Fayfa		
syenite	9.2	41.0
wall rocks	3.8	101.1
Jabal Bani Malik		
syenite	9.4	41.1
wall rocks	1.1	20.8
Pluton southeast of Suq al Ithnayn		
syenite	80.1	245.2
wall rocks	5.7	34.3
Jabal Atwid		
shonkinite	77.6	188.8
wall rocks	63.0	181.8

Table 4.—Mineralogical compositions of 15 splits of a magnetic concentrate from the Jabal Bani Malik area

/Analyses performed by USGS, Denver, Colorado./

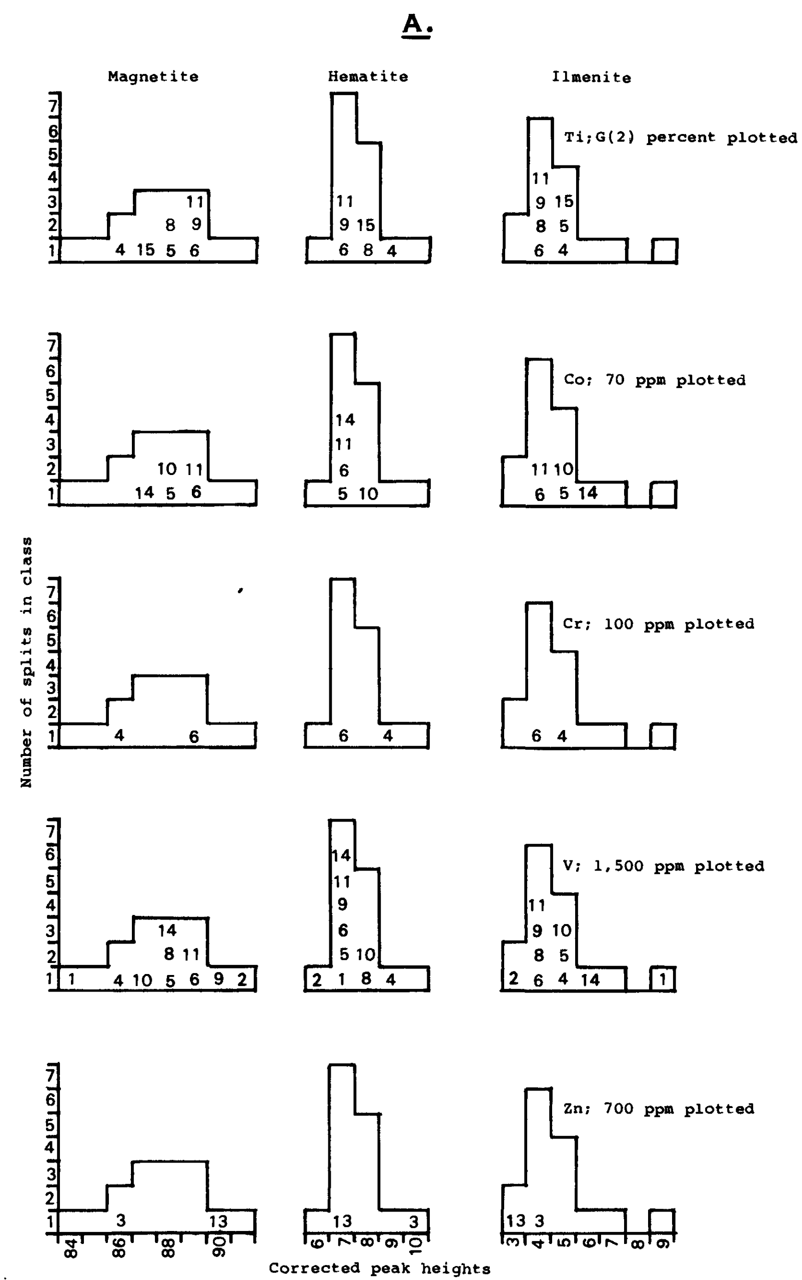
Split Number	Abundances based on peak heights			Abundances corrected to a constant total of 100		
	Magnetite	Hematite	Ilmenite	Magnetite	Hematite	Ilmenite
1	68	6	7	84	7	9
2	60	4	2	91	6	3
3	68	8	3	86	10	4
4	64	6	4	86	9	5
5	66	5	4	88	7	5
6	68	5	3	89	7	4
7	51	5	4	85	8	7
8	70	6	3	88	8	4
9	66	5	3	89	7	4
10	75	7	4	87	8	5
11	77	6	4	89	7	4
12	60	5	3	88	8	4
13	62	5	2	90	7	3
14	74	6	5	87	7	6
15	68	6	4	87	8	5

Figure 5.--Frequency plots of mineral composition of 15 splits of a magnetic concentrate from the Jabal Bani Malik area. Numbers within the histograms refer to the splits listed in table 5 that contain the concentrations of elements shown by the side notation in the figure.

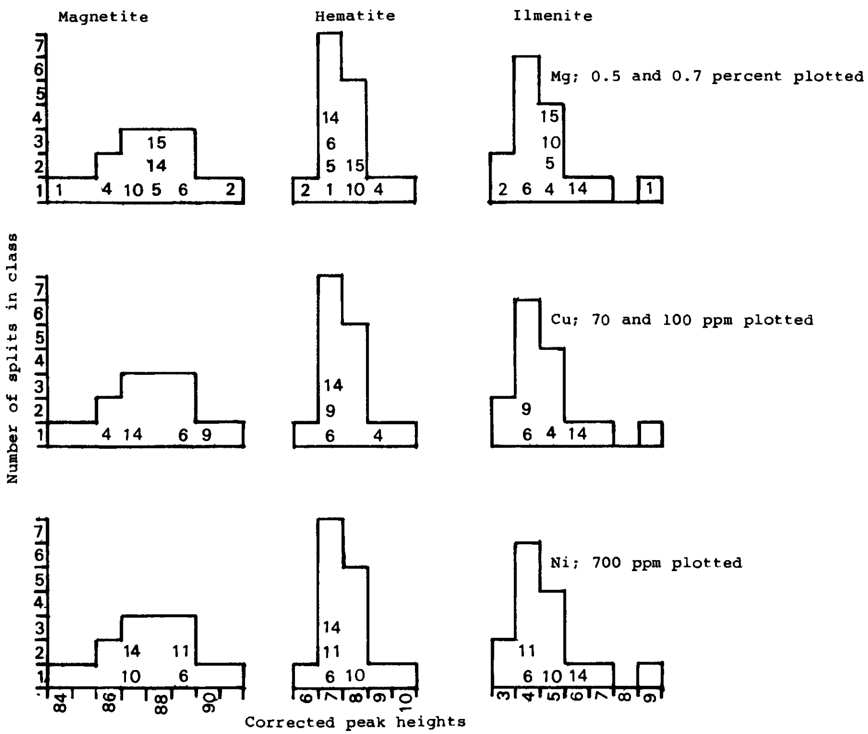
A. Distribution of elements that substitute readily in magnetite

B. Distribution of elements that have limited substitution in magnetite

C. Distribution of elements that do not substitute in magnetite



B.


Magnetite
Hematite
Ilmenite
Mg; 0.5 and 0.7 percent plotted
Cu; 70 and 100 ppm plotted
Ni; 700 ppm plotted
Number of splits in class
Corrected peak heights

C.

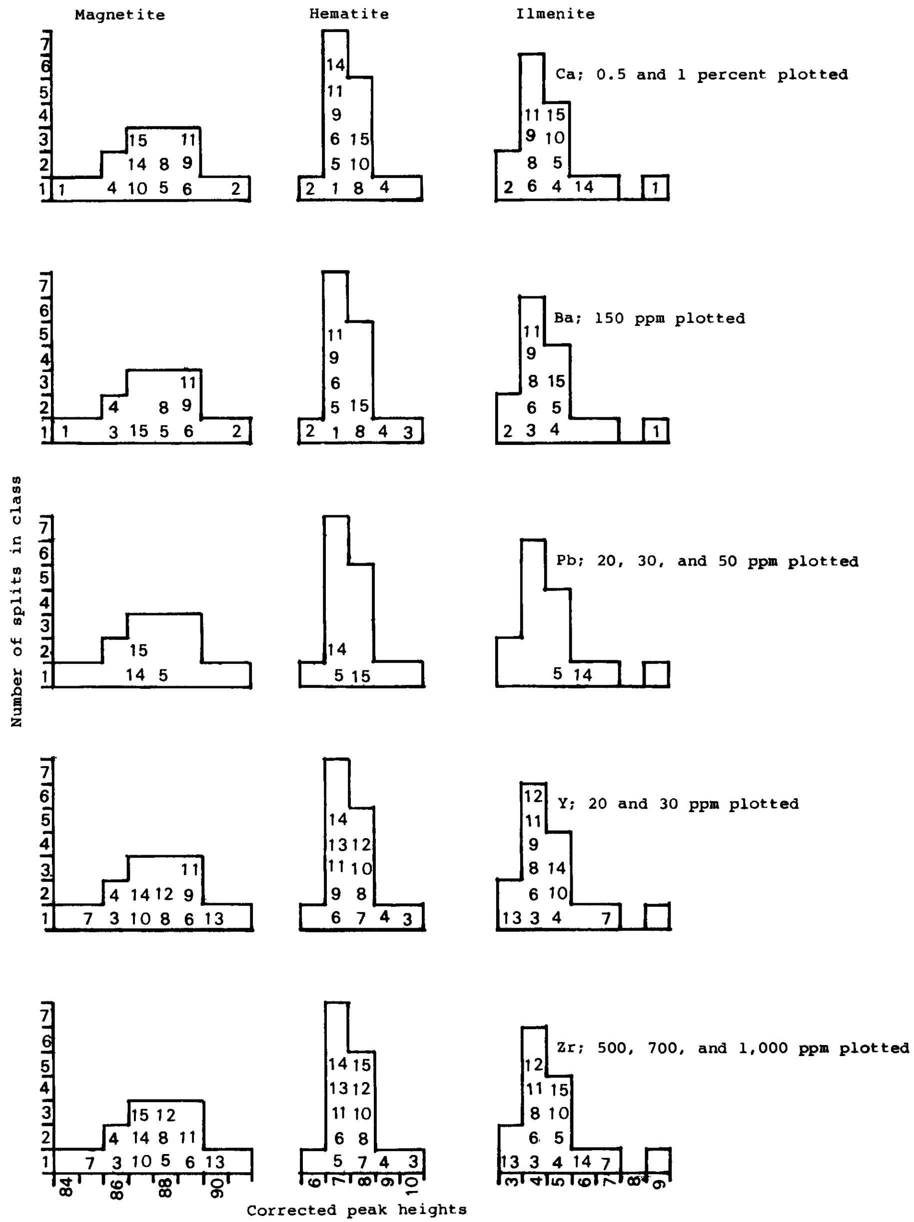

Magnetite
Hematite
Ilmenite
Ca; 0.5 and 1 percent plotted
Ba; 150 ppm plotted
Pb; 20, 30, and 50 ppm plotted
Y; 20 and 30 ppm plotted
Zr; 500, 700, and 1,000 ppm plotted
Number of splits in class
Corrected peak heights

Table 5.—Distribution of detected elements showing variance in 15 splits of a magnetic concentrate from the Jabal Bani Malik area

Replicate analyses and number of split

Element	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
							In percent								
Mg	0.5	0.5	0.2	0.5	0.5	0.5	0.2	0.2	0.2	0.5	0.2	0.2	0.2	0.7	0.5
Ca	.5	1	.3	.5	.5	.5	.3	.5	.5	.5	.5	.3	.3	.5	.5
Ti	2	2	2	G(2)	G(2)	G(2)	2	G(2)	G(2)	2	G(2)	2	2	2	G(2)
							In parts per million								
Ba	150	150	150	150	150	150	100	150	150	100	150	100	100	100	150
Co	50	50	50	50	70	70	50	50	50	70	70	50	50	70	30
Cr	70	70	70	100	70	100	70	70	70	70	100	70	70	70	70
Cu	50	30	30	70	50	70	30	30	100	50	50	30	30	100	50
Ni	50	50	50	50	50	70	50	50	50	70	70	50	50	70	50
Pb	N(20)	N(20)	N(20)	N(20)	30	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	N(20)	20	50
Sc	15	15	15	15	15	20	15	15	15	15	20	15	15	15	15
V	1,500	1,500	1,000	1,500	1,500	1,500	1,000	1,500	1,500	1,500	1,500	1,000	1,000	1,500	1,000
Y	L(20)	L(20)	20	20	L(20)	20	30	20	20	20	20	20	30	20	L(20)
Zn	N(500)	N(500)	700	N(500)	N(500)	N(500)	N(500)	N(500)	N(500)	N(500)	N(500)	N(500)	700	N(500)	N(500)
Zr	300	300	700	500	500	700	500	700	300	500	500	500	500	1,000	500

structure of magnetite. For example, the splits that contain the highest concentrations of titanium show no tendency to occur preferentially with either the splits having high magnetite response or those having high ilmenite response. If the upper limit of determination of titanium had been greater, some reflection of the mineralogy might have been shown by the titanium. Of the other elements that substitute readily in magnetite (Co, Cr, V, and Zn; fig. 5A), only vanadium tends to match high values for the element with high X-ray response for magnetite.

Elements with a limited capacity for substitution in magnetite (Mg, Cu, and Ni; fig. 5B) display no tendency for enrichment in the splits with high response for magnetite.

Among the elements that do not substitute in magnetite (Ca, Ba, Pb, Y, and Zr; fig. 5C) a slight tendency to avoid the high-tail side of the histogram for magnetite can be observed only for lead, but the number of lead-bearing splits is too small to be a reliable guide.

From these comparisons of peak heights for magnetite and the distribution of high values for these elements, the difference in the abundance of magnetite between corrected peak heights of 84 and 91 is insufficient to affect the generally normal distributions of these elements. These distributions reflect acceptable variance in the results of the spectrographic analyses.

INTERGROWTHS IDENTIFIED OPTICALLY

Observation of the magnetic concentrates under the binocular microscope showed that magnetite is 85 percent or more of the concentrates in 47 percent of the samples from the areas of the syenite plutons at Jabal Fayfa and Jabal Bani Malik, in 72 percent of the samples from the syenite pluton to the southeast of Suq al Ithnayn, and 58 percent of the samples from the shonkinite at Jabal Atwid (table 6).

The lower frequency of magnetic concentrates containing 85 percent or more of magnetite in the areas of the syenite plutons at Jabal Fayfa and Jabal Bani Malik than in the other areas is controlled entirely by the larger percentage of samples from the metasedimentary and metavolcanic wall rocks at those localities (fig. 2) than at the other areas (figs. 3 and 4). This distribution also accounts for the fact that magnetic concentrates with 50 percent or less magnetite are more common among the samples from Jabal Fayfa and Jabal Bani Malik, because the magnetic concentrates from the metamorphic rocks contain only small amounts of magnetite. Where the metamorphic rocks yield about as much magnetic concentrate as the igneous rock (as at Jabal Atwid) the percentage of magnetic concentrates with less than 50 percent of magnetite is also small.

Mineralogical differences in the magnetic concentrates reflect not only the source rocks, but also the vigor of the erosion and the alluvial transport in the area. Broken grains and poorly separated intergrowths of minerals are more common in magnetic concentrates from steep source areas (as in the plutons at Jabal Fayfa, Jabal Bani Malik, and Jabal Atwid) than in areas of more subdued relief (as at the syenite pluton to the southeast of Suq al Ithnayn). In areas of low relief (as around the base of Jabal Bani Malik) secondary hematite and limonite forms notable crusts on grains of magnetite and cements mixtures of minerals. These secondary accumulations do not form where the relief of the basin is steep, or if they form, they are subsequently abraded from the host.

Table 6.—Magnetite in syenite and shonkinite plutons

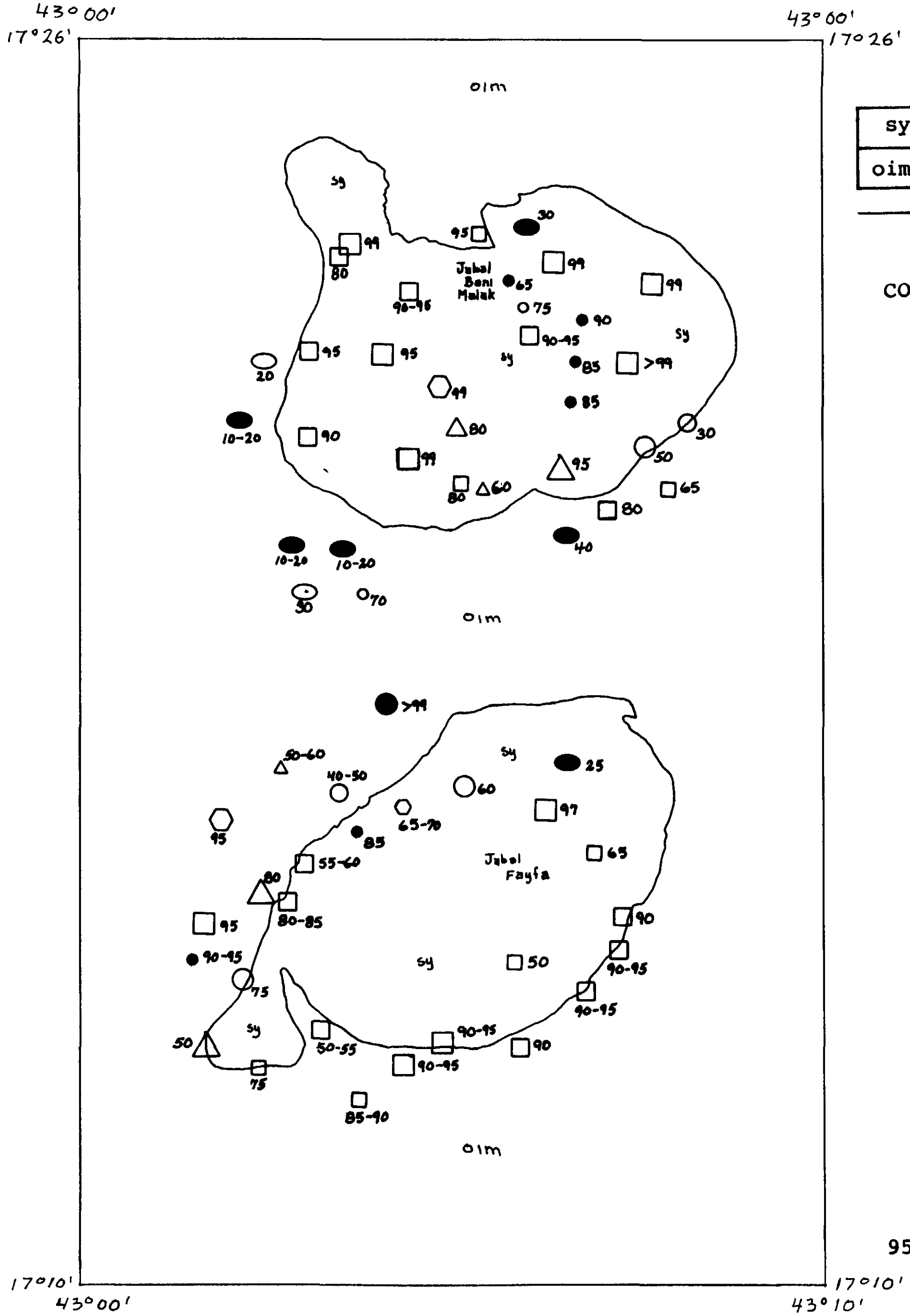
Magnetite in magnetic concentrate (percent)	Percentage of magnetic concentrates with given abundance of magnetite, and number of concentrates from area			
	Syenite plutons			Shonkinite pluton
	Jabal Fayfa (27)	Jabal Bani Malik (34)	Southeast of Suq al Ithnayn (26)	Jabal Atwid (19)
>99	4	3	--	--
99	--	15	--	--
98	--	--	4	--
97	4	--	8	5
95-97	--	--	18	5
95	7	11	18	5
90-95	17	6	4	5
90	7	6	8	27
85-90	4	--	4	11
85	4	6	8	--
80-85	4	--	--	5
80	4	11	--	11
75	7	3	4	--
70	--	3	4	--
65-70	4	--	--	--
65	4	6	4	5
60	4	3	4	11
55-60	7	--	4	5
50-55	4	--	--	--
50	7	3	8	--
40-50	4	--	--	--
40	--	3	--	5
30	--	9	--	--
25	4	--	--	--
20	--	3	--	--
10-20	--	9	--	--
	100	100	100	100

The data from X-ray analysis showed that the grains estimated by optical examination to be the most nearly pure magnetite actually contain some intergrown hematite and ilmenite. Therefore, the visual estimates of the percentages of magnetite refer to the percentages of octahedra, fragments of octahedra, and lamellar grains having the form of magnetite, but probably containing lamellae of hematite and ilmenite.

Syenite Plutons

Jabal Fayfa.--The magnetic concentrate with over 99 percent magnetite (fig. 6), from an area of low relief in greenstone and biotite-muscovite quartzite (fig. 2), is composed of perfect medium- to coarse-grained octahedra with virtually no crystal fragments. Most grains have splendent luster, but a few octahedra are coated with dark-red hematite. Rare fragments of feldspar are attached to a few grains of magnetite. Most concentrates derived from the pluton of syenite at Jabal Fayfa contain 90-97 percent magnetite that typically consists of fine- to medium-grained octahedra showing polysynthetic twinning. Lamellar intergrowths with hematite also produce striations on the crystal faces, but the magnetite with the most conspicuous intergrowths of hematite consists of coarse-grained fragments of octahedra and of platy fragments. Intergrowths of magnetite with grains of pyroxene, biotite, or feldspar are scarce in concentrates with 90-97 percent magnetite, but discrete particles of those minerals are trapped among clusters of grains of magnetite. Where the abundance of magnetite decreases to about 40-85 percent, the decrease is accomplished mainly by increases in the amounts of pyroxene, biotite, titanite, feldspar, and quartz intergrown with the magnetite. Generally, these mixed particles contain fragments of coarse-grained octahedra of magnetite instead of unbroken crystals, which shows that comminution of rock particles is by breaking within, rather than between, minerals. The concentrate with 25 percent magnetite (fig. 6) consists of extremely fine-grained octahedra and fragments of octahedra cemented by hematite and limonite to aggregates of quartz, mica, and feldspar.

Jabal Bani Malik.--The syenite pluton at Jabal Bani Malik (fig. 6) was the source of more magnetic concentrates (containing 99 percent magnetite) than the other areas. One of these concentrates served as the sample for replicate spectrographic and X-ray-diffraction analyses (fig. 2., tables 2, 4, 5). Concentrates with 99 percent magnetite consist of fine- to medium-grained octahedrons and fragments of octahedrons, mainly with splendent luster, but some grains are dull and others have a red hematite stain. Intergrowths of quartz, feldspar, and pyroxene are present, but rare. Where the estimated abundance of magnetite drops to 95 percent, the diluent is generally free grains of feldspar, pyroxene, and quartz. Decline in the amount of magnetite to 50 percent of the concentrate is accompanied by an increase in the amount of rock-forming minerals that are intergrown with the magnetite, as well as intermixed grains and particles of rock with some secondary hematite forming crusts on grains. A concentrate containing less than 50 percent magnetite has as a main-component secondary hematite with weathered magnetite, in which the octahedra are partly husks around cores of hematite or limonite. The other minerals also are weathered and coated with secondary iron oxides, and are cemented into aggregates that include little fresh magnetite; thus, they must be called "magnetic concentrate" instead of "detrital magnetite". Such concentrates are typical of alluvium from broad, low-relief parts of the pluton and from metamorphic rocks in low-relief areas around the foot of Jabal Bani Malik.



EXPLANATION

SYMBOLS USED FOR ROCK UNITS

sy	Syenite
oim	Other igneous and metamorphic rocks

Contact of rock units

SYMBOLS FOR COLORS AND MAGNETITE CONTENT OF POWDERS OF MAGNETIC CONCENTRATES PREPARED FROM ALLUVIUM

Hue 5Y

5Y 4/1 Olive gray

5Y 3/1 Dark olive gray

5Y 2/1 Olive black

Hue 5 GY

5GY 4/1 Dark greenish gray

5GY 2/1 Greenish black

Hue 5 YR

5YR 4/1 Brownish gray

5YR 3/4 Moderate brown

5YR 3/2 Grayish brown

5YR 3/1 Dark brownish gray

5YR 2/1 Brownish black

Hue 10YR

10YR 4/2 Dark yellowish brown

10YR 3/2 Moderate yellowish brown

10YR 2/2 Dusky yellowish brown

Hue 10R

10R 4/2 Grayish red

10R 3/4 Dark reddish brown

95 Estimated percent of detrital magnetite in magnetic concentrate

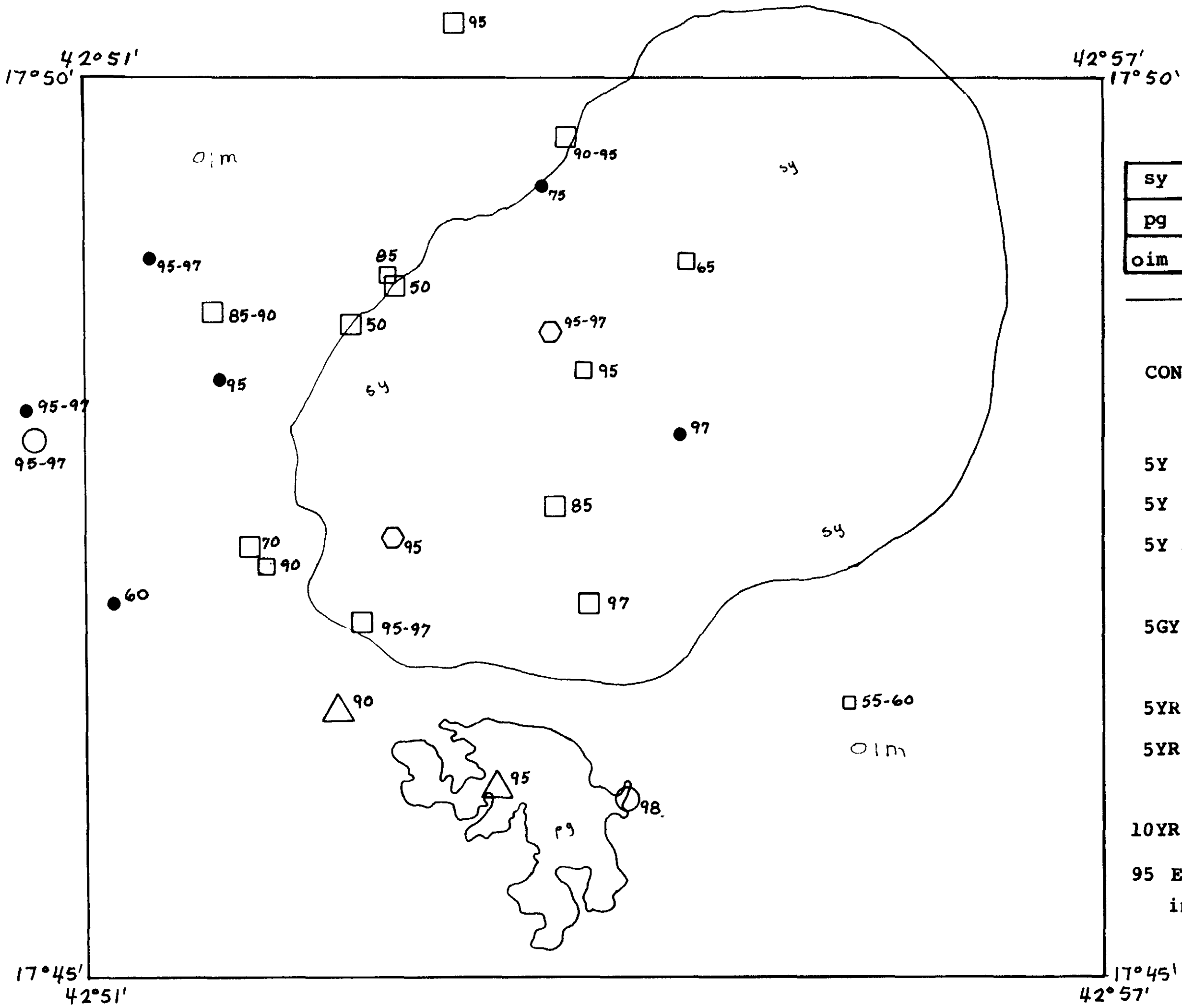
Figure 6.--Map showing the variation in color of powdered concentrates related to sources in the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik.

Pluton to the southeast of Suq al Ithnayn.--Most of the material in magnetic concentrates from the area of the syenite pluton to the southeast of Suq al Ithnayn (fig. 7) consists of fine- to coarse-grained octahedra and fragments of octahedra, where the concentrate contains 95-98 percent of magnetite. These generally have a dull luster, but as the percentage of magnetite increases, the proportion of octahedra with splendent luster also increases. The single concentrate that contains 98 percent magnetite consists of splendent, fine-grained octrahedra striated on crystal faces (possibly the traces of lamellar intergrowths of hematite and ilmentite). As the percentage of magnetite in the concentrate decreases, thin, imperfect coatings of limonite appear and, where present, affect about 10-20 percent of the grains in the concentrate; but none of those grains is fully coated. Coatings of caliche are also locally present, but are less common than limonite. Attached fragments of rock are exceedingly scarce, and intergrowths of magnetite with pyroxene, biotite, quartz, or feldspar are present, but scarce. In concentrates where the percentage of magnetite falls between 75-90, the magnetite loses the splendent luster, becomes uniformly dull, is highly variable in grain size, and increases in its tendency to be intergrown with such minerals as pyroxene, biotite, quartz, feldspar, apatite, titanite, and hematite. Intergrowths of magnetite with rock fragments also become more abundant. Where the amount of magnetite falls below 75 percent of the concentrate, the main contaminants are intergrowths of feldspar and biotite with magnetite or are subangular fragments of pyroxene with copious inclusions of magnetite. Limonite is scarce, but some octahedra of magnetite are martitized. Rare accretionary hematite or pyrite cement grains of magnetite.

Shonkinite pluton at Jabal Atwid

Concentrates from the Jabal Atwid area (fig. 8) that contain 90-97 percent magnetite are composed of mixtures of two sizes of detrital magnetite: one is very fine grained and the other is medium to coarse grained. This division suggests that two episodes of growth or two phases of shonkinite at Jabal Atwid are the source for the magnetite. Perfect octahedra of magnetite are uncommon. Much of the magnetite consists of fragments of octahedra and lamellar grains, but polysynthetic twinning in the octahedra is rare. Feldspar and biotite are the most common minerals to be intergrown with the magnetite, but a little pyroxene and titanite are also attached to a few grains of magnetite. Coatings of caliche or limonite are absent.

Where the amount of magnetite decreases below 90 percent of the concentrate, intergrowths of magnetite with particles of biotite, feldspar, and pyroxene become increasingly more numerous, and discrete grains of biotite or pyroxene with inclusions of magnetite enter the concentrate. Attached particles of rock are uncommon, even among concentrates containing the lowest percentages of magnetite. The scarcity of unfractured octahedra of magnetite, the near absence of secondary surface coatings, and the sparsity of attached fragments of rock are interpreted to indicate that mechanical disaggregation and abrasion are strong factors in the release and transport of detrital grains from the shonkinite at Jabal Atwid.



EXPLANATION

SYMBOLS USED FOR ROCK UNITS

sy	Syenite
pg	Pegmatite and granite
oim	Other igneous and metamorphic rocks
——	Contact of rock units

SYMBOLS FOR COLOR AND MAGNETITE CONTENT OF POWDERS OF MAGNETIC CONCENTRATES PREPARED FROM ALLUVIUM

	Hue 5Y	
5Y 4/2	□	Moderate olive gray
5Y 4/1	□	Olive gray
5Y 3/1	□	Dark olive gray
	Hue 5GY	
5GY 3/2	⬡	Grayish olive green
	Hue 5YR	
5YR 3/2	○	Grayish brown
5YR 3/1	●	Dark brownish gray
	Hue 10YR	
10YR 2/2	△	Dusky yellowish brown

95 Estimated percent of detrital magnetite in magnetic concentrate

Figure 7.--Map showing the variation in color of powdered magnetic concentrates related to sources in the area of the syenite pluton to the southeast of Suq al Ithnayn.

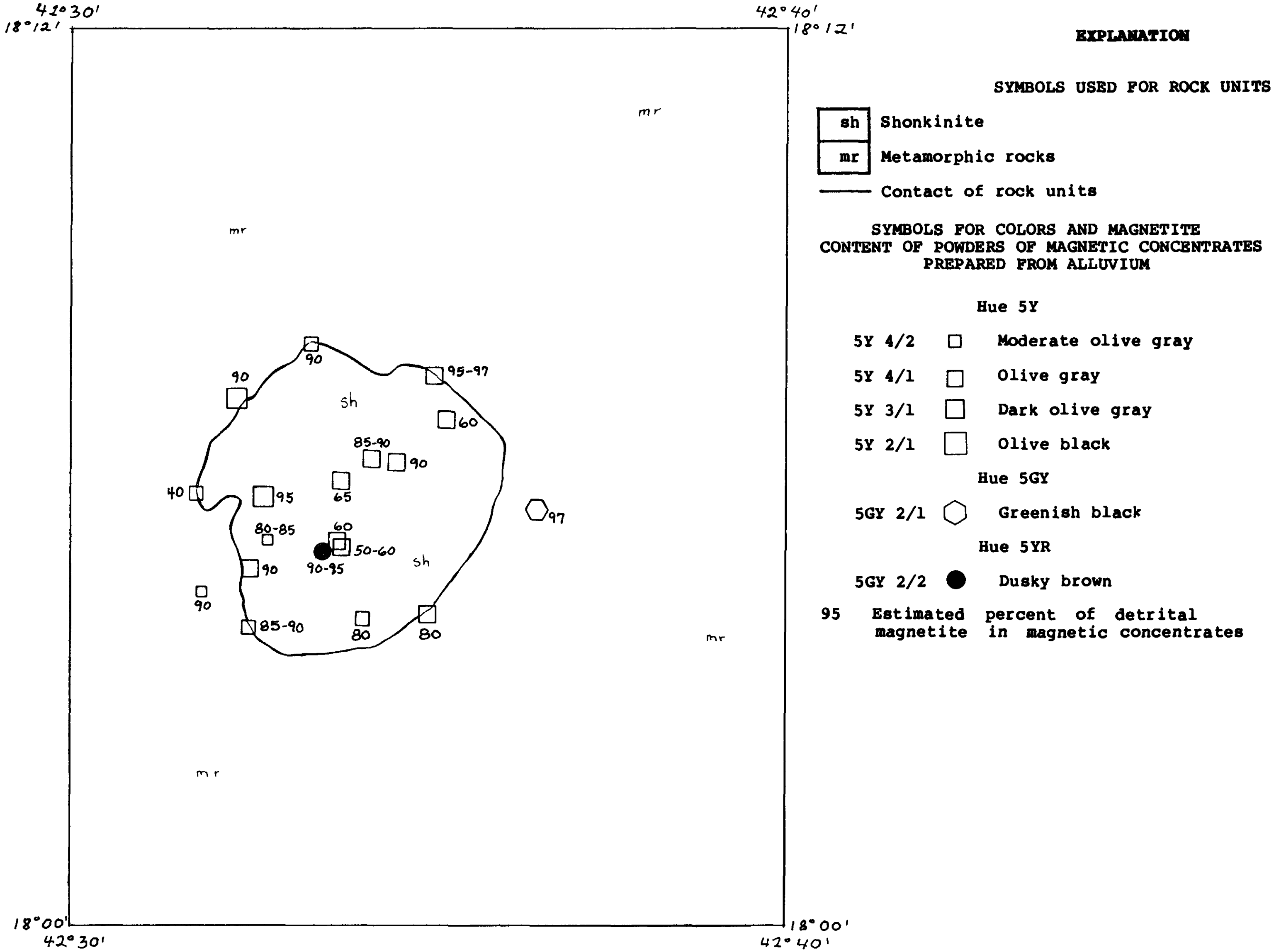


Figure 8.--Map showing the variation in color of powdered magnetic concentrates related to sources in the area of the shonkinite pluton at Jabal Atwid.

RELATION OF COLOR OF POWDERED MAGNETIC CONCENTRATES TO MINERALOGICAL COMPOSITION AND SOURCE AREAS

When the magnetic concentrates were hand-ground to a powder in preparation for spectrographic analysis, the colors of the powders were seen to vary within and among source areas (table 7). The most commonly represented hues are gray and brown (figs. 6-9), generally in dark values (degree of lightness, shown as 2, 3, or 4 before the slash) and of low saturation (chroma, shown as 1, 2, or 4 after the slash). Most grays are associated with the powders of magnetic concentrates from the syenite plutons at Jabal Fayfa and Jabal Bani Malik, as are most blacks, browns, and reds (table 8; figs. 6-8). The greater diversity of colors among the powders of magnetic concentrates from the Jabal Fayfa and Jabal Bani Malik areas results from the larger number of samples from wall rocks in this area, and greater variation in relief than in the other areas, which cause wider differences in the mineralogy of the magnetic concentrates.

The darkest colors among the hues of the powdered concentrates are obtained from the concentrates containing the highest percentages of magnetite (table 8; figs. 6-8). Where notable variation from blacks, grays, or dark browns were observed, as in the Jabal Fayfa and Jabal Bani Malik areas (fig. 6), the concentrates are depleted in magnetite and rich in hematite. The data in table 8 confirm that the magnetite content of the magnetic concentrates is reflected in the color of the powder made from the concentrate.

DISTRIBUTION OF SELECTED ELEMENTS

VALUES AND FREQUENCY OF DETERMINATION

The magnetic concentrates were analyzed in the laboratories of the USGS, Denver, Colorado. Elements reported as below their respective lower limits of determination (table 1) in all 106 magnetic concentrates are Ag, As, Au, Bi, Cd, Sb, W, and Th. The minimum, maximum, and mean values for the other elements are shown by area in table 9, where the standard deviations are also given, as well as a value equal to the mean plus two standard deviations for each element. This last value is considered below in the section on positive anomalous values.

The frequency of determination of each element in magnetic concentrates from the three areas is shown in table 10 according to a modification of the classification used by Lovering (1972, p. 55). The dominant classes in the frequency of determination are "Characteristic" and "Undetermined".

Characteristic elements

Although this category (table 10) includes the range in frequency of determination from 90-100 percent, all elements in this class were determined in 100 percent of the magnetic concentrates from the three areas, except for Sc and Zr in samples from the area of Jabal Fayfa and Jabal Bani Malik, where they were found in 92 and 98 percent of the concentrates, respectively. Scandium is not among the characteristic elements in the magnetic concentrates from the syenite pluton to the southeast of Suq al Ithnayn, where it was determined in 88 percent of the samples. Ti, Mn, Co, Cr, V, and Zn readily substitute isomorphically for

Table 7.—Variation in color of powders of magnetic concentrates from the syenite-shonkinite province

/Notations for color given according to the scheme of the U.S. National Research Council (Goddard and others, 1981)/

Color number	Designation of color	Areas showing number of concentrates and percentages by color		
		Jabal Fayfa and Jabal Bani Malik	Pluton south-east of Suq al Ithnayn	Jabal Atwid
	Hue 5Y	(61)	(26)	(19)
5Y 4/2	Moderate olive gray	--	4	11
5Y 4/1	Olive gray	11	15	21
5Y 3/1	Dark olive gray	22	19	47
5Y 2/1	Olive black	16	--	11
	Hue 5GY			
5GY 4/1	Dark greenish gray	2	--	--
5GY 3/2	Grayish olive green	--	8	--
5GY 2/1	Greenish black	3	--	5
	Hue 5YR			
5YR 4/1	Brownish gray	3	--	--
5YR 3/4	Moderate brown	3	--	--
5YR 3/2	Grayish brown	5	8	--
5YR 3/1	Dark brownish gray	10	38	--
5YR 2/2	Dusky brown	--	--	5
5YR 2/1	Brownish black	2	--	--
	Hue 10YR			
10YR4/2	Dark yellowish brown	3	--	--
10YR3/2	Moderate yellowish brown	2	--	--
10YR2/2	Dusky yellowish brown	5	8	--
	Hue 10R			
10R 4/2	Grayish red	3	--	--
10R 3/4	Dark reddish-brown	10	--	--
	Total	100	100	100

Table 8.—Variation in color of powders of magnetic concentrates related to percentages of magnetite in the concentrates, syenite-shonkinite province

/Notations for color given according to the scheme of the U.S. National Research Council (Goddard and others, 1948)/

Color number	Designation of color	Areas showing number of concentrates and percentages by color: Jabal Fayfa and Jabal Bani Malik (61)	Pluton southeast of Suq al Ithnayn (26)	Jabal Atwid (19)
	Hue 5Y			
5Y 4/2	Moderate olive gray	--	57	87
5Y 4/1	Olive gray	74	83	74
5Y 3/1	Dark olive gray	83	80	66
5Y 2/1	Olive black	97	--	92
	Hue 5GY			
5GY 4/1	Dark greenish gray	67	--	--
5GY 3/2	Grayish olive green	--	96	--
5GY 2/1	Greenish black	97	--	97
	Hue 5YR			
5YR 4/1	Brownish gray	72	--	--
5YR 3/4	Moderate brown	37	--	--
5YR 3/2	Grayish brown	62	97	--
5YR 3/1	Dark brownish gray	85	86	--
5YR 2/2	Dusky brown	--	--	92
5YR 2/1	Brownish black	>99	--	--
	Hue 10YR			
10YR4/2	Dark yellowish brown	60	--	--
10YR3/2	Moderate yellowish brown	80	--	--
10YR2/2	Dusky yellowish brown	72	93	--
	Hue 10R			
10R 4/2	Grayish red	35	--	--
10R 3/4	Dark reddish brown	30	--	--

Table 9.—Ranges in values of 23 elements determined in magnetic concentrates from the syenite-shonkinite province

/S.D. = standard deviation; mean values rounded to the nearest laboratory reporting interval; values shown for mean + 2 S.D. are based on calculated mean plus two standard deviations except where all values are censored/

Abundances of elements

Statistic	In percent					In parts per million						
	Fe	Mg	Ca	Ti	Mn	B	Ba	Be	Co	Cr	Cu	La
Area of syenite plutons at Jabal Fayfa and Jabal Bani Malik (61 samples)												
Minimum	15	0.1	0.2	0.2	300	L(20)	100	N(2)	30	50	20	N(50)
Maximum	50	2	5	G(2)	5,000	50	500	70	200	1,500	200	50
Mean	30	1	1.5	G(2)	2,000	L(20)	200	2	70	700	100	N(50)
S.D.	5.0	0.52	0.88	1.04	1,270.9	5.1	101.6	8.9	45.1	935.3	45.9	3.7
Mean + 2S.D.	40	1.99	3.45	4.2	4,918.8	20.9	416.3	19.9	172.2	2,584.5	213.7	28.1
Area of syenite pluton to the southeast of Suq al Ithnayn (26 samples)												
Minimum	30	0.1	0.2	0.3	1,000	L(20)	150	N(2)	30	70	50	N(50)
Maximum	30	2	2	G(2)	3,000	L(20)	500	N(2)	70	2,000	150	N(50)
Mean	30	0.7	1.5	G(2)	2,000	L(20)	200	N(2)	50	1,000	100	N(50)
S.D.	0	0.5	0.6	1.0	378.8	0	74.0	0	15.8	686	43.3	0
Mean + 2S.D.	30	1.7	2.7	4.2	2,757.6	L(20)	348.0	N(2)	81.6	2,372	186.6	N(50)
Area of shonkinite pluton at Jabal Atwid (19 samples)												
Minimum	30	0.7	0.7	0.5	1,500	L(20)	150	N(2)	50	200	20	N(50)
Maximum	30	2	3	G(2)	3,000	70	300	N(2)	100	5,000	150	N(50)
Mean	30	1	2	G(2)	3,000	L(20)	200	N(2)	70	2,000	70	N(50)
S.D.	0	0.4	0.6	0.7	614.2	13.8	56.5	0	11.9	1,134.4	41.9	0
Mean + 2S.D.	30	1.8	3	3.8	3,833.0	40.7	315.5	N(2)	94.9	4,332	158.6	N(50)

Abundances of the elements in parts per million (cont.)

Statistic	Mo	Nb	Ni	Pb	Sc	Sn	Sr	V	Y	Zn	Zr	
Area of syenite plutons at Jabal Fayfa and Jabal Bani Malik (cont.)												
Minimum	N(10)	N(50)	30	N(20)	N(10)	N(20)	N(200)	150	N(20)	N(500)	N(20)	
Maximum	N(10)	100	300	20	30	50	300	3,000	150	700	1,000	
Mean	N(10)	L(50)	150	N(20)	20	N(20)	L(200)	1,000	30	L(500)	300	
S.D.	0	31.5	62	10.6	8.2	6.9	66.2	488.3	30.9	203.5	273.1	
Mean + 2S.D.	N(10)	102.1	262.2	33.2	35.3	22.0	235.0	2,085.7	91.2	657	931.1	
Area of syenite pluton to the southeast of Suq al Ithnayn (cont.)												
Minimum	N(10)	N(50)	15	N(20)	N(10)	N(20)	N(200)	700	N(20)	N(500)	100	
Maximum	N(10)	N(50)	150	20	20	N(20)	1,000	7,000	100	700	700	
Mean	N(10)	N(50)	70	N(20)	15	N(20)	N(200)	2,000	30	N(500)	500	
S.D.	0	0	47.1	2.7	5.3	0	182.4	1,932	36.9	149.5	176.7	
Mean + 2S.D.	N(10)	N(50)	164.2	13.0	25.6	N(20)	470.6	6,180.2	104	491	782.2	
Area of shonkinite pluton at Jabal Atwid (cont.)												
Minimum	N(10)	N(50)	70	N(20)	10	N(20)	N(200)	1,500	N(20)	N(500)	100	
Maximum	15	N(50)	500	L(20)	30	N(20)	300	2,000	20	700	1,000	
Mean	L(10)	N(50)	300	N(20)	20	N(20)	N(200)	1,500	L(20)	500	500	
S.D.	1.6	0	123.2	0.7	8.4	0	72.5	187.3	5.4	229.4	238.1	
Mean + 2S.D.	13.7	N(50)	524.2	N(20)	35.7	N(20)	239.2	1,953.6	21.9	1.032.4	892.0	

Table 10.--Frequency of determination of elements in magnetic concentrates from the syenite-shonkinite province

/Number of samples shown in parentheses after name of area/

Classification of element	Percent of samples	Areas of syenite plutons: Jabal Fayfa and Jabal Bani Malik (61)	Areas of syenite plutons: Southeast of Suq al Ithnayn (26)	Area of shonkinite pluton at Jabal Atwid (19)
Characteristic	90-100	Fe, Mg, Ca, Ti, Mn, Ba, Co, Cr, Cu, Ni, Sc, V, Zr	Fe, Mg, Ca, Ti, Mn, Ba, Co, Cr, Cu, Ni, V, Zr	Fe, Mg, Ca, Ti, Mn, Ba, Co, Cr, Cu, Ni, Sc, V, Zr
Abundant	50-89	Y	Sc, Y	Zn
Common	10-49	Be, Nb, Pb, Sr, Zn	------------	Mo, Sr, Y
Scarce	2-9	------------	Pb, Sr, Zn	B, La
Rare	<2	B, La, Sn	------------	------------
Undetermined[1]	0	Ag, As, Au, Bi, Cd, Mo, Sb, W, Th	Ag, As, Au, B, Be, Bi, Ca, La, Mo, Nb, Sb, Sn, W, Th	Ag, As, Au, Be, Bi, Cd, Nb, Pb, Sb, Sn, W, Th

[1]Values reported as detected but below the limits of determination (L), or as not detected at the lower limit of determination (N).

Fe^{+2} and Fe^{+3} in magnetite, and all except zinc are characteristic elements. Zinc is a "scarce" or "common" element among the magnetic concentrates from the areas of the syenite plutons, and an "abundant" element in concentrates from the area of the shonkinite pluton. The elements having limited substitution in magnetite (Mg, Cu, Ni, and Sc) are also characteristic elements, with the exception noted above for scandium in magnetic concentrates from the area southeast of Suq al Ithnayn. The characteristic elements Ca, Ba, and Zr do not substitute ismorphically in magnetite; thus, their high levels of determination must be attributed to inclusions, intergrowths, and mechanically trapped particles of pyroxenes, biotite, feldspar, and zircon. Some of these grains, possibly most of them exclusive of the inclusions, could be removed by further processing, but the time required for these operations would be impractical.

For the characteristic elements with a frequency of determination of 100 percent in the magnetic concentrates, the relative abundance of magnetite has no influence (table 8). The abundances of many of these elements, however, show wide variations that reflect the amounts of magnetite present (table 9).

A comparison of the characteristic elements in the magnetic concentrates (table 10) with those in the nonmagnetic concentrates from the same localities (Overstreet and others, 1984a, tables 6-8) shows that the elements are essentially identical in both types of concentrates. The rare exceptions are the presence of yttrium as a characteristic element in nonmagnetic concentrates from the three areas and of strontium as a characteristic element in nonmagnetic concentrates from the Jabal Atwid area. Barium is not a characteristic element in nonmagnetic concentrates from the area of the syenite pluton to the southeast of Suq al Ithnayn. This close similarity in characteristic elements between the two types of concentrates explains why low abundances of magnetite do not reduce the frequency of detection for these elements: the nonmagnetic components of the magnetic concentrate fill the deficit.

Abundant, common, scarce, and rare elements

Most of the rare elements sought in this investigation (Be, La, Mo, Nb, Sn, W, Y, and Zr) are among the categories "abundant, common, and scarce" (table 10). Zirconium is a characteristic element, and tungsten is uniformly "undetermined", but the others appear in one or another of these categories, where they may be accompanied by one or more of the elements B, Pb, Sc, Sr, or Zn. Despite the presence of Y and Zn in categories of determination as high as abundant, and Be, Mo, and Nb in categories as high as common, the actual tenors of these elements are all quite low (table 9). Their low values substantiate the geochemical data based on the nonmagnetic concentrates (Overstreet and others, 1984a) and confirm that economic deposits of the elements sought are absent in the syenite and shonkinite plutons.

Undetermined elements

The array of undetermined elements (table 10) in the magnetic concentrates, which are essentially the same as the undetermined elements in the nonmagnetic concentrates (Overstreet and others, 1984a), confirms the interpretation that base and precious metals, ferroalloy elements, and thorium do not form economic concentrations in the syenite and shonkinite plutons in the southern Asir.

INFLUENCE OF ROCK TYPES

The mean concentrations of elements in the magnetic concentrates (table 9) represent sources among several types of rocks for each area (figs. 2-4). When the mean concentrations of elements determined in the magnetic concentrates from the syenite plutons are compared with those from the shonkinite pluton, and the concentrations obtained from wall-rock concentrates are removed, the differences in the mean concentrations from the sources in syenite and in shonkinite are within one laboratory-reporting interval for all elements except Mn, Be, Cr, Ni, and Zn. Beryllium is more abundant in magnetic concentrates from the plutons of syenite (mean of 2 ppm) than in those from the shonkinite (mean concentration of N(2) ppm). The mean concentrations of Mn (3000 ppm), Cr (2000 ppm), Ni (300 ppm), and Zn (500 ppm) are greater in the magnetic concentrates from the shonkinite than from the syenite (Mn, 2000 ppm; Cr, 1000 ppm; Ni, 150 ppm).

In general, the magnetic concentrates from areas underlain by schist have lower mean concentrations of B (N(20) ppm) and Be (N(2) ppm) than the plutons (B, 15 ppm; Be, 2 ppm in syenite; N(2) ppm in shonkinite), and magnetitic concentrates from the wall-rock granitic gneiss yield lower mean concentrations for Mg (0.5 percent), Mn (1500 ppm), B (N(20) ppm), Ba (150 ppm), Co (50, ppm), Cr (500 ppm), and Ni (70 ppm) than concentrates from the plutons (Mg, 1 percent; Mn, 2000 and 3000 ppm; B, 15 ppm; Ba, 200 ppm; Co, 70 ppm; Cr, 1000 and 2000 ppm; and Ni, 150 and 300 ppm). Other differences in the composition of magnetic concentrates attributable to variations in the lithology of the source rocks and variations among areas include (mean concentrations in ppm for magnetic concentrates; table 11).

The clearest examples that the concentrations of elements in magnetic concentrates vary by lithology of source rocks and area are given by comparison with concentrations reported for other areas in the Arabian Shield. Not many such accounts are available, and the early work is restricted to the determination of Cu, Mo, and Zn in magnetic concentrates; therefore, the comparisons given below are for three elements (table 12).

The magnetic concentrates from the syenite-shonkinite province in the southern Asir have less Mo and Zn, but about the same copper content as magnetic concentrates from other areas and types of rocks in the Arabian Shield.

Correlation coefficients between iron and the other elements in the magnetic concentrates from the syenite-shonkinite province are undefined because of the essential invariance of iron, a result of the technical truncation of nearly all concentrations for iron at 30 percent. Correlation coefficients between pairs of widely determined elements having variable abundances in the magnetic concentrates from the syenite plutons and the shonkinite pluton show some well-defined differences between the two sources, although the coefficients describe less than perfect relations between the pairs (table 13).

Where the correlation coefficients are similar between pairs of elements in magnetic concentrates from both types of plutons, the probability exists that similar minerals are the principal sources for these elements. Such pairs incorporate more of the elements that substitute readily, or to a limited extent, in magnetite (Ti, Mn, Co, Cr, V, Zn, Mg, Cu, Ni, and Sc) than the elements that do not substitute isomorphically in magnetite (Ca, Ba, Pb, Y, and Zr): Mg-Ca, Mg-Sc, Ti-Mn, Ti-Sc, Ti-Zr, Mn-Sc, Mn-Zr, Ba-Pb, Co-Cu, Ni-V, and Zr-Sc. Among the

Table 11.—Analyses of magnetic concentrates from plutons and wall rocks

/mean values in ppm/

Wall rocks and area	Syenite	Shonkinite
Schist from Jabal Fayfa and Jabal Bani Malik		
Cr, 300	1 000	2 000
Zr, 200	500	500
Schist from area southeast of Suq al Ithnayn		
Sr, 300	L(200)	L(200)
Granitic gneisses from areas at Jabal Fayfa, Jabal Bani Malik, and southeast of Suq al Ithnayn		
Y, 70	20	L(20)

Table 12.—Copper, molybdenum, and zinc in magnetic concentrates from areas in the Arabian Shield

Area, number of samples, and reference	Tenors in ppm		
	Cu	Mo	Zn
Wadi Wassat (126)[1]	N(10)-150	N(5)-100	50-1,000
Jabal Bitran (55)[2]	N(10)-100	N(5)-20	N(25)-125
Wadi Tathlith (554)[3]	N(10)-200	N(5)-100	20-2,000
Southern Arabian Shield (49)[4]	80[a]	1.5[b]	199[b]
Jabal Labàbà (6)[5]	15-150	10-50	N(200)-2,000
Southern Asir, syenite(45)[6]	20-150	N(10)	N(500)-700
Southern Asir, shonkinite(15)[6]	20-150	N(10)-15	N(500)-700

[a]Highest value; [b]geometric mean.
[1]Overstreet and Rossman, 1970, fig. 3.
[2]Kahr and others, 1972, fig. 3.
[3]Overstreet, 1978, fig. 4.
[4]duBray, 1981, table 1.
[5]Overstreet and others, 1984c
[6]This report.

Table 13.—Correlation coefficients for pairs of elements in magnetic concentrates

Pairs of elements	Correlation coefficients	
	Syenite plutons	Shonkinite pluton
Mg-Ca	0.64	0.63
Mg-Ba	.06	.81
Mg-Sc	.58	.31
Mg-Sr	.05	.51
Mg-Zn	-.18	-.52
Ca-Ba	.12	.80
Ca-Sc	.27	.69
Ca-Sr	.31	.77
Ca-Y	-.02	.73
Ca-Zn	-.12	-.60
Ti-Mn	.65	.55
Ti-Sc	.76	.69
Ti-Zr	.30	.53
Mn-Co	.57	.02
Mn-Cu	.63	.03
Mn-Nb	.66	--
Mn-Sc	.75	.63
Mn-Zr	.41	.55
Ba-Cu	.18	.61
Ba-Pb	.61	.41
Ba-Sr	.16	.61
Ba-Y	.18	.65
Co-Cu	.61	.63
Co-Pb	-.02	.63
Co-Sc	.62	.02
Cu-Sc	.63	.17
Nb-Zr	.66	--
Ni-V	-.31	-.52
Pb-Zn	-.16	.15
Sr-Zn	-.02	-.76
Zr-Sc	.39	.60

components of these 11 pairs, 16 are elements that will substitute in magnetite and 6 are not.

Correlation coefficients that are strongly dissimiliar in pairs of elements in magnetic concentrates from the syenite and shonkinite plutons tend to incorporate the elements that do not substitute isomorphically in magnetite: Mg-Ba, Mg-Sr, Mg-Zn, Ca-Ba, Ca-Sc, Ca-Sr, Ca-Y, Ca-Zn, Mn-Co, Mn-Cu, Ba-Cu, Ba-Sr, Ba-Y, Co-Pb, Co-Sc, Cu-Sc, Pb-Zn, and Sr-Zn. The elements that do not substitute are represented equally with those that do. Only 11 are elements that readily substitute for Fe^{+2} of Fe^{+3} in magnetite; the other seven have limited substitution.

These differences in correlation coefficients between pairs of elements in magnetic concentrates from the two types of plutons are interpreted to indicate that different mineral assemblages in the syenite concentrates serve as the hosts for these elements than in the magnetic concentrates from the pluton of shonkinite. The chemical composition of individual mineral species in the magnetic concentrates is not known, but the relation of the mean concentrations of selected elements to the colors of powders of the concentrates (table 8) discussed below appears to confirm variation in chemical composition related to the abundance of other minerals in the magnetic concentrates.

EFFECT OF ACCESSORY MINERALS ON THE COMPOSITION OF THE MAGNETIC CONCENTRATES

Comparison of the chemical data (table 14) among the olive-gray (5Y4/1), dark-olive-gray (5Y3/1), and olive-black (5Y2/1) powders of magnetic concentrates from the syenite and shonkinite plutons shows a tendency for the darkest powder (5Y2/1) to contain less magnesium and calcium than the lighter-colored powders. These small decreases are interpreted to reflect the lower percentages of inclusions, intergrowths, and accessory minerals accompanying magnetite. Manganese and chromium decline in abundance in the olive-black powder of magnetic concentrates from the syenite plutons at Jabal Fayfa and Jabal Bani Malik, and Cr, Cu, and Ni show slight declines in mean abundance in the olive-black powders of magnetic concentrates from the shonkinite pluton (table 14). Although these elements substitute in magnetite, they are also constituents of, or are camouflaged in, common femic minerals of the concentrates, such as pyroxenes, amphiboles, and epidote (Overstreet and others, 1984a, table 2); hence, their decrease in abundance suggests that some of the Mn, Cr, Cu, and Ni in the magnetic concentrates is derived from contaminants.

In the grayish-brown (5YR3/2) and dark-brownish-gray (5YR3/1) powders, the contents of Mg, Ca, and Ni do not increase toward the darker color (5YR3/1), although slight decreases take place for Mn and Cr, and a somewhat greater decrease takes place for barium (table 14). Barium is also an element that does not substitute isomorphically in magnetite, but is camouflaged in common accessory minerals (including feldspar) in the magnetic concentrates.

Magnetic concentrates from the plutons include more Mg, Ca, Ti, Cr, Ni, V, and Zr, and less Co and Y, than those from the wall rocks (tables 14 and 15). Within the color phases of the powdered concentrates from schists in the Jabal Fayfa and Jabal Bani Malik areas, the olive-black (5Y2/1) powder contains less Mg, Ca, Ti, Mn, Cr, and Sc than the somewhat lighter powder (5Y3/1). In the brown powders of the magnetic concentrates from the wall-rock schists of the Jabal Fayfa and Jabal Bani Malik areas, Mg, Ca, Ti, Mn, Co, Cr, Ni, and Pb show clear declines

Table 14.—Mean values of selected elements in magnetic concentrates from plutons of syenite and shonkinite, compared to color of powdered concentrate

[Mg, Ca, Ti in percent; other elements in parts per million]

Element	Color of powdered magnetic concentrate by code of U.S. National Research Council (Goddard and others, 1948)				
	5Y4/1	5Y3/1	5Y2/1	5YR3/2	5YR3/1
Syenite pluton at Jabal Fayfa and Jabal Bani Malik					
Mg	1.5	2	0.5	0.7	0.7
Ca	1.5	1.5	1.0	1.5	2
Ti	G(2)	G(2)	G(2)	1.5	1.5
Mn	2,000	3,000	1,500	1,500	1,000
B	L(20)	30	N(20)	N(20)	N(20)
Ba	200	200	150	500	200
Co	70	70	70	70	50
Cr	1,000	700	700	700	500
Cu	100	100	100	150	100
Ni	150	150	150	150	150
Pb	N(20)	N(20)	N(20)	20	L(20)
Sc	20	20	15	15	10
Sr	L(200)	L(200)	L(200)	L(200)	L(200)
V	1,000	1,000	1,000	700	1,000
Y	L(20)	L(20)	L(20)	20	L(20)
Zr	500	500	500	300	300
Syenite pluton southeast of Suq Al Ithnayn					
Mg	1.5	1	No sample	No sample	1
Ca	2.0	1.5	"	"	1.5
Ti	G(2)	G(2)	"	"	G(2)
Mn	1,500	2,000	"	"	1,500
B	L(20)	L(20)	"	"	L(20)
Ba	200	200	"	"	200
Co	70	50	"	"	50
Cr	1,500	1,000	"	"	2,000
Cu	100	100	"	"	70
Ni	70	100	"	"	100
Pb	N(20)	N(20)	"	"	N(20)
Sc	15	20	"	"	15
Sr	N(200)	N(200)	"	"	N(200)
V	3,000	5,000	"	"	7,000
Y	L(20)	20	"	"	N(20)
Zr	100	200	"	"	500
Shonkinite pluton at Jabal Atwid					
Mg	1.5	1	1	No sample	No sample
Ca	2	2	0.7	"	"
Ti	G(2)	G(2)	G(2)	"	"
Mn	3,000	2,000	3,000	"	"
B	L(20)	L(20)	L(20)	"	"
Ba	200	200	150	"	"
Co	70	70	70	"	"
Cr	2,000	2,000	1,500	"	"
Cu	100	70	70	"	"
Ni	300	300	70	"	"
Pb	N(20)	N(20)	N(20)	"	"
Sc	15	15	20	"	"
Sr	L(200)	L 200)	N(200)	"	"
V	1,500	1,500	2,000	"	"
Y	L(20)	L(20)	N(20)	"	"
Zr	500	300	500	"	"

Table 15.—Mean values of selected elements in magnetic concentrates from schist in the vicinity of plutons of syenite, compared to color of powdered concentrate

[Mg, Ca, Ti in percent; other elements in parts per million]

	Color of powdered magnetic concentrate by code of U.S. National Research Council (Goddard and others, 1948)							
	5Y3/1	5Y2/1	5YR3/4	5YR3/2	5YR3/1	10YR2/2	10R4/2	10R3/4
Area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik								
Mg	1	0.5	1.5	1.5	0.2	1	0.3	0.5
Ca	2	.5	5	3	1	1.5	1.5	1.5
Ti	G(2)	1	G(2)	G(2)	.5	G(2)	1.5	1
Mn	3,000	1,000	3,000	2,000	1,000	2,000	3,000	3,000
B	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)	L(20)
Ba	150	150	300	150	150	200	200	300
Co	100	100	150	200	50	150	70	70
Cr	1,500	300	500	200	200	700	500	150
Cu	100	70	200	150	150	150	200	150
Ni	100	70	150	150	50	150	200	150
Pb	N(20)	N(20)	30	20	N(20)	L(20)	N(20)	L(20)
Sc	30	10	20	20	L(10)	20	20	L(20)
Sr	N(200)	N(200)	N(200)	N(200)	L(200)	L(200)	N(200)	N(200)
V	1,500	1,500	1,500	1,500	1,500	1,000	1,000	500
Y	L(20)	L(20)	50	20	20	30	70	100
Zr	300	200	200	150	150	700	200	100
Area of syenite pluton to the southeast of Suq Al Ithnayn								
Mg	0.7	No sample	No sample	0.3	0.5	No sample	No sample	No sample
Ca	1.5	"	"	.5	1.5	"	"	"
Ti	2	"	"	1	1.5	"	"	"
Mn	2,000	"	"	1,500	1,500	"	"	"
B	L(20)	"	"	L(20)	L(20)	"	"	"
Ba	150	"	"	200	200	"	"	"
Co	50	"	"	50	50	"	"	"
Cr	700	"	"	500	300	"	"	"
Cu	100	"	"	100	100	"	"	"
Ni	70	"	"	70	30	"	"	"
Pb	N(20)	"	"	N(20)	N(20)	"	"	"
Sc	15	"	"	L(10)	10	"	"	"
Sr	N(200)	"	"	N(200)	200	"	"	"
V	1,500	"	"	1,000	1,500	"	"	"
Y	70	"	"	N(20)	70	"	"	"
Zr	500	"	"	300	500	"	"	"

toward the darkest color, brownish black (5YR2/1), and several other elements decline somewhat more moderately in abundance in the darkest color (table 15). The two red hues, 10R4/2 grayish red and 10R3/4 dark reddish brown, show some variation in the contents of Cr and V but not in the other elements. Because these reddish powders of the magnetic concentrates contain the least magnetite (table 8), they might be expected to depart radically in composition from the other magnetic concentrates. However, their compositions fall within the narrow range reported for all the concentrates, which indicates that the accessory minerals do not detract from the use of the magnetic concentrates as a geochemical sample medium.

The mean tenors of elements in the magnetic concentrates from the areas around syenite and shonkinite plutons do not provide a strong test of the effect of the accessory minerals on the composition of these magnetic concentrates. The effect is more clearly seen when the relations between positive anomalous concentrations and the percentage of magnetite in the concentrates are considered. Magnetite is less abundant and the accessory minerals are more abundant in concentrates having positive anomalies for the elements that do not substitute isomorphically in magnetite than in concentrates having positive anomalies for elements that do substitute in magnetite.

POSITIVE ANOMALOUS VALUES

The threshold positive anomalous concentrations of the elements determined in the magnetic concentrates were calculated as the respective means plus two standard deviations (table 9) for each of the three areas. When expressed as the nearest laboratory-reporting intervals, the threshold anomalous concentrations vary slightly from area to area (table 16).

Compared with the threshold anomalous concentrations of samples of rocks and -80-mesh wadi sediment (Overstreet and others, 1984a, tables 10-12), the threshold concentrations of Fe, Ti, Mn, Co, Cr, Ni, V, and Zn are greater in the magnetic concentrates, as are Be, Cu, Mo, Nb, Sn, Y, and Zr in some areas. Pronounced depletion in the threshold anomalous concentrations of Mg, Ca, Ba, and Sr takes place between the samples of rocks and minus-80-mesh sediments and the magnetic concentrates. This depletion results from the reduction in the amount of feldspars, pyroxenes, amphiboles, and other rock-forming minerals in the magnetic concentrates compared with rocks and sediments. Little change in threshold anomalous concentrations results for B, La, Pb, and Sc through changes in sample media (table 16).

The threshold concentrations for the magnetic concentrates are higher for Fe, Cr, Ni, V, and Zn than for the nonmagnetic concentrates (table 16). Much lower concentrations are found for the positive anomalous thresholds of Mg and Ca in the magnetic concentrates than in the nonmagnetic concentrates. This relation reflects the dominance of pyroxenes, amphiboles, epidote, and titanite in the nonmagnetic concentrates.

Anomaly enhancement of the elements desired is effected through use of concentrates, with the magnetic concentrate being more useful for niobium than the nonmagnetic concentrate (table 16), and both types of concentrate being better than rock and wadi-sediment samples for tin. Both Be and La are defined better in the nonmagnetic concentrates, but little choice exists between these media for Mo, Y, and Zr. Only the magnetic concentrates enhanced the amount of zinc sufficiently for it to be detected (table 16).

Table 16.—Threshold anomalous values for 23 elements in magnetic concentrates and other sample media from the syenite-shonkinite province

/Data for media other than magnetic concentrates from Overstreet and others, 1984a, tables 10-12; N-A = no anomaly/

Element	Area of syenite plutons at Jabal Fayfa and Jabal Bani Malik				Area of syenite pluton to the southeast of Suq al Ithnayn				Area of shonkinite pluton at Jabal Atwid			
	Rocks	<80-mesh sediment	Nonmagnetic concentrate	Magnetic concentrate	Rocks	<80-mesh sediment	Nonmagnetic concentrate	Magnetic concentrate	Rocks	<80-mesh sediment	Nonmagnetic concentrate	Magnetic concentrate
	In percent											
Fe	10	10	20	G(30)	10	10	G(20)	30	10	15	10	30
Mg	5	5	7	2	7	5	10	1.5	7	10	7	2
Ca	7	7	10	3	10	7	7	3	15	10	20	3
Ti	G(1)	G(1)	G(1)	G(2)	G(1)	G(1)	G(1)	G(2)	G(1)	G(1)	G(1)	G(2)
	In parts per million											
Mn	2,000	1,500	5,000	5,000	2,000	2,000	3,000	3,000	1,500	2,000	3,000	3,000
B	20	10	20	20	N-A	15	N-A	N-A	30	15	N-A	30
Ba	3,000	1,500	150	500	2,000	700	200	300	3,000	1,000	500	300
Be	3	3	7	20	2	1	N-A	N-A	5	3	7	N-A
Co	30	20	150	150	50	30	200	70	70	50	50	100
Cr	500	500	1,000	2,000	500	700	700	2,000	700	1,500	1,000	5,000
Cu	150	100	200	200	70	100	100	200	150	100	70	150
La	50	70	100	L(50)	30	50	20	N-A	150	100	150	N-A
Mo	5	5	10	N-A	N-A	N-A	N-A	N-A	5	N-A	N-A	15
Nb	N-A	N-A	N-A	100	N-A	N-A	N-A	N-A	N-A	N-A	N-A	N-A
Ni	150	150	150	300	100	100	100	150	300	200	150	500
Pb	30	30	150	30	20	10	N-A	L(20)	30	20	20	N-A
Sc	30	30	50	30	50	30	50	30	50	30	50	30
Sn	N-A	N-A	20	20	N-A	N-A	N-A	N-A	N-A	N-A	N-A	N-A
Sr	1,000	1,000	100	200	1,000	700	100	500	1,500	700	500	200
V	300	300	700	2,000	500	500	1,000	7,000	300	500	200	2,000
Y	30	30	100	100	30	50	100	100	50	50	70	20
Zn	N-A	N-A	N-A	700	N-A	N-A	N-A	500	N-A	N-A	N-A	700
Zr	300	G(1,000)	G(1,000)	1,000	200	700	1,000	700	500	300	1,000	1,000

PRINCIPAL POSITIVE GEOCHEMICAL ANOMALIES

The threshold positive anomalous concentrations of elements in the magnetic concentrates from the syenite-shonkinite province of the southern Asir (table 16) are all within the ranges of concentration common to non-ore-associated magnetite from other areas (Overstreet and others, 1978). The values found for the magnetic concentrates confirm the low abundances of ore elements reported for other geochemical sample media from the area (Overstreet and others, 1984a), and support the conclusion that the plutons lack economic deposits of the rare elements, base and precious metals, and ferroalloy elements.

RARE ELEMENTS

The rare elements considered here are Be, La, Mo, Nb, Sn, Y, Zr, and Th. The only detected Be, La, Nb, and Sn were reported for magnetic concentrates from the area of syenite plutons at Jabal Fayfa and Jabal Bani Malik, and the only molybdenum to be detected was in magnetic concentrates from the area of the shonkinite pluton at Jabal Atwid. Yttrium and Zr were generally detected in low abundances throughout the syenite-shonkinite province, but thorium was not detected.

Beryllium, lanthanum, niobium, and tin in the area of Jabal Fayfa and Jabal Bani Malik

The distribution of Be, La, Nb, and Sn in magnetic concentrates from the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik is shown on figure 9. High background and anomalous amounts of these elements are mainly present in magnetic concentrates from the flanks of the plutons and the wall rocks. Owing to the pattern of the drainage in these plutons and to access to wadis for sampling, the anomalies appear close to the margins of the plutons, but the distributive provinces of the concentrates lead well back into the cores of the plutons.

The positive anomalous concentration of 70 ppm beryllium in a magnetic concentrate from Jabal Fayfa (fig. 9) reflects a strong positive anomaly for beryllium in raw concentrates from the same locality (Overstreet and others, 1984a, fig. 5). Because of the unusual amount of beryllium in the two types of concentrates from this locality, the source mineral or minerals for beryllium should be sought.

The intermediate- and high-background beryllium concentrations in the magnetic concentrates extend the areas of positive geochemical anomalies for beryllium, as defined by the raw concentrates, and indicate that the element is more widely distributed in the area than the other geochemical data show. Except for the locality in the north-central part of the syenite pluton at Jabal Fayfa, the amounts of beryllium are about equal to crustal abundance or less.

Magnetite does not appear to be a scavenger of beryllium, because two-thirds of the magnetic concentrates in which beryllium was detected contain 60 percent or less magnetite, and the strongly anomalous sample with 70 ppm beryllium is widely intergrown with feldspar (table 17).

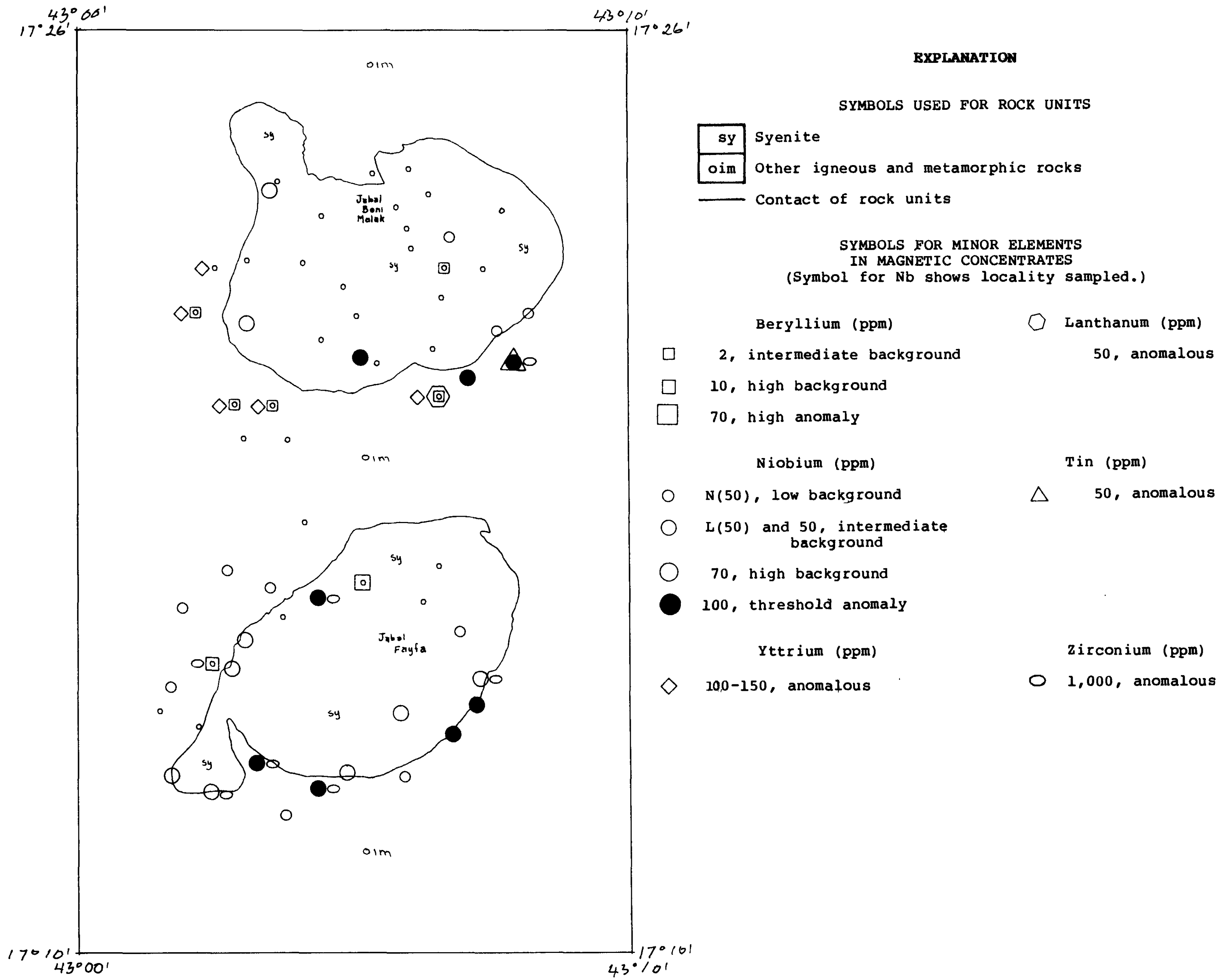


Figure 9.--Map showing the distribution of beryllium, lanthanum, niobium, tin, yttrium, and zirconium in magnetic concentrates from the area of syenite plutons at Jabal Fayfa and Jabal Bani Malik.

The single magnetic concentrate with 50 ppm lanthanum from a site to the southeast of Jabal Bani Malik (fig. 9) contains only 40 percent magnetite. The sample is weathered and the main mineral other than magnetite is secondary hematite. The hematite has probably served as a scavenger of lanthanum from the weathering products of rocks containing very little lanthanum. This is interpreted to be a false anomaly of no economic significance.

Anomalous concentrations of Nb were detected in magnetic concentrates from the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik, but other sample media from the area (table 16) failed to disclose anomalous amounts of the element. This relation indicates that the main source in the Jabal Fayfa-Jabal Bani Malik area is a magnetic mineral of considerable scarcity, as yet unidentified, possibly columbite or tantalite. Common pathfinder elements for niobium, such as Sn and Y, are seldom associated with the Nb-bearing concentrates. Even in the anomalous samples, the quantity of niobium is so small that alluvial (or eluvial) placer deposits of minable size are not expected to exist in the study area.

Tantalum was not sought in the spectrographic analyses, but niobium is an indicator of its probable presence, particularly if the two elements are present in independent, magnetic minerals. The amount of tantalum may also be small, unless the source of the niobium is tantalite. In that event, somewhat more tantalum than niobium would be present.

One magnetic concentrate from a locality to the southeast of the syenite pluton at Jabal Bani Malik contains 50 ppm tin. Although small amounts of tin have been reported in magnetic concentrates, both in the magnetite and in associated accessory minerals (Overstreet and others, 1978, p. 484-490), the source at this locality may be an accessory mineral, because the concentrate contains only 65 percent of magnetite. The amount of tin constituting an anomaly is so small, and only one concentrate contains that little, that the area is interpreted to lack economic potential for tin.

Table 17.—Beryllium and magnetite in magnetic concentrates, Jabal Fayfa and Jabal Bani Malik

Beryllium in magnetic concentrate (ppm)	Magnetite in magnetic concentrates (percent)
70	60
10	80
2	85
2	40
2	10-20
2	10-20
2	10-20

Molybdenum at Jabal Atwid

Two magnetic concentrates from the northwestern flank of Jabal Atwid (fig. 10, table 11) contain the low (15 ppm) anomalous concentrations of molybdenum. Both concentrates are composed of 90 percent magnetite. They are not from the same localities in the shonkinite pluton as samples of rocks that were found to have small positive anomalies of molybdenum (Overstreet and others, 1984a, fig. 7). Apparently, the pluton is not a potential source for the element because the magnetic fraction of concentrates tends to be enriched in molybdenum compared to other sample media (Overstreet and others, 1978, p. 471), the anomalies from magnetic concentrates and from rocks do not coincide, and, particularly, molybdenum is sparse in the rock samples containing anomalies.

Yttrium and zirconium

Low anomalous concentrations of Y and Zr in the magnetic concentrates from the three areas (table 16) and sparsity of localities with anomalous amounts of these elements (figs. 9-11) confirm previous observations that the syenite and shonkinite plutons are not potential sources of ore minerals containing these elements (Overstreet and others, 1984a).

Jabal Fayfa and Jabal Bani Malik.--Magnetic concentrates containing anomalous amounts of yttrium are restricted to the southern and western wall rocks of Jabal Bani Malik where chlorite-sericite schist of the Sabya Formation is intruded by small masses of granite (fig. 2). Anomalous concentrations of beryllium are present in most of the magnetic concentrates, along with anomalous amounts of yttrium, but positive anomalies of niobium are absent. One of these magnetic concentrates contains 40 percent magnetite; the other four have only 10-20 percent magnetite. Most of each of the concentrate consists of crusts of secondary hematite with which the yttrium is probably associated.

Anomalous amounts of zirconium are most common in magnetic concentrates from the southern side of the syenite pluton at Jabal Fayfa (fig. 9). Two of the concentrates containing anomalous zirconium contain 90-95 percent magnetite, but the others have only 50-80 percent magnetite. The zirconium may thus be attributed to accessory minerals present in the magnetic concentrates. Six of the seven concentrates containing anomalous amounts of zirconium are also sources for anomalous amounts of niobium, but none is a source for an anomalous tenor in yttrium. These relationships tend to indicate that the Nb-bearing mineral has a rather simple composition lacking yttrium, of which the most common examples among the more magnetic minerals are columbite or tantalite. Pyrochlore or microlite are also relatively simple in composition, but they have very low magnetic susceptibility. Inasmuch as the nonmagnetic concentrates from the same localities do not contain anomalous amounts of niobium, these minerals are probably absent. The correlation of magnetic concentrates anomalous for both Zr and Nb might indicate that the niobium is camouflaged in zircon, but this option is untenable because of the absence of niobium in the nonmagnetic concentrates where zircon is common (Overstreet and others, 1984a, table 2). Therefore, the relationship of Nb, Y, and Zr in the magnetic concentrates is thought to support the interpretation that small amounts of a paramagnetic niobium-bearing mineral are present in the syenite pluton at Jabal Fayfa.

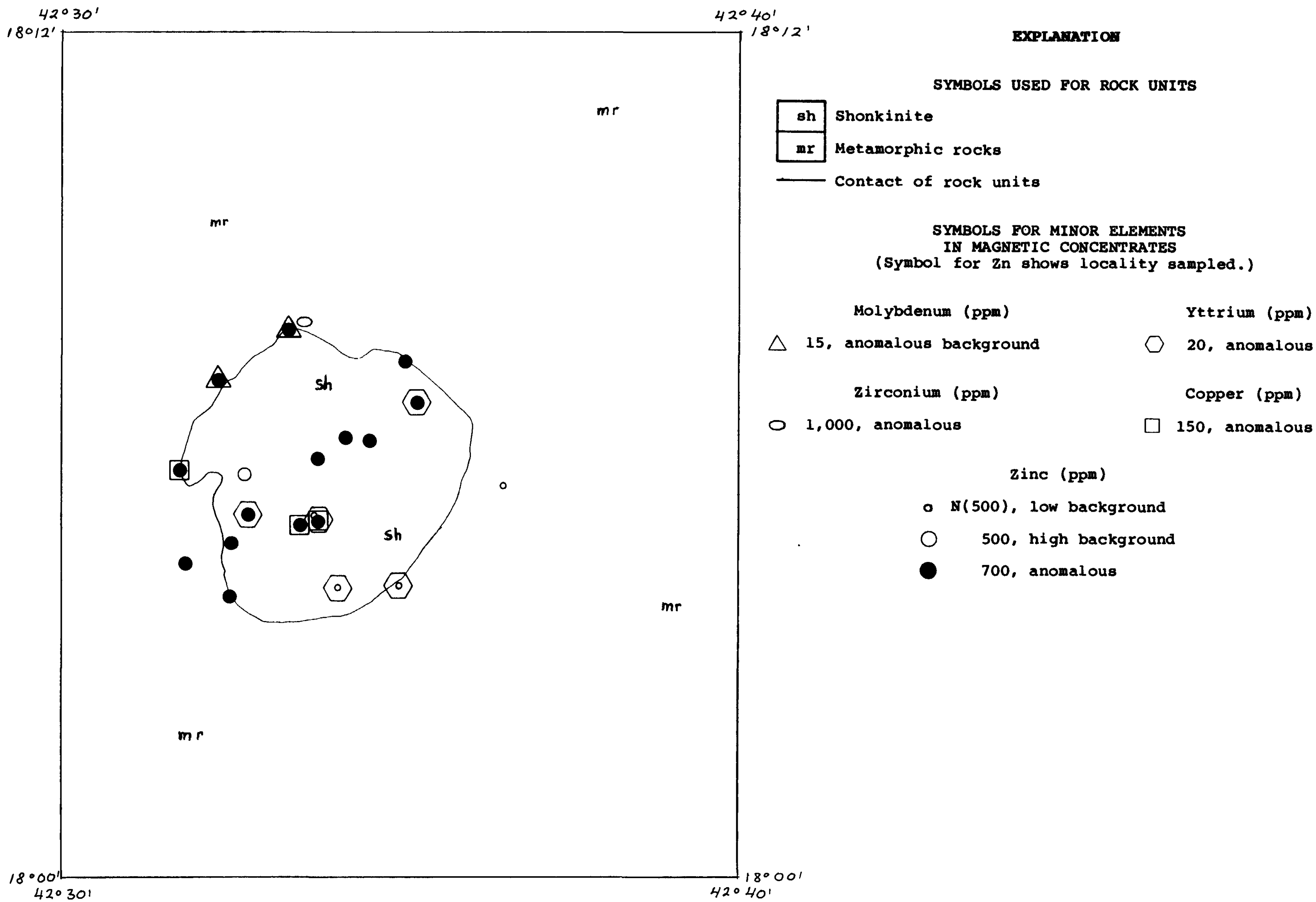


Figure 10.--Map showing the distribution of molybdenum, yttrium, zirconium, copper, and zinc in magnetic concentrates from the area of the shonkinite pluton at Jabal Atwid.

Pluton to the southeast of Suq al Ithnayn.--The low anomalous concentration (100 ppm) of yttrium was determined using four magnetic concentrates from the wall rock of the Khamis Mushayt complex (Fairer, 1982) to the west of the syenite pluton exposed to the southeast of Suq al Ithnayn (fig. 11). Other rare elements (except zirconium at one locality) are not anomalously abundant in these concentrates. The degree of freedom of the magnetite in the concentrates from accessory minerals makes little difference in the abundance of yttrium; these concentrates contain 50-97 percent magnetite. Most of the concentrates with anomalous amounts (700 ppm) of zirconium are also from areas underlain by the Khamis Mushayt complex. The samples with anomalous concentrations of zirconium are also variable in magnetite content (which ranges from 75 to 95 percent of the concentrate. It must be noted, however, that these rather clean magnetic concentrates have a lower threshold anomalous concentration than that of the somewhat more contaminated magnetic concentrates from the vicinity of Jabal Fayfa (fig. 9). Hence, the presence of anomalous amounts of both Y and Zr is attributed to other minerals intergrown or mixed with the magnetite.

Jabal Atwid.--The low threshold (20 ppm) for anomalous amounts of yttrium in the magnetic concentrates from the area of the shonkinite pluton at Jabal Atwid (table 16; fig. 10), and the rarity of concentrates with even this small amount of yttrium confirm the previously reported scarcity of this element in the Jabal Atwid area (Overstreet and others, 1984a). Contaminated concentrates containing 50-85 percent magnetite were the source of the yttrium anomalies. Only one concentrate, consisting of 90 percent magnetite, contains an anomalous zirconium (1000 ppm) (fig. 10). Magnetic concentrates indicate that there is less yttrium and zirconium in the shonkinite than in the syenite.

Thorium

Thorium was not found at the lower detection limit (N(200) ppm) in the magnetic concentrates from the areas underlain by syenite and shonkinite plutons. It was also not found in other sample media from these areas (Overstreet and others, 1984a), but the absence of identifiable concentrations in the magnetic concentrates is interpreted to indicate that the syenite and shonkinite plutons are not potential sources of thorium.

In other areas, syenite was the source rock for anomalously radioactive magnetic concentrates (Pan and others, 1980, p. 30-31); but the radioactivity was caused by uranium in crusts of hematite on the magnetite. The few samples from the syenite-shonkinite province in the southern Asir (where the hematite crusts are present) were not measured for radioactivity because the background radioactivity at the sample localities was quite low, as can be seen by comparing the radioactivity (fig. 2) with the colors of powdered magnetic concentrates (fig. 6) and the percentages of magnetite (table 8).

BASE AND PRECIOUS METALS

Low anomalous concentrations of Cu and Zn were detected in the magnetic concentrates from the three areas, and very small amounts of lead were found in concentrates from the syenite plutons (table 16). There is no evidence to indicate the presence of a potential source of these metals in the areas; an appraisal supported by the absence of Ag, As, Au, Bi, Cd, and Sb at their respective lower limits of determination (table 1). The distribution of the base-metal anomalies in the magnetic concentrates reflects the ease of substitution of the element in magnetite.

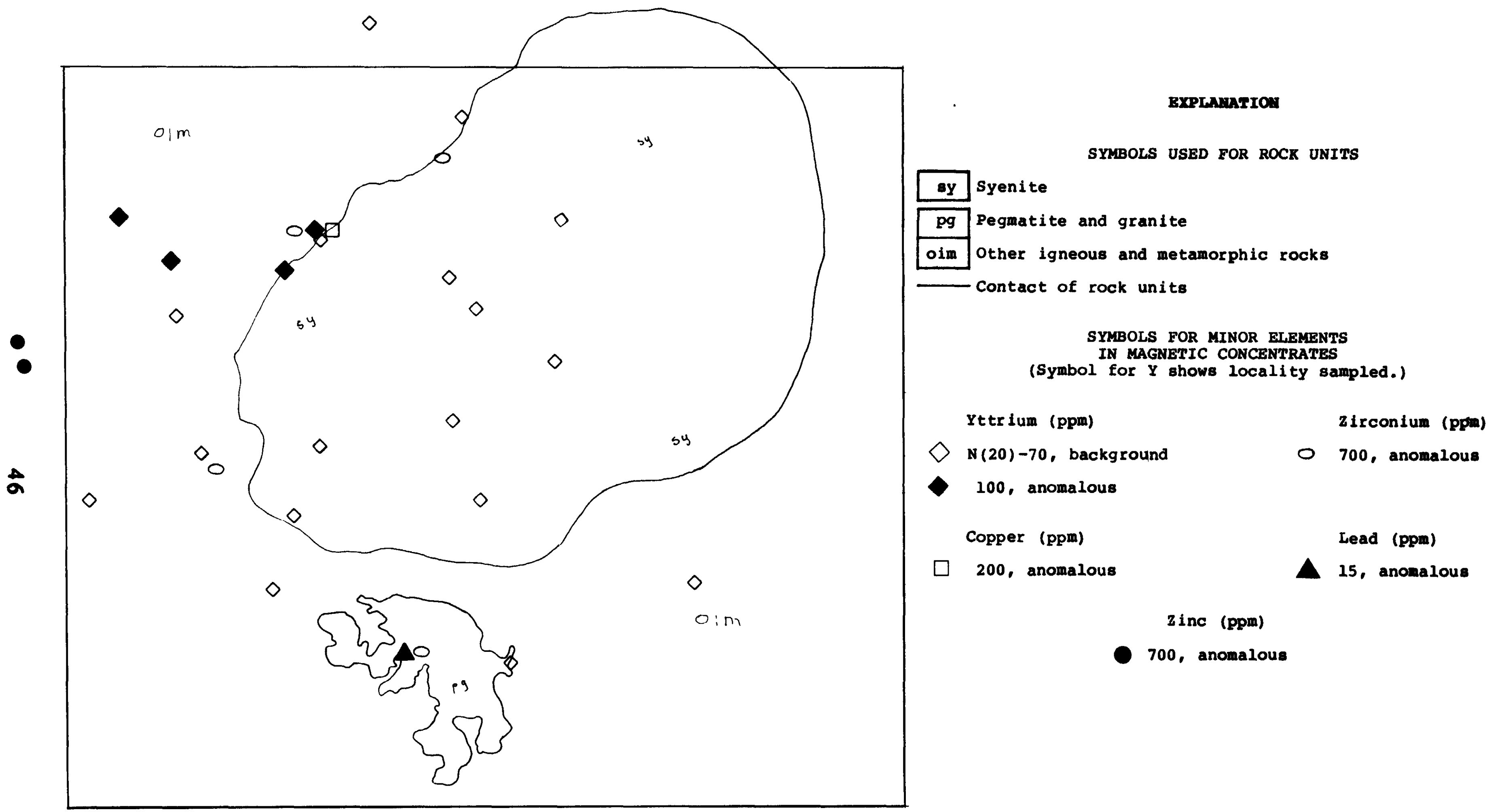


Figure 11.--Map showing the distribution of magnetic concentrates containing anomalous amounts of yttrium, zirconium, copper, lead, and zinc in the area of the syenite pluton to the southeast of Suq al Ithnayn.

Jabal Fayfa and Jabal Bani Malik

Low-level Cu, Pb, and Zn anomalies are present in magnetic concentrates from the syenite pluton at Jabal Bani Malik and its wall rocks, but only one copper anomaly was detected in the area of the pluton at Jabal Fayfa, and that was in the wall rocks (fig. 12). None indicates base-metal mineralization.

Zinc readily substitutes for Fe^{+2} in magnetite (Overstreet and others, 1978). In the seven magnetic concentrates containing high-background and positive anomalous concentrations of zinc from the syenite pluton at Jabal Bani Malik, two concentrates consist of 99 percent magnetite, two each have 90 percent and 80 percent magnetite, and one has only 50 percent magnetite (fig. 12). This last is the high-background sample situated just inside the southeastern boundary of the pluton where the greater part of its source area is the wall rocks to the east. The other magnetic concentrates from the wall rocks to the south and west of Jabal Bani Malik (fig. 12) that have positive zinc anomalies contain 10-40 percent magnetite. Magnetite from the syenite pluton is unweathered and has a splendent luster in contrast to magnetite from the schist, which is weathered, stained, and coated with, or cemented by, secondary hematite and limonite. Magnetite in the concentrates from the syenite is thought to have scavenged zinc during original magmatic crystallization when the zinc substituted for Fe^{+2}; but in the weathered concentrates from the schist, magnetite is probably not the principal source of the zinc. In those concentrates, the main residences of the zinc are probably the secondary iron oxides.

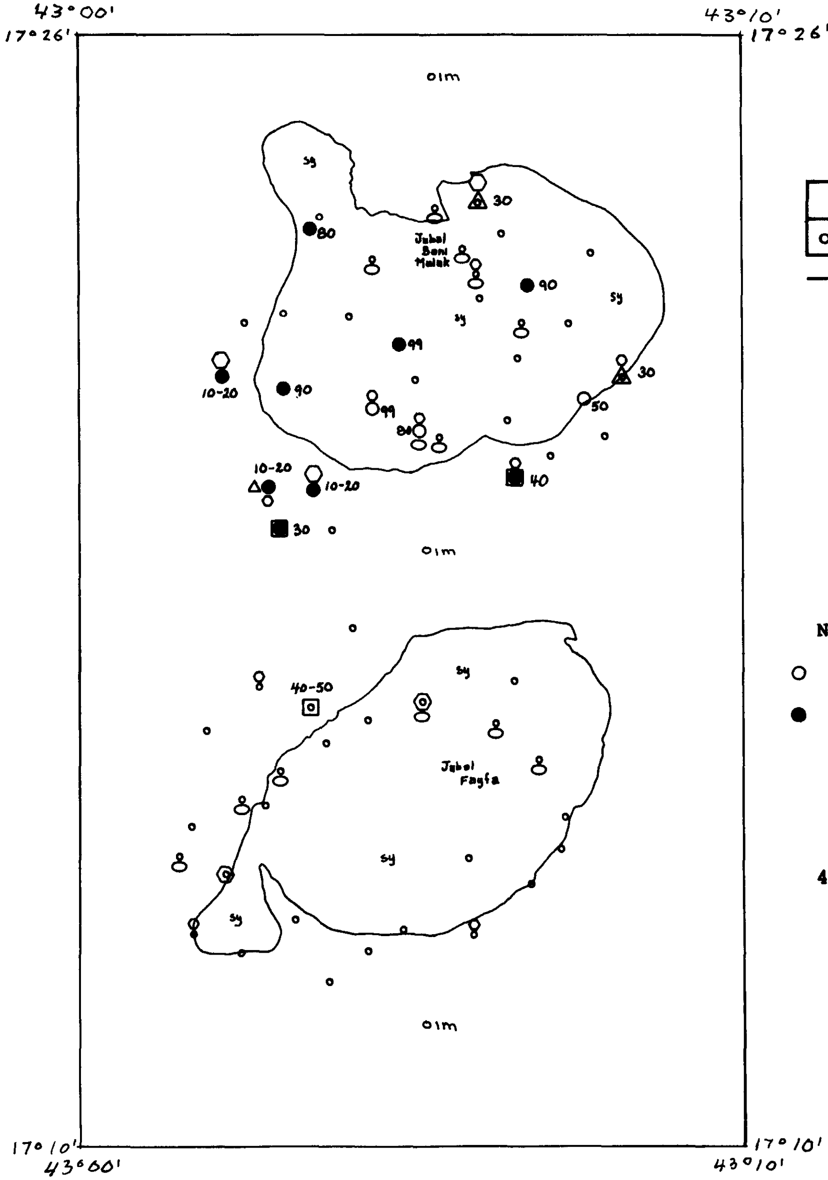
Copper has limited substitution in magnetite but is commonly absorbed on, or coprecipitated with, secondary iron minerals. The three magnetic concentrates with positive copper anomalies contain 30-50 percent magnetite (fig. 12).

Lead does not substitute isomorphically for iron in magnetite. The three concentrates with positive lead anomalies contain 10-30 percent magnetite (fig. 12).

Syenite pluton to the southeast of Suq al Ithnayn

Base-metal anomalies in the area of the syenite pluton to the southeast of Suq al Ithnayn are scarce and, where present, are found in magnetic concentrates from the wall rocks (fig. 11). Concentrates with anomalous concentrations of zinc contain 95-97 percent magnetite, and the concentrate with a copper anomaly contains 50 percent magnetite. However, the concentrate with an anomalous amount of lead is also magnetite-rich, containing 96 percent of the mineral, and so does not follow the pattern of Pb-bearing samples being associated with reduced percentages of magnetite.

These low-level positive anomalies for the base metals in magnetic concentrates confirm other geochemical data that indicate base- and precious-metal deposits are absent from this pluton (Overstreet and others, 1984a).



EXPLANATION

SYMBOLS USED FOR ROCK UNITS

sy Syenite

oim Other igneous and metamorphic rocks

——— Contact of rock units

SYMBOLS FOR MINOR ELEMENTS
IN MAGNETIC CONCENTRATES
(Symbol for Zn shows locality sampled.)

Copper (ppm)

□ 200, anomalous

Lead (ppm)

△ 30, threshold anomalous

△ 50-70, anomalous

Zinc (ppm)

N(500), low background

○ 500, high background

● 700, anomalous

Barium (ppm)

○ 300, high background

⬡ 500, anomalous

Strontium (ppm)

⬭ 200-300, anomalous

40 Percentage of magnetic in selected concentrates

Figure 12.--Map showing the distribution of magnetic concentrates containing anomalous amounts of copper, lead, zinc, barium, and strontium in the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik.

Jabal Atwid

Low-level copper anomalies are scarce in magnetic concentrates from the shonkinite pluton at Jabal Atwid; lead anomalies are absent, but positive zinc anomalies are common (fig. 10). Eleven out of 16 positive anomalous concentrations of zinc are present in samples with 80-97 percent magnetite; the other five contain 40-65 percent magnetite. Copper is erratically distributed with respect to the percentages of magnetite in the concentrates: one each of the three samples contain 90-95, 50-60, and 40 percent magnetite. The apparent preferential distribution of the zinc anomalies with high tenors of magnetite and of the copper anomalies with intermediate tenors of magnetite in the magnetic concentrates persists into samples from the shonkinite. Neither base-metal nor precious-metal deposits are indicated for the pluton of shonkinite from the geochemical data developed from the magnetic concentrates.

FERROALLOY ELEMENTS

The ferroalloy elements Ti, Mn, Co, Cr, Ni, and V substitute readily in the magnetite structure and are found in the accessory minerals observed in the concentrates: ilmenite, chromite, hematite, limonite, pyroxenes, and amphiboles. The resulting abundances of these elements in the magnetic concentrates depends on factors such as: (1) the ability of the ferroalloy element to substitute for Fe^{+2} and Fe^{+3} in the crystal lattice of magnetite; (2) the concentration of the element in the rock in which the magnetite crystallized; (3) the partition of the ferroalloy elements between magnetite and the other minerals with which the magnetite crystallized; and (4) the amount and the species of accessory minerals in the magnetic concentrates.

With the possible exception of vanadium in the magnetic concentrates from the syenite pluton to the southeast of Suq al Ithnayn, and the general exception of titanium because of the technical truncation of higher concentrations, none of these elements is abundant enough in the magnetic concentrates to be indicative of economic concentrations.

The weights of magnetic concentrates from standard samples of alluvium were shown to be low, which indicates that large magmatic segregation deposits of magnetite are not present in these syenite plutons.

Titanium

The upper reporting value of titanium at G(2) percent in the magnetic concentrates prevents determination of the highest anomalous concentrations of titanium in the areas of the syenite and shonkinite plutons (figs. 13-15), but titanium may reach as high as 5-6 percent in the magnetite itself. This estimate is based on a value of 10.95 percent TiO_2 (equal to 6.6 percent titanium) reported for segregations of magnetite in the pyroxenite-hornblendite core of the layered complex of syenite and gabbro at Lakathah, Saudi Arabia (Martin and others, 1979, table 1). Positive anomalous concentrations for titanium in the magnetic concentrates relate more closely to the source rocks of the concentrate than to the amount of magnetite in the concentrate, showing that the source influences the titanium content. For example, concentrates from the Sabya Formation in the Jabal Fayfa and Jabal Bani Malik areas contain as little as 0.2 percent titanium in a concentrate consisting of 99 percent magnetite, whereas concentrates from the syenite plutons can contain as much as G(2) percent titanium in the presence of only 50-60 percent magnetite. The fact that titanium readily substitutes in magnetite does not mean that the most magnetite-rich concentrates contain the highest tenors in titanium, which shows that other minerals are also sources for the element. Unless the titanium content is great enough to permit the by-product recovery of the element, ores with more than a few tenths of a percent of titanium are unsatisfactory, and their use as a source of iron depends upon the economic separation of iron from titanium (United Nations, 1970).

Manganese

Anomalous concentrations of manganese are absent in magnetic concentrates from the syenite plutons at Jabal Fayfa and Jabal Bani Malik (fig. 13), but they are common in concentrates from the wall rocks of the pluton at Jabal Bani Malik. The samples from the wall rocks are generally weathered, rich in secondary hematite, and contain only 10-65 percent magnetite. In these magnetic concentrates, the manganese appears to be enriched in the secondary hematite. The only manganese anomaly in the magnetic concentrates from the area of the syenite pluton to the southeast of Suq al Ithnayn (fig. 14) is in a concentrate containing 50 percent magnetite. Manganese anomalies are most common in the magnetic concentrates from the area of the shonkinite pluton at Jabal Atwid (fig. 15). Considerable variation (40-97 percent) in the abundance of magnetite, is represented in the anomalous samples, but the principal accessory minerals are quartz, feldspar, biotite, and pyroxene with only traces of limonitic stain. The amount of limonite does not appear to be sufficient to be a factor in the manganese anomalies. The magnetite itself is thought to be the source of anomalous concentrations of manganese at Jabal Atwid.

Cobalt, chromium, and nickel

The low positive anomalous concentrations for Co and Ni are somewhat more common in magnetic concentrates from the wall rocks of the syenite plutons than in concentrates from the plutons themselves (figs. 13-14). Chromium is more commonly anomalous in magnetic concentrates from the plutons than from the wall rocks. Both Cr and Ni in the magnetic concentrates reflect the abundances in the rocks of the source areas, but cobalt does not, according to a comparision of mean and anomalous amounts of the elements in the rocks and concentrates (values given in table 18 for rocks are from Overstreet and others, 1984a, tables 3-5 and 10-12).

Although the mean concentrations of chromium in the rocks of the syenite plutons is 300 ppm, anomalous concentrations of chromium in the magnetic concentrates are 2000 ppm. The rise in the mean chromium concentration to 500 ppm in the shonkinite pluton is accompanied by a rise in the anomalous concentration of chromium in the magnetic concentrates to 5000 ppm. Although the mean value for nickel drops from 50 ppm in the rocks at Jabal Fayfa and Jabal Bani Malik to 30 ppm in the syenite pluton to the southeast of Suq al Ithnayn, the respective anomalous concentrations in the magnetic concentrates fall from 300 to 150 ppm. Although the mean value for nickel rises to 100 ppm in samples of rock from the shonkinite pluton at Jabal Atwid, the anomalous value for the element in magnetic concentrates increases sympathetically to 500 ppm.

The anomalous concentrations for cobalt in the magnetic concentrates decrease as the mean concentrations for cobalt in the rocks increase. This effect is the product mainly of the highest anomalous value for cobalt being in magnetic concentrates from the wall rocks of the pluton at Jabal Bani Malik, where the concentrates contain mainly 60-80 percent magnetite with common secondary

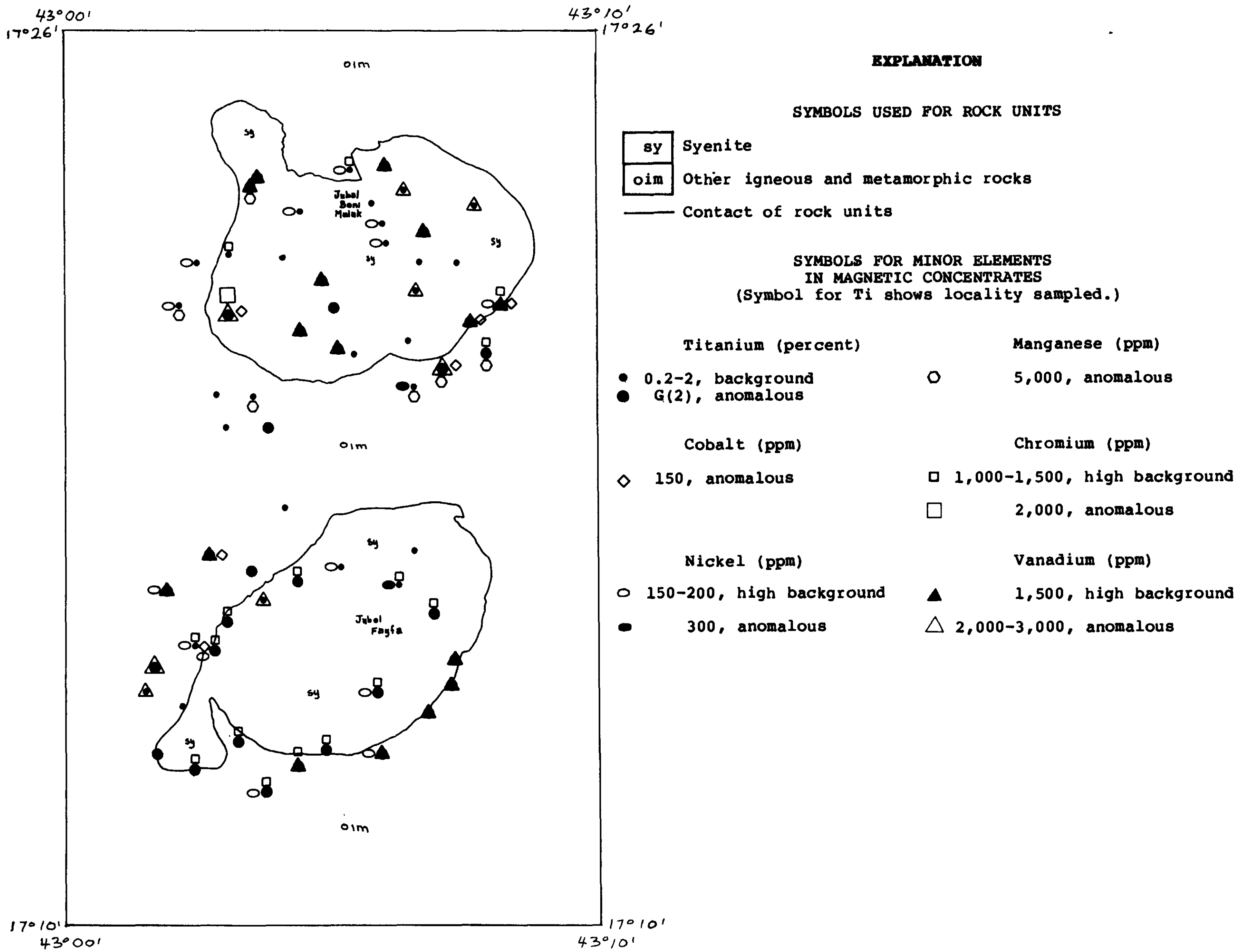


Figure 13.--Map showing the distribution of magnetic concentrates containing anomalous amounts of titanium, manganese, cobalt, chromium, nickel, and vanadium in the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik.

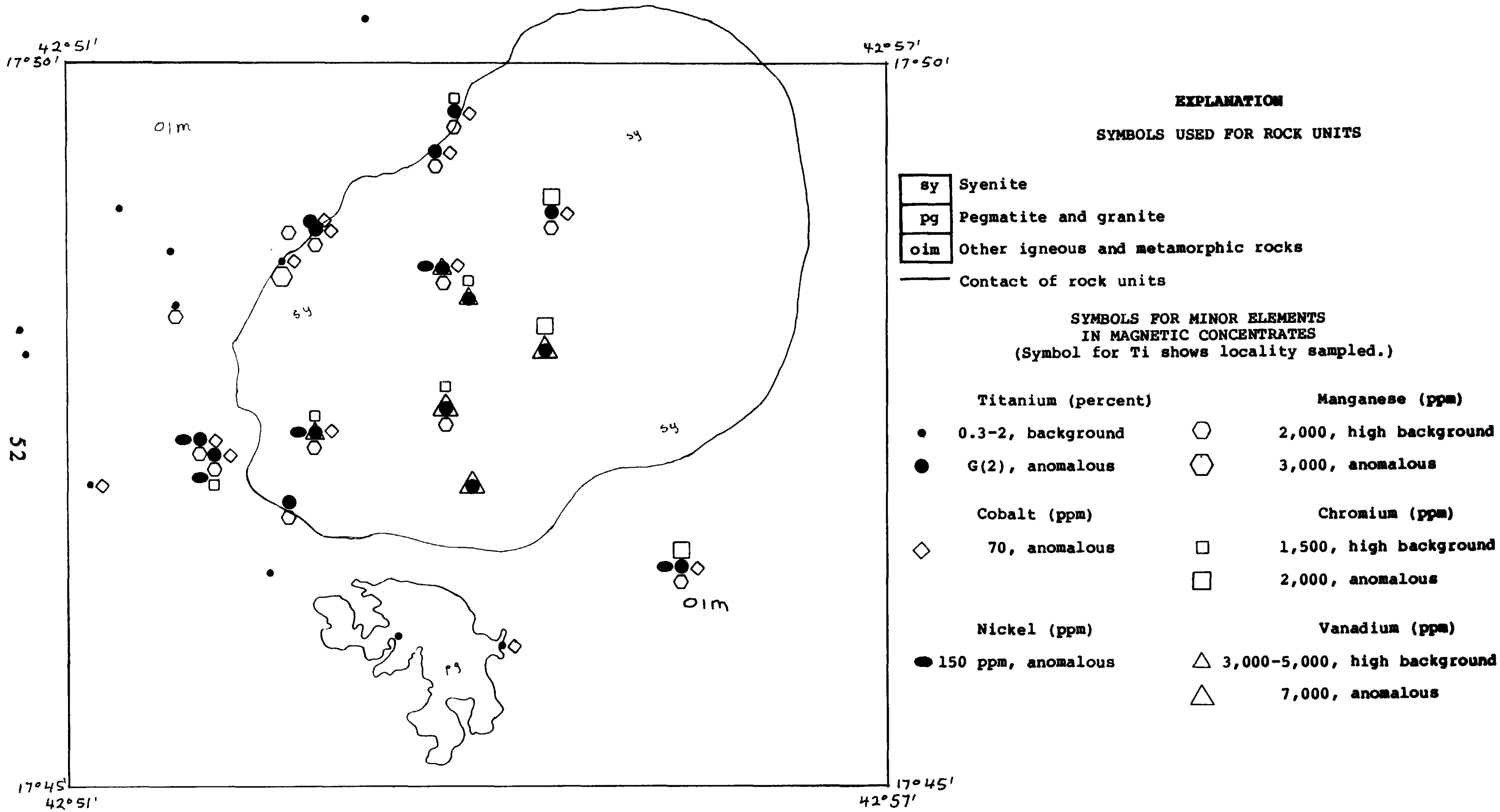


Figure 14.--Map showing the distribution of magnetic concentrates containing anomalous amounts of titantium, manganese, cobalt, chromium, nickel, and vanadium in the area of the syenite pluton to the southeast of Suq al Ithnayn.

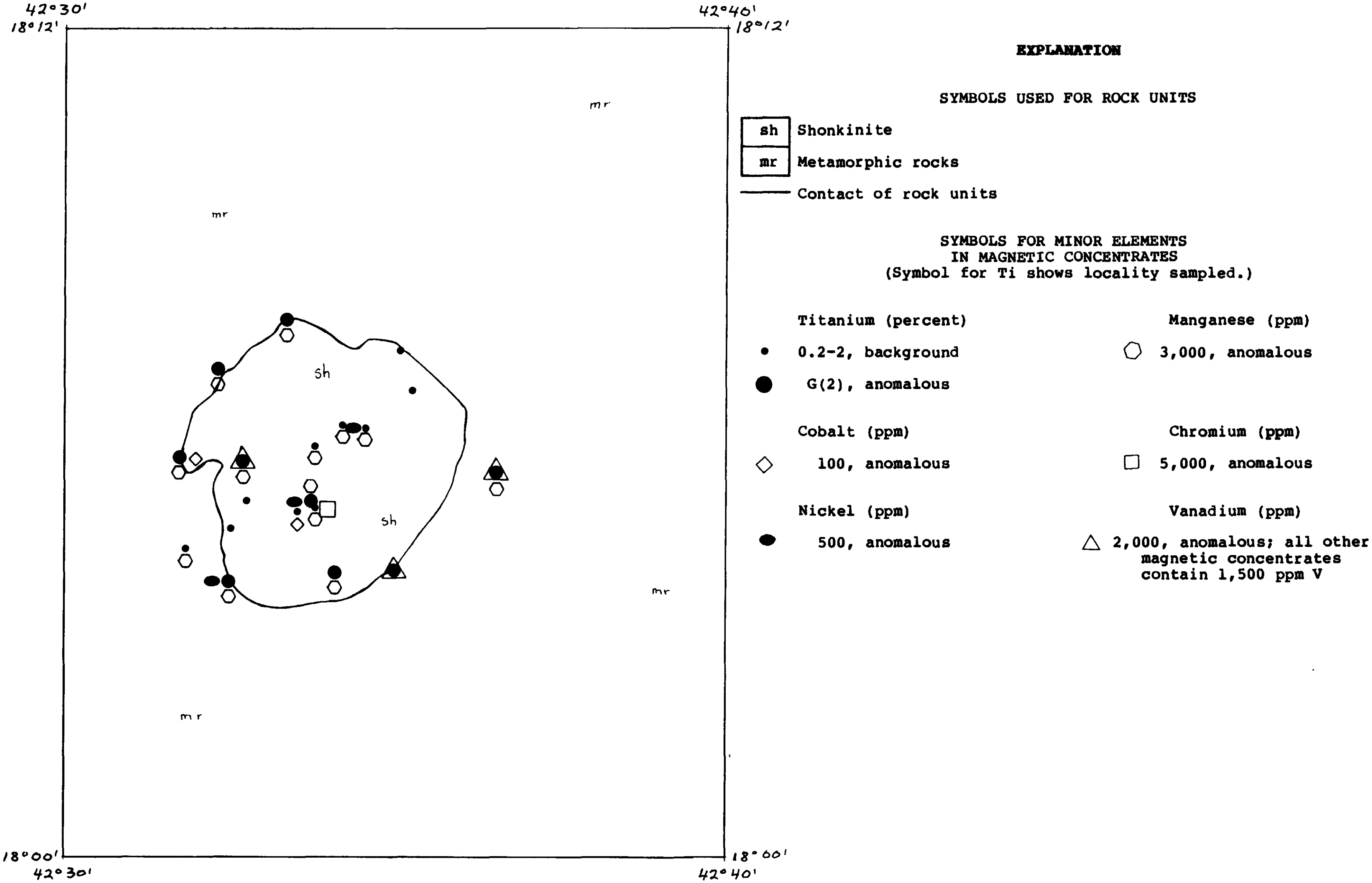


Figure 15.--Map showing the distribution of magnetic concentrates containing anomalous amounts of titanium, manganese, cobalt, chromium, nickel, and vanadium in the area of the shonkinite pluton at Jabal Atwid.

hematite. The rise in the cobalt content of this material reflects secondary processes of coprecipitation of Co and Fe in the hematite. Primary magmatic influence on the cobalt content of the magnetic concentrate is thus obscured.

Table 18.—Cobalt, chromium, and nickel analyses of rocks and magnetic concentrates

Areas and sample media	Values in parts per million		
	Co	Cr	Ni
Jabal Fayfa and Jabal Bani Malik			
Rocks			
Mean	10	300	50
Anomalous	30	500	150
Magnetic concentrates			
Mean	70	700	150
Anomalous	150	2,000	300
Plutons southeast of Suq al Ithnayn			
Rocks			
Mean	15	300	30
Anomalous	50	500	100
Magnetic concentrates			
Mean	50	1,000	70
Anomalous	70	2,000	150
Jabal Atwid			
Rocks			
Mean	30	500	100
Anomalous	70	700	300
Magnetic concentrates			
Mean	70	2,000	300
Anomalous	100	5,000	500

Vanadium

The amounts of vanadium in the magnetic concentrates most clearly reflect the percentages of magnetite of any of the ferroalloy elements. In the area of Jabal Fayfa and Jabal Bani Malik, the three anomalous magnetic concentrates and 16 of the 21 concentrates with high background values for vanadium consist of 80-97 percent magnetite. Five concentrates with high background values are composed of 40-65 percent of magnetite. Even higher percentages of magnetite are present in magnetic concentrates from the area of the syenite pluton to the southeast of Suq al Ithnayn where all concentrates with anomalous and high-background contents of vanadium are composed of 85-97 percent magnetite. In the area of the shonkinite pluton at Jabal Atwid, the three magnetic concentrates with positive vanadium anomalies consist of 80, 95, and 97 percent magnetite.

The mean vanadium concentration in the rocks in the area of the syenite pluton to the southeast of Suq al Ithnayn is 200 ppm (Overstreet and others, 1984a, table 4). A threshold anomalous value (7000 ppm) for vanadium in the magnetic concentrates shows that magnetite has an enormous capacity to scavenge vanadium. The much lower threshold anomalous value of 1000 ppm for the nonmagnetic concentrates (Overstreet and others, 1984a, table 11), combined with the mean value of vanadium for the rocks, indicate that other vanadium-bearing titaniferous minerals, such as ilmenite or rutile, are not unusually abundant or unusually enriched in vanadium in this pluton.

Although the threshold anomalous concentration of vanadium (7000 ppm, or 0.7 percent) in magnetic concentrates from the pluton of syenite to the southeast of Suq al Ithnayn is equal to the grade of vanadium in magnetite used for vanadium ore in some other parts of the world (Fischer, 1973, p. 685), the mean of 2000 ppm vanadium (table 9) is on the low side, and the amount of magnetite is small. These geochemical objections to the pluton as a possible source for vanadium are based on the results of reconnaissance sampling on wide spacing. More closely spaced sampling, including evaluation of detrital sources of magnetite, is required to determine the economic potential of the pluton as a source for vanadium-bearing magnetite for use as an ore of vanadium.

BARIUM AND STRONTIUM

The distribution of magnetic concentrates containing positive Ba and Sr anomalies for the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik, for the area of the syenite pluton to the southeast of Suq al Ithnayn, and for the shonkinite pluton at Jabal Atwid is shown on figures 12, 16, and 17, respectively. Neither element substitutes isomorphically in magnetite. Accessory minerals and inclusions are the principal sources for these elements in the magnetic concentrates. These sources are reflected in the tendency for lower percentages of magnetite to be in the concentrates with anomalous amounts of these elements rather than in the concentrates with high-background amounts of Ba and Sr (table 19).

The Ba and Sr geochemical anomalies in the magnetic concentrates does not indicate unusual local enrichment of the plutons in these elements. However, the distribution of strontium anomalies along the trace of a major fault in the northeastern part of the syenite pluton at Jabal Bani Malik (fig. 12) conforms with distribution of Be, Mo, and Sn in other sample media from the pluton (Overstreet and others, 1984a, fig. 5) and may indicate the presence of weak hydrothermal alteration associated with the fault.

Table 19.—Barium and strontium analyses of magnetite from magnetic concentrates

	Percentage of magnetite in magnetic concentrates					
	Jabal Fayfa and Jabal Bani Malik		Pluton to the southeast of Suq al Ithnayn		Jabal Atwid	
Element	Range	Average	Range	Average	Range	Average
Ba						
High background	10-90	60(9)*	50-98	85(23)	60-97	85(15)
Anomalous	10-75	40(5)	60-95	80(3)	40-80	65(4)
Sr						
High background	10-99	70(48)	50-98	85(25)	40-97	75(17)
Anomalous	55-95	75(13)	60	60(1)	80	80(2)

*Number in average.

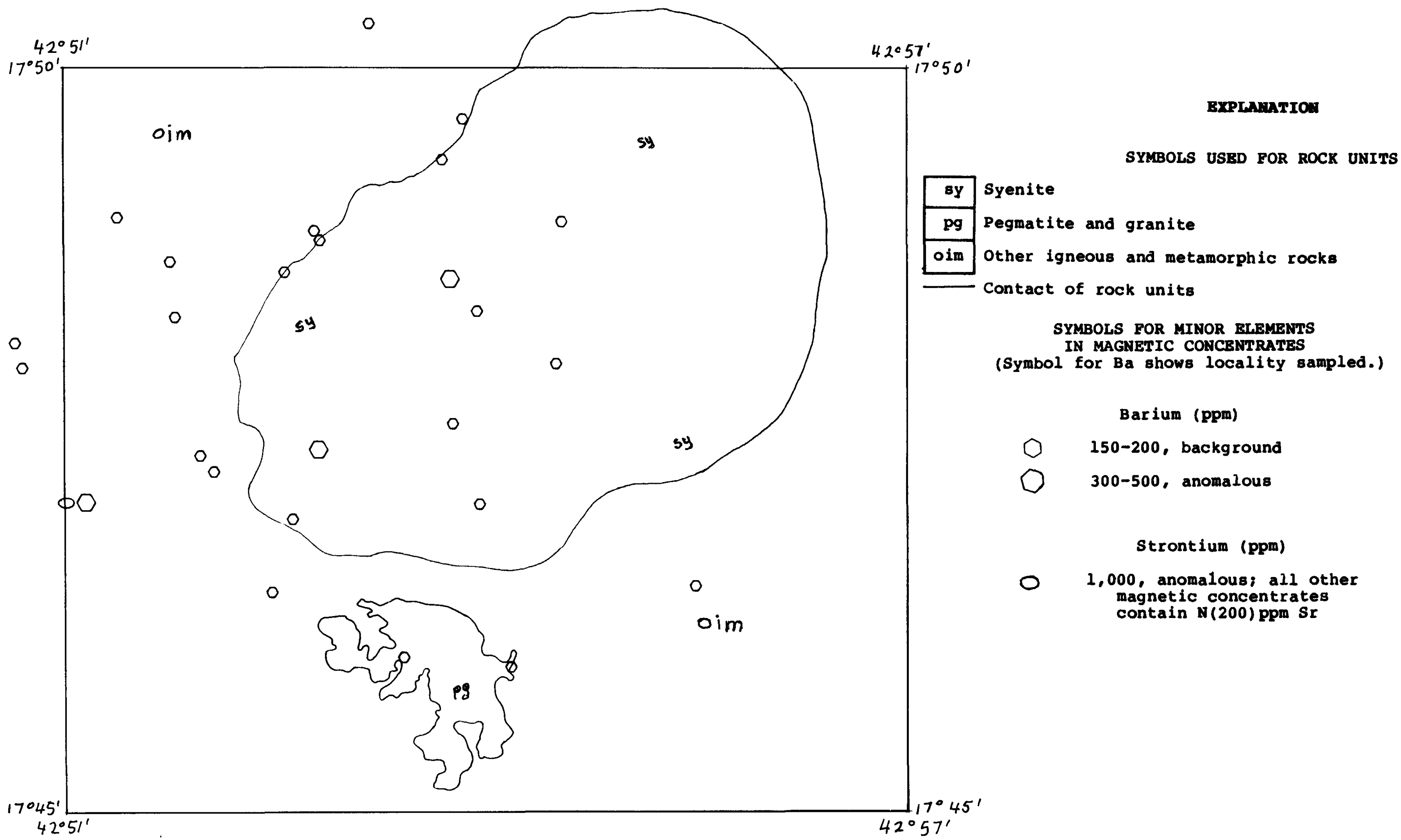


Figure 16.--Map showing the distribution of magnetic concentrates containing anomalous amounts of barium and strontium in the area of the syenite pluton to the southeast of Suq al Ithnayn.

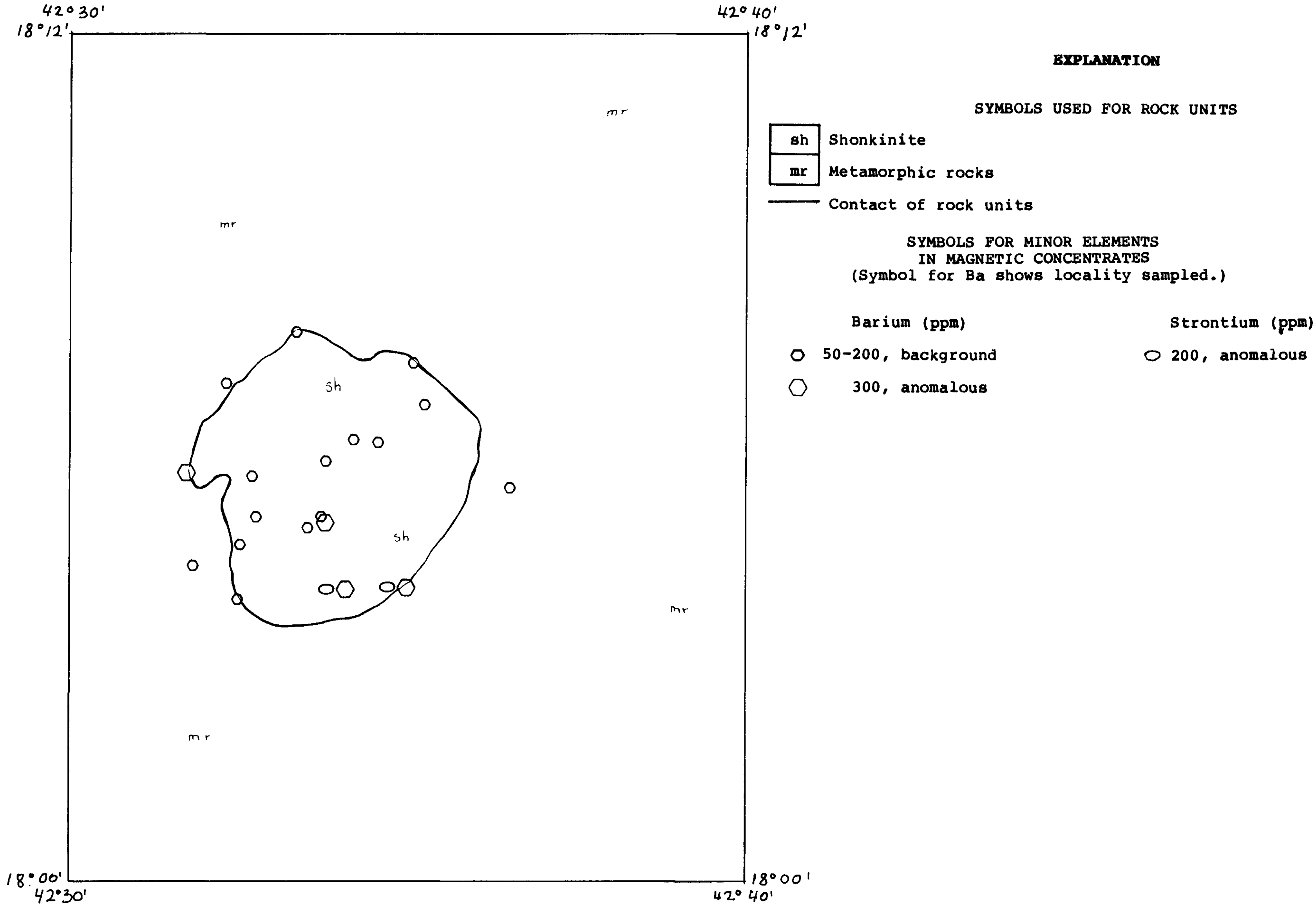


Figure 17.--Map showing the distribution of magnetic concentrates containing anomalous amounts of barium and strontium in the area of the shonkinite pluton at Jabal Atwid.

APPRAISAL AND RECOMMENDATIONS

Use of magnetic concentrates as a geochemical sample medium in the syenite-shonkinite province of the southern Asir provided anomaly enhancement for Be, Nb, and V over results obtained by the use of rocks, wadi sediments, raw concentrates, and nonmagnetic concentrates (Overstreet and others, 1984a). Data on weights of the concentrates from standard samples of wadi sediment permitted the interpretation that these syenite plutons and the shonkinite pluton are not accompanied by large magmatic segregations of magnetite.

Despite this expansion of data over that obtained from more usual geochemical sample media, the magnetic concentrate must be regarded as a special medium. These concentrates can be introduced where needed in programs of geochemical exploration where the results from conventional sample media are insufficient and the chemical characteristics of ferromagnetic and paramagnetic minerals would enhance the identification of anomalies. The factors that would influence the selection of magnetic concentrations as a geochemical exploration medium are scavenging by magnetite of Co, Cr, Cu, Mo, Ni, Sn, V, and Zn (table 16); incorporation in the magnetic concentrate of paramagnetic minerals containing Nb and(or) Ta; and the inclusion in magnetite of micron-sized grains of precious metals that might not appear in the other media.

SYENITE-SHONKINITE PROVINCE

Strong geochemical anomalies are essentially lacking in magnetic concentrates from the syenite-shonkinite province of the southern Asir.

Possible paramagnetic Nb-bearing minerals

The few niobium anomalies in magnetic concentrates from the area of the syenite plutons at Jabal Fayfa and Jabal Bani Malik (fig. 9) are interpreted to indicate the presence of a paramagnetic niobium-bearing mineral. Anomalous concentrations are too low to have economic significance, but the implication of the observation is that paramagnetic niobium-bearing minerals could be present elsewhere in the Arabian Shield and may be lost through processing of raw concentrates to remove magnetite. In other areas where niobium appears in anomalous amounts in nonmagnetic concentrates, it is recommended that the magnetic fraction from the same concentrate be examined for possible paramagnetic niobium-bearing minerals. This examination could only be made if the magnetic fractions resulting from the preparation of nonmagnetic concentrates were properly archived.

Beryllium at Jabal Fayfa

One magnetic concentrate from the syenite pluton at Jabal Fayfa contains a strong (70 ppm) beryllium anomaly (fig. 9). Raw concentrates from the same locality also show a strong beryllium anomaly (Overstreet and others, 1984a, fig. 5). The mineral causing the anomaly should be identified, and the area in the vicinity of the sample locality should be further tested for beryllium.

Vanadium in the syenite pluton southeast of Suq al Ithnayn

Although six magnetic concentrates from the syenite pluton to the southeast of Suq al Ithnayn contain high concentrations of vanadium (fig. 14), the mean value (2000 ppm) is low, and the amount of magnetite in the pluton does not appear to be great. However, these vanadium anomalies are the strongest geochemical anomalies observed in the syenite-shonkinite province; hence, further study of the pluton for vanadium in magnetite is recommended.

Prior to further investigaton of the vanadium content of magnetite from the syenite pluton to the southeast of Suq al Ithnayn, vanadium determinations should be made on the titaniferous magnetite contained in drill core from the intrusive complex at Lakathah (Martin and others, 1979). If vanadium does not reach high tenors in the magnetite from the layered intrusive complex at Lakathah, where the volume of magnetite is large, then further work on vanadium in magnetite from the syenite pluton to the southeast of Suq al Ithnayn would not be indicated, because magnetite is not abundant.

POSSIBLE APPLICATIONS ELSEWHERE IN THE ARABIAN SHIELD

As a special-purpose geochemical sample medium, magnetic concentrates have been successfully applied in several areas of exploration, including, but not restricted to, discrimination of intrusive rocks of different ages; identification of igneous rocks that are potential sources for the ores of Ag, Be, Co, Cr, Cu, Mo, Nb, Ni, Pb, Pt-group elements, Sn, W, and Zn; and localization of these metals in volcanic and metamorphic rocks. Some possible ways the medium could be used to improve knowledge of the distribution of metallic ore deposits in Saudi Arabia are recommended below; each would involve research into the most favorable analytical methods to use in order to locate the desired metals.

Blind base-metal sulfide deposits in metavolcanic rocks

Advantage might be taken of the scavenging effect of magnetite on zinc to explore for blind base-metal sulfide deposits in metavolcanic rocks of the Arabian Shield. The numerous outcropping base-metal sulfide deposits of the Arabian Shield, commonly accompanied by Au and Ag (van Daalhoff, 1974, pl. 1), include many syngenetic deposits in metavolcanic and metasedimentary rock units with a subvertical dip. The presence of outcropping deposits in subvertical strata at the present plane of erosion is evidence that similar, but blind deposits, are to be discovered at variable depths below that plane. However, drainage sediments, although shown to be a satisfactory geochemical sample medium in the southern Arabian Shield (Riofinex Geologic Mission, 1978, p. 10), did not prove to be successful in defining blind deposits. Magnetic concentrates where the abundance of zinc is enhanced compared to its tenor in alluvium, could be more effective, because an aureole of zinc-enriched magnetite could be expected to surround a sulfide body, and the proximate edge of the aureole intersected by the present plane of erosion could be expected to release zinc-rich magnetite into wadi sediments, although erosion has not reached the sulfide deposit itself. The presence of other elements, such as Ag, As, Au, Bi, Cd, Co, Cu, Hg, Mo, Ni, Pb, Sb, Se, Te, and Tl, might also be expected in the magnetite in anomalous amounts at some distance from the sulfide body. Development of techniques to determine these 76 elements, particularly the more volatile members of the group, in the presence of overwhelming amounts of iron would be needed to extract the maximum data from the magnetite for use in supporting interpretations of sources in blind sulfide deposits. Methods for determining Ag, Bi, Cd, Co, Cu, Ni, Pb, and Zn in single solution are readily available (Nakagawa, 1975).

A suitable area for investigation would be the vicinity of the Al Masane Zn-Cu-Ag-Au mine (lat 18°10' N., long 43°50' E.). Detrital magnetite would be collected from small wadis in the vicinity of the mine and analyzed for the broad spectrum of elements included in the above list to develop suitable methods for analysis and to compare the abundances of these elements in the magnetic concentrates with their abundances in rocks and ores at the mine. If clear evidence for the presence of ore metals and indicator elements were found in the magnetite, then the method could be used in the steeply dipping metavolcanic and metasedimentary rocks bounded by lat 17°30' N. and 18°30' N., and by long 43° E. and 44°30' E. The presence in this area of plutons of postorogenic granitic rocks that are potential sources for Be, Mo, Nb, Sn, Ta, Th, and the rare-earth elements (Stoeser and Elliott, 1979, fig. 6) adds to the attractiveness of a test of possible applications of magnetic concentrates as a geochemical sample medium in the Arabian Shield.

Platinum-group elements

An anomaly-enhancement technique used in the search for micron-sized platinum-group elements in layered mafic intrusive rocks has been developed by the senior author through the analysis of detrital magnetite from the placer-platinum deposits at Squirrel Creek, in the Goodnews Bay area, Alaska. The conceptual basis for the technique derives from the discovery of micron-size gold in ore at Carlin, Nevada. Micron-sized particles of gold do not accumulate in alluvial placers; thus, the technique of panning for gold concentrates is not applicable. Platinum of fine size may also not accumulate in placer deposits or be found in panned concentrates. Micron-sized platinum-group metals that precipitated in the early stages of the cooling of a mafic igneous rock, and did not increase in size owing to multiple centers of nucleation combined with low rates of migration, might serve as centers of nucleation in late-forming minerals such as magnetite and chromite. If magnetite from appropriate rocks contained inclusions of micron-sized platinum minerals, then the opportunity for the discovery of micron-sized platinum-group metals in these rocks is greatly enhanced, because detrital magnetite from those rocks could be recovered readily from alluvium. The test made at the Goodnews Bay deposits showed that platinum-group elements are indeed included as micron-sized particles in detrital magnetite. Their abundance is essentially in inverse correlation with the grain size of the detrital magnetite. The highest concentrations of the platinum-group metals (as much as 1100 ppm Pt) were in the finest-grained magnetite.

This work showed that detrital magnetite can be used successfully to enhance the opportunity for the discovery of platinum-group metals, but the method of analysis employing fire assay and emission spectroscopy (Cooley and others, 1976) is too slow for applied geochemical exploration. However, induction-coupled plasma spectrometry (ICP) techniques afford a feasible analytical method for production-line determination of the platinum-group elements.

Layered mafic plutons at Jabal Sha'i' (lat 18°45' N., long 42°53' E.), Jabal al Ashsha (lat 19°08' N., long 43°49' E.), and Hishshat al Hawi (lat 20°23' N., long 42°38' E.) (Coleman and others, 1972; 1977) are recommended for testing. A simple way to test these plutons for the presence of platinum-group elements would be to prepare panned concentrates from sediments in small wadis in the plutons, remove the magnetite with a hand magnet, sieve the magnetic concentrate to several size fractions, and analyze the sieved fractions of the cleaned magnetic concentrate. Previous experience in Alaska showed that satisfactory sieve sizes are by decreasing grain size of Tyler Standard Mesh sieves with mesh number 12(1.410 mm), 24(0.70 mm), 42(0.354 mm), 80(0.177 mm), and 170(0.088 mm), including material passing through the 170-mesh sieve. The nonmagnetic fraction of the concentrates should be archived for future study if platinum-group elements are identified in the magnetic concentrates.

DATA STORAGE

DATA FILE

Analytical data of magnetic concentrates analyzed in the laboratories of the USGS, Denver, Colorado, U.S.A., are stored there in Report No. 33829 in the Rock Analysis Storage System (RASS) as sample numbers EIW-131 through EIW-251.

Data and work materials used in preparation of this report are also stored in Data-File USGS-DF-04-43 (Overstreet and others, 1984d) at the office of the U.S. Geological Survey Mission in Jeddah, Saudi Arabia.

MINERAL OCCURRENCE DOCUMENTATION SYSTEM (MODS)

No updated information was added to the Mineral Occurrence Documentation System (MODS) data bank, and no new files were established.

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