THE MINERAL RESOURCE POTENTIAL OF THE WADI HABAWNAH AND NAJRAN QUADRANGLES, SHEETS 17/44 A AND 17/44 C, KINGDOM OF SAUDI ARABIA

by

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ABSTRACT

The metallic resource potential of the Wadi Habawnah and Najran quadrangles in the southern Precambrian Arabian Shield has been determined primarily by reconnaissance rock geochemistry, limited wadi-sediment and colluvium geochemistry, and gossanous and ferruginous outcrop geochemistry. These surveys were guided by geological information acquired during previous reconnaissance mapping.

Locally anomalous areas in alkalic and calc-alkalic granitic terrane are possible sources of niobium-zirconium-thorium-fluorite, tin-tungsten, and copper-molybdenum, although the potential of these areas does not appear to be outstanding. The reconnaissance geochemistry of the layered volcanic terrane and the geochemistry of gossanous and ferruginous outcrops indicate that the potential for stratiform base metal sulfide deposits is low.

INTRODUCTION

Location and purpose

This report records the study of the mineral resource potential of the Wadi Habawnah (17/44 A) and Najran (17/44 C) quadrangles (fig. 1). These quadrangles are located between lat 17°15' and 18°00' N. and long 44°00' and 44°30' E., about 675 km southeast of Jiddah.

Other resource assessments

Previous resource assessments in the Wadi Habawnah and Najran quadrangles by U.S. Geological Survey (USGS) personnel have been limited to local reconnaissance sampling of rocks, wadi sediments, and gossanous materials (Sable, 1982a,b; Elliott, USGS, unpub. data). During 1978-1980, the Riofinex Geological Mission conducted a detailed exploration program to assess the mineral potential of the Kutam-Al Halahila district to the west of the Wadi Habawnah quadrangle (Parker, 1982). As part of this program, 374 wadi sediment samples

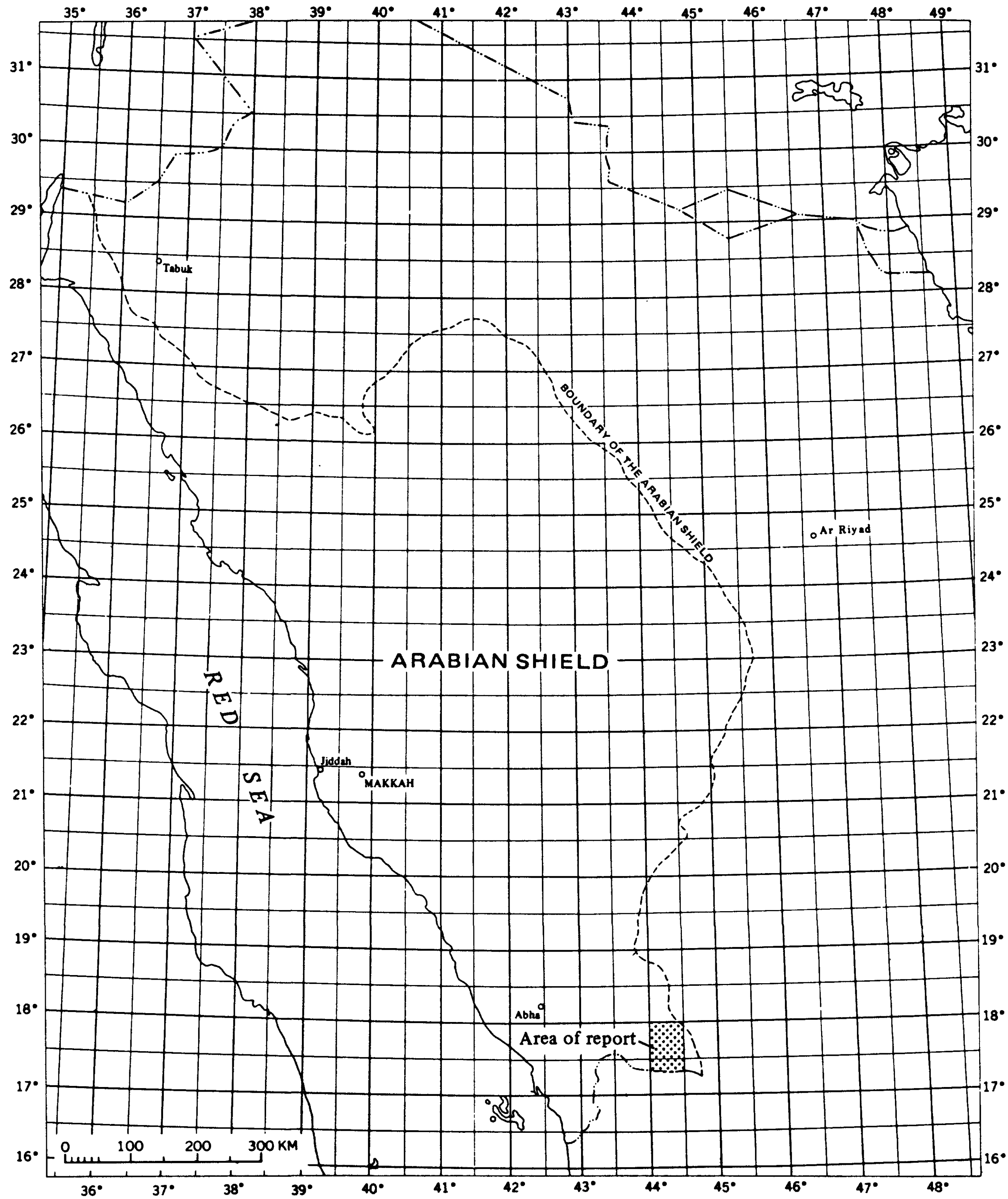

Figure 1.–Index map of western Saudi Arabia showing location of area of report.

were collected from the layered volcanic and volcaniclastic terrane at the western border of the Wadi Habawnah quadrangle. The sampling density was 3.7 samples/km^2. Only one anomaly was considered worthy of attention and its source was found to be pyritic, graphitic schist.

The Riofinex Geological Mission surveyed the area of layered volcanic rocks in the central part of the Wadi Habawnah quadrangle where Sable (USGS, unpub. data) had mapped many gossanous and ferruginous outcrops (Parker, 1982). A total of 645 wadi sediment samples was collected from an area of approximately 200 km^2, resulting in a sampling density of 3.2 samples/km^2. Seven anomalies were investigated and satisfactorily explained. After 3 years of work in the Wadi Habawnah and Mayza quadrangles, Riofinex recommended that further exploration could not be justified (Riofinex Geological Mission, 1981a, p. 15; 1981b, p. 12).

Present study

In areas with a history of mining it has been common practice to limit exploration to the vicinity of abandoned mines or sites of known mineralization. Now it is possible to identify deposits by exploring areas where geological reasoning suggests that ore bodies might be found, although no direct evidence of their presence may exist. An efficient and economical way to begin evaluating the mineral resource potential of a quadrangle is to identify areas having geology similar to that of known areas of mineralization and to determine large-scale geochemical variability within and between major rock units. Chemical variation of wall rock around mineralized zones and chemical zoning on a regional scale have long been recognized, and rock geochemistry is a recognized technique for the detection of mineralization over great distances. Any areas identified during the reconnaissance rock geochemistry survey as having a high resource potential can be explored in detail by using appropriate geological, geochemical, and geophysical methods. This approach is not designed to locate ore, but it will identify anomalous areas having significant potential as orebody hosts.

In the present study, samples were selected for analysis from the rock collection of E. G. Sable (137000- and 145000-sample number series). Extra samples were collected where coverage was inadequate (161000-sample number series). In addition to determining the regional rock geochemistry, gossans and ferruginous outcrops identified during geological mapping were evaluated.

An XRF spectrometer was used to determine the potassium, molybdenum, rubidium, strontium, yttrium, niobium, zirconium, thorium, and arsenic contents of rock samples. These analyses were performed by the author and by F. Elsass and A. H.

El Bazli. Copper, lead, zinc, gold, silver, nickel, cobalt, and chromium were measured using standard atomic absorption methods by the Directorate General of Mineral Resources (DGMR)/USGS chemical laboratory in Jiddah. Chemical analyses reported by Sable (USGS, unpub. data) and by Elliott (in press) were also used in this study. Analytical data for samples listed in this report are stored in U.S. Geological Survey Rock Analysis Storage System (RASS) computerized data file available from the office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah (Wilch, 1979).

ACKNOWLEDGEMENTS

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ROCK GEOCHEMISTRY CASE HISTORIES

An efficient and economical way to begin study of the mineral resource potential of a large region is to use bedrock geochemistry as a tool for broad mineral reconnaissance. Orientation studies on both mineralized and barren volcanic-sedimentary sequences and granitic plutons show that the variability of certain geochemical characteristics within and between major rock units may be helpful as guides toward economic mineralization. The following orientation studies were selected from a rapidly expanding literature because they describe techniques that could be used with the available laboratory facilities.

Plutonic terrane

Trace base metals are normally used in regional geochemical exploration of felsic plutonic igneous rock areas under the assumption that rock units having a high potential for base metal deposits will have a correspondingly high local background. In general, this relationship is probably true, especially on a regional scale. Warren and Delavault (1969) pointed out that during the decade prior to their study important mineralization had not been discovered in any areas in British Columbia where the copper content and the copper to zinc ratio (aqua regia acid leach) of the plutonic rocks were normal. Yet, in areas where plutonic rocks had highly anomalous copper contents and copper to zinc ratios, important mines were discovered, namely, the Bethlehem and Brenda mines. Wolfe (1974) also found that copper (hot nitric acid leach) and molybdenum (colorimetric) are highly enriched in granitic rocks that host mineralized quartz veins in the Setting Net Lake Stock, Ontario. Copper is enriched nearly eightfold and molybdenum 15-fold in the mineralized part of the stock. Unfortunately, the distribution of copper and molybdenum is generally erratic, reflecting its principal mode of occurrence as irregular sulfide veins, fracture fillings, and disseminations.

The Jurassic Younger Granites of northern Nigeria, comprising about 50 individual multiphase intrusions, constitute a tin province in which tin and niobium deposits are confined almost exclusively to biotite granite (Olade, 1980). More specifically, mineralization occurs as disseminations in albitized granite and as greisen lodes and veins. Most of the granitic rocks have higher than normal concentrations of tin. The genetically associated, peralkaline albite-riebeckite granite contains high concentrations of tin as well as enhanced niobium, beryllium, thorium, zirconium, and vanadium concentrations. Olade found that tin concentrations are erratic, and mean values show only a subtle contrast between tin-rich and tin-poor granite. However, the high coefficient of variation for tin in mineralized granite is a good criterion, along with niobium, rubidium, lithium, yttrium, zirconium, zinc, and lead, to identify granite having economic potential. Bowden and Kinnaird (1978) reported that zinc is an important constituent in vein-controlled mineralization consisting of sphalerite and genthelvite (zinc-iron-beryllium silicate). Commonly sphalerite exceeds the amount of cassiterite in the quartz veins and their greisen borders. Thus, zinc may serve as a pathfinder element toward the potentially commercial metals.

It has been generally accepted that because the ionic and atomic properties of rubidium and potassium are similar, these two elements should be strongly positively correlated. Rubidium, however, is commonly enriched relative to potassium in residual liquids resulting from fractional crystallization, perhaps as a result of the slightly larger ionic radius of rubidium. In contrast, the strontium ion is slightly smaller than calcium, and therefore, during magmatic differentiation strontium is depleted in residual liquids. For these reasons, K/Rb ratios are lower and Rb/Sr ratios are higher in strongly differentiated granite and pegmatite (Taylor and others, 1956; Heier and Taylor, 1959; Armbrust and others, 1977).

Rubidium and strontium are also very susceptible to metasomatic changes during metallization and alteration and hence provide sensitive indicators of these processes. Strontium is consistently depleted wherever hydrothermal activity involves alteration of plagioclase and the formation of potassium feldspar, sericite, or kaolinite. A study of the distribution of rubidium, K/Rb, and Rb/Sr may be useful to locate favorable alteration zones. Caution must be exercised because of the possible influence of weathering conditions on the Rb/Sr ratio. The removal of strontium during weathering may result in falsely anomalous Rb/Sr ratios.

After studying three major porphyry copper deposits in Chile, Armbrust and others (1977) concluded that rocks that have experienced potassic, sericitic, or propylitic alteration exhibit a two- to threefold increase in rubidium content and low K/Rb ratios. For example, at the El Teniente (Braden) mine, rubidium contents range from an average of 43 ppm in background andesite through 85 ppm in the propylitic zone to 155 ppm in biotite-altered rocks. Similarly, the K/Rb ratios range from 447 through 181 to 178. These types of alteration around porphyry copper deposits in British Columbia are also characterized by high Rb/Sr ratios as well as by high rubidium concentrations (Olade and Fletcher, 1976).

Lawrence (1975) studied the trace element variability of the lower Devonian Galway granite of western Ireland, which consists of adamellite and a porphyritic adamellite that is bounded by the Murvey granite, a leucogranite that is in turn cut by aplite and quartz veins. Molybdenum sulfide mineralization is confined to garnetiferous zones in the Murvey granite and the aplite veins and more commonly in quartz veins. The quartz veins carry tourmaline and fluorite and are the last fraction of the parental magma to crystallize. Hydrothermal alteration is restricted to very minor sericitization of potassium feldspar and chloritization of biotite. The Rb/Sr ratio increases away from the adamellite with a sixfold increase in the Murvey granite and a 20-fold increase in the garnetiferous Murvey granite. The aplite veins are enriched in rubidium as shown by a Rb/Sr ratio of nearly 43. The Rb/Sr ratio is an indicator of the fractionation sequence of the magma, and the anomalously high Rb/Sr ratio seems to be a diagnostic indicator of potential sulfide mineralization because molybdenum sulfides are restricted to garnetiferous Murvey granite, aplite veins, and quartz veins.

At the Blue Tier batholith, Tasmania, Groves (1972) found that the average K/Rb ratio of the tin-bearing biotite-muscovite granite is a low 37, relative to the older, barren biotite granite-adamellite, which has an average K/Rb ratio of 108. The Rb/Sr ratio of barren rocks is 5, in contrast to 207 for the mineralized granite. Olade (1980) provided confirmation in northern Nigeria, where tin-bearing granite is characterized by low K/Rb ratios that average 94.

At Wolfram Camp, Australia, the Rb/Sr ratio ranges from 17 in fresh or very slightly altered granite, to 25 in seriticized granite, to a maximum of 83 in muscovite-rich greisen that contains economic deposits of tungsten, molybdenum, and bismuth (Plimer and Elliott, 1979).

Extreme magmatic differentiation and subsequent sericitization and greisenization during a late-stage hydrothermal event result in gains and losses of various trace elements. For this reason, certain trace element abundances and ratios may serve well as regional guides to late-stage and altered differentiates that are potentially mineralized, but supplemental determinations of volatile content are required in areas of potential interest defined by these ratios because mineralization of any significance probably will not be present unless volatile content of the magma was adequate. Tauson and Kozlov (1973) and Sheraton and Black (1973) reported that tin-mineralized plutons had higher volatile contents, as indicated by higher lithium, boron, beryllium, and fluorine concentrations, than those in unmineralized granites.

Tischendorf (1977, 1979) has proposed averages for some trace elements that are normally found in enriched concentrations in "specialized" granites, which would include granitic bodies having the potential of carrying tin, tungsten, niobium, lithium, and molybdenum. These abundances, which are listed in table 1, may be compared with the abundances of elements in tin-bearing granites of Australia and Nigeria and in "normal" granitic rocks. Table 2 lists trace element contents for peralkaline granites that are sources of niobium, tin, zirconium, thorium, uranium, fluorite, gold, silver, and rare-earth elements.

Volcanic belts - syngenetic deposits

Base metal massive sulfide deposits associated with volcanic rocks and their sedimentary derivatives constitute an intrinsic part of these rocks, and the geochemistry of any particular group of these rocks might be expected to reflect deposits within them. In fact, several studies have demonstrated that it is possible to predict the existence of these deposits by determining the abundances of certain trace elements in the rocks, and these techniques may be generally applicable.

Zinc must be given consideration in searching for an element to discriminate between ore-bearing and barren volcanic rocks. It is a universal constituent of the massive sulfides of Precambrian shields and, unlike copper, shows only moderate variation from basic to acidic rocks. This latter feature is an important consideration in practical exploration because it dispenses with the need for a precise estimation of the silica content of samples for rock classification.

Table 1.--Trace element contents of specialized (tin) granites and normal granites

[All data are in parts per million. Leaders indicate no data available. Means are shown with ranges of values in parentheses. References: [1] Tischendorf (1977); [2)]Gerasimovsky (1974); [3] Taylor (1964, 1966, 1968); [3a] Turekian and Wedepohl (1961); [4] Tischendorf (1977, 1979); [5] Sheraton and Black (1973); [6] Olade (1980); [7] Groves (1972)]

	Normal granites			Specialized (tin) granites			
	[1]	[2]	[3]	Average [4]	NE Queensland, Australia [5]	Nigeria [6]	Tasmania, Australia [7]
Rb	200	200	145	580±200	366(291-427)	405(180-860)	1035
Sr	-	-	285	-	59(26-88)	(15-100)	5
Nb	-	20	20	-	-	130(50-300)	-
Y	-	-	40	-	-	200(35-480)	-
Zr	-	200	180	-	-	260(110-610)	-
Th	-	-	17	-	26(14-46)	50	-
Cu	-	-	10	-	7(6-8)	-	-
Pb	-	-	20	-	-	-	-
Zn	-	-	40	-	49(32-79)	(75-860)	-
Sn	-	-	3	30±20	9(5-16)	<30	49
W	-	-	2	7±3	-	-	-
Mo	-	-	2	3.5±2	-	-	-
F	-	-	735[3a]	3700±1500	-	4330(2200-6000)	10200
Li	-	-	30	400±200	-	80(14-347)	-
Be	-	-	5	13±6	-	-	-
K/Rb	-	-	240	<100	109(92-143)	94	-
Rb/Sr	-	-	0.5	-	8(4-16)	-	207
Nb+Y+Zr	-	-	240	-	-	590	-

Table 2.--Trace element contents of peralkaline granitic rocks

[All data in parts per million. Leaders indicate no data available. Means are shown in parentheses. References: [1] Radain and Kerrich (1979); [2] Drysdall (1979), Douch and Drysdall (1980); [3] Drysdall (1979); [4] Harris and Marriner (1980); [5] Harris and Marriner (1980), Drysdall (1979)]

	Average [1]	Jabal Tawlah[2]	Wadi Qaraqir[3]	Ghurrayyah [4]	Jabal Sayid[5]
Rb	356	-	-	2718-3319	-
Sr	11	-	-	58-234	<200
Nb	126	3244	530(293-1025)	1938-3311	70
Y	201	6460	1066(490-1900)	552-2559	50-300
Zr	1653	3730	6600(2000-8900)	2070-8830	700->1000
Th	-	912	80(37-194)	160-625	-
Cu	-	-	-	-	-
Zn	-	3071	105(84-152)	-	40-160
Sn	-	578	54(49-58)	321	<10
F	-	-	-	3400	-
K/Rb	92	-	-	9	-
Rb/Sr	32	-	-	11-57	-
Rb/Zr	0.22	-	-	-	-
Nb+Y+Zr	1980	47004	>2783	12400	>920

Davenport and Nichol (1973) investigated the geochemistry of the volcanic rocks of a portion of the Birch-Uchi Lakes greenstone belt, Ontario, Canada, in order to determine if it is possible to distinguish the Confederation Lake cycle, which contains an economic ore deposit and several similar subeconomic deposits, from the Woman Lake cycle, which contains no economic deposits. They found that the sulfide deposits of the Confederation Lake cycle are relatively richer in zinc and poorer in copper, cobalt, and nickel than those of the Woman Lake cycle and that the acid and intermediate rocks of the Confederation Lake cycle contain significantly higher zinc and lower copper, cobalt, nickel, potassium, and chromium than the corresponding rocks of the Woman Lake cycle. They suggested that the distribution of certain elements, in particular zinc (perchloric-nitric acid leach), in the intermediate and felsic rocks of volcano-sedimentary belts may be useful in identifying favorable areas for economic base metal mineralization.

Cameron (1975) and Wolfe (1975) have confirmed in the Bear and Slave provinces and the Superior province of Canada, respectively, the observation of Davenport and Nichol (1973) that increased amounts of zinc (nitric acid leach) are in volcanic strata bearing zinc-copper ore deposits. Cameron also emphasized the potential of zinc (nitric acid leach) in carbonaceous shales as a guide to massive sulfide deposits. Stratiform sulfide ore deposits in volcanic sequences developed on or near the sea floor by hydrothermal activity during intervals of active volcanism. During such times of quiescence, pyritic, carbonaceous shales were deposited in stagnant environments, which were ideal for the simultaneous precipitation of zinc and other metals that were dispersed in seawater from nearby hot springs. Carbonaceous shales from Timmons, Ontario, Canada, where several significant economic ore deposits exist, were found to be highly anomalous in several metals, especially zinc (Cameron and Baumann, 1972). Similarly, Lambert and Scott (1973) determined that in the region of Australia containing the McArthur zinc-lead-silver deposit favorable areas for locating deposits of this type should contain pyritic, high-potash, carbonaceous shales that contain zinc contents of 0.5 percent or more and significant lead and arsenic anomalies.

Garrett (1975) also conducted a lithogeochemical survey of the Proterozoic felsic volcanic rocks in the Bear province. The area contains high-level granite and granodiorite that are overlain by a volcano-sedimentary pile of basalt, andesite, conglomerate, red-bed sedimentary rocks, and ignimbritic tuffs and felsic flow rocks, which are intruded by younger granitic rock. The felsic flow rocks and tuffs, referred to as porphyries and having compositions varying from dacite to rhyolite, are the sites of mineralization. Silver is in veins with copper, cobalt, nickel, and uranium.

Copper is both in stratiform bodies related to iron formation, chert, and jasper units within the volcano-sedimentary pile and disseminated in altered andesites. Total and sulfide-held copper and zinc contents in the mineralized porphyries were determined, and high geometric means and arithmetic coefficients of variation were found to be useful indicators of mineralization.

The studies described above emphasize felsic intermediate sequences of volcanic rock, whereas Warren and Delavault (1969) studied andesite to basalt volcanic rocks that are located in British Columbia. Preliminary work suggested that exploration efforts would be justified in any area where more than 25 percent of the volcanic rock samples contain anomalous copper contents and (or) copper to zinc ratios (aqua regia acid leach). Warren and Delavault recommended that wherever there is more copper than zinc in a volcanic rock further sampling should be undertaken.

Cagatay and Boyle (1977) conducted a geochemical study of mineralized calc-alkalic volcanic rocks in the Eastern Black Sea metallogenic province of Turkey. In that province, massive stockwork and vein base metal and precious metal deposits are in the Upper Cretaceous dacites and andesites. Chemical exhalite zones associated with the massive sulfide orebodies do not consist of the typical iron-magnesium carbonates, cherts, jasperoids, or iron formations but instead are limited to hematized pumice tuffs (violet tuffs) or other hematized volcanic rocks. On a reconnaissance level, lead and zinc (nitric acid leach), arsenic, and fluorine effectively detected both blind and exposed mineralization. Because copper (nitric acid leach) is anomalous in the mineralized dacites as a whole, it is not a good indicator element for specific deposits. Hematitic tuffs overlying the sulfide deposits are enriched in some or all of arsenic, fluorine, copper, lead, zinc, cadmium, silver, and barium.

Bampton and others (1977) suggested that exploration in the Mount Isa region of Queensland, Australia, should be conducted to locate ironstones and other prospective stratigraphic units in dolomitic and carbonaceous sediments that contain anomalous amounts of copper. They cautioned against using the subsurface continuation of ironstones as drilling targets because most are not gossans; rather, the ironstones developed by precipitation of iron oxides either along fault zones or within permeable stratigraphic zones.

Rubidium and strontium show some potential as pathfinder trace elements in the search for stratiform base metal deposits in volcanic-sedimentary sequences. In Chile, enrichment of a copper-mineralized andesite ignimbrite in rubidium and depletion in strontium have resulted in a high Rb/Sr ratio relative to unmineralized rock (Losert, 1972; Oyarzun, 1975).

At Broken Hill, Australia, where no alteration zone is recognizable, the Rb/Sr ratio of the wall rocks has been increased, primarily by strontium depletion (Plimer and Elliott, 1979).

Volcanic belts - epigenetic deposits

Low-grade disseminated and fracture-filling copper mineralizations in volcanic and sedimentary sequences are commonly associated with intrusive complexes and include deposits classified as porphyry, skarn, replacement, and pyrometasomatic types. Gunton and Nichol (1975) found rubidium and strontium, along with copper and potassium, to be useful for identifying mineralized rocks in British Columbia, where a series of lavas and coarse pyroclastic rocks are bounded by low-silica intrusive complexes. Mineralization, which includes major copper deposits, occurs as disseminated and fracture-filling copper sulfides that increase in abundance adjacent to the intrusive complexes. Potassium, rubidium, strontium, total copper, and sulfide-held copper are enriched near the intrusions, and strontium, copper (perchloric-hydrochloric leach), and sulfide-held copper (ascorbic acid-H_2O_2 leach) are markedly richer in rocks associated with the major deposits.

WADI HABAWNAH QUADRANGLE - PRECAMBRIAN GEOLOGY

The following descriptions of rock units for the Wadi Habawnah quadrangle are extracted from Sable (USGS, unpub. data), who mapped the quadrangle at the reconnaissance level. Subsequent geochemical studies reported here are based on his observations of geology and geochemistry.

Metavolcanic flow rocks

Three north-trending belts of andesitic and basaltic flow rocks, sedimentary rocks, and greenstones (mvf) crop out along the western border, in the south-central part, and in the northeastern part of the quadrangle. The distribution of other flow rocks, which crop out as small, discontinuous masses engulfed by intermediate intrusive rocks, suggests a past continuity between the latter two separate volcanic belts.

Andesitic to basaltic flow rocks are dark, dense, aphanitic to finely crystalline, partly porphyritic, and partly amygdaloidal. Pillow structures and flow breccia have been observed. Interlayered tuff, breccia, siltstone, and shale are minor associates. Greenstones in all three belts consist of chloritic rocks and amphibolite. Interlayered, porphyritic felsophyre units may be contemporaneous flows of felsic composition, younger sills, or metasomatic alteration products.

Pyrite is locally common as disseminations and replacements. Both pyrite and pyrrhotite were observed in massive form in association with gossans (see below).

The flow rocks are clearly intruded and locally altered by granitic rocks of different compositions and inferred ages. The relationships between flow rocks and dioritic and gabbroic intrusive rocks are less certain, although local intrusive contacts with intermediate plutons have been observed. Otherwise, contacts, as observed on aerial photographs, appear to be gradational or faults.

The metavolcanic flow rocks are believed to be the oldest layered rocks in the quadrangle. They are compositionally similar to those of the Wassat formation of the Jiddah group mapped in the Wadi Wassat quadrangle (Greenwood, 1980) and to the metavolcanic unit of the Jiddah group mapped in the Mayza quadrangle (Anderson, 1979).

Metavolcanic and metasedimentary rocks

The metavolcanic and metasedimentary rock unit (mvs) consists of about 50 percent greenstone and andesitic flow rocks, 30 percent slate and wacke, 10 percent or less pyritic, graphitic slate and schist, and 10 percent or less dacitic crystal and lithic tuff. The unit includes mafic to felsic sills and a discontinuous belt of flinty porphyritic rhyolite or dacite (rd) near the western border of the quadrangle.

Andesitic flow rocks are similar to those in the underlying metavolcanic flow unit (mvf). The immature slates and wackes are poorly sorted, with appreciable amounts of interstitial clay. Dacitic tuff and tuffaceous wacke contain lapilli, glass shards, and considerable amounts of dark carbonate. Thin, discontinuous beds of marble contain interstitial graphite and sericite and, in places, irregularly shaped, dismembered fragments of black chert. Some slates and schists contain laminations and lenticular concentrations of graphite, many with pyrite.

Metasedimentary rocks

The metasedimentary rock unit (ms) is mostly slate, schist, mudstone, tuff, and tuffaceous wacke with less than 20 percent graphitic slate and schist, less than 10 percent carbonate rocks, and less than 10 percent flow rocks and sills. These rocks are similar to those lower in the sedimentary sequence, but they exhibit lighter hues and higher quartz contents.

Paragneiss

Paragneiss, including possibly orthogneiss, crops out in three small belts within the southern part of the Wadi Habawnah quadrangle (mdsa, pgsa). The units consist mostly of tonalite, quartz diorite, and amphibolite gneiss with some greenschist, quartz-microcline-albite-biotite-muscovite schist, and garnetiferous quartzofeldspathic gneiss. The rocks are layered on a gross scale, and some are mineralogically layered in outcrop.

Intrusive gneiss complex of Wadi A'Ashiba

A large area of foliated rocks in the east-central part of the quadrangle contains quartz diorite, quartz monzodiorite, tonalite, granodiorite, and monzogranite that are intruded discordantly by granite and quartz syenite. This gneiss complex has been mapped by Sable (USGS, unpub. data) as three gradational units: biotite-tonalite gneiss (tbg), tonalite-granodiorite gneiss (tgdg), and granodiorite-monzogranite undivided (gdmg). Apparently, some of the more felsic rocks are a result of metasomatism that accompanied extensive migmatization and granitic intrusion.

Metadiorite and metagabbro

Dark- to light-colored hornblende-biotite gabbro, diorite, and amphibolite with septa of andesite and greenstone (dg) have complex intrusive relationships with younger granitic rocks throughout a large part of the quadrangle. Melanocratic, fine-grained gabbro appears to dominate the unit to the northwest, whereas diorite seems more common near the northern border of the quadrangle. The unit also contains quartz diorite, tonalite, leucogabbro, leucodiorite, and albite-quartz pegmatites.

Olivine-hornblende gabbro and diorite

Massive, melanocratic olivine-oxyhornblende gabbro and minor diorite (gbd) are locally associated with metagabbro and metadiorite (dg). These appear to be posttectonic bodies injected into the older metamorphosed units.

Granitic rocks

Granitic rocks in the form of stocks and small batholiths occupy more than one-third of the Wadi Habawnah quadrangle. Modal data from plutonic granites indicate that there are two distinct types of granitic rocks: a two-feldspar, biotite-hornblende calc-alkalic granite and a one-feldspar alkalic granite. The first group is subaluminous to metaluminous, and it is commonly monzogranite, ranging to syenogranite.

Some monzogranite contains arfvedsonite and riebeckite, possibly a result of soda metasomatism originating from alkalic granite plutons. The second group is mostly metaluminous to peraluminous, and it includes syenogranite to alkali-feldspar granite. The corresponding syenite is characterized by sodic amphibole and to a lesser extent by sodic and other pyroxenes.

According to the degree and kind of deformation and alteration that are interpreted from the crystal fabric and mineralogy, the monzogranite and syenogranite appear to have been emplaced in both syntectonic and posttectonic stress environments. The alkalic granite bodies apparently were intruded and cooled in a passive, posttectonic environment.

Mixed layered and intrusive units

Several units of mixed rocks are mapped in the quadrangle: 1) complex migmatite terrain containing granite, metadiorite, and metagabbro (dggu, sgd); 2) rocks partly altered to felsophyric texture by metasomatism (fpmv, fp, fpdg); 3) granitic gneissic rocks, which were apparently altered by potassium metasomatism from rocks of tonalitic to granitic composition (tgdg, gdmg); and 4) intrusive rocks with isolated septa of invaded rocks of similar composition, such as andesite and basalt metavolcanic flow rocks intruded by the metadiorite-metagabbro unit (dgv). The last unit contains numerous ferruginous bodies, some of which are associated with sulfide minerals.

NAJRAN QUADRANGLE - PRECAMBRIAN GEOLOGY

The following descriptions of rock units are from Sable (USGS, unpub. data), who mapped the quadrangle at the reconnaissance level. Subsequent geochemical studies reported here are based on his observations of geology and geochemistry.

Metavolcanic flow rocks and greenschist

Dark andesitic to basaltic volcanic rocks containing interlayered dark-greenish schist (mvfs) are dominant in a belt at the western border of the quadrangle. The rocks are dense and massive or schistose, and some are amydaloidal and porphyritic. Thin sodic schist beds interlayered with the volcanic flow rocks are thought to be of sedimentary origin with later sodic alteration from the adjoining plutonic intrusion. Rocks in this unit are continuous with, and similar in composition to, metavolcanic rocks to the north in the Wadi Habawnah quadrangle.

Felsophyre

A cryptocrystalline to fine-grained felsophyre (fp) is adjacent to the granitic pluton at the northwestern corner of the quadrangle. It is similar to the felsophyre described in the Wadi Habawnah quadrangle and the granophyre in the adjacent Mayza quadrangle (Anderson, 1979). Rocks are light in color, flinty, sometimes porphyritic, and rhyolitic to dacitic in composition. Disseminated pyrite is locally abundant. The felsophyre may be a flow or sill of felsic composition or an alteration product of older andesitic flow rocks.

Metasedimentary rocks

Metasedimentary rocks (ms) resting on volcanic flow rocks at the western border of the quadrangle include tuffaceous(?) schist and slate, graphitic slate and schist, amphibolite, and ferruginous-graphitic marble. This unit is a continuation of the metasedimentary rocks at the western border of the Wadi Habawnah quadrangle.

Tonalite and paragneiss

A complex, U-shaped, synclinally folded belt of tonalite-granodiorite-quartz diorite, with minor interlayered paragneiss, microgabbro, marble, and quartzite (tpg), is in the west-central part of the quadrangle. The rocks seem in part to have reached pyroxenite facies metamorphism, but they have since regressed to greenschist facies. Sodium metasomatism was probably caused by the introduction of the adjacent granitic pluton.

Paragneiss, schist, and amphibolite

In the eastern part of the quadrangle, a complex unit of light-colored, fine- to medium-grained gneissic and schistose rocks (fqg, qmh) is interlayered with amphibolite (pgsa). The rocks are quartz-biotite-garnet gneiss, quartz-microcline-oligoclase-biotite gneiss, amphibolite schist and gneiss, quartz-microcline-almandine garnet gneiss, gneissic quartz-oligoclase quartzite, and mica schist.

These gneiss and schist units may have been well-winnowed quartzofeldspathic sandstone prior to metamorphism, whereas the amphibolite represents volcanic flows. The rocks closely resemble the paragneiss and schist (mdsa, pgsa) to the north in the Wadi Habawnah quadrangle.

A thick unit of gneissic garnet quartzite and quartzite (fqg) is interpreted to underlie the gneiss unit (pgsa). A hornblende-quartz monzonite gneiss (qmh) may be interpreted to be a metaquartzofeldspathic sandstone unit underlying the quartzite (fqg) unit.

Biotite tonalite gneiss

The biotite tonalite gneiss unit (tbg) includes minor amounts of amphibolite, quartz diorite, diorite, and quartz monzonite. It is fine to medium grained and gneissic to schistose, with rough mineral layering. This gneissic unit is believed to be an orthogneiss that structurally overlies the adjacent paragneiss, schist, and amphibolite unit (pgsa) as a result of thrusting.

Metasedimentary rocks, diorite-gabbro, and amphibolite undivided

Greenschist, quartz-mica schist, amphibolite, metadiorite, metagabbro, quartz diorite, and quartz monzodiorite (msda) are intruded by granite along the Yemen border in the south-central part of the Najran quadrangle. These roughly layered rocks resemble the dioritic, amphibolitic, and tonalitic gneiss and schist in the Wadi Habawnah quadrangle to the north.

Granitic rocks

Distinctly different peraluminous (nearly peralkaline) and metaluminous (calc-alkalic) granites crop out in the Wadi Habawnah and Najran quadrangles. A granite that is intermediate to these two and compositionally variable also crops out in the Najran quadrangle.

The western part of the Najran quadrangle is underlain by the distinctive Najran pluton that ranges from perthite syenogranite to perthite alkali-feldspar granite and quartz syenite (sgpa). It is highly sodic with sodic amphiboles and is nearly peralkaline. Along the western side of this pluton, two distinctly different rock facies may be fine-grained border phases of the pluton. One is an alkali perthite-epidote syenogranite (sgpc), whereas the other is a fine-grained syenogranite (sgpf) that is compositionally equivalent to the main pluton.

The Wadi Vulm pluton in the middle of the area (gbac) consists of syenogranite to monzogranite. The rocks are less sodic and less perthitic than those in the granitic Najran pluton to the west, and apatite and fluorite are less abundant. The granite surrounds xenoliths, roof pendants, or infaulted blocks of biotite quartz diorite, tonalite, diorite, amphibolite, and greenschist. The two plutons are considered to be comagmatic, and the Wadi Vulm pluton is considered to be slightly older than the Najran pluton.

Two clearly discordant plutons at the Yemen border, the Wadi Selah pluton and the Wadi Farah pluton, are believed to be the youngest granitic plutons in the quadrangles because their unaltered mineral composition is similar to that of the presumed youngest granitic plutons in the Wadi Habawnah and Wadi Wassat quadrangles (Greenwood, 1980). The rocks are predominantly biotite-muscovite granites (mgm) with minor syenogranite to alkali-feldspar granite.

SULFIDE-BEARING AND FERRUGINOUS ROCKS

Sable (USGS, unpub. data) reported occurrences of locally ferruginous units, some of which include massive and disseminated sulfides. These ferruginous and gossanous rocks are mostly associated with andesitic to basaltic volcanic flow rocks, but some are in granitic rocks. Most of these occurrences are located in the central part of the Wadi Habawnah quadrangle (pl. 1). Spectrographic data retrieved from the RASS system for 22 samples of ferruginous rock collected from the Wadi Habawnah quadrangle by E. G. Sable and Ghanim Jeri Al Harbi (prospector, USGS Saudi Arabian Mission) show low metal concentrations (sample numbers 73982-983, 73985-987, 73989-990, 137010-013, 137033-036; 137038, 137520-522, 137584-585, 137587).

Massive pyrite was found in one gossan by Sable (1980, written commun.; area F7, pl. 1), and X-ray diffraction analysis detected pyrite and pyrrhotite as the only sulfide components in 17 rock samples (Sable, USGS, unpub. data). The present author found massive pyrite in only one gossan (area F23). The gossans and ferruginous rocks described below are practically barren of base and precious metals.

Plate 1 shows the locations of more than 40 ferruginous rocks. The author visited 36 of these locations and sampled 23 of them.

The terms "sulfide-bearing rocks" and "gossans", as used by Sable (USGS, unpub. data), appear after field inspection by the author to refer to any fine-grained material, mostly of volcanic origin, which has distinctive yellow-brown, maroon, lavender, pink, or red colors that indicate various proportions of iron and manganese oxides. In some places, the sides of large hills are multicolored and the colors may be visible for considerable distances (plate 1, area F14). At the other extreme are earthy, ferruginous rocks in areas of less than 10 m^2 (areas F2, F17, F18). Some of the exposures were not obviously discolored, altered, or sulfide bearing (areas F3, F4, F8, F9, F11, F12, F13, F19).

At area F6, fine- to medium-grained granitic rock surrounds about 8 m^2 of fine-grained ferruginous rock. Nearby, a quartz-filled shear zone about 0.3 m wide and 40 m long cuts the granite. The quartz vein has been partially excavated, presumably by ancient prospectors, to form a shallow trench less than 1 m and 20 m long. Minor quartz veining also occurs at areas F9, F10, F11, F12, and F13.

Areas F8 and F9 are prominent ridges underlain by thick granitic dikes. Area F10 is underlain by very fine grained, dark-gray to green volcanic rock that weathers brown, gray, and tan. Ferruginous rocks weathering red, pink, and yellow are very localized and minor. Area F1, which is reported to extend over a distance of 5 km^2 appears to consist of a few small, isolated, unrelated exposures of weathered volcanic rock.

Composite chip samples of ferruginous materials and supplementary alluvium and colluvium adjacent to the ferruginous outcrops were collected for chemical analysis. Table 3 shows that gold and silver contents did not exceed 0.06 and 2.1 ppm, respectively. One sample contained 140 ppm copper and the other 27 samples averaged 25 ppm copper. One sample contained 130 ppm zinc and the remaining samples contained an average zinc content of 35 ppm. Wadi-sediment samples were sieved into four fractions and each fraction was analyzed separately. All wadi-sediment and colluvium samples contained very small amounts of both copper and zinc (table 4).

REGIONAL ROCK GEOCHEMISTRY

The objective of the interpretation of exploration geochemical data is the recognition of samples that belong to a mineralized population. In order to recognize this anomalous population, it is first necessary to recognize a homogeneous background distribution that may be used as a standard for comparison. Histograms of the geochemical data are often used to identify the background distribution of trace elements, but such frequency distributions of data from apparently homogeneous sources are usually positively skewed. This empirical fact led Ahrens (1954) to postulate his "law of lognormality." Thus, data are transformed logarithmically prior to statistical analysis.

Ahren's contention has not gone unopposed (Chayes, 1954; Miller and Goldberg, 1955; Aubrey, 1956). It has been argued that there is no known satisfactory theoretical reason why an element distribution in a homogeneous parent population should be lognormal, and, where adequate control data are available, the samples in the higher concentration tail of the distribution often can be shown to belong to a different population (Govett and Pantazis, 1971; Govett, 1972). Some geochemists insist that a logarithmic transformation is self-defeating for exploration purposes because anomalous values tend to be eliminated (Chork and Govett, 1979). The need to assume that the background population has a normal or lognormal distribution prior to statistical treatment of data may

Table 3.--Trace element contents of ferruginous and gossanous rocks and vein quartz, Wadi Habawnah quadrangle

[All data are in parts per million. Leaders indicate not detected. Area locations shown on plate 1. Analyses by atomic absorption. Sample types: V = intermediate to mafic volcanic rock, GR = granitic rock; Q = quartz]

Area	Sample	Type	Au	Ag	Cu	Pb	Zn
F1	161314	V	0.06	1.3	30	10	15
F2	161305	V	.06	1.0	30	15	130
F3	161152	GR	.06	<0.5	5	<10	15
F4	161301	V	0	.8	30		55
F5	161308	V	.06	1.3	15	<10	25
F6	161307	V	.06	.8	30	<10	15
	161255	Q	0	< .5	15	0	60
F7	161316	V	.06	.9	35	10	10
F8	161151	GR	.06	.8	15	15	65
F9	161241	GR	.06	.7	25	10	50
	161242	GR	.06	< .5	10	10	35
	161294	V	<.05	< .5	< 5	<10	33
	161295	V	<.05	0	<10	<10	55
F10	161240	Q	0	< .5	5	10	10
	161292	V	.06	.6	20	-	55
	161293	V	0	.6	60	-	60
F11	161262	V	0	< .5	5	-	25
F12	161296	V	0	.3	15	-	20
F13	161243	GR	.06	< .5	10	<10	20
F14	161309	V	.06	.7	30	0	10
	161302	V	0	.9	45	-	60
F15	161310	V	.06	1.0	40	15	5
F16	161311	V	0	1.1	70	<10	15
F17	161303	V	.06	2.1	35	10	15
F18	161304	V	.06	1.7	140	10	85
F19	161263	V	0	.9	20	-	50
F20	161315	V	.06	.8	35	15	10
F21	161312	V	.06	1.6	35	10	25

Table 4.--Trace element contents of wadi sediments (Qal) and colluvium (Qc) associated with ferruginous rocks, Wadi Habawnah quadrangle

[All data are in parts per million. Area locations shown on plate 1. Analytical methods: Cu and Zn = atomic absorption, hot nitric acid extraction; CxCu and CxZn = atomic absorption, cold hydrochloric acid extraction]

Area	Sample	Type	ATSM mesh	Cu	Zn	CxCu	CxZn
F1	161366	Qc	-18 +60	55	65	15	20
F2	161365	Qc	-18 +60	50	75	30	45
F5	161387	Qc	-18 +60	15	40	5	10
F22	161371	Qal	-18 +35	50	55	20	30
	161376	Qal	-35 +70	55	70	25	35
	161381	Qal	-70 +200	40	55	20	30
	161386	Qal	-200	40	60	25	40
F9	161357	Qc	-18 +60	20	70	< 5	45
	161358	Qc	-18 +60	20	65	< 5	50
	161359	Qc	-18 +60	40	70	25	50
	161360	Qc	-18 +60	75	45	50	30
F10	161353	Qc	-18 +60	30	105	15	60
	161354	Qc	-18 +60	40	100	20	50
	161355	Qc	-18 +60	40	105	20	65
	161320	Qc	-18 +60	95	70	48	35
F12	161362	Qc	-18 +60	15	40	20	55
F13	161361	Qc	-18 +60	30	70	15	45
F14	161367	Qal	-18 +35	15	30	10	17
	161372	Qal	-35 +70	20	35	13	20
	161377	Qal	-70 +200	20	35	13	20
	161382	Qal	-200	40	50	30	30
	161368	Qal	-18 +35	50	30	25	17
	161373	Qal	-35 +70	50	30	28	17
	161378	Qal	-70 +200	35	35	28	20
	161383	Qal	-200	45	45	35	32
F16	161369	Qal	-18 +35	40	40	23	20
	161374	Qal	-35 +70	50	45	30	23
	161379	Qal	-70 +200	30	40	25	23
	161384	Qal	-200	30	50	23	30
F17	161363	Qc	-18 +60	60	45	47	35
	161364	Qc	-18 +60	65	40	35	20

be circumvented by using a nonparametric statistical technique such as the Mann-Whitney U-Test, which does not rely on the assumption of normality, and by using a block-averaging technique, which is a form of the commonly used moving-average method.

Plutonic terrane

Plutonic terrane in the Wadi Habawnah and Najran quadrangles was surveyed to determine the potential for copper-molybdenum, tin-tungsten, and niobium-zirconium-thorium-rare earth element mineralization. The block-averaging method was used to evaluate gold, silver, copper, lead, zinc, rubidium, strontium, yttrium, niobium, and zirconium rock geochemistry data.

According to the central-limit theory, the frequency distribution of the means of a trace element variable of samples collected from nonoverlapping blocks of ground will tend toward normality if the variable has a random spatial distribution throughout the surveyed area (Chork and Govett, 1979). If the spatial distribution of the measured variable is not random, the tendency will be toward a polymodal or positively skewed distribution. Ideally, the frequency distribution of block averages of copper content, for example, from an unmineralized plutonic terrane will have a random spatial distribution (background conditions) and will tend toward normality. The frequency distribution of block averages of copper for a mineralized plutonic terrane, however, will be skewed or polymodal, depending on the relationship between the size and position of the blocks in relation to the proportion of anomalous samples, the real size of the anomalous zone, and the number of anomalous zones. The averaging process tends to reduce sampling errors and minor local trace element fluctuations, thereby eliminating insignificant anomalies.

The Wadi Habawnah and Najran quadrangles were divided into a series of nonoverlapping blocks, each 3 km on a side, and the means of zinc and yttrium content were calculated for each block using analyses for rocks within the block. This procedure was repeated for two additional series of blocks having dimensions of 4 km and 5 km to determine if the size of the block significantly influences the threshold for the variable. Figures 2 and 3 illustrate the procedure whereby three histograms (3-km, 4-km, and 5-km block averages) are used to determine the thresholds of yttrium and zinc. Because the size of the blocks did not influence the threshold values in these two cases, the 3-km block was selected for the calculation of the means of the remaining elements. Histograms were constructed for a total of 11 elements, and anomalous values were identified by inspection of the skewed or bimodal distributions.

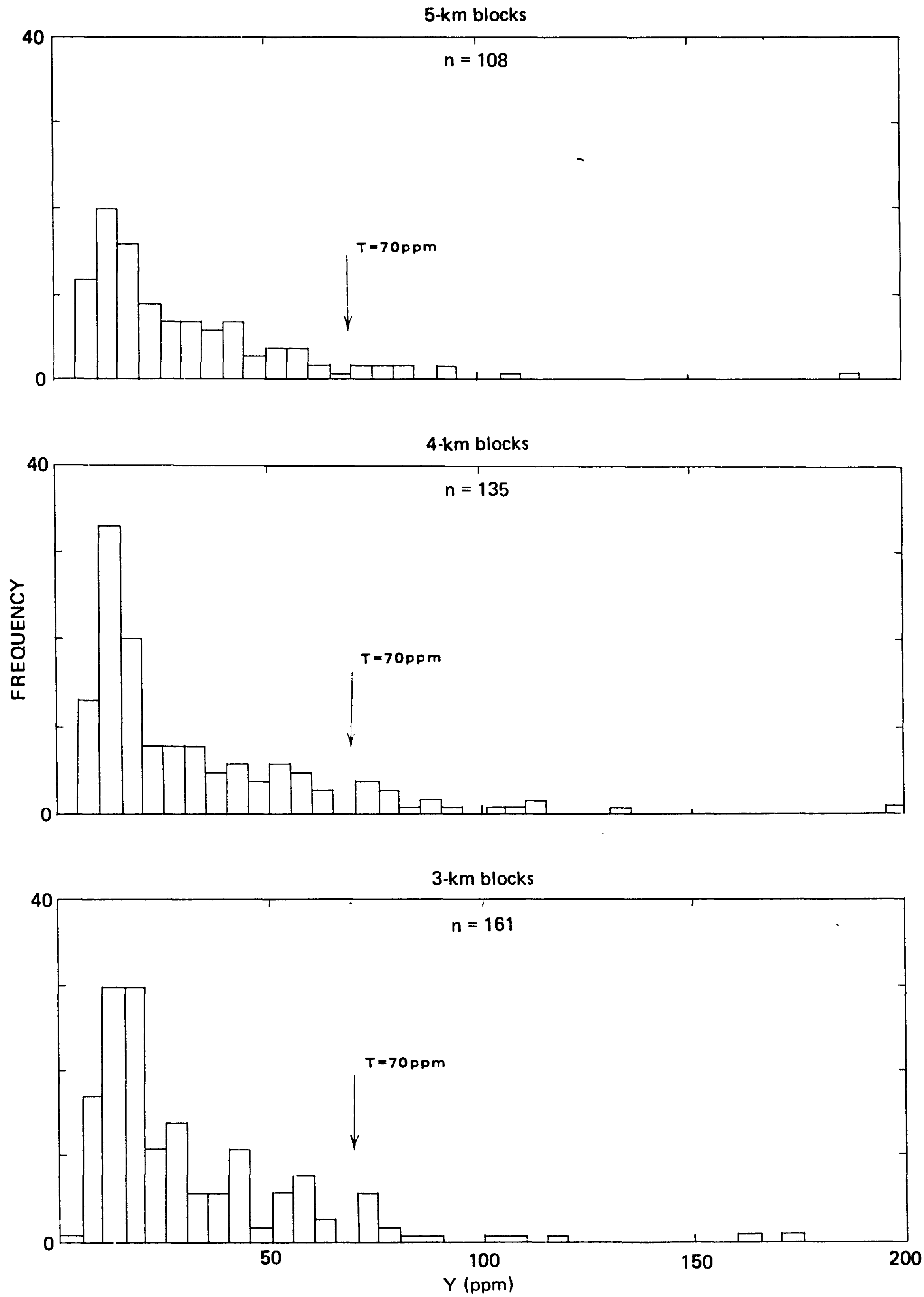

Figure 2.--Frequency distributions of block averages of yttrium in plutonic rocks, Wadi Habawnah and Najran quadrangles. (Analyses by XRF; n= number of block averages; T = threshold, 90th percentile, 70 ppm.)

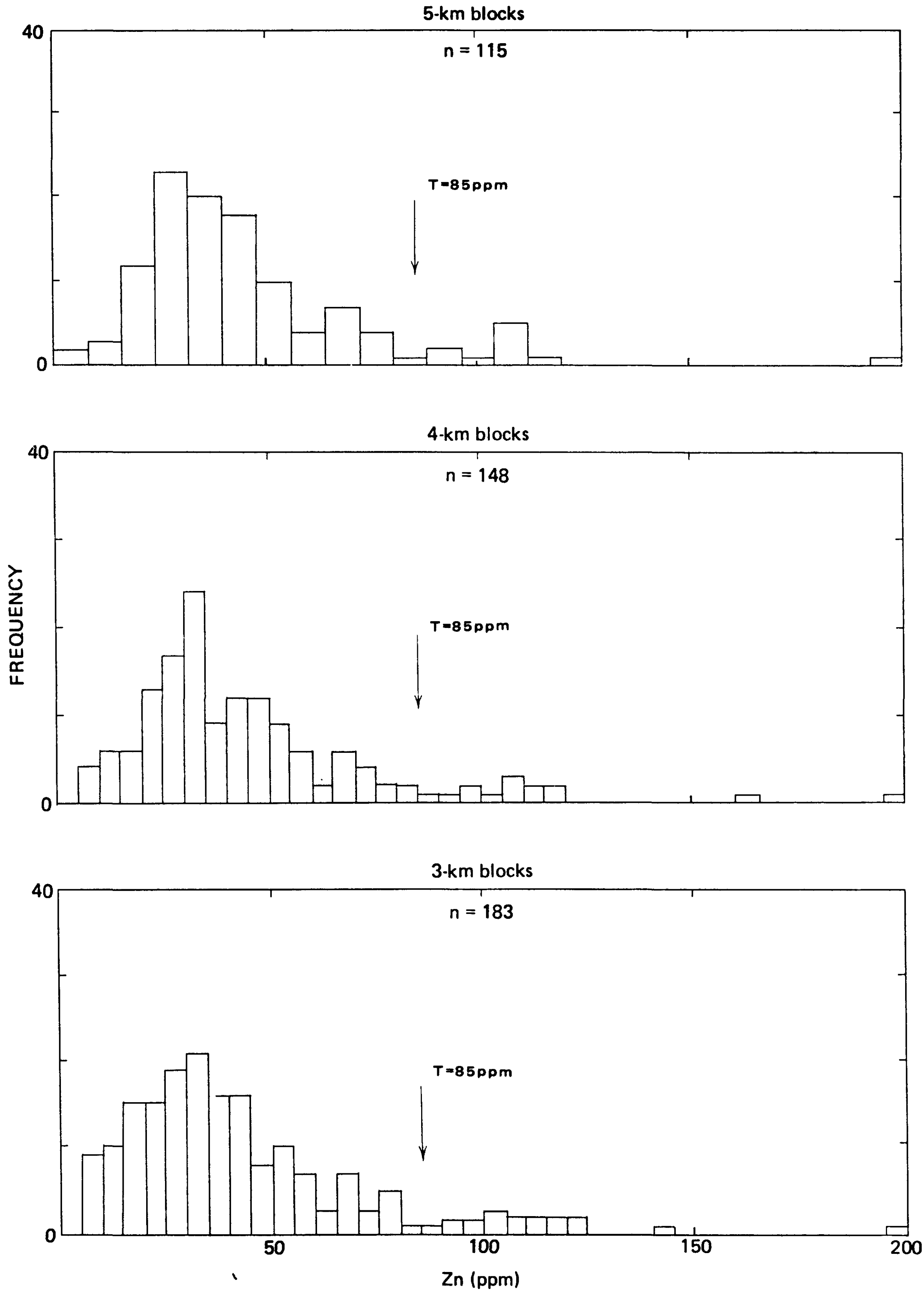

Figure 3.–Frequency distributions of block averages of zinc in plutonic rocks, Wadi Habawnah and Najran quadrangles. (Analyses by AA; n=number of block averages; T=threshold, 90th percentile, 85 ppm.)

All anomalous block-average values were plotted on the geologic map, and clusters of anomalous values were outlined as areas having potential for mineralization. Plate 1 shows both locations of the anomalous areas and the locations of samples within these areas that were collected by the author (161000-number series) and by Sable (137000-and 145000-number series). Five anomalous areas are described in table 5 as well as 15 additional anomalous samples that are geographically isolated and unrelated.

Areas A and B (pl. 1) are within the large Najran pluton that was classified as alkaline by Sable (USGS, unpub. data). Area A was defined by anomalously high block averages for niobium, yttrium, zirconium, lead, zinc, and rubidium and Rb/Sr and low strontium, whereas Area B has anomalous niobium, yttrium, zirconium, and zinc (table 5). All samples within Area A contained less than 28 ppm thorium, with the exception of sample 145176, which contained 34 ppm. A significant molybdenum content of 16 ppm was detected in sample 137717 from area A. Fluorine content of rocks collected by Sable from granite and adjoining felsophyre exceeded 640 ppm. A rock sample (137195) contained 63 ppm lithium, 1,760 ppm fluorine, and 10 ppm tin, and a sample (145144) from the felsophyre unit contained 20 ppm tin. Scintillometer readings were as high as 230 counts per second (cps), but the average of 35 measurements is 125 cps (table 6). The trace element chemistry of areas A and B is clearly not normal for granite, but the values for trace element contents do not reach the extreme levels characteristic of peralkalic granite.

Area C (pl. 1), which is defined by anomalous block averages of niobium, yttrium, zirconium, and zinc, encloses the Wadi Silah pluton on the North Yemen border (table 5). The pluton is unique because of its anomalous thorium content. Sable (USGS, unpub. data) noted a compositional similarity between the Wadi Silah pluton and the tin-bearing Jabal al Gaharra pluton about 70 km to the north-northwest, which was described by Elliott (in press). Sable also reported a rock sample (137830) from the pluton containing 20 ppm tin and 83 ppm lithium. Three rocks that he collected contained from 2,400 to 3,600 ppm fluorine. Radioactivity measurements averaging 315 cps (ranging from 200 to 540 cps) are the highest in the region table 6).

Area D, which is defined by three rock samples having low but anomalous copper content (45 to 95 ppm) and Cu/Zn ratios of as much as 3.0, is in the biotite-tonalite gneiss intrusive complex of Wadi A'Ashiba. Area E, which is defined by two rock samples containing anomalous copper (from 55 to 110 ppm), is a very small exposure of tonalite-granodiorite gneiss.

Table 5.--Anomalous areas in plutonic terrane defined by rock geochemistry, Wadi Habawnah and Najran quadrangles

[All elemental data are in parts per million. Leaders indicate not detected. Copper, lead, zinc, and silver are by atomic absorption analysis; all others are by XRF analysis]

Area	Samples	Nb	Y	Zr	Th	Rb	Sr	Rb/Sr	Mo	Pb	Zn	Ag	Cu	Cu/Zn	K/Rb
A	137062	17	82	813	<28	68	79	0.9	<11	35	125	-	-	-	-
	137151	37	111	439	<28	174	<10	>17.4	<11	10	25	-	-	-	-
	137712	26	80	482	<28	158	14	11.3	<11	15	50	-	-	-	-
	137713	23	73	470	<28	132	19	6.9	<11	<10	30	-	-	-	-
	137714	39	154	389	<28	220	12	18.3	<11	15	20	-	-	-	-
	137716	13	49	312	<28	126	33	3.8	<11	10	40	-	-	-	-
	137717	96	264	2333	<28	266	320	.8	16	<10	40	-	-	-	-
	137720	57	255	1451	<28	284	13	21.8	<11	30	200	-	-	-	-
	137723	17	139	338	<28	235	13	18.1	<11	<10	75	-	-	-	-
	137743	27	75	340	<28	169	23	7.3	<11	20	100	-	-	-	-
	137746	30	107	488	<28	152	28	5.4	<11	15	100	-	-	-	-
	137888	25	87	458	<28	141	43	3.3	<11	20	100	-	-	-	-
	145085	56	88	412	<28	200	25	8.0	<11	10	20	-	-	-	-
	145093	35	108	259	<28	290	<10	>29.0	<11	20	95	-	-	-	-
	145146	22	75	411	<28	147	23	6.4	<11	0	115	-	-	-	-
	145165	21	69	505	<28	169	87	1.9	<11	265	300	-	-	-	-
	145172	27	69	943	<28	90	13	6.9	<11	15	30	-	-	-	-
	145176	11	41	172	34	178	70	2.5	<11	10	30	-	-	-	-
	161252	22	54	634	<28	85	61	1.4	<11	<10	75	-	-	-	-
	161253	27	87	789	<28	105	56	1.9	<11	10	100	-	-	-	-
B	137878	27	78	815	-	-	-	-	-	-	85	-	-	-	-
	145136	22	72	397	-	-	-	-	-	-	200	-	-	-	-
	145138	19	58	592	-	-	-	-	-	-	100	-	-	-	-

Table 5.--Anomalous areas in plutonic terrane defined by rock geochemistry, Wadi Habawnah and Najran quadrangles-Continued

Area	Samples	Nb	Y	Zr	Th	Rb	Sr	Rb/Sr	Mo	Pb	Zn	Ag	Cu	Cu/Zn	K/Rb
C	137831	32	71	-	41	305	-	-	-	-	95	<.5	-	-	-
	137832	8	41	-	34	177	-	-	-	-	110	<.5	-	-	-
	137933	112	115	-	85	283	-	-	-	-	-	-	-	-	-
	145041	24	59	-	38	201	-	-	-	-	85	<.5	-	-	-
	145043	33	79	-	55	247	-	-	-	-	85	<.5	-	-	-
	145304	29	64	-	54	240	-	-	-	-	70	5.0	-	-	-
D	161223	-	-	-	-	-	-	-	-	-	-	-	95	2.1	-
	161233	-	-	-	-	-	-	-	-	-	-	-	50	1.0	-
	161237	-	-	-	-	-	-	-	-	-	-	-	45	3.0	-
E	161199	-	-	-	-	-	-	-	-	-	-	-	110	-	-
	161346	-	-	-	-	-	-	-	-	-	-	-	55	-	-
	161154	-	-	-	-	-	-	-	-	25	125	-	-	-	-
	137915	31	-	-	-	-	-	-	-	-	105	-	-	-	-
	137853	67	-	277	-	-	-	-	11	30	-	-	-	-	-
	161229	43	-	-	-	1061	-	-	-	40	-	-	-	-	30
	161254	44	-	-	-	331	-	6.9	-	-	-	-	-	-	104
	161192	-	-	-	-	-	-	-	-	-	-	-	70	1.6	-
	161247	-	-	-	-	-	-	-	-	-	-	-	70	3.5	-
	137426	-	-	349	-	-	-	-	-	-	-	-	55	1.6	-
	161227	-	-	-	50	-	-	-	-	-	-	-	65	-	-
	145057	-	-	604	-	-	-	-	-	-	150	-	-	-	-
	161351	-	-	-	-	-	-	-	-	-	-	0.8	-	-	-
	161352	-	-	-	-	-	-	-	-	-	-	0.8	-	-	-
	137963	-	-	-	-	-	-	7.2	12	-	-	-	-	-	-
	161256	-	-	-	-	-	-	-	19	-	-	-	-	-	-
	137469	-	-	-	36	-	-	-	-	-	-	-	-	-	-

Table 6.--Scintillometer readings of granitic plutons, Wadi Habawnah and Najran quadrangles

[From Sable, unpub. data. Scintillometer having 43.1-cm^3 NaI crystal used]

Pluton	Approximate location (north latitude, east longitude)		Number of readings	Range (cps)	Approximate mean (cps)
Wadi Silah	17°24'	44°20'	13	200 - 540	315
Wadi Gidda'h	17°47'	44°08'	5	220 - 280	225
Wadi Farah	17°24'	44°15'	8	150 - 240	200
Wadi Vulm	17°27'	44°18'	34	70 - 250	170
Wadi Ghezm	17°57'	44°03'	8	70 - 220	165
Najran	17°32'	44°05'	35	80 - 230	125
Jabal Waleh	17°55'	44°17'	4	70 - 160	120
Jabal Ya'arah	17°57'	44°25'	17	85 - 170	115
Wadi Thar	17°57'	44°12'	4	80 - 130	80

Of the remaining anomalous rock samples listed in table 5, samples 161229 and 161254 have high rubidium and niobium contents and are the only ones having anomalously low K/Rb ratios (30 and 104, respectively). Only two samples (161351 and 161352) contained anomalous amounts of gold (0.8 ppm).

In 1977, J. E. Elliott (USGS) collected rock and wadi-sediment samples from the Wadi Ghezm pluton in the northwestern corner of the Wadi Habawnah quadrangle. One of the rock samples (124077) contained 300 ppm tungsten, 30 ppm molybdenum, 2,760 ppm fluorine, and 193 ppm lithium (Elliott, unpub. data). Another sample (124078) contained 20 ppm molybdenum and 540 ppm fluorine. Nonmagnetic pan concentrates from wadi sediments contained as much as 100 ppm tin (124579) and 1,500 ppm zinc (124588 and 124589). The analyses suggest that the pluton has some potential as a site of mineralization. Eight additional rock samples were collected by the author in an attempt to confirm Elliott's data. Only one (sample 161154) of eight additional rock samples is anomalous in yttrium (74 ppm), lead (25 ppm), and zinc (125 ppm).

A few areas of interest were identified by Sable (USGS, unpub. data), one of which is the two-mica granite of the Wadi Farah pluton at the North Yemen border (pl. 1). One rock sample (137923) contained 20 ppm tin. Fluorine contents of four rocks from the pluton ranged from 1,008 to 4,400 ppm. Abundant quartz veins and some weak copper carbonate staining are at lat 17°27'59" N. and long 44°22'37" E., near the contact between hornblende quartz monzonite and the paragneiss schist-amphibolite unit (pgsa). Other sample locations are listed in table 7.

Layered volcanic terrane

Davenport and Nichol (1973) used the nonparametric Mann-Whitney U-Test to compare two layered sequences of Precambrian volcanogenic rocks, one of which is an economic source of zinc and copper. Descriptions of the U-test are in Siegel (1956) and Freud (1967, p. 320). This test determines if the difference between the means of two populations at a specified confidence level is significant. Copper and zinc data were tested to determine if certain volcanic areas might have a significant potential as hosts for stratiform base metal deposits.

Two major zones of layered volcanic flows and sedimentary rocks are in the Wadi Habawnah and Najran quadrangles (pl. 1). The zone exposed at the western edge of these two quadrangles and in the adjacent quadrangles has been described by Sable (USGS, unpub. data) as a sequence of basalt and andesite flows, dacitic tuffs, volcaniclastic sedimentary rocks, marble, chert, and possibly felsic sills. The proportion of sedimentary rocks and of felsic to mafic volcanic rocks in

Table 7.--Trace element analyses of granitic rock, Wadi Habawnah quadrangle

[All values in parts per million. Leaders indicate no data available. From Sable, unpub. data. Fluorine by specific ion electrode analysis; lithium and silver by atomic absorption analysis; all other elements by emission spectrographic analysis]

Sample number	Sn	F	Li	Cu	Mo	Ag	Zr	Ni	Cr	Location (latitude north longitude east)
137158	10	252	41	0	5	-	150	-	0	17°35'24" 44°07'10"
137188	10	880	10	0	<5	-	300	-	0	17°40'51" 44°03'40"
137559	15	0	0	5	5	-	1000	-	110	17°43'33" 44°04'34"
137980	10	1140	13	0	5	-	500	-	0	17°53'58" 44°06'51"
137833	-	-	-	2000	-	24	-	1000	5000	17°24'44" 44°21'21"
137923	20	-	-	-	-	-	-	-	-	17°25'00" 44°15'36"

this western zone increases to the west, and there seems to be a mafic to felsic differentiation sequence from east to west. A sequence of predominantly basaltic to andesitic flows and sedimentary rocks forms a northeast-trending zone in the central part of Wadi Habawnah quadrangle. This zone was divided into three areas by subsequently emplaced plutons and contains numerous sulfide-bearing gossans or ferruginous rocks.

The western zone is compositionally similar to sequences of differentiated volcanic flow rocks and sedimentary rocks that contain stratiform zinc and copper deposits, whereas the central zone of predominantly andesitic to basaltic flow rocks is not expected to host zinc (or copper) mineralization. Therefore, the U-test was first used to determine if the zinc and copper contents of the felsic to intermediate component of the western zone are distinctive relative to those of the central zone. Rocks used in the test were first classified as felsic or intermediate by using the Rb/Sr ratio as an index of differentiation and alteration. Rocks having Rb/Sr ratios greater than 0.4 were considered to be either felsic or altered; those having ratios of from 0.2 to 0.4 were considered to be intermediate. These ratios were based on average rubidium and strontium values for mafic, intermediate, and felsic rocks listed in Levinson (1974, p. 43-44). In this way, 13 of the 36 rocks from the western zone were identified as felsic and 12 as intermediate; 54 rocks from the central zone included 6 rocks identified as felsic and 24 identified as intermediate. The U-test indicated that the zinc and copper contents of the felsic components of the western and central zones were the same at the 99 percent confidence level, whereas the intermediate component of the western zone had a significantly higher zinc content than that of the central zone (table 8).

A sequence of volcanogenic rocks having economic zinc and copper mineralization may exhibit an increase in zinc content through the mafic to felsic sequence (Davenport and Nichol, 1973; Wolfe, 1975). Therefore, two additional comparisons were made of rocks from the western zone: felsic versus intermediate rocks and felsic versus mafic rocks. U-test results show no significant difference in the zinc contents among the three rock groups.

The U-test was used to determine if the trace element analyses of the central zone, which contains the ferruginous outcrops, were significantly different in copper content from analyses made in areas of volcanogenic rocks to the north and south that did not contain known ferruginous outcrops. No significant difference was found in the copper contents of the northern, central, and southern areas of the central zone of layered rocks at the 95 percent confidence level (table 9).

Table 8.--Geometric mean and deviation of copper and zinc contents in rocks from the western and central layered volcanic and volcaniclastic zones, Wadi Habawnah quadrangle
[All values are in parts per million; N = number of samples. Felsic, intermediate, and mafic rocks are arbitrarily defined as having Rb/Sr ratios of >0.4, 0.2-0.4, and <0.2, respectively]

	Copper		Zinc	
	Western zone	Central zone	Western zone	Central zone
Felsic rocks	N=13	N=6	N=13	N=6
Geometric mean	9	9	40	27
Geometric deviation	2	5	2	2
Intermediate rocks	N=12	N=24	N=12	N=24
Geometric mean	11	22	58	28
Geometric deviation	2	2	1	2
Mafic rocks	N=11	N=24	N=11	N=24
Geometric mean	21	53	31	26
Geometric deviation	3	3	2	2

Table 9.--Geometric mean and deviation of copper content in mafic and intermediate rocks from the central layered volcanic and volcaniclastic zone, Wadi Habawnah quadrangle
[All values are in parts per million; N = number of samples]

	Northern and southern areas	Central area
Mafic rocks	N=16	N=8
Geometric mean	46	52
Geometric deviation	4	2
Intermediate rocks	N=9	N=15
Geometric mean	17	26
Geometric deviation	2	2

CONCLUSIONS

The reconnaissance rock geochemistry survey, conducted to determine if the Wadi Habawnah and Najran quadrangles contain potential sources for metals, shows six anomalous areas in granitic terrane. Areas A and B of alkalic granitic rocks have anomalous niobium, yttrium, zirconium, rubidium, zinc, Rb/Sr, lithium, and fluorine. Small peralkaline units carrying niobium-zirconium-thorium-rare earth element mineralization may be present within these areas. Area C is the Wadi Silah two-mica granite, which is anomalous in tin, niobium, yttrium, rubidium, zinc, thorium, lithium, and fluorine. Detailed wadi-sediment surveys in these three areas and analyses of heavy mineral concentrates will either reduce the size of the areas for later detailed mapping or eliminate them from further consideration.

Areas D and E of intrusive gneiss are slightly anomalous in copper. Reconnaissance wadi-sediment surveys would be appropriate to further evaluate these areas. The remaining 15 single-sample anomalies will require inspection and additional geochemical sampling to determine their significance.

Abundant quartz veins and some weak copper carbonate staining found near the contact of quartz monzonite and a paragneiss schist-amphibole unit (lat 17°27'59" N., long 44°22'37" E.) require further evaluation.

Areas of layered volcanic and volcaniclastic rocks at the western border of the Wadi Habawnah and Najran quadrangles (western zone) and in the center of the Wadi Habawnah quadrangle (central zone) have been considered as possible hosts of stratiform base metal sulfide deposits. Analyses of felsic rocks from the western zone do not show the zinc enrichment relative to more mafic rocks of the sequence that has been observed in economically important volcanic sequences in Canada. The zinc and copper contents of these felsic rocks also do not differ significantly from those of similar rocks elsewhere in the quadrangle. These data suggest that the potential for economic stratiform base metal deposits in the western zone of layered volcanogenic rocks is low. Extensive exploration activity by the Riofinex Geological Mission, which included detailed wadi-sediment geochemistry and drilling, has also led to the conclusion that volcanogenic rocks of the western zone that extend into the Mayza quadrangle do not contain mineral deposits of economic significance.

More than 40 gossanous and ferruginous outcrops were discovered during regional mapping, although subsequent work could not confirm the presence of 12 of them. Most of these outcrops are in the central zone of predominantly mafic to intermediate volcanic rocks. Chemical analyses of rock, wadi-sediment, and colluvium samples from 23 of these outcrops suggest that none is related to significant deposits of base metals. These data, as well as analyses of unaltered rocks, suggest that the volcanic sequence of the central zone has a low potential for economic stratiform base metal deposits. This conclusion is supported by the results of a detailed wadi-sediment survey by the Riofinex Geological Mission.

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