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A GEOLOGICAL AND GEOCHEMICAL RECONNAISSANCE OF THE TATHLITH ONE-DEGREE QUADRANGLE, SHEET 19/43 KINGDOM OF SAUDI ARABIA

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ABSTRACT

The Tathlith one-degree quadrangle occupies an area of 11,620 sq km in the northeastern Asir region of the Kingdom of Saudi Arabia, in the southeastern part of the Precambrian shield. In the eastern part of the quadrangle the Precambrian rocks are covered by exposures of easterly-dipping sandstone of Cambrian or Ordovician age. A well-developed and highly integrated drainage system trending northward is worn into the Precambrian rocks, but for most of the year the wadis are dry.

The Precambrian rocks of the quadrangle consist of an old, non-metamorphosed to variably metamorphosed sequence of volcanic and sedimentary rocks intruded by three main successions of plutonic and hypabyssal igneous rocks. The interlayered volcanic and sedimentary rocks occupy arcuate, north-trending fold belts in which old, rather tight north-trending folds have been refolded at least once by open folds with nearly east-trending axes. Old, north-trending left-lateral faults are associated with the fold belts and are themselves intersected by younger, northwest-trending faults. Motion on both sets of faults has been reactivated several times.

The interlayered volcanic and sedimentary rocks are an eugeosynclinal sequence of graywacke and andesite with sparse marble, quartzite, and rhyolite. Andesite is the dominant component of the sequence. Plutonic or hypabyssal equivalents of the andesite intrude the volcanic-sedimentary sequence. In many places these rocks are essentially non-metamorphosed, but elsewhere they are faintly to strongly metamorphosed, or even polymetamorphosed. Dynamothermal metamorphism associated with the northerly folding, and contact metamorphism are the principal kinds of metamorphism. The metamorphic grade is mostly greenschist facies or albite-epidote amphibolite facies.

The largest intrusive in the area is a batholith of regional dimension, the east side of which intrudes and divides the fold belts. Granite gneiss and granodiorite gneiss are the main components of the batholith.

Biotite granite of calc-alkaline composition, and somewhat younger than the granite gneiss and granodiorite gneiss, forms northerly elongate to subcircular plutons in the gneisses and the rocks of the volcanic-sedimentary sequence.

An igneous differentiation suite ranging in composition from gabbro to quartz porphyry forms prominent homogeneous to zoned subcircular granitic plutons and stocks of gabbro and diorite in the older rocks. Pyroxene is present in some of the granitic rocks, and the suite itself is called the peralkalic magma series. Geochemically, the granites of the series are characterized by greater amounts of beryllium, gallium, lanthanum, niobium, lead, yttrium, and zirconium than the older granites, and magnetite from the series is typically enriched in zinc.

These Precambrian rocks are overlain in the east by the Cambrian-Ordovician ferruginous Wajid Sandstone. Patches of uneroded saprolite are locally present on the surface of the Precambrian rocks under the sandstone.

Earlier and more extensive weathering was a factor in supplying silt to certain valleys in the southern part of the area. Evidence for cyclic climate change is preserved in these silts. A series of interrelated research projects is needed to study the silts and other materials, including sabkhahs, Quaternary deposits, and associated anthropological, archaeological, and historic evidence, to evaluate the factors and processes of regional climate change in Arabia. Research of this type might also allow estimates to be made of the possibility for the existence of factors that could reverse the trend to regional aridity.

The major ore deposit in the area is the Ash Sha'ib ancient mine for which G. H. Allcott (1970) estimated 2,170,000 tons of sulfide ore to a depth of 170 m worth $40 million for the contained zinc, copper, and silver. However, only $20 million of the ore was estimated to be worth $25 per ton or more; hence, the deposit was regarded as too small to exploit. Detailed geologic work is needed to determine if there are other similar deposits nearby.

Chrysotile asbestos of good quality is present a few kilometers south of the quadrangle, and considerable anthophyllite is present near Hamdah. Further evaluation of these deposits is needed; the airborne magnetic surveys to support the evaluation are completed.

A geophysical survey of the zoned peralkalic pluton at Jabal Al Hassir is recommended to learn if fractures at depth in the pluton might serve as a reservoir for groundwater.

INTRODUCTION

Location

The Tathlith one-degree quadrangle, so designated from the name of the principal community, occupies an area of 11,620 sq km in the northeastern Asir region of the Kingdom of Saudi Arabia (fig. 1). The one-degree quadrangle, commonly referred to in this report as the area, is in the southeastern part of the Arabian

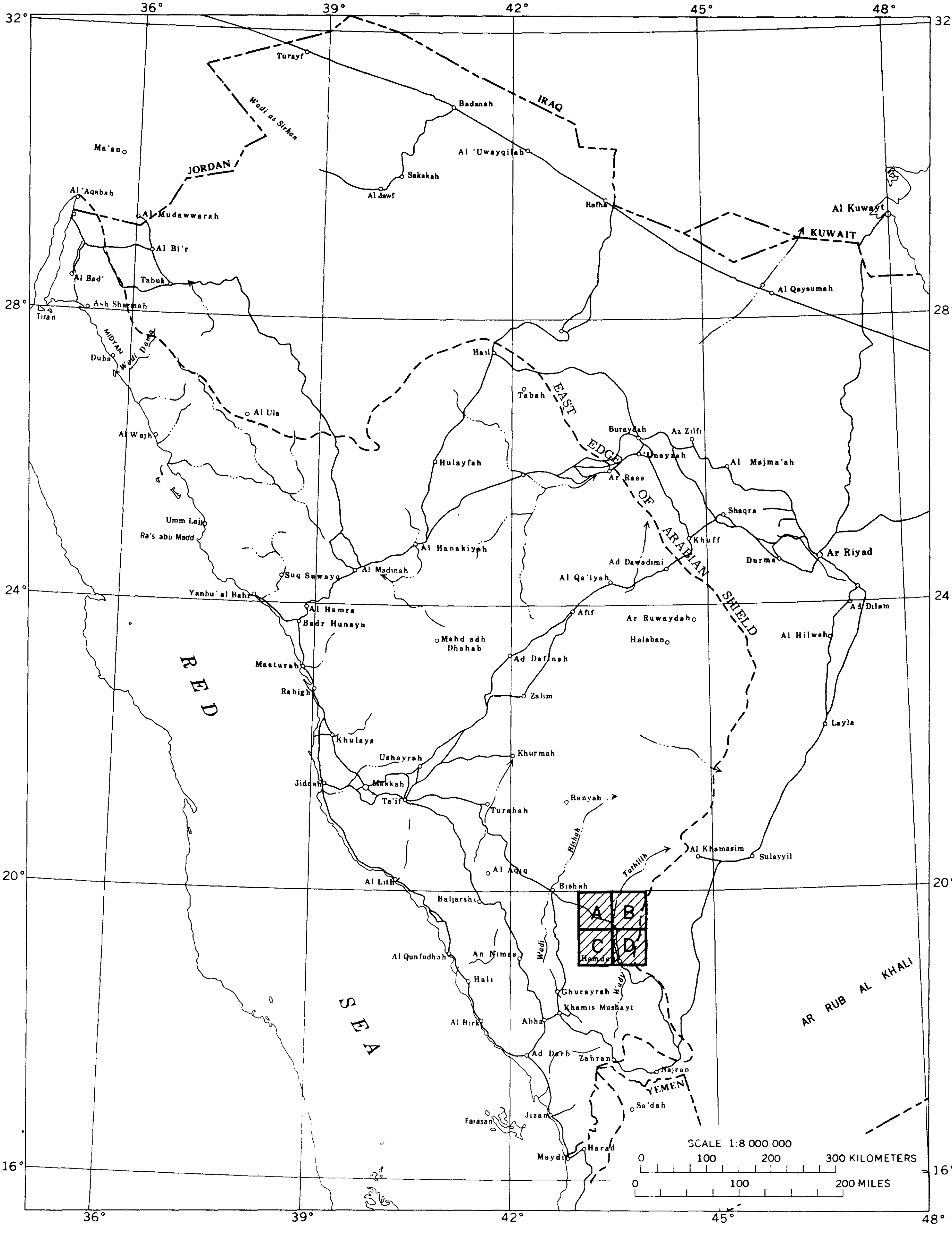

Figure 1.- Index map of western Saudi Arabia showing the location of the Tathlith one-degree quadrangle. A - Plate 1 (Al Hassir quadrangle, sheet 19/43A) B - Plate 2 (Wadi Haraman quadrangle, sheet 19/43B) C - Plate 3 (Duthur as Salam quadrangle, sheet 19/43C) D - Plate 4 (Hamdah quadrangle, sheet 19/43D).

Precambrian shield, and along the eastern part of the quadrangle the Precambrian rocks of the shield disappear beneath easterly-dipping Cambrian-Ordovician sandstone. A well-developed and highly integrated drainage system trending northward is worn into the exposed Precambrian rocks. From west to east the main dry watercourses composing this drainage system are named Wadi Thafin, Wadi Salim, Wadi Tarib, Wadi Tathlith, and Wadi Na'am. The lower end of Wadi Na'am is lost in the sandstone mountains east of the quadrangle, but the valleys to the west are tributary to Wadi Tathlith which extends northeastward to its junction, outside the area of the quadrangle, with Wadi ad Dawasir, the major east-trending regional base level. Altitudes of the higher peaks range from more than 1,400 m near the southern edge of the quadrangle to less than 1,000 m near the northern edge (Brown and Jackson, 1959).

The major wells at the community of Tathlith, near the center of the quadrangle, are the most important source of water in the area, and the largest cultivation of dates is at Tathlith. These wells are in Wadi Tathlith where the principal road between Qal'at Bishah and Najran crosses the wadi. Other important settlements are at As Subaykhah in the southwest on the road between Bani Thawr and Tathlith, and Hamdah in the southwest on the Qal'at Bishah-Najran highway. Several wells, in addition to those at the oasis communities mentioned above, are used by nomadic herdsmen. These include Bi'r Malah and Bi'r al Hafayir in the northwest quarter of the area, Bi'r Pothbut and wells near Kitmah and Jaash in the southwestern quarter, Bi'r el Marwah, Bi'r Umm az Ziba, and Bi'r az Zurq in the southeastern quarter, and Bi'r Murayzham in the northeastern quarter.

Access to the area is good. Qal'at Bishah with its commercial airfield is about 50 km by main unpaved road from the northwestern edge of the quadrangle. This road extends east-southeastward nearly to Tathlith, where it turns southward; it crosses the southern edge of the quadrangle near Hamdah. Connecting unimproved roads radiate southwestward and northeastward from the main road in the vicinity of Tathlith. All major wadis are routes that can be followed in four-wheel-drive vehicles. Many gravel-covered pediment surfaces in the area are suitable to the operation of light aircraft.

The principal administrative and commercial center of the region is Qal'at Bishah and of the quadrangle is Tathlith.

For purposes of representing the geology, geochemistry and mineral resources of the Tathlith one-degree quadrangle on available base maps, the area is divided into four 1:100,000-scale, 30'x 30' quadrangles to which the following names are assigned:

	Quadrant of the Tathlith one-degree quadrangle	Name assigned 1:100,000-scale, 30'x 30' sheet
Plate 1	Northwestern	Al Hassir quadrangle
2	Northeastern	Wadi Haraman quadrangle
3	Southwestern	Duthur as Salam quadrangle
4	Southeastern	Hamdah quadrangle

Previous work

The Tathlith one-degree quadrangle is in the northern part of the 1:500,000-scale Asir quadrangle and was mapped geologically by Brown and Jackson (1959). No other geologic work was done in the quadrangle prior to that described here except for a study of the Avala and Al Lugatah gold mines in 1956 by D. F. Schaffner (1956a; 1956b; 1964) for the Directorate General of Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, and examinations of the Higera mine, outside the quadrangle about 15 km southeast of Hamdah, made in the 1950's by Dr. Fadil K. Kabbani, Deputy Minister for Mineral Resources, Directorate General of Mineral Resources, and D. F. Schaffner (1957), and in the 1960's by Kareh, Keller, and Kahr (1962). Some asbestos prospects were sampled at Dr. Kabbani's request by Hassan Ghanim al Messfer of Hamdah around 1964-5.

The area covered by photomosaic 160, adjoining the Al Hassir quadrangle to the west, was examined for mineral deposits during June and July 1964 by C. L. Hummel, U. S. Geological Survey (USGS) and Hashim Hakim, Directorate General of Mineral Resources (DGMR) (Hummel, C. L., 1964, written commun.). The region west of the Duthur as Salam quadrangle was the subject of reconnaissance geologic and geochemical studies by J. W. Mytton, USGS, and A. O. Ankary, DGMR, during May-July 1964 (Mytton and Ankary, 1967).

Present work

The work described here was done during parts of two field trips made in 1965. Field work in the eastern half of the Tathlith one-degree quadrangle was divided June 8-16, 1965, in the Hamdah quadrangle and June 17-24, 1965, in the Wadi Haraman quadrangle. November 20 to December 6, 1965 was spent in the Duthur as Salam quadrangle, and December 7-18, 1965, in the Al Hassir quadrangle. Preliminary accounts of the results of this field work were made in U.S. Geological Survey Project reports 39 and 40 open filed March 27, 1968 (Overstreet, 1968a; 1968b). A trip in October 1966 was made to the area of the ancient Ash Sha'ib zinc-copper prospect, found the previous year in the Hamdah quadrangle.

Results of this trip were transmitted as Project report 84, released on January 20, 1969 (Overstreet, Bahijri, and Shararahly, 1969). An opportunity to summarize the results of these investigations was offered in 1971-2 when the period July 12, 1971, through March 12, 1972, was spent in preparing the present maps and text.

Subsequent work

The main geologic activities in the Tathlith one-degree quadrangle area between October 1966 and the preparation of the present report in 1971-2 have been investigations of the Ash Sha'ib zinc-copper prospect (CAMS, 1967; Kiilsgaard, T. H., 1968, written commun.; Kiilsgaard, T. H., and Tompkins, F. V., 1968, written commun.; Sander Geophysical Ltd., 1968; Allcott, 1969; 1970; Davis and Kazzaz, 1970) and regional airborne magnetic surveys conducted under a contract let by the Saudi Arabian Mission of the Bureau des Recherches Géologiques et Minières, France. Data from the airborne magnetic survey were being compiled during 1971-2 by Gordon Andreasen, U. S. Geological Survey, into regional magnetic maps at 1:500,000-scale. Manuscript copy of the magnetic data covering the area was kindly furnished the writer by Andreasen on December 17, 1971.

Adjoining areas to that covered by the Tathlith one-degree quadrangle have been the subject of a variety of investigations after 1965, ranging from reconnaissance geology, geochemistry, and placer evaluations, to thorough studies of petrography, stratigraphy and tectonics. To the north of the Al Hassir and Wadi Haraman quadrangles, the area of photomosaic 155 was covered by geological and geochemical reconnaissance in 1966 by J. W. Whitlow, USGS (Whitlow, J. W., 1966, written commun.), and was examined for alluvial placers in 1967-8 by Louis Gonzalez, USGS (Gonzalez, Louis, 1970, written commun.). Detailed geologic mapping was being done in 1972 by D. L. Schmidt, USGS, in the Bishah quadrangle (Schmidt, D. L., 1973, oral commun.) to the northwest of the Al Hassir sheet, and by H. R. Cornwall in the Wadi Harjab quadrangle to the west of the Al Hassir map.

Acknowledgments

The writer wishes to acknowledge the support he received from officials of the Directorate General of Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia in the conduct of this investigation. The surveys described below are part of the broad program of mineral exploration being conducted by the Directorate for the Royal Government. These findings are in partial fulfillment of a work agreement between the Ministry and the United States Geological Survey.

A particular appreciation is herewith acknowledged for the estimable services of the guides Maeith Rejad and Homud el Shebany and of the drivers Misri Madaq, Khalif Ali, and Homud Saud, who participated in one or more of the three trips upon which this report is based.

GEOLOGY

The Precambrian rocks of the Tathlith one-degree quadrangle, as interpreted in 1965, were thought to consist of an old, non-metamorphosed to variably metamorphosed sequence of volcanic and sedimentary rocks intruded by three main successions of plutonic and hypabyssal igneous rocks (plates 1-4). The extent to which this concept must be modified to fit the new stratigraphic interpretations is described in a subsequent section of this report and on a regional geologic map (fig. 2). Along the eastern edge of the quadrangle (plates 2 and 4) the Precambrian rocks are overlain unconformably by the Permian or older Wajid Sandstone. Throughout the quadrangle, surficial deposits of Quaternary age, consisting of alluvial or aeolian sand, silt, and gravel, cover valley floors and erosional depressions.

The interlayered volcanic and sedimentary rocks occupy arcuate, north-trending fold belts in which old, rather tight north-trending folds have been refolded at least once as open folds with nearly east-trending axes. Old north-trending left-lateral faults are associated with the fold belts and are themselves offset by younger, northwest-trending faults. Apparently both sets of faults were active several times. The north-trending faults appear to have been more of a factor than the northwest-trending faults in the localization of the auriferous lodes mined in antiquity at several places in the quadrangle.

The fold belts of interlayered sedimentary and volcanic rocks consist of a eugeosynclinal suite dominated by graywacke and andesite. Small amounts of marble and quartzite are present, and the volcanic rocks include rhyolitic elements. Plutonic or hypabyssal equivalents of the andesite are exposed as old diorite and microdiorite in some of the deeper parts of the eugeosynclinal pile. In many places these rocks are essentially non-metamorphosed. Elsewhere they are faintly metamorphosed to strongly metamorphosed and even polymetamorphosed. Dynamothermal metamorphism associated with the tighter northerly folding may be the sole source of metamorphism, or the sole source may be thermal metamorphism along the intrusive contacts of the older granite gneiss and granodiorite gneiss. Locally, the latter is superimposed on the former. Along the major northerly faults some rocks have been retrogressively metamorphosed. Contact metamorphism is not a prominent factor around the younger granitic intrusives. Variable serpentinization of the basic and ultrabasic rocks in the volcanic sequence has taken place in the southern part of the area near Hamdah, and has led to the designation of Hamdah ultrabasic belt for the folded sequence of volcanic and sedimentary rocks.

The largest intrusives in the area are old granite gneiss and granodiorite gneiss that divide and separate the fold belts of the volcanic-sedimentary sequence. Indeed, the rocks of the volcanic-sedimentary sequence form large septa between the granite gneiss and granodiorite gneiss. In the area covered by the Tathlith one-degree quadrangle, the bodies of granite gneiss and granodiorite gneiss are the eastern part of an intrusive batholith shown by Brown and Jackson (1959) to extend south and west of the quadrangle.

Granite somewhat younger than the granite gneiss and granodiorite gneiss forms northerly elongate to subcircular plutons in the gneisses and the rocks of the volcanic-sedimentary sequence. Typically this granite is porphyritic, and locally it has blue quartz. The origin of the granite is not adequately understood; apparently included in it are rocks of several ages and origins. Some features of this granite, particularly the large grains of feldspar, may have been produced by growth in the solid state.

An igneous differentiation suite ranging in composition from gabbro to quartz porphyry and including prominent homogeneous to zoned subcircular granitic plutons intrudes the older rocks in the area. Pyroxene is present in some of the granitic rocks of the suite, and the suite itself is referred to as the peralkaline magma series. Geochemically, the granites of the series are characterized by greater amounts of beryllium, gallium, lanthanum, niobium, lead, yttrium, and zirconium than the older granites. An isotopic age for rocks of the peralkalic magma series, 576 m.y., suggests that these rocks may be late Precambrian to Cambrian.

The Wajid Sandstone is a strongly crossbedded ferruginous sandstone that was deposited on the weathered and deeply eroded surface of the Precambrian rocks. Patches of the original weathered material are present locally under the Wajid.

Weathering of the Precambrian rocks is still underway, despite the sparse rainfall of the region, leading to the development of thin rinds of saprolite on exposed crystalline rocks--particularly gabbro and diorite--near the floors of some wadis. Earlier and more extensive weathering was a factor in supplying silt to certain wadis in the southern part of the area. Evidence for cyclic climatic changes is preserved in these silts. The present cycle of erosion shows rejuvenation, possibly in Holocene time, after a period when chemical weathering of the rocks aided in the degradation of the land surface.

Rock units as interpreted in 1965

Sequence of volcanic and sedimentary rocks in the Hamdah belt

Owing to the prominence of serpentinite in rocks of the volcanic-sedimentary sequence near Hamdah, the fold belts of these rocks have long been known as the Hamdah ultrabasic belt, and the belt itself extends from beyond the northern limits of the Tathlith one-degree quadrangle southwestward nearly to the Yemen border (Brown and Jackson, 1959). Actually, the dominant rocks of the belt are andesite and graywacke, with silicic volcanic rocks present in the upper part. Owing to variable metamorphism, the stratigraphic units of the belt persist through a variety of lithologies up to and including metamorphic rocks of the lower subfacies of the amphibolite facies.

Non-metamorphosed to weakly metamorphosed andesite and graywacke.--The volcanic-sedimentary sequence in the Hamdah belt is of great but unknown thickness and is dominated by andesitic volcanic rocks or their metamorphosed equivalents. Clastic sedimentary rocks and minor layers of carbonate are interbedded with the volcanic rocks, but these sedimentary rocks constitute perhaps no more than 35 percent of the total volume of the sequence.

Included in the andesitic rocks are massive andesite, andesite porphyry, trachytic andesite, bedded andesitic crystal lithic tuff, andesitic lithic tuff, and andesitic agglomerate. The massive andesite is locally in layers as much as several hundred meters thick with remarkable uniformity of texture and mineral composition. Generally epidote and chlorite are sparsely developed in the andesitic rocks, but seldom in sufficient abundance to produce massive greenstone. Feldspar phenocrysts in the andesite porphyry may reach 5x20 mm, and are commonly free from epidotization.

Interbedded with the andesitic volcanic rocks are graywacke siltstone, graywacke sandstone, graywacke conglomerate, and limestone. The graywacke tends to form thin-bedded or rhythmically-bedded sequences. Graded bedding is common, and ripple marks are present on the siltstones, suggesting deposition in fairly shallow water, where thin beds of limestone also formed. Limestone beds, never thicker than a few meters, are present in the andesitic agglomerate. Some of the graywacke conglomerates contain pebbles of detrital andesite and argillite, and fragments of feldspar from andesite porphyry. In some pebble beds the andesite pebbles and fragments of feldspar are epidotized and chloritized, but the matrix of the pebble beds is not altered to epidote or chlorite. From these relations it is inferred that at least some of the epidotization and chloritization of the andesite is deuteric in origin.

The upper part of the sequence of interlayered andesite and graywacke seems to contain more clastic material than the lower part, which has the main massive andesite flows.

In the northeastern part of Al Hassir quadrangle (plate 1) in the vicinity of station 22913 a vertical sequence of graywacke conglomerate, maroon argillite, red hematitic rhyolite agglomerate, and andesite are interbedded. The graywacke conglomerate contains pebbles and cobbles of andesite, quartz, and the maroon argillite. The strikingly bright colors of the maroon argillite and red hematitic rhyolite agglomerate are different from the usual dark brown to greensih brown of the rocks of the volcanic-sedimentary sequence. Although these brightly colored rocks are not shown separately on plate 1, the possibility exists that they may be a small remnant of the Abla Formation described by Brown and others (1962) about 100 km to the west-northwest.

Pyritized andesite.--Pyritized andesite forms a prominent unit in the southeastern part of the Duthur as Salam quadrangle (plate 3). In this rock, disseminated cubes of pyrite from dust-sized particles to grains 1 mm across make up from 0.5 to 3 percent of the andesite, and the surface exposures of the pyritized andesite are stained with limonite and goethite. These stains are most prominent about 200 m east of a breccia zone forming the west contact of the pyritized andesite. Interbedded with the pyritized andesite are graywacke pebble beds practically devoid of pyrite. However, what little pyrite is present in the conglomerate replaces other minerals in the conglomerate, just as pyrite replaces individual minerals in the andesite.

The low flats west of the pyritized andesite are underlain by granite saprolite, and the wadi at station 22725 shows andesite converted to saprolite. Possibly the pyrite in the ridge-forming rocks has acidified the ground water and helped to form the saprolite along the adjacent wadi floors.

Rhyolite.--Massive flows of light gray, red, brown, or nearly black rhyolite, and rarely rhyolite porphyry, are common in the upper part of the volcanic-sedimentary sequence. Hypabyssal intrusives of similar rhyolite form dikes, sills, and plugs. At most exposures it is difficult to determine from the contact relations whether the rhyolite flows are penecontemporaneous with the andesite and graywacke or are substantially younger. The rhyolite bodies tend to be massive and much less affected by epidotization and chloritization than the associated andesite. They are probably part of the late volcanic succession.

Locally the rhyolite contains 0.1-0.2 percent of finely disseminated pyrite. Weathered surfaces of this pyrite-bearing rhyolite assume a yellowish-brown limonitic stain. Some dikes of this older rhyolite contain spherulites up to 4 mm in diameter.

Meta-andesite and metagraywacke.--The terms meta-andesite and metagraywacke are used on plates 1-4 for parts of the sequence of volcanic and sedimentary rocks where metamorphic minerals have developed, but the rocks still have preserved recognizable aspects of andesites and graywackes. The andesites are not converted to schists, but epidote and chlorite are common, joints are usually coated with quartz or epidote, quartz gash veins are common, and unakite veins are rarely present. In vesicular andesite, the vesicles are filled with white quartz. The coarse detrital rocks, like conglomerate and agglomerate, show development of chloritic matrix, and of stretched pebbles with elongations 3 to 10 times more than the smallest axis. The finer-grained graywacke sediments are quartzite or argillite, and the carbonate sediments are recrystallized to marble.

Commonly the meta-andesite and metagraywacke have fracture cleavage, primary foliation, or cataclastic cleavage. In the latter two, the growth of new minerals like chlorite and quartz defines the cleavage or forms linear features on the cleavage surfaces.

Chlorite schist, chlorite-sericite schist, and sericite-chlorite schist.--With increasing metamorphism the meta-andesite and metagraywacke pass into schists, the main varieties being chlorite schist, chlorite-sericite schist, and sericite-chlorite schist. Often these schists are found along or near the north-trending fault zones, suggesting that tectonic processes were involved in their formation. This is further confirmed by the strongly developed linear features found in the chlorite- and sericite-bearing schists. These include oriented chlorite and quartz on foliation planes, stretched clastic grains, striations, and intersections of cleavages.

In general the chlorite-rich schists were formed from the andesitic volcanic rocks, and the sericite-rich schists from the argillaceous rocks. Some chlorite-sericite schist developed through the metamorphism of graywacke sandstone or conglomerate with a fairly large component of andesitic detritus, but in general this rock seems to be derived from andesite with intercalations of siltstone and graywacke. Some fine-grained, black, chlorite-sericite schist in the Hamdah quadrangle (plate 4) was formed by the retrogressive metamorphism of biotite-hornblende schist.

Brecciated and limonite-stained milky quartz veins with calcite, ankerite, and chlorite are common in joints or sub-parallel to the foliation in most of the areas of chlorite schist and chlorite-sericite schist. These veins appear to lack sulfide minerals. They are probably products of metamorphic differentiation at the greenschist facies.

Hornblende schist and hornblende gneiss.--Rocks shown on plates 1-4 as hornblende schist and hornblende gneiss are parts of the sequence of volcanic and sedimentary rocks in the Hamdah ultrabasic belt where the regional metamorphic grade has reached the epidote-amphibolite facies and lower subfacies of the amphibolite facies. They are derived mainly from the andesitic lavas or andesitic lavas with minor sedimentary partings. Mostly the hornblende schist and hornblende gneiss appear to have been formed by regional dynamothermal metamorphism at the time of the major northerly folding, but some fine-grained phases of the hornblende gneiss are a product of thermal metamorphism along intrusive contacts of the granite gneiss and granodiorite gneiss.

Hornblende schist and hornblende gneiss are shown on the geologic maps where those lithologies are dominant. By far the commonest condition, however, is for hornblende schist and hornblende gneiss to be interlayered with biotite schist, biotite-muscovite schist, biotite-muscovite gneiss, quartzite, and marble, thus preserving in those metamorphic facies the elements of compositional layering present in the non-metamorphosed rocks.

Hornblende schist and hornblende gneiss, formed from rocks of the volcanic-sedimentary sequence, tend to be fine-grained and well-layered. At places both types can be traced along strike into weakly metamorphosed andesite. Interestingly, gradation from hornblende schist through chlorite schist to andesite was not observed along strike, but gradation from hornblende schist to chlorite schist was seen along strike.

Rarely, some of the hornblende schist has 0.5 to 1.0 percent of disseminated pyrite in small cubes 0.2-0.5 mm across, in this respect resembling pyritized andesite.

At station 22317, in the northwestern part of the Hamdah quadrangle, thin partings of magnetite quartzite and magnetite-quartz schist are interlayered with biotite-hornblende gneiss. These layers conform to the foliation. The magnetite-rich rocks contain 20 to 40 percent of magnetite in grains less than 0.5 mm across intimately intergrown with quartz or quartz and biotite in layers rarely thicker than 2-3 cm which alternate with feldspathic layers 2-4 mm thick and free of magnetite. This sequence of magnetite-bearing quartzitic layers and magnetite-free feldspathic layers is only about 75 cm thick.

Pod-shaped masses and thin discontinuous boudins of calc-silicate rock, commonly rich in epidote, are sporadically present in the units of hornblende schist and hornblende gneiss. These masses seem originally to have been small lenticles of impure carbonate-rich graywacke containing copious volcanic ash and sand. The originally purer carbonate bodies form layers of marble, dolomitic marble, and siliceous marble in the hornblende schist and hornblende gneiss.

White quartz veins, with calcite and chlorite or epidote, fill sporadic fractures in the hornblende schist or hornblende gneiss, but thin stringers of gray quartz parallel to the foliation or vuggy masses of gray quartz with singly terminated crystals are more common.

<u>Biotite schist and biotite gneiss</u>.--Very fine-grained to fine-grained biotite schist, biotite-quartz schist, biotite-muscovite schist, biotite gneiss, and biotite-muscovite gneiss appear to be metamorphic equivalents of the sedimentary rocks in the volcanic-sedimentary sequence. These schists are of low to middle metamorphic grade. Transformation of the non-metamorphosed rocks of the volcanic-sedimentary sequence to the biotite schists and gneisses can be traced both along and across strike. Regional dynamothermal metamorphism associated with the northerly-trending folds seems to have been the main factor in the formation of the biotite schists and gneisses, but locally they were produced by thermal metamorphism at contacts between the graywacke sediments and the intrusive granite gneiss. The biotite schists and gneisses of contact metamorphic origin are usually fine grained.

Where the biotite schists and gneisses are mapped separately, they are the dominant lithology. Typically, they constitute a smaller part of the layered metamorphic rocks than the hornblende schists and gneisses, just as graywacke, siltstone, and the clastic sedimentary rocks are a smaller part of the volcanic-sedimentary sequence than the andesitic lavas.

Some of the biotite schists and gneisses have formed from fragmental volcanic rocks, like andesite agglomerates, instead of the graywackes, but the dominant source for the layered biotitic metamorphic rocks is the sedimentary part of the sequence. This is further shown by the common presence of thin layers of muscovite schist, quartz schist, quartz-muscovite schist, muscovitic quartzite, hornblendic quartzite, biotite quartzite, quartzite, and marble in the biotite schists and gneisses. Compositional layering and foliation of these rocks is generally parallel.

Included with the biotite schists and gneisses are small bodies of graphitic chloritoid schist, graphite-muscovite schist, graphitic phyllite, and sericite schist. At the scale of the mapping, and in the time available for the work, it was not possible to show these distinctive lithologies separately.

Pods of limonite-stained, fine-grained, biotite-muscovite schist are rarely and sporadically present in the layering of the biotite schists and gneisses. These pods are 3-4 m wide and 6-10 m long parallel to the strike of the foliation. The source of the limonite was not determined. Elsewhere, small lenticular masses of hornblendic metadiorite and hornblendic metagabbro lie in the foliation of interlayered biotite gneiss and hornblende gneiss. These lenticular masses are about 5 cm thick and 30-40 cm long. They may be boudins of dikes or sills of the early diorite, microdiorite, and gabbro that intruded the growing volcanic-sedimentary pile. Or they may be metamorphic differentiation products like pseudodiorite. Small layers of calc-silicate rocks are present parallel to the foliation of the biotite schists and gneisses, but they are not so common as in the hornblende schists and gneisses.

White quartz veins, some with small amounts of pyrite, are more common in the biotite schists and gneisses than in the hornblende schists and gneisses. Lit-par-lit stringers and selvages of white to pink granite and pegmatite are, perhaps, somewhat more common in the layered biotitic rocks than in the hornblende schists and gneisses. Locally these stringers are complexly folded with the layers of biotite schist and gneiss, forming distinctive migmatite.

Layered gneiss.--The term layered gneiss is used on plates 1-4 for sequences of hornblende schist and hornblende gneiss interlayered with biotite schist and biotite gneiss where the individual layers are too thin to be mapped separately in reconnaissance-type field work. The layered gneiss thus defined consists of undivided parts of the volcanic-sedimentary sequence that have been metamorphosed generally to the albite-epidote amphibolite facies and the lower subfacies of the amphibolite facies.

Limestone and marble.--The carbonate sediments of the volcanic-sedimentary sequence include blue to black brecciated to massive, conchoidally-breaking limestone in rare, thin interbeds in andesite, and white, gray, blue, green, brown, black, and red marble interbedded variously with meta-andesite, meta-agglomerate, chlorite schist, hornblende schist, metagraywacke, and biotite schist. Some marble is included in the granite gneiss and granodiorite gneiss; such inclusions form conspicuous low ridges that rise about the pediment surface of the granite gneiss. Fossils and stromatolitic structures are lacking in all the limestone or marble examined.

Only two of the carbonate layers known in the area were thought to be limestone; the rest were classed as marble owing to recrystallization. At station 22896, near the east-central edge of Al Hassir quadrangle (plate 1) a brecciated blue to black, dolomitic limestone at least 30 m thick is exposed for 800 m in andesite. At station 22724 in the southeastern part of the Duthur as Salam quadrangle (plate 3), thin-bedded, black, pyritiferous, fine-grained, conchoidally fracturing limestone is interbedded with meta-andesite. It contains less than 1 percent pyrite, but it has layers of siderite 1-2 m thick. Similar siderite-bearing limestone, or siderite-bearing marble was not seen elsewhere. The pyrite is probably syngenetic.

No large stratigraphic units of marble are present but each of the four geologic maps (plates 1-4) shows from one to three mapped units of marble between 1 km and 5.5 km long and from 12 m to more than 60 m thick. The marble tends to be white, gray, or brown, and less commonly black. The rocks are of variable purity, tending to be dolomitic or siliceous in the darker colors but purer in the lighter colors. Mostly they are interbedded with meta-andesite. Many of these masses of marble are strongly fractured and jointed if not actually greatly contorted and cleaved.

Spectacular green marble, or green layers in white, gray, brown, and yellow marble, was noted at several localities including 22902 in the south-central part of Al Hassir quadrangle (plate 1), 22756 in the northeastern part of the Duthur as Salam quadrangle (plate 3), and 22212 in the southwestern part of the Hamdah quadrangle (plate 4).

Marble in the area commonly is intruded by dikes and other masses of gabbro and granitic rocks, but the contacts seldom are coarsened or recrystallized. Notable exceptions are seen in the southwest-central and west-central parts of the Wadi Haraman quadrangle (plate 2) at stations 22481 and 22526. At station 22481 a prominent ridge of very pure gray marble occupies an area 2.5 km long and 0.1 to 0.5 km wide. The grains in the marble are less than 1 mm across, generally about 0.5 mm, except where intruded by gabbro, where the grains are coarsened to 4 mm. White, gray, and blue, fine- to coarse-grained marble at station 22526 is intruded by monzonite and the marble grains are coarsened from an average size of 0.4 mm to 5-8 mm at the contact. The recrystallized marble at the contact contains about 0.1 percent of a metallic dark gray to black platy mineral.

Slate, felsite, and quartzite.--Rocks described by Brown and Jackson (1959) as light to dark gray, locally schistose, slate, felsite, and quartzite, and shown as being among the oldest stratified rocks in the area, crop out in the extreme northeastern corner of the Wadi Haraman quadrangle (plate 2).

Relations among the rocks of the volcanic-sedimentary sequence more than 150 km to the south suggest the slate, felsite, and quartzite may occupy a higher stratigraphic position than that assigned to it by Brown and Jackson (1959). Some aspects of the original description, as well as the location of the rocks in the Wadi Haraman quadrangle, suggested to the writer the alternative possibility that the slate, felsite, and quartzite may be equivalent to or identical with the dominantly clastic sedimentary units in the upper part of the volcanic-sedimentary sequence in the quadrangle. This possibility was not tested by the field work of 1965-6, but in May 1972 the area was visited and was determined to be underlain by late Precambrian rocks of the Murdama Group.

Serpentinite

Serpentinite is present in each of the four map areas (plates 1-4) but only a very small amount is found in the northwestern quarter of the area. This serpentinite is on a major north-trending fault at the northern edge of Al Hassir quadrangle (plate 1). A major north-trending fault also is the locus for a large, northerly elongate mass of serpentinite up to 2.5 km wide and 17 km long near the eastern edge of the Duthur as Salam quadrangle (plate 3) and a smaller mass farther to the north. The largest bodies of serpentinite in the area are not associated with north-trending faults, but are in mafic rocks in the Hamdah belt east and northeast of Hamdah and in the northeastern and northwestern parts of the Hamdah quadrangle (plate 4), and north of Tathlith in the southwestern corner of the Wadi Haraman quadrangle (plate 2).

The northerly elongate exposures of serpentinite in the eastern part of the Duthur as Salam quadrangle (plate 3) consist of multiple pod-shaped masses of serpentinite up to 100 m thick and 500 m long in a sequence of andesite with interbedded marble and old gabbro and diorite. The serpentinite masses appear to be controlled by the major shear planes of the fault zone; they strike generally about N.10^{o}E. and dip vertically. In many places the serpentinite and andesite are intensely brecciated and strong cataclastic foliation is present in all the rocks. Small lenticular masses of calcite are associated with the serpentinite and the host rocks, but magnesite is absent. In the southern part of this serpentinite zone, some masses of serpentinite contain as much as 10 percent of chromite in disseminated grains generally 2-3 mm in maximum dimension. No large masses of chromite were seen. The small disseminated grains are probably a normal accessory mineral in the original ultramafic rock from which the serpentinite was derived. Farther north along this body of serpentinite, the accessory chromite disappears. Traces of slip-fiber asbestos are present in a few shear zones in the serpentinite, but no cross-fiber asbestos was seen.

Chromite and asbestos also appear to be lacking in the small body of serpentinite in the same fault north of Jaash.

The large masses of serpentinite east and northeast of Hamdah in the Hamdah quadrangle (plate 4) are intrusive into andesite, diorite, and hornblende schist with layers of siliceous marble, form dikes cutting these rocks, and replace andesite, gabbro, pyroxenite, and hornblende schist. The relations are quite complex and are further disguised by the extensive alteration of the serpentinite to asbestiform minerals (see section on Asbestos under Mineral Resources). Variable but small amounts of magnesite are associated with the serpentinite in the Hamdah quadrangle, locally forming veins up to 0.5 m thick, but chromite is quite rare, being seen only at station 22300 where dunite intrusive into hornblende schist is largely altered to serpentinite. The younger gabbros and associated rocks of the peralkalic magma suite intrude the serpentinite and are not themselves altered to serpentinite. Small amounts of poor-quality soapstone are locally present in the serpentinite as lenticular masses less than 1 m thick and 7 m long.

The exposures of serpentinite in the Wadi Haraman quadrangle (plate 2) are extremely altered, but a gabbro dike intrusive into the serpentinite is unaltered. The serpentinite is converted into a punky brownish-green substance with joints filled by veins of calcite and limonite. The alteration appears to be related to secular weathering, and might be described as saprolite or gossan. It should be examined for nickel.

In the Wadi Haraman quadrangle the serpentinite is associated with meta-andesite, meta-andesite prophyry, and lenticular masses of brown marble. Evidently the serpentinite has formed from ultramafic intrusives in the andesite and marble. A little ilmenite and a trace of chromite were found in wadi sands around the area of exposure of the serpentinite, but no large masses of chromite were seen, nor was asbestos observed.

The serpentinite intrudes rock as young as the andesite of the volcanic-sedimentary sequence and was mobilized in the north-trending faults that cut rocks of the andesite and graywacke unit of the volcanic-sedimentary sequence. It is not certain, however, that the asbestos veins in the serpentinite were formed so early, but these veins are cut at least by the rocks of the peralkalic magma series and later by a Tertiary(?) diabase plug.

Diorite and microdiorite

The map unit called diorite and microdiorite, and meta-andesite associated with diorite and microdiorite, includes the older dioritic rocks and gabbro that are the plutonic equivalents of the andesitic lavas. These rocks intrude and are associated closely with the rocks of the volcanic-sedimentary suite and are intruded by dikes that were feeders for later parts of the volcanic pile, particularly rhyolite dikes feeding the silicic volcanic rocks in the upper part of the volcanic-sedimentary suite. Diorite, microdiorite, and gabbro are intruded into the lower parts of the volcanic-sedimentary sequence and both types commonly are metamorphosed to amphibolites and various porphyroblastic, generally non-layered, biotite-rich gneisses. The microdiorite grades imperceptibly into andesite with decrease in grain size, and with increase in grain size becomes diorite. At places it has the aspect of feldspathized andesite.

Doubtless plutonic intrusives more mafic than gabbro were originally represented in this unit, but in the Hamdah ultramafic belt they have been converted to the serpentinite.

Biotite diorite, biotite-hornblende diorite, quartz diorite, generally intruded into andesite or cut by andesite dikes, are the commonest intrusives. Where strongly metamorphosed these dioritic rocks are converted into dark gray, non-layered, biotite-rich, quartz-poor porphyroblastic gneisses with metacrysts of microcline up to 2x2x6 mm, or into layered porphyroblastic biotite gneiss, or non-layered porphyroblastic biotite-hornblende gneiss.

Amphibolite

The amphibolite in the Hamdah ultrabasic belt is the massive, generally non-layered, metamorphic equivalent of old mafic plutonic rocks that intruded basal parts of the volcanic-sedimentary sequence as the volcanic pile built up. Gabbro probably was the original rock from which the amphibolite was derived, but it may also have included andesite porphyry. These amphibolites are intruded by the granite gneiss and granodiorite gneiss. Locally, lit-par-lit intrusive contacts exist between the amphibolite and the granite gneiss and granodiorite gneiss. The amphibolites are also intruded by the mafic units of the peralkalic magma series such as gabbro and pyroxenite, and by the younger granites of the series. In part the amphibolite is replaced by serpentinite.

Biotite granite gneiss and biotite-hornblende granodiorite gneiss

Non-layered biotite granite gneiss and biotite-hornblende granodiorite gneiss form a batholith that is the largest geologic feature of the region (Brown and Jackson, 1959). In its central part at a point about 50 km southwest of Hamdah, the batholith is 150 km wide. Its long axis strikes N.15°W. and it is exposed for 235 km in the Asir quadrangle (Brown and Jackson, 1959). The long axis of this batholith appears to plunge southward in the southern part of the batholith and northward in the northern part of the body.

The batholith of granite gneiss and granodiorite gneiss is interpreted to be a late kinematic feature in terms of the early northerly folding, because its contacts are grossly concordant and harmonious with the wall rocks of the volcanic-sedimentary sequence, but in detail they are locally strongly discordant. The granitic and granodioritic gneisses of the batholith contain inclusions of the rocks of the volcanic-sedimentary sequence, commonly more or less metamorphosed. The inclusions are thought to be fragments from the lower and middle parts of the volcanic-sedimentary sequence, and from the early basic and ultramafic intrusives into the volcanic pile. Inclusions of upper elements of the volcanic-sedimentary sequence, such as rhyolite and slate, have not been observed, suggesting the possibility that these rocks were deposited after intrusion of the granite gneiss and granodiorite gneiss. Bodies of biotite granite in the granite gneiss and granodiorite gneiss may be rheomorphic or metasomatic developments from the gneisses at the onset of the tectonism giving the cross folds. The mafic and granitic intrusives of the peralkalic magma series are post-tectonic.

The rock is called biotite granite gneiss in those areas where it is characteristically granitic in mineral composition. The term biotite-hornblende granodiorite gneiss is used as the more general term to include both areas where the rock is typically granodioritic and also to include areas where it has not proved to be feasible to map separately a granite gneiss unit and a granodiorite gneiss unit. Gradation has been observed between the granite gneiss and granodiorite gneiss, and dikes and sills of granite gneiss have been seen in the granodiorite gneiss, but granodiorite gneiss was not observed to intrude granite gneiss. From these relations, the granite phase is interpreted to be a little younger than the granodiorite phase. At a few localities the granodiorite gneiss grades into diorite gneiss, but this seems to be very rare.

Dark dikes are much more common in the granite gneiss and granodiorite gneiss than they are in the younger granites of the area. Mainly these dikes seem to be related to the gabbro, diorite, and pyroxenite of the peralkalic magma series. The possibility exists that some of these dark dikes are actually feeders for late increments to the volcanic rocks in the volcanic-sedimentary sequence, intruded near the end of the northerly folding after the granite gneiss and granodiorite gneiss were emplaced. Some of these dark dikes are foliated parallel to the flow banding or later cataclastic foliation of the granite gneiss and granodiorite gneiss.

The two gneisses are light gray to gray. They are generally equigranular and fine- to medium-grained; only rarely are coarse-grained varieties exposed. The gneissic banding in both rocks is obviously a primary flowage feature marked by well-oriented inclusions. The orientation of planar features like schistosity in the inclusions may be either parallel to the primary flowage structure in the gneisses or athwart it. Actually, the best evidence for primary flowage of the gneisses is where the foliation of the inclusions is athwart the flowage of the gneiss. Elsewhere the gneissic structures may be tectonically imposed. Examples of cataclastic foliation are also found in these gneisses, with recrystallized cataclastic lineations preserved, or porphyroclasts of biotite and feldspar defining the lineation.

Contacts between the granite gneiss and granodiorite gneiss are intrusive although they are locally modified by faulting. In general the primary flow banding of the granite gneiss and granodiorite gneiss is parallel to contacts and the contacts tend to be parallel to bedding or foliation in the host rocks. In detail, however, there are many cross-cutting relations of which the most evident are dikes of granite gneiss and granodiorite gneiss in the host rocks, and, near contacts, swarms of host-rock fragments in the gneisses making classic examples of igneous breccia. In some igneous breccias, particularly those formed from andesite and meta-andesite, the inclusions tend to be angular and seldom larger than 50 cm. Inclusions of microdiorite, diorite, and gabbro of the older unit of mafic rocks tend to be egg-shaped and seldom larger than 30 cm. Where best developed, for example near station 22762 in the northwest-central part of the Duthur as Salam quadrangle (plate 3), there are literally thousands of small inclusions in the igneous breccia. Primary flow banding in dikes of granite gneiss and granodiorite gneiss tends to be parallel to the walls of the dikes and across the bedding or foliation of the host rock.

Evidently the intrusion of the granite gneiss and granodiorite gneiss was locally sufficiently forceful to create shear zones and dragged areas at some contacts. The shears are particularly common along amphibolite and gabbro of the older unit of mafic rock, and at contacts with hornblende schist. There the shearing made the walls of the host rock schistose, and sills and stringers of the gneisses intrude the foliation in the host.

Pegmatite dikes and quartz veins attributable to the granite gneiss and granodiorite gneiss are extremely sparse. Rare ptygmatic pegmatite stringers and folded quartz veins in the gneisses, or lenticular masses of pegmatite or quartz oriented in the primary flow banding of the gneisses, seem to be attributable to the gneisses as a source. However, the bulk of the granitic and felsitic dikes seem to be related to the peralkalic magma suite.

Calc-alkalic biotite granite

Granitic rocks mapped as calc-alkalic biotite granite and porphyritic biotite granite form northerly elongate to sub-circular plutons younger than the granite gneiss and granodiorite gneiss and older than the rocks of the peralkalic magma series. The rocks are gray to pink and tend to be porphyritic with large microcline or orthoclase crystals especially common in the border facies. Quartz in the porphyritic granite tends to be bluish, and associated pegmatite and aplite are rare. Compositional variations include biotite-hornblende granite and hornblende granodiorite. Generally the rock is massive, but locally it is gneissic. Primary flowage features tend to be lacking. Inclusions are present but not common. They consist of granodiorite gneiss and material from the volcanic-sedimentary sequence, particularly andesite, diorite, and gabbro.

The contacts between the calc-alkalic biotite granite and porphyritic biotite granite and the older granite gneiss and granodiorite gneiss tend to be nebulous at many places. The early gneiss appears to grade into the massive calc-alkalic granites through decrease in grain size and quantity of biotite, disappearance of hornblende, and increase in potassium feldspar. In these nebulitic areas epidote and epidote-quartz stringers are common.

The phenocrysts of the porphyritic facies of the calc-alkaline granites commonly appear to be metacrysts formed in the solid state after, possibly long after, the host rock crystallized. In areas where numerous inclusions are present in the biotite granite, the large metacrysts of potassium feldspar are present in the inclusions and in the biotite granite, and these metacrysts also extend across the contact between the inclusion and the biotite granite. Even flow bands in the granite around the inclusion are cut by the metacryst; half the metacryst is in the inclusion and half is in the granite, but the flow bands that follow the outline of the inclusion are not deflected around the metacryst.

Some of these metacrysts resemble the orthoclase crystals in Rapakivi-type granites in that they have thin white rims of plagioclase around the pink orthoclase. Locally, large potassium feldspar crystals in pink to light gray biotite granite have included trains of biotite flakes oriented parallel to the main faces of the feldspar crystal. At least three such biotitic zones are present in the crystals, and a selvage of biotite surrounds the faces of the feldspar crystal. These biotitic zones are interpreted to be caused by successive stages of growth of the feldspar. They are found in crystals in porphyritic granite and in crystals growing across the boundary between granite and inclusions. Because they persist undisturbed across the boundary, it is inferred that the zoned crystals are metacrysts formed in the solid state. Thus, the possibility exists that the porphyritic facies of the massive calc-alkalic biotite granite in large parts of the area was made "porphyritic" by widespread addition of potassium and that these large feldspars grew in a solid state. However, the pervasiveness of possible potash metasomatism in the rocks was not evaluated.

One of the most distinctive features of the distribution of the bodies of calc-alkakic biotite granite in the area of the Asir quadrangle (Brown and Jackson, 1959) is the linear northerly arrangement of these bodies along the Hamdah belt from about 80 km south of the Tathlith one-degree quadrangle to north of Tathlith. At the south end of the belt of granitic bodies and extending southward is a large synformal mass of the slate, felsite, and quartzite unit, whereas at the north end of the belt rhyolite is found to be a component of the volcanic-sedimentary sequence of rocks (Overstreet, 1968a, p. 13). The plutons of calc-alkalic granite, interestingly, are associated with extensive areas of diorite and microdiorite.

Peralkalic magma series

The term peralkalic magma series was introduced by Overstreet and Rossman (1970, p. 14) in the Wadi Wassat quadrangle to identify a probable magmatic differentiation sequence of igneous rocks that ranges in composition from gabbro and diorite to granite, rhyolite, and syenite. The silicic members of the suite commonly have aluminous pyroxene and amphibole and form subcircular homogeneous to zoned plutons. The plutonic rocks of the series tend to be intruded by the hypabyssal rocks of the series. Generally the older hypabyssal rocks tend to form interior dikes in the plutonic rocks, and the younger hypabyssal rocks commonly are exposed as dike swarms exterior to the plutonic rocks of the peralkalic magma series. Many dike swarms are concentrated in roof pendants of the volcanic-sedimentary sequence or granodiorite gneiss over unbreached masses of plutonic members of the magma series. At such localities, it is common to see sheeted joints in the cover rock of the unbreached intrusives.

Gabbro, diorite, and anorthosite in intrusive masses.--The oldest rocks of the peralkalic magma series are masses and subcircular plutons of gray to nearly black, fine- to coarse-grained gabbro and diorite. These rocks intrude andesite, hornblende schist, and marble of the volcanic-sedimentary sequence and contain inclusions of the sequence. The gabbro and diorite also intrudes the granite gneiss and granodiorite gneiss and contains inclusions of those gneisses. Thus the gabbro and diorite is younger than the units of microdiorite, diorite, gabbro, and amphibolite that are plutonic equivalents of the volcanic rocks in the volcanic-sedimentary sequence. The younger gabbro and diorite of the peralkalic magma series is intruded by dikes and masses of the granitic rocks of the series, and inclusions of this gabbro and diorite are in the younger granites.

The gabbro is generally massive and non-metamorphosed. Locally along faults the gabbro is sheared, schistose, or brecciated, but ordinarily it tends to lack closely-spaced joints. Many of the small plutons of gabbro are layered, and the layering is both compositional and textural. The commonest layered plutons consist of gabbro and diorite. Contacts between layers may be either sharp or gradational. At a few localities, thin selvages of anorthosite are interlayered with the gabbro. Locally, dikes of pyroxenite, bronzitite, and pegmatite intrude the gabbro. The pegmatite tends to have coarse blades of biotite, and quartz cores of the pegmatites are the sources of quartz detritus that make conspicuous white splays on the gabbro.

Contacts between the gabbro and intrusive masses of granite and felsite are generally sharp with scant alteration of the walls. The most common mineral formed along these contacts is epidote, which tends to occupy cracks and joints in the granite dikes instead of selvages on the walls. At such contacts, the diorite seems to have been more susceptible to alteration than the gabbro, and the biotite in the diorite is more commonly altered to chlorite than is the amphibole or pyroxene in either the diorite or the gabbro.

Prominent ridge-forming dikes of gabbro, as at station 22207 in the southwest corner of the Hamdah quadrangle (plate 4), are locally altered to saprolite on the lower slopes and near the wadi floors.

Biotite diorite is more common but hornblende diorite, biotite-hornblende diorite, and biotite-quartz diorite are represented. The rock is less massive than the gabbro; thus, schistose and gneissic varieties are more common than they are to the gabbro. Locally, the diorite forms igneous breccia along its contacts with older rocks, particularly with massive andesite. Near station 22933 in the north-central part of Al Hassir quadrangle (plate 1) the diorite contains copious septa and angular inclusions of epidotized and chloritized andesite which forms the roof of the dioritic intrusion. Considerably textural and compositional variation exists in the diorite. These variations are inferred in part to reflect irregularities in the shape of the roof of the pluton, and in part reflect mineral and chemical differences related to magmatic segregation at the border of the pluton.

The light colored selvages of massive anorthosite are mainly too small to show individually on the geologic maps. The anorthosite tends to be associated with coarse-grained gabbro and to be intruded by dikes of fine-grained gabbro. Locally the anorthosite itself forms small dikes in layered gabbro plutons. In at least one locality, station 22430 in the south-central part of the Wadi Haraman quadrangle (plate 2), the anorthosite contains about 1.5 percent of ilmenite.

Layered gabbro and norite intrusive complex.--A composite layered gabbro and norite intrusive complex is shown on the geologic map of the Hamdah quadrangle (plate 4). The gabbro and norite are massive and give a resonant note when struck with a hammer. Two ring-structure plutons of the complex intrude hornblende schist. The layering is parallel to the walls of the structures. The northerly, larger, and more perfect of the two plutons may be younger than the southwesterly pluton and intrude it, or the southwesterly pluton may have been faulted southward from the main pluton. Clearly defined layering in the southwesterly pluton, at its contact with the northerly pluton, as seen on the aerial photographs, indicates the northerly pluton is younger and intrusive into the southerly pluton. Primary layering in the northerly pluton also is interpreted as cutting across the southerly pluton.

Pyroxenite and bronzitite dikes.--Practically all pyroxenite and bronzitite dikes noted in the area are intrusive into gabbro, and, indeed, in a few places coarse-grained gabbro grades into selvages of pyroxenite. Some large inclusions of layered, chloritized pyroxenite are present in fine-grained biotite granite of the peralkalic magma series at station 22810 in the extreme northwestern corner of the Duthur as Salam quadrangle (plate 3); this is almost certainly part of the young pyroxenite of the magma series. Inclusions of essentially unaltered pyroxenite were found in the serpentinite at station 22282 in the southwestern part of the Hamdah quadrangle (plate 4), but this is thought to be old pyroxenite related to the ultramafic rocks of the volcanic-sedimentary series. Also, at station 22261 in the southwestern part of the Hamdah quadrangle, small bodies of pyroxenite of irregular shape intrude hornblende schist and in turn are intruded by granite dikes of the peralkalic magma series. These small bodies of pyroxenite are partly altered to poor-quality soapstone. Their age is uncertain, but they may belong to the younger pyroxenite of the peralkalic magma series.

Some of the pyroxenite is biotite pyroxenite, in part possibly formed by alteration of the pyroxene to biotite. In the west-central part of the Hamdah quadrangle (plate 4) at station 22216 the pyroxenite dikes are dark brown bronzitite composed essentially of bronzite.

Dikes of gabbro, diabase, diorite, dacite, and andesite.--In addition to the plutons of gabbro and diorite described above, there are related hypabyssal dikes of gabbro, diabase, diorite, dacite, and andesite in the peralkalic magma series. These dark dikes occupy satellitic swarms in and around the plutons of gabbro and diorite. The dikes are older than most of the granitic rocks of the magma series, and granitic dikes intrude the dark dikes even where the trends of the dikes are the same. The textures and mineral composition of the gabbro dikes and diorite dikes are similar to those of the plutons. Among the diorite dikes there is some diorite porphyry not represented in the plutons. Diabase, dacite, and dacite porphyry dikes are rather rare. They intrude rocks of the volcanic-sedimentary sequence, granodiorite gneiss, and gabbro, and are cut by granitic dikes of the peralkalic magma series.

The andesite dikes are of varied chronological ages. Swarms of andesite dikes cut the gabbro and diorite units of the peralkalic magma series and are intruded by the granitic rocks of the series. However, a later group of andesitic dikes are also present in the area. These late dikes are associated with lamprophyre dikes and intrude some of the youngest granitic rocks in the series. Some of the older andesite dikes are porphyries, with feldspar phenocrysts up to 5x25 mm; with general increase in grain size, the andesite dikes grade into diorite dikes.

The andesite dikes are rarely metamorphosed. They are cataclastically deformed where later faults have intersected them, and some are even schistose where faulted. Where they are cut by granitic dikes, there is a sparse development of epidote or chlorite, and at a few places where they intrude gabbro, minor amounts of epidote are on the walls of the dikes.

Biotite granite, biotite-pyroxene granite, and porphyritic biotite granite in homogeneous subcircular plutons.--The oldest plutonic granitic rocks in the peralkalic magma series are biotite granite, biotite-pyroxene granite, and porphyritic biotite granite that form homogeneous subcircular plutons in contrast to the somewhat younger biotite granite and biotite-pyroxene granite in zoned subcircular plutons. These granitic rocks are generally pink, but the color grades from white to red. The non-porphyritic varieties are massive and fine- to medium-grained. The equigranular granites are generally finer grained at their contacts than in the body of the mass. The contacts may be of knife-edge sharpness or may be complex zones of igneous breccia in which inclusions of the host rocks range from egg-size, round to angular fragments to septa several thousand meters long. The matrix material in zones of igenous breccia tends to be biotite-quartz monzonite and biotite granodiorite instead of biotite granite. Primary flow-banding along the contacts is not common. The more central parts of the plutons of the biotite granite and biotite-pyroxene granite may have areas where swarms of small, egg-shaped inclusions of fine-grained diorite are present. It is possible that these are cognate. Locally, the contacts of red phases of these granites show as bleached zones on the aerial photographs, but no physical reason for the appearance could be found in the rocks themselves. Where faulted, local and spectacular cataclastic foliation and lineation commonly develop in the granites. At station 22233 in the south-central part of the Hamdah quadrangle (plate 4) biotite streaks up to 10 cm long and blade-shaped aggregates of quartz up to 1 cm long have formed in a cataclastic foliation along a minor fault.

Pyroxene-bearing and pyroxene-free varieties of the biotite granite grade into each other.

Porphyritic varieties of the peralkalic biotite granite lack the blue quartz of the older calc-alkalic porphyritic biotite granite and inclusions are perhaps less common than in the non-porphyritic varieties. Microcline phenocrysts give this granite its porphyritic texture. Measured phenocrysts in different parts of individual plutons and in separate plutons showed sizes of 1x1x3 cm, 2x3x5 cm, 2x3x6 cm, 3x3x8 cm, and 4x4x7 cm. Many of the phenocrysts have rounded ends like the Rapakivi-type crystals, but they lack the rim of plagioclase that is part of the Rapakivi-type crystal and which is present on the microcline metacrysts in the calc-alkalic porphyritic granite. The microcline phenocrysts of the peralkalic porphyritic biotite granite rarely have trains of included biotite and mantles of biotite like those seen on feldspar crystals in the calc-alkalic granites. Also, some inclusions of fine-grained diorite contain microcline phenocrysts of the same size and shape as those in the peralkalic porphyritic granite.

The similarities of these microcline phenocrysts, or metacrysts, in granitic rocks of separate ages and possibly of quite different origin is unexplained. It is part of the general problem of the ages, correlation, and origin of the granitic rocks in the southern Arabian shield.

At station 22217 in the west-central part of the Hamdah quadrangle (plate 4) a mass of strongly zoned, white, biotite granite, too small to be shown on the map, intrudes gabbro and pyroxenite.

The stock grades inward from a granitic wall zone up to 40 m thick to a coarse-grained alaskitic inner zone up to 1.5 m thick surrounding a barren white quartz core. The alaskitic inner zone has films of muscovite on the crystal faces of the potassium feldspar, and rare books of strongly rived colorless muscovite up to 3x4 cm. The quartz core is lenticular, pinches and swells, and is up to 5 m thick. In many textural and mineralogical relations, this little stock resembles the granitic dikes of the peralkalic magma series that grade through granite and graphic granite to simple eutectic pegmatites with sparse muscovite and to quartz veins.

Zoned subcircular plutonic differentiates.--Late tectonic to posttectonic differentiates of the peralkalic magma series, with respect to the late easterly folding and west-northwest faulting, form strongly zoned subcircular plutons, small stocks, and dike swarms intrusive into the earlier rocks in the area. The zoned plutons, the most characteristic structural unit of the peralkalic magma series, are composed of an outer rim of pink to red, coarse-grained, locally porphyritic biotite-pyroxene granite which grades inward to a central mass of fine-grained biotite granite around a core of coarse-grained biotite granite. Narrow and intermittent selvages of fine-grained pyroxene granite are found locally on the exterior walls of the pluton. Weak primary flow banding defined by primary layering, oriented feldspar and pyroxene crystals, and small inclusions suggest that the plutons are funnel shaped, and that the plunge of the axis of vertical elongation of the plutons is asymmetric. The large pluton of Jabal Al Hassir is broken around its periphery by a number of short vertical faults caused by outward expansion of the core rocks against the rocks of the wall zone. For this reason, principally, the wall-zone coarse-grained biotite-pyroxene granite is thought to be older than the central fine-grained biotite granite and the core of coarse-grained biotite granite.

The pink to red, coarse-grained, equigranular to porphyritic biotite-pyroxene granite of the wall zone is a generally massive rock with local poorly developed primary flow banding. A faint lineation of oriented pyroxene crystals is present in the plane of flow banding. Pyroxene is variably present and may be absent. Some phases of this rock are quartz rich. Where it is porphyritic, the phenocrysts are red microcline.

The central fine-grained biotite granite into which the coarse biotite-pyroxene granite of the wall zone grades is a pink to red, massive, equigranular fine-grained rock. Locally it is light gray, and these gray phases intrude the coarse-grained red granite of the wall zone. Inclusions are rare; those observed are large septa of hornblende schist. This granite grades into a coarse-grained pink massive biotite granite with closely spaced planar structure that forms the core of the zoned pluton.

In the main Jabal Al Hassir pluton several small selvages of fine-grained, pink, massive pyroxene granite are along the steep east exterior wall of the pluton. An inconspicuous primary flow banding is present. The same rock forms the west half of the small, partly unroofed composite granitic pluton at Jabal Aruwayyuk in the northern part of Al Hassir quadrangle (plate 1). This fine-grained pyroxene granite may be an early phase of the zoned plutons.

Fine-grained, massive, red biotite-pyroxene granite makes up the east half of the small pluton at Jabal Aruwayyuk. It has a crude primary flow banding faintly defined by a layering of feldspar crystals and a linear arrangement of pyroxene grains and biotite. Sheeted joints in older rocks to the west of the small zoned pluton at Jabal Aruwayyuk indicate that the main mass of the pluton has not been breeched by erosion.

Coarse-grained, massive, pink biotite-pyroxene syenite is associated with the zoned pluton of the peralkalic magma series in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, p. 19-20), but in the Tathlith area the syenite is some distance to the east of the main zoned pluton at Jabal Al Hassir. The syenite forms a shoulder on a pluton of peralkalic biotite granite in the southeastern corner of Al Hassir quadrangle (plate 1).

Practically no epidote is present on joints in the granites of the zoned plutons. Quartz veins and pegmatite are quite scarce in the plutons, and most dikes are exterior dikes. From these observations it is inferred that the zoned plutons were formed from relatively dry magma.

That the zoned plutons are older than quartz porphyry, felsite, and rhyolite of the peralkalic magma series is shown by the presence of rare dikes.

Pink to red granite porphyry.--Small masses of pink to red granite porphyry are present in the northeastern part of the Duthur as Salam quadrangle (plate 3) and long dikes are present in the southwestern part of the quadrangle. In the southwestern part of the Hamdah quadrangle (plate 4) small dikes and masses of red granite porphyry are present. The northerly mass of red granite porphyry forms a selvage along the southwestern edge of a pluton of peralkalic biotite granite. This selvage has prominent planar flow structures visible on the aerial photographs. Also, the red granite porphyry is strongly sheared locally with copious epidote developed on fracture surfaces. Masses of coarse-grained red granite porphyry too small to show at the scale of the map were observed in the fault valley northeast of Jaash (plate 3). This granite porphyry has a strong cataclastic foliation in which porphyroclasts of quartz are preserved. Minerals in the groundmass include feldspar, quartz, biotite, and hornblende.

The long dike in the southwestern part of the Duthur as Salam quadrangle grades along strike from granite porphyry to granite and felsite. In the Hamdah quadrangle small plugs and dikes of pink granite porphyry intrude gray granite gneiss. The granite porphyry contains sparse brown spots apparently derived from the weathering of tiny grains of allanite. These plugs and dikes are a few kilometers north of a pluton of peralkalic biotite granite from which allanite was collected by Glen F. Brown for isotopic age determination (see section on Isotopic age data).

Quartz monzonite and quartz monzonite porphyry.--Scarce sills, dikes, and plugs of quartz monzonite and quartz monzonite porphyry crop out in the Hamdah quadrangle (plate 4). Both rocks are fine- to medium-grained and gray. The quartz monzonite sills are locally gneissic parallel to their walls, but the dikes and plugs are massive. Biotite is present in the quartz monzonite and in the porphyry, and the porphyry differs only in having small phenocrysts of potassium feldspar and very fine-grained biotite. Dikes of fine-grained red granite and felsite intrude the quartz monzonite.

Dikes of granite, felsite, aplite, and pegmatite.--Dikes of white, pink, or red granite, graphic granite, and felsite, white to pink aplite, and white to red pegmatite are apophyses and differentiates from the granitic rocks of the unzoned and zoned plutons of peralkalic granites. The dikes tend to strike northwest and west-northwest parallel to the direction of late faulting and fracturing in the area. That this direction of weakness was repeatedly opened is shown by the variety of rocks that occupy fractures in this direction, by the fact that some of these dikes were fractured and opened along the northwesterly direction, and by the number of faults and fractures that strike northwesterly but are not occupied by granitic dikes and, in fact, probably cut the Wajid Sandstone. The most persistent of these dike swarms are associated with peralkalic plutons in Al Hassir (plate 1) and Duthur as Salam (plate 3) quadrangles.

The granite dikes commonly grade along strike into graphic granite, felsite, and pegmatite. These dikes are generally massive, equigranular, and rarely have chilled margins. Most of them are biotite-bearing, and a few contain muscovite or biotite and muscovite, but pyroxene is very scarce to absent. The fact that they contain biotite instead of pyroxene conforms to the internal mineralogical zoning of the Jabal Al Hassir pluton: the youngest rock in the core is biotite granite whereas the older rocks are pyroxene granites and biotite-pyroxene granites.

Felsite dikes grade into dikes of granite or pegmatite, but locally the felsite dikes are younger. Biotite and other femic minerals commonly are lacking in the felsite dikes; however, some of them contain garnets, or magnetite, or pyrite, or else are sheathed with massive selvages of epidote. Some felsite dikes contain a few percent of biotite and hornblende.

Aplite dikes are uncommon, and were observed only in the Hamdah quadrangle (plate 4) where they intrude serpentinite, gabbro, and pink biotite granite. They tend to be associated with dikes of granite and pegmatite, but gradational relations of aplite to these rocks were not observed.

Few pegmatite dikes in the area are as much as 1 m thick and 100 m long, and virtually none is zoned. The pegmatite dikes are typically nearly eutectic mixtures of pink orthoclase and white quartz, essentially devoid of mica and accessory minerals. Rarely, pyrite or allanite is present, and a few pegmatites have amazon stone or singly terminated crystals of clear quartz. Perthitic feldspar is quite rare, and is present mainly in quartz-poor pegmatites. Where zoning has developed, it consists of a prominent white quartz core surrounded by a normal pegmatitic outer zone. Most pegmatite dikes are granitic in origin, but a few associated with plutons of diorite and gabbro are syenitic.

Quartz veins and masses.--Quartz veins and masses of several ages and origins are present in the area. Those of largely metamorphic origin have been commented on earlier, and the mineralized quartz veins are described below in the section on Mineral Resources. The quartz veins and masses discussed here are the barren segregation products from the pegmatite and granite dikes. The larger veins and masses of quartz form splays of rubble that are readily visible on the aerial photographs. Some of the largest barren veins are as much as 30 m thick and 2.5 km long, consisting of massive to banded milky quartz. Large, barren masses of platy milky quartz form hills and coalescing aprons of white scree in diorite and gabbro of the Duthur as Salam quadrangle (plate 3)). The smaller veins and masses of quartz develop gradationally along or across strike of dikes of granite, graphic granite, and pegmatite.

Quartz porphyry.--Intrusive masses or dikes of gray, pink, or red quartz porphyry and biotite-quartz porphyry of rhyolitic composition intrude all the older rocks in the area, and individual dikes cut host rocks of several ages. A dike of coarse-grained red quartz porphyry that intrudes the northwestern part of the Jabal Al Hassir pluton (plate 1) has a sharply defined core of minette, but most of the quartz porphyry dikes are not composite. Where the quartz porphyry dikes are transected by shear zones, the rock may be mylonitized and extensively replaced by epidote. Locally, diorite and gabbro intruded by red quartz porphyry may have many unakite veins, or the gabbro may be partly chloritized. Muscovite is present but uncommon in the quartz prophyry.

The small stocks and masses of quartz porphyry are intrusive except at Al Lugatah (Farage) mine in Al Hassir quadrangle (plate 1) where the quartz porphyry is a tectonic slice caught between bodies of chlorite schist in a major north-trending fault zone. Where stocks and small masses of quartz porphyry are intrusive, the contacts tend to be knife-edge sharp with no reaction in the wall rocks and with chilled margins up to 300 m thick in the porphyry. Dikes and apophyses of quartz porphyry run out into the wall rocks from the stocks. Inclusions of wall rocks were not seen in the stocks; however, possible faint primary foliation parallel to the contacts was noted in at least one small mass of quartz porphyry.

Lamprophyre and other dark dikes.--The minette in the dike of quartz porphyry mentioned above is one of the lamprophyre and other dark dikes younger than the quartz porphyry, felsite, and granite dikes. A rather wide range of these young dark dikes was observed in the area where they were identified megascopically as dacite, diorite, and andesite. It is thought, however, that a microscopic study of these late dikes would show that they are mainly syenitic lamprophyres, possibly mainly kersantites.

Rhyolite.--Rhyolite dikes and sills of several ages are intrusive into the rocks of the peralkalic magma series and the older rocks in the area. The youngest of these rhyolite dikes intrude the lamprophyre and other late dark dikes. Some rhyolite dikes, however, are intruded by the lamprophyre and other young dark dikes. Rhyolite dikes intrude the quartz porphyry unit, and rhyolite dikes are intruded by some felsites. From the various intersecting relations observed, the oldest rhyolites of the peralkalic magma series are inferred to be penecontemporaneous with the peralkalic biotite granite; thus, the rhyolite dikes appear to be chilled small-mass equivalents of the various granitic rocks of the series, but are seemingly more common as late than as early intrusives.

The rhyolite dikes are dark gray, brown, or red, and locally have strong primary flow banding parallel to their walls. Thin dikes are hard and tough, and break with a conchoidal fracture. Thick dikes tend to grade along strike into felsite or fine-grained granite or granite porphyry. Rarely, some thick dikes grade inward into felsite or fine-grained granite; thus, many of the felsite and granite dikes apparently were emplaced under about the same conditions of temperature and pressure and at about the same time as the rhyolite dikes. The youngest rhyolite dikes are, however, the youngest igneous rocks of the peralkalic magma series. Where the rhyolite dikes have been involved with later faults, they may be strongly brecciated. These breaks are usually unhealed.

Mostly the minerals in the rhyolite are too fine grained to be identified megascopically, but in some of the thick dikes tiny grains of quartz, biotite, and garnet were seen. Epidote is very rare.

Wajid Sandstone

The Wajid Sandstone of Cambrian-Ordovician age (Schmidt and others, 1973, table 1) overlies unconformably the metamorphic and igneous rocks of Precambrian age in the eastern part of the area (plates 2 and 4). The sandstone dips gently eastward to southeastward and is much dissected by erosion. It is a reddish-brown, yellow or tan cross-bedded sandstone with ferruginous cement and concretions. Thin beds of conglomerate, composed of rounded quartz pebbles, are present, as are lenticles of clay. Locally, the underlying Precambrian rocks are weathered to saprolite for a depth of a few meters. This condition indicates the saprolite was more pervasive but was removed by erosion before the Wajid Sandstone was deposited. The weathered and eroded products were incorporated in the Wajid in part as lenticles of clay.

No dikes or plugs of igneous rocks were observed to intrude the Wajid Sandstone despite the fact that a few plugs of Tertiary(?) basalt are present in the crystalline rocks west of the Wajid.

The Wajid Sandstone may be cut by two major fault systems: an older northerly system and a younger northwesterly system. Northwest-trending faults appear to be more common than northerly faults in the Wajid, suggesting that late activity or more probably readjustment was more common along the northwesterly lines. Thus, old fault systems active in Precambrian time may still have been active after the consolidation of the Wajid Sandstone. The faults in the Wajid appear to be mainly normal faults of possibly no more than 100 m displacement; hence, late motion on these systems of faults was small and of a different sense than earlier displacements.

The faults were projected on plates 4 and 2 through the Wajid Sandstone from interpretation of string lineaments on the aerial photographs. From observations made outside the mapped area, vertical faults with up to 100 m displacement were seen in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970) and in areas farther to the south (Overstreet, 1968c, p. 40-41). A westerly dipping normal fault was seen in the Wajid Sandstone about 15 km northeast of the northeastern corner of the Wadi Haraman quadrangle. It is possible that some of the lineaments interpreted as faults will prove to be compaction structures in the Wajid where the sandstone was deposited over local features of steep relief in the Precambrian rocks, those features being attributable to the Precambrian faults.

Diabase and basalt plugs and dikes of Tertiary(?) age

Several small dikes of non-metamorphosed basalt, striking west-northwesterly to westerly and dipping 60°N., in the northwestern part of the Duthur as Salam quadrangle (plate 3) and a small plug of unaltered diabase that intrudes serpentinite in the southwestern part of the Hamdah quadrangle (plate 4) may be Tertiary in age and may be related to the Tertiary basalts in the southwestern part of the Asir quadrangle (Brown and Jackson, 1959). The freshness of these rocks, and their texture and mineralogy, resemble the basalts identified by Brown and Jackson (1959) in the As Sarat mountains some 200 km to the south-southwest of the Duthur as Salam and Hamdah areas. Similar small plugs were noticed in the intervening area, and their presence is increasingly common south-southwestward in the direction of the As Sarat (Overstreet, 1968a, p. 15). Thus, it is possible that scattered centers of Tertiary volcanism, now removed by erosion except for a few feeder dikes and plugs, were present in the shield for about 200 km north of the main erosional remnants of basalt at the As Sarat.

Surficial deposits of Quaternary age

The surficial deposits of Quaternary age shown on plates 1-4 are gossan, alluvial fan and terrace deposits, silt, and alluvial and aeolian sand. All are products formed by the disintegration of the older rocks in the area.

Gossan.--Small gossans crop out in the Hamdah quadrangle (plate 4). The largest is a circular area about 700 m in diameter and 4 to 6 m thick at station 22263 in the west-central part of the quadrangle, where the gossan is composed of limonite and jasper. The gossan overlies serpentinite and sericite-chlorite schist, but it forms so complete a cap that the source rock for the limonite and jasper could not be identified. It could have been pyritiferous schist or even ferruginous marble. The possibility of a carbonate source rock is suggested by the presence of calcite with the jasper. Copper stain is lacking.

Near station 22315 (plate 4) a small limonitic gossan about 1 m thick and 100 m long is parallel to the foliation of biotite-hornblende schist intruded by gabbro dikes and a lode zone occupied by thin stringers of quartz. The gossan follows the lode, but the quartz and schist are barren of sulfide minerals.

One of the strongest-developed gossans in the Hamdah quadrangle is the limonitic gossan with nodules of hydrozincite at the Ash Sha'ib ancient mine in the northwestern part of the area. It is described in the section on Mineral Resources.

Very small patches of gossan overlie faintly pyritiferous and magnetite-bearing quartzite near station 22225 (plate 4) on a low, brown, limonite-stained ridge about 170 m long and 120 m wide at the widest. The quantity of pyrite in the quartzite, less than 0.1 percent, seems too sparse to be the source of the limonite stain and gossan; magnetite may be the source.

Other very small gossans are on ferruginous marble in serpentinite and in a shear zone in hornblende schist where the schist is replaced by jasper, limonite, and hematite.

Alluvial fan and terrace deposits.--Alluvial fan and terrace deposits of gravel and coarse sand were identified on the aerial photographs and plotted on the geologic maps. The alluvial deposits mainly form coalescing fans at the toes of steep erosional scarps, and the terrace deposits commonly spread out from these slopes for several kilometers. Some of the most extensive of these deposits are around Jaash in the northeastern part of the Duthur as Salam quadrangle (plate 3).

Silt.--Laminated silt, sand, and clay form conspicuous sedimentary deposits upstream from constrictions in the wadis in the Duthur as Salam, Hamdah, and Wadi Haraman quadrangles (plates 3, 4, and 2). These deposits are shown on the geologic map of the Asir quadrangle (Brown and Jackson, 1959) as being Quaternary in age, and were interpreted to be flood-laid sediments. At least some of the silt is Holocene, however, and was deposited in historic times under conditions controlled by man in irrigated agricultural enterprises (Overstreet, 1968a, p. 15-19). The evidence for this, and its connotations in terms of cyclic climatic changes in Arabia during Quaternary time are taken up below in the section on Rock Weathering and Evidence for Climate Change. Good examples of this type of silt are present in Wadi Tathlith south of Hamdah and in Wadi Tarib south of As Subaykhah.

The sequence of silt in Wadi Tathlith south of Hamdah consists of silt and mud laminae up to 3 cm thick which alternate with micaceous, sandy lenticular cross-bedded layers up to 12 cm thick (Overstreet, 1968a, p. 18-19). All the sediment is poorly sorted. The laminae of silt and mud commonly contain plant fossils, mostly reeds, but the layers of sand tend to be free of plant megafossils. Tubular, iron-stained zones normal to the bedding and up to 1.5 cm in diameter are generally filled with coarse sand but locally contain carbonized roots. The sand-filled tubes may be animal or insect borings, which would show that the upper surfaces of some beds were exposed to the action of the wind in drifting sand. The total thickness of the silt is about 14 m. Approximately 7 m below the top of the section, crusts of NaCl are on exposed faces of the sandy lentils, reflecting freer movement of water in the lentils of sand than in the beds of silt. The mica in the silt sequence is brassy yellow, weathered, hydrobiotite. In the upper part of the silt, gypsum crystals up to 1.5 cm are common. The base of the silt overlaps from normal wadi sand and gravel to the crystalline rocks of the wadi wall.

The beds of mud are very thin and make up but a small percentage of the total thickness of the silts. Platelets of clay from these beds curl strongly at the edges. Intense curling of mud chips suggests non-kaolinitic clay, probably montmorillonite-type clay. Montmorillonite is a typical weathering product of basic rocks.

A sample (2206) of geologically similar silt from the Wadi Bishah drainage near Hasmi (19°53'N.; 42°31'E.) was taken by C. L. Hummel, USGS, in 1964 and examined by P. D. Blackmon, USGS. Blackmon divided the silt into two size fractions at 44 microns (325 mesh); 45 percent of the sample was coarser than 44 microns and 55 percent was finer. Semiquantitative X-ray analyses disclosed considerable mineralogical similarity between the two sieve fractions, and only low percentages of clay minerals in the <44-micron fraction (Blackmon, P. D., 1965, written commun.).

Mineral	>44 microns	<44 microns
Gypsum	<10	-
Calcite	<10	10
Quartz	10+	10
Feldspar	20+	<10
Chlorite	10	20
Mica	10+	20 (highly weathered)
Amphibole	10+	<10
Bassanite	trace	-
Zeolite	trace	-
Iron oxide	-	trace
Montmorillonite	-	<10
Vermiculite	-	<10
Kaolinite	-	trace

The results of these analyses were interpreted by C. W. Sweetwood, U. S. Bureau of Mines (written commun., 1965) to show that, though weathering had taken place to produce the extremely fine-sized particles, little in the way of through alteration had taken place in the original source area for the silt or at the site of sedimentary deposition. The sample was said to exhibit the normal characteristics of a loose, unconsolidated sediment, questionably loess, containing materials from a wide variety of source areas.

The question of the local derivation of the silt in contrast to its possible derivation by aeolian transport from distant sources might be partly resolved by a study of the mineralogy of the agricultural silts near 'Usran in the west-central part of the As Sarat mountains, 125 km southwest of Hamdah. These silts are in a unique lateritic area where, if they are largely locally derived, they could be expected to have more plentiful kaolinite than the usual silts. Also, alunite is sparsely present in the laterite. Some alunite might be expected to be in the silts if local sources were a major factor in their derivation.

Present erosion is removing this silt. Gully erosion is extending into the silt from the present channel of the wadi, and intricate badlands topography is being developed on the silt. On the upslope edges of the silt, broad fans of pebbles and cobbles are locally being developed. These fans are more common in the upstream areas to the south of the area. Where pebble and cobble gravel overlie the silt, they protect it from erosion. It is inferred that these overlying fans reflect a more vigorous erosion than obtained when the silt was deposited, and may be regarded as a return to the normal conditions of erosion. Thus, periods of rapid deposition of the silt may have been interposed between periods of normal deposition of gravel and sand. Some evidence for possible local renewed uplift is present in the form of knick-points along most of the small tributary wadis a few kilometers or less upstream from their junction with Wadi Tathlith and Wadi Tarib.

Alluvial and aeolian sand.--The commonest surficial deposits in the area are the alluvial and aeolian sands that cover the floors of wadis and mantle other catchment surfaces. The deposits consist of dominantly white to buff, poorly sorted alluvial and aeolian sand and gravel with rare small encrustations of calcium carbonate and gypsum. Sand derived from the Wajid Sandstone is notably redder than the other sands, and sand from the mafic rocks is typically very dark gray. This sand is laid by intermittent floods and sheet wash in the wadis, and shifted constantly by winds. Where wind is a major component in shaping the surficial deposits, the deposits were mapped as aeolian sand.

Aeolian sand.--Aeolian sand is found in Al Hassir and Wadi Haraman quadrangles (plates 1 and 2). It consists of sharp-crested longitudinal dunes separated by sand valleys, mainly aeolian sand of types II and III of R. A. Bramkamp's classification (Powers and others, 1966, p. 100). Most of the northern half of the Wadi Haraman quadrangle is covered by wind-blown sand that has been mapped as alluvial and aeolian sand; only where the dunes are developed is it shown as aeolian sand.

Isotopic age data

The only isotopic age available for rocks in the area, at the time the field work was done in 1965, was for a sample of allanite from a pegmatite about 12 km northwest of Hamdah (plate 4). The allanite was collected in 1952 by Glen F. Brown, and an age of 576 m.y., based on U-Th-Pb, was determined for it by T. W. Stern (Brown, 1968, p. 2). The pegmatite from which the allanite was taken is believed to be associated with biotite granite of the per-alkalic magma series shown on plate 4. The age of 576 m.y. reported for the allanite is close to the whole rock K/Ar ages of 562±28 m.y. and 554±16 m.y. reported respectively for granite porphyry and felsite and to the Rb/Sr age of 598±24 m.y. reported for microcline from pegmatite intrusive into granite porphyry of the peralkalic magma series in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, table 1). These ages are interpreted to mean that the granitic rocks of the peralkalic magma series are late Precambrian or early Cambrian in age.

Stratigraphy, structure, and metamorphism

The sequence of volcanic and sedimentary rocks in the area was interpreted in 1965 to consist of two nearly continuous, north-trending sinuous fold belts of andesite with interlayered graywacke intruded by a succession of mafic and silicic igneous rocks. These belts together are referred to as the Hamdah ultrabasic belt after the village of Hamdah (19°02'N.; 43°38'E.) and for conspicuous exposures of serpentinite. The belt, from 10 km to 40 km wide, is a definable lithologic feature from the northern edge of the Tathlith one-degree quadrangle, southward completely across that quadrangle, and thence farther southeastward and southward for some 170 km from Hamdah to a point about 35 km north of the Yemen border (Brown and Jackson, 1959). The belt actually contains a far larger volume of intermediate rocks such as gabbro, diorite, and andesite, and sedimentary rocks such as graywacke than true ultramafic rocks like peridotite, pyroxenite, and dunite. Owing to the metamorphism which has affected them, many of the old ultramafic rocks have been altered to serpentinite.

The Hamdah belt was interpreted to be a great septum in the non-layered granite gneiss and granodiorite gneiss of the central batholith of the Asir quadrangle and was thought to close southwestward at and south of the Yemen border with a wider septum of similar rocks entering from the northwest (Brown and Jackson, 1959). Both septa were inferred to be relicts of the same sequence of volcanic and sedimentary rocks.

The rocks of the Hamdah septum were interpreted to have been deposited early in a geosynclinal cycle along the axial part of the geosyncline. Coarse clastic sediments are rare, volcanic rocks dominate, and these rocks were invaded by early intrusions of peridotite and pyroxenite which were altered to serpentinite prior to the intrusions of the various granitic rocks. The serpentinites of the Hamdah belt may be ophiolites. On a regional scale the Hamdah belt would be a zone of negative gravity anomalies if these serpentinites are part of an ophiolite sequence.

The Hamdah belt includes a sequence of slate, felsite, and quartzite (Brown and Jackson, 1959) which is here thought to overlie the thick volcanic sequence and serpentinite exposed near Hamdah. The probable equivalent of these rocks is shown in the extreme northeastern corner of the Wadi Haraman quadrangle.

Metamorphism of the rocks in the Hamdah septum is quite variable thereby giving rise to diverse lithologic units. In general, regional dynamothermal metamorphism associated with the strong northerly folding was the most important factor in the progressive metamorphism of the rocks in the volcanic-sedimentary sequence. The grades reached by regional metamorphism range from greenschist facies to the lower subfacies of the amphibolite facies. Lower grades of metamorphism are more common than higher grades. The extreme variability of the grades of metamorphism may be attributable to variations in the competence of the rocks and to variations in connate water in them. The post-kinematic intrusive granites have produced highly variable, generally sparse, contact metamorphic effects. Although hornfels and hornblende schists are locally attributable to these granite plutons, there are places where the reaction along the walls of a pluton actually was retrogressive and pre-existing hornblende schist was converted to chlorite-biotite schist.

The distribution of serpentinite and veins of magnesite permit an inference to be made about the composition of the original ultramafic rocks in the Hamdah belt. Where serpentinite is formed from olivine-bearing rocks more magnesium is set free than where serpentinite is formed from olivine-free rocks. Magnesite is much more common in and around the serpentinites exposed in the part of the belt south of Hamdah than it is north of Hamdah. From this distribution it is inferred that peridotite and dunite were originally more common among the old plutonic rocks of the belt than pyroxenite in the area south of Hamdah and less common north of Hamdah.

The andesite of the Hamdah belt is widely chloritized and epidotized. Doubtless both minerals were formed from a variety of geologic processes extending from the actual volcanic deposition of the andesite and the initial folding of the rocks to the close of igneous activity in the area. The layered sequence of volcanic and sedimentary rocks in the Hamdah belt contains the principal mineral deposits of the area.

The major activity on the old north-trending faults appears to have been strike-slip movement with left-lateral displacement. These old faults, in part at least, were reactivated several times, including activity after emplacement of the peralkalic magma series. The last motions on these northerly faults appear to have been normal high-angle faulting with displacement of the Wajid Sandstone of up to about 100 m.

The major northerly folds and faults seemingly have had some control over the distribution of the calc-alkalic biotite granite plutons, and possibly also over their shapes, because they tend to be elongated northerly. If the peralkalic biotite granite formed through rheomorphism of the granite gneiss and granodiorite gneiss, the favorable localities for remobilization have been at intersections of the old northerly structural trends and the younger northwesterly to nearly easterly folds and faults.

Inclusions, lineations, and primary flow banding in the granitic plutons of the peralkalic magma series define an upward flowage of the granitic magma in funnel-shaped masses with relatively steep walls and tilted axes resulting in west walls that dip eastward less steeply than east walls dip westward. Push from the interior by ascending magma caused the walls of the plutons to fracture and blocks of wall-zone rock to be forced differentially outward. Sheeted contacts and joints outside the smaller plutons of the peralkalic magma series are interpreted to show that the main masses of these small plutons are still unbreached by erosion.

The final movements on the northwest normal faults perhaps affected the Wajid Sandstone normal faults with up to 100 m displacement. Veins and dikes are absent from the faults in the Wajid.

The last igneous activity in the area is reflected by the sparse dikes and plugs of Tertiary(?) basalt and diabase.

Possible correlations with stratigraphic and tectonic concepts of 1972

Advances in understanding the stratigraphy and tectonics of the southern part of the Precambrian shield in Saudi Arabia (Schmidt and others, 1972) were used as a guide to recast the lithologic maps (plates 1-4) of this report into a reduced figure showing possible correlations of the lithologic units in terms of revised stratigraphic terminology (fig. 2). For details of these new concepts the reader is referred to the report of Schmidt and associates (1972).

Large parts of the granodiorite gneiss, granite gneiss, layered gneiss, and hornblende schist (plates 1-4) evidently constitute a migmatitic basement equivalent to the Khamis Mushayt Gneiss and Hali Group of Schmidt and others (1972, p. 8-9). The orthogneisses do not form an intrusive batholith which has had extensive contact metamorphic effect on the sequence of volcanic and sedimentary rocks of the Hamdah belt.

Volcanic and sedimentary rocks, identified on plates 1-4 as the oldest rocks and inferred to have been in part altered by dynamothermal metamorphism associated with folding along north-trending axes and in part modified by contact metamorphism from the intrusive plutonic rocks, are seen from the work of Schmidt and others (1972, p. 7-20) to include at least five and possibly more major stratigraphic units. These units are shown on figure 2 as the Baish Group, Bahah Group, Jiddah Formation, Halaban Group, and Murdama Group. The stratigraphic names are taken from table 1 of Schmidt and others (1972) for a best approximate fit to the lithologies described on plates 1-4.

Descriptions of stratigraphic units from Schmidt and others (1972).

Murdama Group - marble, conglomerate, sandstone, siltstone, slate, and argillite

---------------- Unconformity ---------------

Halaban Group - metavolcanic-sedimentary rocks with a predominantly clastic lower part, a predominantly andesitic middle part, and an upper part with silicic flow and pyroclastic rocks; found in the axial parts of north-trending, synformal tectonic blocks bounded by major, highly sheared, north-trending fault zones with local serpentinite

---------------- Disconformity ---------------

78-1072

Figure 2. - Reconnaissance geologic map of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia, showing possible stratigraphic relations.

EXPLANATION

PLUTONIC ROCKS

qp / rgp / qmp / cbg / bpg | fbg / cpg | sy | fpg / gp | pgp

Peralkaline granite

Biotite granite undivided (gp), porphyritic biotite granite (pgp), coarse-grained pyroxene granite (cpg), syenite (sy), fine-grained pyroxene granite (fpg), fine-grained biotite-pyroxene granite (bpg), fine grained biotite-granite (fbg), coarse-grained biotite granite (cbg), quartz-monzonite porphyry (qmp), red granite porphyry (rgp), quartz porphyry (qp); time sequence above cbg not implied

gb | gbp | gba | gbn

Gabbro, pyroxenite, anorthosite and norite

Gabbro (gb), gabbro and pyroxenite undivided (gbp), gabbro and anorthosite undivided (gba), layered gabbro-norite complex

s

Serpentinite

Serpentinite (s) mobilized along north-trending faults; replaces older ultra-mafic rocks

gr

Biotite granite

Red calc-alkaline granite, commonly porphyritic (gr)

gdr

Granodiorite

Granodiorite (gdr), relative age uncertain, may be older than Halaban group

di | dg / md

Diorite and gabbro

Diorite (di); diorite and gabbro undivided, diorite dominant (dg); microdiorite and metadiorite (md)

VOLCANIC AND SEDIMENTARY ROCKS

CAMBRIAN AND ORDOVICIAN

OЄw

Wajid Sandstone

Brown, red, and white, crossbedded sandstone

UNCONFORMITY

PRECAMBRIAN

mg / mgf

Murdama Group

Grayish-green metasedimentary rocks; conglomerate, massive slate and argillite, local red sandstone, shale, and rhyolite (mg); white, blue, black, and brown Farida marble (mgf) near base

UNCONFORMITY

hr / h | hs / hm / hc

Halaban Group

Green conglomerate (hc) derived from andesitic rocks; dark-gray marble (hm); green, massive, commonly deuterically altered andesitic flows and tuffs (h) that may contain undivided massive andesite of Jiddah Group; locally converted to hornblende schist (hs) in contact metamorphic aureoles; buff to dark-red or brown rhyolite in upper part (hr)

jdg?

Jiddah Group

Massive greenstone and meta-andesite, possibly Jiddah Group (jdg?)

UNCONFORMITY

VOLCANIC AND SEDIMENTARY ROCKS (CONTINUED)

PRECAMBRIAN

bhg

Bahah Group

Sericite-chlorite schist, schistose fine-grained graywacke

DISCONFORMITY

bg / bm

Baish Group

Meta-basalt, greenstone, chlorite schist (bg), local dark marble (bm)

UNCONFORMITY

amu | amb / am | ams | gg

Basement complex

Two basement units of undivided age; (1) a dominantly schistose unit, possibly equivalent to the Hali Group, consisting of amphibolite, hornblende schist, hornblende gneiss, and marble (am); locally serpentinized hornblende schist (ams); and biotite schist, biotite gneiss, and garnetiferous biotite gneiss (amb); undifferentiated (amu) and (2) a dominantly orthogneissic unit, possibly equivalent to the Khamis Mushayt Gneiss, consisting of coarse-grained granite gneiss, granodiorite gneiss, common septa of hornblende schist, biotite schist, and numerous dike swarms (gg); includes younger undivided granitic rocks

SYMBOLS

Contact

—?—?—
Fault

Dashed and queried where position or presence is uncertain

Possible sheeted contacts or small domes in gneiss

Antiform and synform
Showing direction of plunge of axis

Jiddah Formation - andesitic unit regionally metamorphosed to the greenschist facies

---------------- Unconformity ----------------

Bahah Group - sericite-chlorite schist, separated by a major angular unconformity from the overlying Jiddah Formation, derived mostly from well-bedded, generally thin-bedded, siltstone, mudstone, siliceous slate, and fine-grained sandstone with subordinate carbonaceous siltstone, ferruginous quartzite, marble and conglomerate

--------------- Disconformity ? ---------------

Baish Group - greenstone is characteristic, derived from mafic volcanic rocks, chiefly basalt with local andesite, agglomerate, flow breccia, andesitic tuff, slate, and chlorite schist

---------------- Unconformity ----------------

Hail Group - several thick units of quartz-biotite-garnet schist interlayered with amphibolite; layers of marble, pebble-conglomeratic schist, and rhyolitic schist are subordinate

--------------- Unconformity ? ---------------

Khamis Mushayt Gneiss - in type area coarse-grained banded orthogneiss and migmatite with lesser amounts of paragneiss, paraschist, and amphibolite; relation between Khamis Mushayt Gneiss and rocks of the Hali Group has not been worked out

Most of the stratigraphic units identifed by Schmidt and associates (1973) are separated by unconformities and basal conglomerates. Few localities displaying these features were observed in the field work of 1965. This is particularly true of the amphibolitic rocks and biotite-garnet schists. They were thought to be xenolithic masses included in intrusive granodiorite gneiss and granite gneiss. Marble and thick conglomerates are present near the base of the Murdama Group at Bi'r Malah (plate 1).

Rocks of probable basement complex and Murdama affinities are the most readily separated on figure 2 from the lithologic units on plates 1-4. The Bahah Group is almost certainly represented among the sericite-chlorite schists below the andesites in the south-central part of the quadrangle, and a reasonable upward stratigraphic succession is seen to pass to the north through these sericite-chlorite schists (Bahah Group), into meta-andesite (Halaban Group), or into marble, graywacke, and andesite (Murdama Group). The probable north-trending narrow synform thus defined occupies the center of the Tathlith one-degree quadrangle and, though much modified by north-trending faults, is flanked to the east and west by broad, complex, anticlinal structures that expose the basement complex consisting of undivided rocks of the Khamis Mushayt Gneiss and Hali Group.

The unit of slate in plate 2 appears upon examination to be part of the Murdama Group. It consists of dark to light green and gray-green conglomerate with very dark green to nearly black matrix containing small, well-rounded pebbles of red granite, conglomerate, andesite, and chert. The conglomerate is interlayered with gray-green siltstone and slate. Thus, the unit is far younger than was shown on the geologic map of the Asir quadrangle (Brown and Jackson, 1959), and in this respect fulfills the interpretation, given earlier in this report, that the unit is among the youngest, not oldest, in the area.

The sericite-chlorite schists of the northeastern quarter of the area are more uncertainly situated stratigraphically than those in the south-central part of the area. Possibly they are also Bahah.

Identification of the Jiddah Formation as a separate unit from the Halaban Group on figure 2 has proved to be uncertain. The same may be said for the Baish Group. Assignments to these two units have generally involved a greater consideration of the lithologies of adjacent units than a positive identification by the descriptions of the lithology of the Jiddah and Baish.

Age relations of the younger granitic rocks have been retained on figure 2 from plates 1-4. Of great importance, however, are the recent observations that show a considerable separation in time between the emplacement of the late granites and syenite and the intrusion of diorite, quartz diorite, and gabbro (Schmidt and others, 1973, table 2). Thus, the inclusion of diorite and gabbro as the earliest intrusives of the peralkalic magma series is abandoned, and the diorite and gabbro are pushed back in time. Even the term "peralkalic" may not be applicable to the late granites (Greenwood, W. R., 1972, oral commun.).

The Wajid Sandstone has recently been designated Cambrian-Ordovician in the areas of the Khamis Mushayt and Khaybar quadrangles (Coleman, R. G., 1971, written commun.) to the southwest of the Tathlith one-degree quadrangle. Thus, the rock weathering and erosion leading to the present land forms may have a longer record than was thought when the Wajid was considered pre-Permian (Brown and Jackson, 1959).

A number of isotopic ages for rocks in the area of the Tathlith one-degree quadrangle have been determined in the late 1960's and early 1970's. They are not as yet formally reported, but they tend to support the tectonic interpretations of Schmidt and associates (1973), and show more periods of plutonism than are indicated by the interpretations given earlier in this report. They show that the plutonic episodes were of relatively short duration, unlike the lengthy episode credited to the peralkalic magma series in the Wadi Wassat area (Overstreet and Rossman, 1970, table 1).

The gross structure of the area of the Tathlith one-degree quadrangle apparently emerges as a central synform that is extensively cut by north-trending left-lateral wrench faults, and antiformal blocks to the east and west that are composed of basement rocks.

Rock weathering and evidence for climate change

Saprolite and gossan, both of which are produced by chemical weathering, are present in the Tathlith one-degree quadrangle. Small areas of gossan are shown on the geologic map of the Hamdah quadrangle (plate 4), but the distribution of saprolite is not shown. The two materials together constitute the main evidence for rock weathering.

Saprolite is a product of the chemical weathering of rocks in which the original texture and structure of the rocks is preserved in a pulverulent rind consisting largely of quartz, clay, residual fragments of feldspar, weathered mica, pyroxene, and amphibole. Saprolites are often thought to have developed through the complete or nearly complete conversion of plagioclase feldspar to clay minerals. Although this development of clay minerals is typical, a less well known condition, but one with important connotations for rock weathering in Saudi Arabia, is the disaggregation of plagioclase grains into myriads of particles of plagioclase having the sizes usually associated with clay (Kessler, T. L., 1954, oral commun.). Such saprolites have very little true clay minerals. Saprolite is soft and easily removed by erosion. The chemical solution leading to the formation of saprolite is usually ascribed to heavy rainfall in humid regions (Persons, 1970, p. 6; Loughnam, 1969, p. 67-74; Carroll, 1970, p. 19-21), but the actual composition of the rainwater and mixtures of rainwater and soil water are also factors (Carrol, 1962). Evidently some saprolite can form under conditions of greatly reduced rainfall, even as little as perhaps 20 cm per year, because erosional relicts of saprolite from 1-2 m thick are found on granite (west of station 22726), andesite (station 22725), gabbro (stations 22207 and 22427), and granodiorite gneiss (station 22531) in the Duthur as Salam and Wadi Haraman (plates 3 and 2) quadrangles.

Gossan is the product of the chemical weathering that leads to the concentration of iron-rich rock materials. It is partly residual on the source rocks and partly transported short distances away from the source. The small gossans in the area seem to have formed during the present erosion cycle, in contrast to the large gossans in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, p. 25-26), which have a long geologic history. In some areas of gossan in the area, the gossan grades downslope into Holocene saprolite, and the saprolite appears to be forming at the present time along with the gossan. This is a special condition for the formation of saprolite possibly related to strongly acid waters draining from oxidizing pyritized rock under the gossan. These acid waters are dissolving the rocks at a vastly accelerated rate compared to the chemical action of normal rainwater and groundwater. In general, the presence of gossan probably indicates wetter conditions in the near geologic past than presently prevail (Overstreet and Rossman, 1970, p. 32; Allcott, 1970, p. 22-25).

The saprolites in the area, instead of the gossan, are the clues to probable climate change in this part of Arabia. The preservation of these materials relates to the younger geologic history and geomorphology (Brown, 1960) of Saudi Arabia.

Pre-Ordovician and Tertiary weathering

Small relict veneers of saprolite underlie the Wajid Sandstone in the area, but they are much less common than they are farther south (Overstreet and Rossman, 1970, p. 31). They are preserved in shallow depressions on the erosion surface of the Precambrian rocks where they were overlain by the Wajid before it was removed. They show that chemical weathering of the Precambrian rocks was a factor at the time deposition of the Wajid commenced.

Eocene(?) laterite up to 130 m thick was identified by Brown and Jackson (1959) in the As Sarat mountains some 200 km southwest of the southern part of the Tathlith one-degree quadrangle, but no evidence of laterite or deep rock weathering of Eocene age was found in the area covered by plates 1-4. Inasmuch as the formation of thick laterites requires warm humid conditions, regional conditions rather than a local function of climate, it is probably correct to assume that the climatic conditions of the As Sarat in Eocene time reached to the area of the Tathlith one-degree quadrangle. Any laterite that may have formed was subsequently removed by erosion. The absence of laterite could also mean that the Wajid Sandstone covered the Precambrian rocks at that time and protected them from weathering; thus, laterite did not form on the Precambrian rocks in the area. Also, the laterite in the As Sarat is protected under Tertiary basalt flows, which are lacking in the area of the Tathlith one-degree quadrangle. There is no evidence to suggest that the saprolite in the area is older than Quaternary.

Quaternary weathering

All saprolite seen in the mapped area is on the exposed surfaces of rocks subject to abrasion in the present erosion cycle. This saprolite seems to be remnants of more widespread saprolite now removed. Possibly, the saprolite formed mainly during Pleistocene time with small amounts developing during Holocene time.

Saprolite in the area farther south is a possible source material for the silt deposits commented upon above. It was earlier shown (Overstreet, 1968a, p. 17-18) that throughout the basins of Wadi Tathlith and Wadi Tarib remnants of saprolite are exposed on projections of rocks in the wadi floor and along the lower slopes of the wadi walls. In some large pediment areas like the Sahl al Amk (18°34'N.; 43°38'E.) south of Hamdah, an irregular mantle of saprolite is preserved on the crystalline rocks. A period of relative stability or slow uplift with enough rainfall to permit chemical weathering to take place is necessary for the formation of saprolite. In this part of Arabia the present rainfall is about 5 cm per year. Farther west at the escarpment near Khamis Mushayt and Abha where saprolite is common, the present rainfall is 10-20 cm per year. Perhaps 20 cm of rain a year is sufficient to have formed the late Pleistocene(?) and Holocene(?) saprolite in Wadi Tathlith, Wadi Tarib, and adjacent areas. A drying from the postulated 20 cm to the present 5 cm of rainfall per year has evidently taken place in the Wadi Tathlith basin. Before the present regimen of rainfall was reached, agriculture was established in the valley, sizeable communities based on agriculture were erected, and they have since shrunk with the drying to the little remnant at Hamdah and the larger communities downstream to the north.

Granite and granite gneiss are more resistant to chemical weathering and erosion in this region than are the mafic and ultramafic rocks. Granite peaks stand 300 m higher than the serpentinite hills in the basin of Wadi Tathlith. White to buff silt and clay is spatially associated with the mafic rocks. It is found upslope on them, and appears to be a weathering product. It is also present on the granite slopes, but not as common as on the weathered mafic rocks. Possibly an inequilibrium condition formerly existed such that when saprolite was thick the terrane was less rugged. With climatic change the more deeply saprolitized mafic rocks yielded a part of the wadi sediment. These areas are possibly the source of much of the fine-grained debris of which the silt is composed. No large units of silt are present along the major wadis in wholly granitic terrain in the Asir quadrangle (Brown and Jackson, 1959).

The silt, as discussed in a preceding section on silt from Wadi Bishah, lacks the abundant clay minerals that would be expected if the silt had been derived from clay-bearing saprolite. It was also shown that saprolite can have rather small amounts of clay with largely disaggregated plagioclase feldspar, but the relative distribution of clay and particles of feldspar in saprolite in the area has not been investigated. The silt from Wadi Bishah was also shown to have the textural and mineralogical composition of wind-deposited loess (Sweetwood, C. W., written commun., 1965). D. L. Schmidt (written commun., 1972) has also considered most of the silt to have originated as aeolian sediment reworked by streams, and he regards the period of deposition to have been short. He further commented that in Wadi Bishah the sediment beneath the silt is sand and gravel similar to present sediments. Against the walls of Wadi Bishah, unweathered granite gneiss forms short intertonguing contacts with the silt relfecting that the rate of accumulation of the silt was high relative to the rate of erosion. It is conceivable, Schmidt writes, that a mantle of saprolite formed during the latest pluvial cycle might have become unstable and might suddenly have washed into the wadis to accumulate as aggradational deposits. In this view, the present silt terraces are mostly preserved in the large wadis where accumulation was greatest.

If the origin of the silt is ascribed to aeolian and alluvial processes, the present restriction of the silt deposits to certain wadis, and even to certain reaches of the wadi, becomes difficult, because wind-borne particles should be more generally distributed.

The silt sequences in Wadi Tathlith and Wadi Tarib are built up near constrictions in the wadis or where the gradients of the wadis are locally lowered. This geographic relation is a mechanical necessity whether the silt is deposited behind natural or man-made barricades. The sequence of silt near Hamdah, described above, has had an economic importance since antiquity as a source of material for the walls of houses, and, where there is enough water, for agricultural cultivation. In the Wadi Tathlith area there is archaeological evidence that the silts had greater economic importance in antiquity than they do now, and that the decline in their value relates mainly to a decrease in the present supply of water.

In ancient times water for cultivation was available upstream along Wadi Tathlith at least as far as the mouth of Wadi Malahah (18°32'N.; 43°37'E.) about 90 km south of Hamdah. At this point the rectilinear outlines of former cultivated fields on silt can be seen on aerial photographs. Vestigial rectilinear erosion suggestive of former cultivation is visible in the narrower part of the great silt deposits on Wadi Tathlith and tributaries at Jabal al Amlah (18°47'N.; 43°42'E.). Extensive ruins of an agrarian community skilled in the construction of dams and the diversion and conservation of water are established on the silt in Wadi Tathlith at Al Ji'ayfirah (18°57'N.; 43°38'E.) about 5.5 km northwest of the Higera mine and 9 km southeast of Hamdah.

At the present time, Hamdah is the first point downstream in Wadi Tathlith where enough water can be obtained to support date palms and kitchen gardens. The amount of land cultivated at Hamdah is much smaller than the areas formerly cultivated upstream along Wadi Tathlith. From these relations it is inferred that the agricultural development of Wadi Tathlith has declined, and that the decline is consequent upon a lesser flow of water in the wadi, which is caused by a decrease in rainfall in the basin.

The antiquity of the ruins at Al Ji'ayfirah (Brown and Jackson, 1959) seems to be greater than the Khalifate ruins at the Higera gold mine, and the ruins at Higera show no evidence of settled cultivation. Stone work at Al Ji'ayfirah resembles structures some 2,000 years old found in South Arabia (Bowen, 1958a, p. 43-44, figs. 60-61). At Al Ji'ayfirah man-made structures are both on the present surface of the silt and partly buried in the silt. The buried parts demonstrate the deposition in historic time of at least that part of the silt overlying the construction. At the ruined Khalifate village downslope from the Higera mine, all construction, tailings piles, and artifacts are on the silt. Nothing seems to be partly buried in silt. Thus, the sedimentary process creating the silt came to a halt before the last structures were built at Al Ji'ayfirah and before any structures were erected at Higera. At least the last layers of silt deposited at Al Ji'ayfirah were laid down in ponds formed behind man-made dams subparallel to the east wall of the wadi. If the upper part of the silt at Al Ji'ayfirah was deposited through the activity of man, then the question arises of how much silt in Wadi Tathlith was deposited under the control of man? In South Arabia silt up to 18 m thick (Bowen, 1958a, p. 43) was trapped on a wide scale behind man-made dams possibly contemporaneous with the former community of Al Ji'ayfirah. Al Ji'ayfirah is on an ancient caravan route leading northward from Najran, and ancient routes from South Arabia converged on Najran (Bowen, 1958b, pl. 33).

The question of the role of man in the formation of the silts in Wadi Tathlith, and the age of the silts, cannot be answered with the data presently available. However, the data show that a long and intricate geologic evolution was needed to create the weathered rock products of which the silt is formed, and that these evolutionary processes were related to climate change and change in stability of the land surface.

GEOLOGIC RELATIONS OF SELECTED ELEMENTS

Samples of -30-mesh+80-mesh wadi sand weighing about 100 g were collected at 566 localities in the study area, and smaller samples of detrital magnetite were taken at 554 of these localities The wadi sand samples were analyzed spectrographically and the detrital magnetites were analyzed chemically for selected elements to extend the data on possible mineralization. Prior to analysis, the sand was examined under ultraviolet light for scheelite and powellite.

Semiquantitative spectrographic analyses for 27 elements were made by C. E. Thompson, U.S. Geological Survey, and Kamal Shahwan, Directorate General of Mineral Resources, in the Jiddah

Laboratory of the Directorate. Chemical analyses of the magnetite were made by Ibrahim Baradja and L. Aldugaither. Methods used for the spectrographic analyses (Theobald and Thompson, 1968, p. 2) were adaptations of techniques used by the U.S. Geological Survey, and the wet chemical analyses followed normal procedures for trace-elements analysis.

Results of the analyses are shown by histograms (figs. 3 and 4), where it can be seen that 23 of the 27 elements sought were detected in the spectrographic analyses. Elements sought but not found, and their limits of detection, are: cadmium, 50 ppm (parts per million); germanium, 20 ppm; antimony, 200 ppm; and tungsten, 50 ppm. When the abundances of the 23 detected elements are compared with the regional abundances found for 1787 samples of wadi sand in the area of the Asir quadrangle, it is seen that 22 of the 23 elements reach threshold abundance and 21 of the 23 elements reach anomalous abundance (table 1). The values used for threshold and anomalous abundance were determined by inspection of histograms for the 1787 samples from the Asir quadrangle, which tend to give slightly higher values for threshold than the values defined by means plus two standard deviations for threshold (Hawkes and Webb, 1962, p. 30). Thus, the lower cutoffs for threshold values tend to be conservatively high. The amomalous values may be somewhat low.

The values of copper, zinc, and molybdenum in detrital magnetite from the area of the Tathlith one-degree quadrangle (fig. 4) were compared with the results of the analyses of 1634 samples of magnetite from the Asir quadrangle, and the number of threshold and anomalous values are shown in table 1. The threshold and anomalous values in detrital magnetite are nearly an order of magnitude greater for molybdenum and zinc than they are for these elements in wadi sand, but they are about the same for copper in each medium.

The distribution of samples with threshold and anomalous values in the Tathlith one-degree quadrangle is shown on plates 1-4.

Several notable groupings of threshold and anomalous trace elements are associated with specific rock units, as can be seen on plates 1-4. The most apparent of these associations is the relation of beryllium, gallium, lanthanum, niobium, lead, tin, yttrium, and zirconium with the granitic rocks of the peralkalic magma series. Other associations are cobalt, chromium, nickel, manganese, titanium, and scandium with the andesite unit of the volcanic-sedimentary sequence and with mafic intrusive rocks, and copper, molybdenum, and zinc with diorite, gabbro, and andesite.

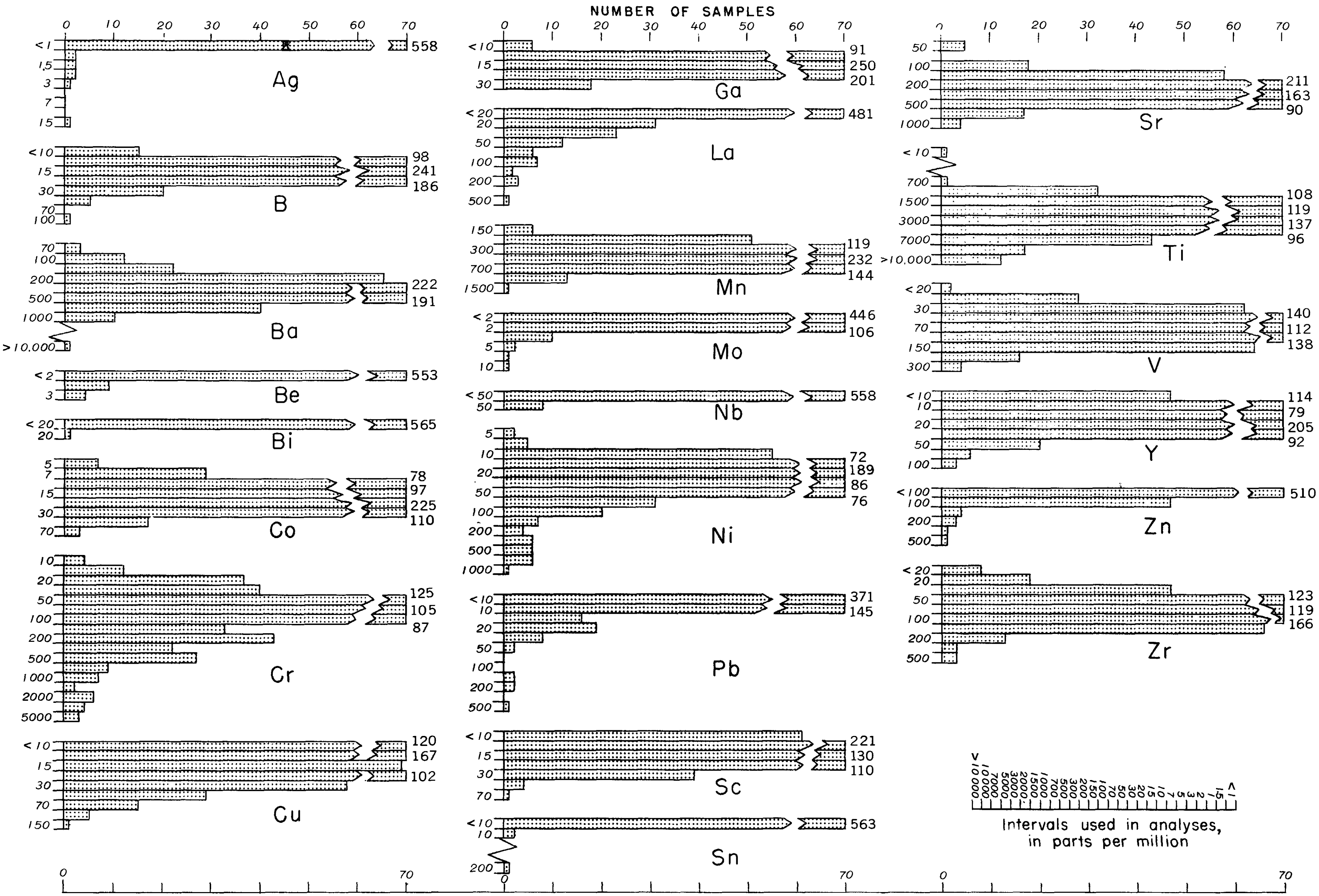

Figure 3.- Histograms of 566 spectrographic analyses of wadi sand in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia.

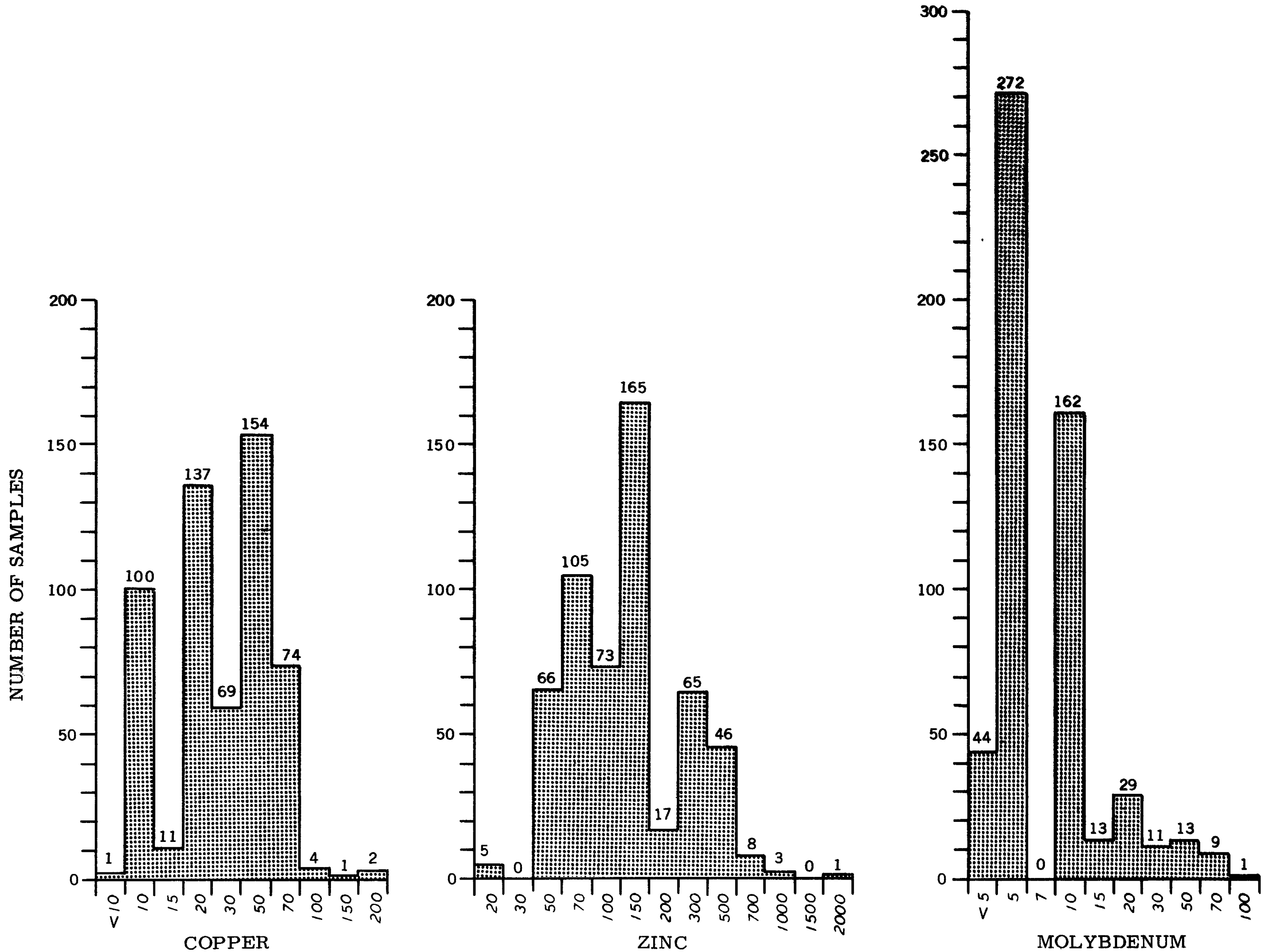

Figure 4.- Histograms showing parts per million of copper, zinc, and molybdenum in 554 samples of detrital magnetite (analyzed chemically) from the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia.

Table 1. Threshold and anomalous values for selected elements in wadi sand (determined by semiquantitative spectrographic analyses) and detrital magnetite (analyzed chemically) from the area of the Tathlith one-degree quadrangle, compared to values recovered from Asir quadrangle.

Element	Regional values from Asir quadrangle, ppm		Number of samples from Tathlith one-degree quadrangle at or above regional values	
	Threshold	Anomalous	Threshold	Amomalous
Wadi sand (a)				
Silver	1-7	10+	7	1
Boron	30-50	70+	25	1
Barium	700-1,000	1,500+	50	1
Beryllium	2	3+	9	4
Bismuth	--	20+	--	1
Cobalt	50	70+	17	3
Chromium	300-500	700+	49	31
Copper	70-100	150+	20	1
Gallium	30-50	70+	18	--
Lanthanum	50	70+	12	19
Manganese	1,000	1,500+	13	1
Molybdenum	3-5	7+	12	2
Niobium	50	70+	8	--
Nickel	150	200+	7	23
Lead	20-30	50+	27	7
Scandium	30	50+	39	5
Tin	10-15	20+	2	1

Table 1. Threshold and anomalous values for selected elements in wadi sand (determined by semiquantitative spectrographic analyses) and detrital magnetite (analyzed chemically) from the area of the Tathlith one-degree quadrangle, compared to values recovered from Asir quadrangle (cont'd.)

Element	Regional values from Asir quadrangle, ppm		Number of samples from Tathlith one-degree quadrangle at or above regional values	
	Threshold	Amomalous	Threshold	Anomalous
Strontium	700	1,000+	17	4
Titanium	7,000-10,000	>10,000	60	12
Vanadium	150-200	300+	80	4
Zinc	100	150+	47	9
Yttrium	50	70+	20	9
Zirconium	150	200+	66	19
Detrital magnetite (b)				
Copper	100	150+	4	3
Zinc	700	1,000+	8	4
Molybdenum	30-50	70+	24	10

(a) Represents 1787 samples in the Asir area and 566 samples in the Tathlith one-degree quadrangle.

(b) Represents 1634 samples in the Asir area and 554 samples in the Tathlith one-degree quadrangle.

Beryllium, gallium, lanthanum, niobium, lead, tin, yttrium, and zirconium

Peralkalic magma series

The association of beryllium, gallium, lanthanum, niobium, lead, tin, yttrium, and zirconium at threshold or anomalous levels in wadi sand from the rocks of the peralkalic magma series was first identified at Jabal Ashirah in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, p. 38-41). The full suite of these elements at threshold or anomalous abundances is not present in any sample of wadi sand, but various restricted suites consisting of one or more of these elements at threshold or anomalous abundance is characteristic of sands from the granitic rocks of the peralkalic magma suite (table 2). Beryllium, lanthanum, yttrium, and zirconium tend to be enriched in the same samples, and the association lanthanum-yttrium-zirconium is more common than the four elements. Niobium-enriched samples are invariably rich also in lanthanum and zirconium, and are nearly always enriched in beryllium and yttrium, but the converse is not true. Lead is commonly but not invariably enriched in niobium-bearing samples. Niobium and tin are the least commonly enriched elements in the full suite. Indeed, in the area studied no sample of sand derived entirely from the granitic rocks of the peralkalic magma series is enriched in tin: the one anomalous tin-bearing sample (22243) is from a mixture of sheared quartz porphyry of the series and metasedimentary rocks and serpentinite in the Hamdah quadrangle (plates 4 and 2), and the two samples with threshold tin, 22215 in the Hamdah quadrangle and 22879 in Al Hassir quadrangle (plate 1) are from amphibolite, metasedimentary rocks, and diorite intruded by pegmatite, granite, and felsite dikes related to the peralkalic magma series. Threshold amounts of zirconium tend to be accompanied by threshold amounts of other elements where the sample is largely from granitic rocks of the peralkalic magma series.

Threshold and anomalous lead in sand from the peralkalic magma series is most common in the later granitic rocks of the zoned plutons of Al Hassir (plate 1) and Duthur as Salam (plate 3) quadrangles. The core of coarse-grained biotite granite (22826), fine-grained biotite granite (22808-9, 22825, 22827, 22830, and 22831), and fine-grained biotite-pyroxene granite (22828) of the zoned plutons yielded many more lead-rich samples of sand than the coarse-grained, locally porphyritic, biotite-pyroxene granite (22833 and 22838). Even younger exterior masses of the peralkalic magma series were also the sources of lead-enriched sand: quartz porphyry in Al Hassir (plate 1) quadrangle (22881 and 22882) at the Al Lugatah mine and in the Duthur as Salam (plate 3) quadrangle at stations 22785 and 22786; and quartz monzonite porphyry at station 22206 in the Hamdah quadrangle (plate 4). The peralkalic biotite granite and porphyritic biotite granite was the source of five lead-bearing sands of which four (22393, 22398, 22418, and 22419) in the Hamdah and Wadi Haraman (plate 2) quadrangles were from the porphyritic

Table 2. Number of samples of wadi sand from rocks of the peralkalic magma series with threshold or anomalous values of beryllium, gallium, lanthanum, niobium, lead, tin, yttrium and zirconium compared to total number of threshold and anomalous samples in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia.

Element	Threshold		Anomalous	
	Peralkalic magma series	Tathlith one-degree quadrangle	Peralkalic magma series	Tathlith one-degree quadrangle
Beryllium	8	9	4	4
Gallium	14	18	--	--
Lanthanum	10	12	16	19
Niobium	7	8	--	--
Lead	17	27	3	7
Tin	--	2	--	1
Yttrium	16	20	7	9
Zirconium	37	66	16	19

phase and one (22797) in Al Hassir quadrangle was from the equigranular phase. In the sands from the younger granites and quartz porphyries the lead is commonly accompanied by threshold or anomalous beryllium, niobium, lanthanum, yttrium and zirconium, which are lacking from the lead-rich sand of the older peralkalic granites.

Yttrium is a characteristic element in sands derived from the zoned plutons of peralkalic granitic rocks. In both anomalous and threshold amounts it is more likely to be found in the younger, interior and core rocks of the plutons--fine-grained biotite granite (7 samples), fine-grained biotite-pyroxene granite (1 sample), and coarse-grained biotite granite (1 sample)--than in the older wall-zone, coarse-grained, locally porphyritic, biotite-pyroxene granite (3 samples). The young exterior stocks of the peralkalic magma series also yield sands enriched in yttrium: 2 samples from quartz porphyry in the Duthur as Salam (plate 3) and Hamdah (plate 4) quadrangles. Yttrium is also present in the peralkalic biotite granite (8 samples). In sands from the older phases of the series, yttrium tends to be associated with a restricted suite of elements, generally lanthanum and zirconium, and rarely with no other threshold or anomalous element. In the younger phases the suite of associated threshold and anomalous elements widens to include beryllium, gallium, lanthanum, niobium, lead, and zirconium. None of the anomalous values for yttrium indicates a potentially minable source.

Zirconium also is a characteristic element in sand from the rocks in the peralkalic magma series beginning with the early mafic rocks of the series (5 samples) and persisting through the full sequence to reach highly anomalous abundances in sand from the youngest units. The most complete suites of elements are found in sand from the fine-grained biotite granite and fine-grained biotite-pyroxene granite where zirconium is present in threshold abundances. Where anomalous abundances of zirconium are present in the sand, the most complete suite of associated elements is in sand from the somewhat older coarse-grained, locally porphyritic biotite-pyroxene granite. The early peralkalic biotite granite and porphyritic biotite granite is the source of zirconium-enriched sands typically lacking the other minor elements characteristic of the granites of the peralkalic magma series. None of the sampled localities with anomalous zirconium affords a minable source of zirconium.

Wadi sands from the older granitic rocks of the peralkalic magma series such as the biotite granite and porphrytic biotite granite of the homogeneous plutons lacks beryllium, niobium, and tin in threshold and anomalous amounts, and rarely contains gallium or lanthanum. Zirconium in threshold amounts is the characteristic element, and lead and yttrium in threshold amounts are next most common.

Wadi sand from the peralkalic granitic rocks of the zoned plutons characteristically has a variation in composition related to the relative age of the rock units. The oldest unit of the zoned plutons--coarse-grained, locally porphyritic biotite-pyroxene granite--yields sands that generally resemble in minor-element composition the sands from the older peralkalic biotite granites except that at some places the sands from the coarse-grained locally porphyritic granite contain threshold or anomalous beryllium, threshold niobium and lead, and both threshold and anomalous yttrium. Zirconium is common, but it tends to be in anomalous amounts instead of threshold quantities. Gallium is less common than in the older granites. The sand from the youngest unit in the zoned plutons--the coarse-grained biotite granite--tends to have anomalous beryllium, lead, yttrium, and zirconium, and threshold lanthanum and niobium. Sand from the rocks intermediate between the core and wall--fine- grained biotite-pyroxene granite and fine-grained biotite granite--is characterized by threshold beryllium, gallium, and lead, and threshold or anomalous lanthanum, yttrium, and zirconium. Niobium is rarely present. The pyroxene syenite yields sand enriched in zirconium. In the exterior hypabyssal rocks like quartz porphyry, beryllium, niobium, and lead at threshold levels are characteristic. Appropriate samples are unavailable for the fine-grained pyroxene granite, red granite porphyry, and quartz monzonite of the peralkalic magma series.

None of the elements in the full suite of elements characteristic of the peralkalic magma series is sufficiently enriched at the anomalous levels to require further search for an economic source of these elements at these stations.

The chemical data from the Jabal 'Ashirah pluton in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, p. 38-41) and the Jabal Al Hassir pluton and other subcircular zoned bodies of peralkalic granite in the Tathlith one-degree quadrangle disclose the same suites of enriched elements and also show that different lithologic phases of the peralkalic magma series have different partial suites of the characteristic trace elements.

Other rocks

Beryllium.--The one sample of sand with threshold beryllium not from the peralkalic magma series is from a small pluton of pink to gray biotite-muscovite granite (station 22264) in the Hamdah quadrangle (plate 4). The granite is intrusive into hornblende schist and serpentinite, and the sample of sand has threshold beryllium and anomalous chromium, relfecting its source in both granitic and mafic rocks. The granite was identified as the calc-alkalic biotite granite older than the peralkalic magma series. The possibility exists, however, that this small stock is actually one of the younger exterior granitic rocks of the magma series, and is not related to the calc-alkalic granite.

Gallium.--Four threshold values for gallium in sand derived from rocks other than the granites of the peralkalic magma series are in the Hamdah quadrangle (plate 4). The source rocks for these gallium-bearing sands are diverse, but most are intruded by granitic dikes or stringers of pegmatite or quartz: 22244 from hornblende schist and intrusive ring complex of gabbro and norite in the magma series; 22324 layered biotite gneiss and biotite-hornblende gneiss with stringers of pyrite-bearing white quartz; 22333 old gabbro intruded by dikes of andesite; and 22375 amphibolite with stringers of pegmatite. Inasmuch as each of the four samples has only 30 ppm of gallium, the minimum threshold value, these samples may represent only normal analytical variation.

Lanthanum.--The source for one (22338, plate 4) of the two samples of sand with threshold lanthanum and two (22339 and 22734) of the three with anomalous lanthanum are plutons of calc-alkalic granite. At station 22792 in the Duthur as Salam quadrangle (plate 3) the anomalous lanthanum in sand from the calc-alkalic granite is associated only with threshold barium, an element commonly enriched in the calc-alkalic granite. However, at stations 22338 and 22339 in the Hamdah quadrangle (plate 4), which are both in the same pluton of calc-alkalic granite, the threshold lanthanum is associated with threshold lead and the anomalous lanthanum is associated with threshold niobium and lead. These associations of minor elements suggest that the unit should be mapped as peralkalic biotite granite. At station 22734 in the Duthur as Salam quadrangle (plate 3) anomalous lanthanum is associated with anomalous zirconium. The sample was taken in an area of diorite and gabbro near a contact with quartz porphyry of the peralkalic magma series. Evidently more sand was derived from the quartz porphyry than the diorite and gabbro, because threshold values are lacking for elements like chromium, nickel, and cobalt, commonly associated with sand derived from mafic rocks. In Al Hassir quadrangle (plate 1) at station 22921 a sand sample contains threshold lanthanum but lacks other elements at the threshold or anomalous levels. The sand is derived from granodiorite gneiss in an area of sheeted contacts and dikes of granite and felsite over what may be an unbreached plug of peralkalic granite.

Niobium.--Sample 22339, of sand from a pluton mapped as calc-alkalic granite in the Hamdah quadrangle (plate 4), has a threshold abundance of niobium, and was mentioned under lanthanum. Almost certainly this pluton is part of the peralkalic magma series.

Lead.--Ten threshold and four anomalous lead-bearing sands are shown in Al Hassir (plate 1), Hamdah (plate 4), and Wadi Haraman (plate 2) quadrangles. Sample 22846, from Al Hassir quadrangle, was taken in an area of gabbro of the peralkalic magma series intruded by a swarm of felsite dikes adjacent to the major Al Hassir pluton. The felsite dikes more than the gabbro appear to have contributed the lead. Two samples with threshold lead (22338 and 22339) in the Hamdah quadrangle also contain threshold lanthanum and one has threshold niobium. The rock from which they came was mapped as calc-alkalic granite, but this assemblage of minor elements suggests it may be the peralkalic biotite granite. Elsewhere in the Hamdah quadrangle threshold lead is associated with threshold barium in sand from calc-alkalic granite at station 22260, with threshold boron (22209) and threshold chromium (22277) in sand from granodiorite gneiss, and is alone in sand from layered gneiss (22325).

Threshold lead is associated with threshold copper and anomalous molybdenum in sand from a fault in diorite (22437) in the Wadi Haraman quadrangle (plate 2). Threshold and anomalous lead are variously associated with threshold boron, silver, zinc, and titanium in sand from around the workings of the ancient Avala mine in andesite.

The anomalous values for lead in wadi sand associated with the ancient mines range from 50 ppm to 500 ppm and average 200 ppm. The single anomalous value for lead in sand in the four quadrangles not associated with ancient mines is 50 ppm from the coarse-grained biotite granite in the core of Al Hassir pluton. The associated metals in sands with anomalous lead from ancient mines, boron, silver, titanium, and zinc, are notably different from the suite characterized by beryllium, niobium, lanthanum, yttrium, and zirconium found with the anomalous lead associated with the peralkalic magma series.

Tin.--The relations of the two samples with threshold tin and one with anomalous tin were discussed above, where it was shown that the probable source of the tin was sand from late-stage intrusives of the peralkalic magma series instead of the older rocks. The anomalous value for tin, +20 ppm, is too low to be associated with economic deposits of tin.

Yttrium.--Only four of the threshold values for yttrium in wadi sand and two of the anomalous values are derived from rocks other than the granites of the peralkalic magma series. Sample 22889 in Al Hassir quadrangle (plate 1) is from sand derived from the calc-alkalic biotite granite. It lacks other threshold or anomalous elements and in this respect resembles sand from the older peralkalic biotite granite. Layered gneiss (22819) and granodiorite gneiss (22762) in the Duthur as Salam quadrangle (plate 3) yielded single samples of sand with threshold values of yttrium and zirconium. Sericite-chlorite schist (22214) in the Hamdah quadrangle (plate 4) was the source of sand with threshold yttrium and cobalt and anomalous chromium, copper, and nickel. Anomalous yttrium is associated with threshold manganese, molybdenum, vanadium, and zinc in a sample (22310) of layered gneiss from the Hamdah quadrangle. Anomalous yttrium is in sand from a sample (22887) derived from rhyolite and rhyolite porphyry of the volcanic-sedimentary sequence in Al Hassir quadrangle.

Zirconium.--The 29 samples of sand with threshold zirconium and three samples with anomalous zirconium come from many source rocks of which the most common are granodiorite gneiss and granite gneiss (10 samples), calc-alkalic granite (5 samples), hornblende schist (4 samples) and biotite schist (3 samples). The others are derived from amphibolite, microdiorite and diorite, chlorite-sericite schist, andesite and graywacke. The minor elements associated with the zirconium in these sands are quite variable and appear to bear no real relations with the zirconium.

Silver and bismuth

Seven samples of sand have threshold silver and one has anomalous silver in the area (table 1). The anomalous sample (22231), in the Hamdah quadrangle (plate 4), is sand derived from biotite granite gneiss, where the gneiss has a sheeted structure possibly formed over an unbreached pluton of peralkalic granite. No other minor metals are present in the sample in threshold or anomalous amounts, and other evidence for mineralization was not seen at the station. The 15 ppm silver in this sample is greater than the amounts of silver detected in sands from ancient mines in the area; therefore, further examination should be made at this station.

Two samples of sand (22881 and 22882) derived from quartz porphyry and the quartz veins of the ancient Al Lugatah mine in Al Hassir quadrangle (plate 1) contain threshold silver with anomalous lead. Threshold zinc is also present in 22882.

A northwest-trending fault in peralkalic biotite granite in the Duthur as Salam quadrangle (plate 3) was the source of a sample of sand (22777) with threshold silver, molybdenum, titanium, and zinc, and anomalous bismuth, manganese, and zirconium. No evidence for mineralization was seen along the fault, and northwest-trending faults in general lack mineralization in the area, but this locality should be re-examined because of the combination of anomalous bismuth with threshold silver and molybdenum.

Threshold silver is associated with threshold barium in sand derived from layered hornblende-biotite gneiss at station 22330 in the Hamdah quadrangle. Scattered small vuggy quartz veins are present in the gneiss, but no evidence of sulfide mineralization was seen. Nevertheless, the station should be re-examined for possible mineralization.

In the Wadi Haraman quadrangle (plate 2) threshold silver is accompanied by anomalous lead in sand derived from andesite and quartz veins at ruins of the ancient Avala mine (22454). Threshold silver and vanadium are found in sand (22446) from gabbro near a northwest-trending fault and threshold silver lacking accompanying threshold or anomalous elements is present in sand (22449) derived from diorite grading into massive biotite-hornblende granodiorite. No evidence of mineralization was observed at either locality, but threshold silver is sufficiently uncommon in the area to justify a further examination of these two localities.

Nickel, chromium, and cobalt

The 23 samples of sand having anomalous amounts of nickel in the area (table 1) are invariably also anomalous in chromium. Four of the seven samples with threshold nickel have anomalous chromium and two with threshold nickel have threshold chromium. Only one sample with threshold nickel lacks threshold or anomalous chromium. The converse, however, does not apply, because there are 80 samples with threshold or anomalous chromium and only 30 samples with threshold or anomalous nickel.

Serpentinite is the main source rock for sand with anomalous nickel. For example, 14 samples are from serpentinite whereas three samples are from hornblende schist, three from chlorite-sericite schist, and one sample each from diorite and gabbro, gabbro and pyroxenite, and andesite. Sand with threshold nickel comes from a diverse suite of rocks comprising three samples from serpentinite and one each from amphibolite, gabbro and norite layered pluton, gabbro, and layered gneiss. By far the largest number of samples with anomalous nickel are, therefore, in the area of the Hamdah quadrangle (plate 4), where serpentinite is most widely exposed. For the most part, the reported abundances of nickel (plates 1-4) are about what would be expected in debris from serpentinite, gabbro, hornblende schist, and other mafic rocks.

Samples with anomalous values of 700 ppm nickel or more, including 22204, 22248, 22259, 22262, 22281, and 22283 in the Hamdah quadrangle and 22516 in the Wadi Haraman quadrangle (plate 2), represent localities where further investigation for possible nickel might be made. The two areas probably most favorable geologically for nickel, the layered complex of gabbro and norite in the Hamdah quadrangle (plate 4) and the weathered ultrabasic rocks around station 22508 in the Wadi Haraman quadrangle, however, contain many anomalous samples. Only one sample from the layered complex has nickel at the threshold level and none at the anomalous level (plate 4). Perhaps this results from a nearly complete removal of weathering products of these rocks from this area. Allcott (1970, table 1) showed that weathering products were enriched in nickel and chromium over the source rocks at the Ash Sha'ib mine.

Seventeen of the 37 samples of sand with anomalous chromium are derived from serpentinite, four are from diorite, gabbro, and pryoxenite, three from hornblende schist, two each from the layered complex of gabbro and norite and the granodiorite gneiss, and sericite-chlorite schist. Sand with threshold chromium typically is derived from diorite, gabbro, and pyroxenite of the peralkalic magma series (18 samples), andesite and chlorite schists (9 samples), amphibolite and hornblende schist (7 samples), and serpentinite (5 samples). Layered gneiss, granodiorite gneiss, microdiorite, and coarse-grained biotite-pyroxene granite were the sources of the other sands with threshold chromium.

Of the four stations (22237, 22273, 22274, and 22300) at which chromite was observed in the Hamdah quadrangle (plate 4), threshold chromium was detected only in the sand at 22273. Threshold chromium also was found in the sample (22749) of sand from the single station in the Duthur as Salam quadrangle (plate 3) where chromite was noted. In the Wadi Haraman quadrangle (plate 2) anomalous chromium was determined in the sample of sand from station 22749 where megascopic chromite was seen. Serpentinite was the source of the chromite at the seven observed localities.

The threshold values for chromium for the most part are expectable in sands derived from these mafic rocks, and the same can be said for the lower anomalous values for chromium. However, where there is 3,000-5,000 ppm chromium in the sand, a further investigation of the sources of the chromium might be undertaken as part of another study such as the evaluation of the deposits of asbestiform minerals. Stations with 3,000 ppm chromium are 22750 and 22795 in the Duthur as Salam quadrangle (plate 3), 22337 in the Hamdah quadrangle (plate 4), and 22520 in the Wadi Haraman quadrangle (plate 2). Stations with 5,000 ppm chromium are 22783 (plate 3), and 22259 and 22262 in the area of plate 4. It is possible that these high values for chromium, where they are also combined with high values for nickel, may be attributable to an accumulation of weathering products from the source rocks. Allcott (1970, table 1) showed that these two elements are greatly enriched in weathering products. Where anomalous nickel is lacking, the anomalous chromium is probably derived from a chromium-enriched source rock.

Cobalt in anomalous amounts (table 1) is found only in sands derived from gabbro (22332 and 22761) or gabbro and pyroxenite (22689) of the peralkalic magma series in the Duthur as Salam (plate 3) and Hamdah (plate 4) quadrangles. The anomalous cobalt is associated with threshold or anomalous titanium and vanadium, and in two of the three samples is associated with anomalous or threshold zinc. Nickel is absent from the samples with anomalous cobalt, and chromium, in threshold abundance only, is present in one sample with anomalous cobalt. Where the samples contain threshold cobalt, however, anomalous or threshold chromium is present in ten of the 17 samples, and nickel is only present in four samples. One or more of the elements titanium, vanadium, and zinc in threshold or anomalous quantities is present in ten of the 17 samples with threshold cobalt. Thus, there is a sub-association of cobalt, titanium, vanadium, and zinc, generally in sands from gabbro and pyroxenite of the peralkalic magma series. The other samples of sand with threshold cobalt are derived mainly from hornblende schist, chlorite schist, layered gneiss, andesite, and serpentinite.

None of the cobalt-bearing samples is associated with any visible evidence of mineralization, which is in contrast to observations in the Wadi Wassat quadrangle where andesite with interlayered massive sulfide deposits was found to yield sands with greater amounts of cobalt, chromium, nickel, copper, molybdenum, and zinc than the sulfide-free sequences of andesite (Overstreet and Rossman, 1970, p. 42). The principal pyritized body of andesite in the area, just east of Duthur as Salam (plate 3), lacks any enrichment of cobalt or the other elements found to be indicators of massive sulfides in the Wadi Wassat quadrangle. Seemingly, cobalt in sands in the area is in expectable quantities for mafic rocks, and the cobalt is most common where the source rock is gabbro and pyroxenite of the peralkalic magma series.

Manganese, titanium, and scandium

The one sample of sand with anomalous manganese (22777) was taken from a northwest-trending fault in peralkalic biotite granite in the Duthur as Salam quadrangle (plate 3) and is notable because of the anomalous bismuth and threshold silver. Most of the threshold values for manganese are found in sand derived from hornblende schist (22766, 22241, 22245, 22246, and 22257) in the Duthur as Salam and Hamdah (plate 4) quadrangles or gabbro of the peralkalic magma series (22761, 22307, 22485, and 22504) in the Duthur as Salam, Hamdah, and Wadi Haraman (plate 2) quadrangles. Layered gneiss (22310 and 22326) and old diorite (22333) in the Hamdah quadrangle and biotite schist (22500) in the Wadi Haraman quadrangle were the source rocks for the other samples of sand with threshold manganese. Manganese-enriched samples are lacking from Al Hassir quadrangle (plate 1). No strong association was found between manganese and other elements, but weak associations of manganese with titanium, vanadium, zinc, cobalt, and copper are seen. None of the manganese-bearing samples indicates a potential source for manganese in the area.

Nearly half of the samples of sand in the area with anomalous or threshold titanium (table 1) are derived from the older rocks of the peralkalic magma series, mainly diorite, gabbro, anorthosite, biotite granite, coarse-grained porphyritic biotite-pyroxene granite, and syenite. Hornblende schist, serpentinite, amphibolite, and andesite account for most of the others. Only one of the 12 samples with anomalous titanium is associated with megascopically visible ilmenite: station 22430 in the Wadi Haraman quadrangle where massive gabbro of the peralkalic magma series has selvages of anorthosite which contain up to 1.5 percent of ilmenite. The other localities noted for small amounts of visible ilmenite, stations 22520 and 22527 in the Wadi Haraman quadrangle (plate 2) and 22218 in the Hamdah quadrangle (plate 4), were not the sources of either threshold or anomalous titanium in sand. Each of the anomalous samples contains 2 percent (20,000 ppm) of titanium, enrichments expectable in sand derived from rocks like those cited above; therefore, it is unlikely that any are associated with exploitable sources of ilmenite. However, the stations at which anomalous titanium was found are noted so that they might be re-examined if other geologic work were to be done in the area. They are: 22683, 22691, 22731, 22761, 22766, and 22795 in the Duthur as Salam quadrangle; 22207, 22236, and 22241 in the Hamdah quadrangle; and 22485 in the Wadi Haraman quadrangle.

The samples of sand with threshold titanium commonly contain threshold zinc or vanadium, but the strongest relation is an antipathetic one: titanium-enriched samples are seldom enriched in copper. This appears to be a result of the tendency for titanium to be in sand derived from plutonic mafic rocks and for copper to be in sand derived from volcanic rocks (Overstreet and Rossman, 1970, p. 43).

Scandium has a strong tendency to be associated with sand derived from the mafic plutonic rocks of the peralkalic magma series, particularly where these rocks are intruded by granite dikes of the series. Four of the five samples of sand with anomalous scandium are from this environment (plates 1 and 3). No strong correlations exist between scandium and other elements in sand samples, and only a weak correlation exists with titanium. The highest anomalous value for scandium is only 70 ppm, and no sources for this element are indicated for this area.

Copper, zinc, and molybdenum

Copper, zinc, and molybdenum were determined in both wadi sand and detrital magnetite in the area, and the abundances of these elements in the separate media are shown on plates 1-4. The three elements are strongly differentiated from each other in the wadi sands. The separation of copper and zinc is particularly strong, there being only four copper-bearing samples that contain zinc, and neither metal where they are associated exceeds threshold values. This partition reflects the tendency of the copper to be slightly enriched in volcanic rocks or their metamorphic equivalents and the zinc to be enriched in plutonic rocks, particularly the mafic units of the peralkalic magma series. Molybendum, which is less common in threshold and anomalous amounts than zinc, is also associated with copper in four samples; thus, the antipathetic relation between copper and molybdenum is less strong than that between copper and zinc. The data from the copper, zinc, and molybdenum in wadi sand cannot be interpreted to indicate the possible presence of massive pyrite deposits like those in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, p. 44-45).

Wadi sand

Threshold and anomalous values for copper, zinc, and molybdenum in wadi sand are, with the exception of a single threshold value for zinc (22455) at the ancient Avala mine in the Wadi Haraman quadrangle (plate 2), entirely unassociated with the old mines in the area. Actually very few anomalous values were obtained for these three metals (table 1).

The single anomalous value for copper (22214) is from sand that was derived from pyroclastic rocks metamorphosed to sericite-chlorite schist near the contact of granodiorite gneiss intrusive in the Hamdah quadrangle (plate 4). White, massive to rarely vuggy quartz veins occupy bc joints in the schist, but sulfide minerals were not observed. The sample also contains anomalous chromium and nickel with threshold cobalt and yttrium. Possibly the copper, chromium, cobalt, and nickel in the sand reflect high normal tenors of these elements in the original pyroclastic rock with no economic concentration effected. If other work is done in the area, the locality should be examined.

Threshold copper is distributed in sands from a variety of source rocks, mainly mafic, including hornblende schist (5), diorite and gabbro (4), layered gneiss (3), gabbro-norite complex (2), andesite (2), and one each from serpentinite, biotite schist, granodiorite gneiss, and calc-alkalic granite. Vanadium is a common associate of threshold copper.

Anomalous zinc, like threshold zinc, in the wadi sands is quite commonly associated with threshold or anomalous titanium, confirming the tendency for zinc-enriched sands to come from the mafic units of the peralkalic magma series (plates 1-4). Indeed, the most anomalous value for zinc, 500 ppm at station 22430 in the Wadi Haraman quadrangle (plate 2), is in sand derived from gabbro with selvages of anorthosite in which grains of ilmenite can be distinguished. Evidence for sulfide mineralization at this locality is lacking, as it generally is at the other sites where threshold or anomalous zinc was found in the samples of sand. The distribution of zinc in wadi sand appears to reflect expectable variations in the source rocks.

The sample of wadi sand (22226) with anomalous molybdenum in the Hamdah quadrangle (plate 4) is derived from gabbro intrusive into sericite schist and quartzite. The schist and quartzite form a low, brown ridge east of the gabbro. Limonite stain is common throughout the schist and quartzite, and small fragments of gossan are mixed with the talus on the hill. Actual gossan is exposed in place in several small patches up to 1.5 m long, associated with faintly pyritiferous and magnetite-bearing quartzite. The pyrite is quite rare; thus, limonite in the gossan and in widespread coatings on joints came possibly from the magnetite. The iron-stained ridge is about 170 m long and, at its widest, 120 m wide. Throughout the ridge are sparse brown stringers of glassy to granular quartz that are subparallel to the foliation of the schist. They seldom exceed 3 cm in thickness and 5 m in length, and are not spaced sufficiently close to form a lode. Other base metals are not associated with the molybdenum in the sample of sand, but the locality ought to be examined more closely for possible base metals and gold.

The other sample of sand with anomalous molybdenum (22437) is from a fault zone trending N.15°W. and dipping 30°W. in fine-grained gabbro and diorite in the Wadi Haraman quadrangle. The faults are filled by veins of milky quartz containing 1-3 percent of pink microcline and less than 1 percent of pyrite in cubic crystals up to 2 cm across. The quartz veins are about 1 m thick, 40 m long, in an en echelon group of at least 6 veins.

Intermittent exposures of white quartz veins extend N.15^{o}W. for 2 km. No mineralization other than the pyrite was observed, but because threshold copper and lead are associated with the anomalous molybdenum, it is recommended that the vein system be appraised.

Threshold molybdenum is associated with anomalous bismuth in sample 22777 from the Duthur as Salam quadrangle (plate 3) which was described above. Threshold molybdenum was found in sand at station 22417 in the Wadi Haraman quadrangle where the local porphyritic biotite granite of the peralkalic magma series was quarried in antiquity for grindstones for use in gold mines. Other samples of threshold molybdenum appear to be normal local variations of the element.

Detrital magnetite

A total of 554 samples of detrital magnetite from the area were analyzed chemically for copper, zinc, and molybdenum. These samples were taken at the same sites as the samples of wadi sand. However, very few magnetite concentrates were found to contain threshold or anomalous concentrations of copper, zinc, or molybdenum (table 1), and only two samples of magnetite yielded a threshold or anomalous value for these metals at the same stations where wadi sand had threshold or anomalous values. One sample with threshold copper (22881) came from the Al Lugatah ancient mine in Al Hassir quadrangle (plate 1), but none of the other magnetites with threshold or anomalous metals are from old mined areas.

None of the copper-enriched magnetites is enriched in zinc or molybdenum, but about half of the zinc-enriched magnetites are also enriched in molybdenum.

Only four samples of magnetite had threshold copper and three had anomalous copper. The three samples of magnetite with anomalous copper (22247, 22250, and 22271) are from the Hamdah quadrangle (plate 4) near the layered complex of gabbro and norite, but each sample was derived from a different source rock: serpentinite, gabbro-norite complex, and hornblende schist. The two samples with threshold copper (22217 and 22257) in the Hamdah quadrangle are also from gabbro and hornblende schist, which suggests that magnetite from the mafic rocks is locally enriched in copper. Magnetite with threshold copper (22525) from the Wadi Haraman quardangle (plate 2), however, is derived from granite gneiss, and that from the Al Lugatah ancient mine (22881) in Al Hassir quadrangle (plate 1) is derived from quartz porphyry.

Magnetite from rocks of the peralkalic magma series, particularly the older rocks in the series, tends to be enriched in zinc. Gabbro and diorite from the Hamdah and Wadi Haraman quadrangles are the source of two samples (22236 and 22481) with threshold zinc. Peralkalic biotite granite is the source of four samples with threshold or anomalous zinc: 22870, Al Hassir; 22778, Duthur as Salam; and 22228 and 22233, Hamdah quadrangles. Sample 22233, with 2,000 ppm zinc, is the most zinc-rich magnetite in the area. Coarse-grained porphyritic biotite-pyroxene granite was the source of two samples of magnetite with threshold zinc (22823 and 22837). The other anomalous samples are from serpentinite (22783) in the Duthur as Salam quadrangle and calc-alkalic biotite granite (22327) in the Hamdah quadrangle. Hornblende schist (22235) in the Hamdah quadrangle and amphibolite (22496) in the Wadi Haraman quadrangle were the sources of magnetite with threshold zinc. No evidence of zinc mineralization is present at sampled localities.

Molybdenum-enriched magnetite is dominantly from the granitic rocks of the peralkalic magma series (table 3). Enrichment in molybdenum must be regarded as a geochemical characteristic of the granites of the peralkalic magma series. The single magnetite with anomalous molybdenum (22929) is derived from a pluton of calc-alkalic granite extensively intruded by dikes of granite and felsite related to the peralkalic magma series in the northern part of Al Hassir quadrangle (plate 1). The 12 magnetite samples with threshold molybdenum include three from diorite and gabbro; two each from calc-alkalic granite, granodiorite gneiss, and hornblende schist; and one each from andesite and rhyolite of the volcanic-sedimentary series, and layered gneiss. None appears to reflect a mineralized area.

Barium and Strontium

The weak association of barium and strontium with wadi sand derived from rocks of the peralkalic magma series noted in the Wadi Wassat quadrangle (Overstreet and Rossman, 1970, p. 47-48) persists into the Tathlith one-degree quadrangle. The single sample with anomalous barium, 22735 in the Duthur as Salam quadrangle (plate 3), is sand from peralkalic biotite granite. Three of the four samples of sand with anomalous strontium are derived from rocks of the peralkalic magma series: quartz porphyry (22243) and porphyritic biotite granite (22395) in the Hamdah quadrangle (plate 4), and porphyritic biotite granite (22438) in the Wadi Haraman quadrangle (plate 2). The fourth sample of sand with anomalous strontium (22704) is from calc-alkalic granite in the Duthur as Salam quadrangle. Among the 50 samples of sand with threshold barium, 11 are derived from granitic rocks of the peralkalic magma series and six from the mafic rocks of the series. The relation between barium-enriched sands and the other granitic rocks of the area is fairly strong. Eleven samples with threshold barium are from the calc-alkalic granite and eight are from the granite gneiss and granodiorite gneiss. The layered gneiss is the source of five samples with threshold barium; two samples each are from the old diorite, serpentinite, and metagraywacke; and one sample each from hornblende schist, chlorite-sericite schist, and andesite. Threshold strontium was found in four sand samples from granitic rocks of the peralkalic magma series, one

Table 3. Relations of molybdenum-enriched magnetites to granitic plutons of the peralkalic magma series in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

Name of pluton	Rock unit in the peralkalic magma series	Molybdenum in magnetite: Threshold (Sample no.)	Molybdenum in magnetite: Anomalous (Sample no.)
Al Hassir quadrangle (plate 1)			
Jabal Bani	Peralkalic biotite granite	-----	22851
Bisqan	Coarse-grained biotite granite	-----	22852
-do-	Peralkalic biotite granite	-----	22853
-do-	-do-	-----	22854
-do-	-do-	22855	-----
-do-	-do-	22857	-----
-do-	Fine-grained biotite-pyroxene granite	-----	22860
Jabal El Adg	Peralkalic biotite granite	-----	22869
(see Duthur as	-do-	22870	-----
Salam quadrangle)	Biotite-pyroxene syenite	22873	-----
Jabal Aruwayyuk	Fine-grained biotite-pyroxene granite	22928	-----
Jabal Al Hassir	Coarse-grained locally porphyritic biotite-pyroxene granite	22837	-----

Table 3. Relations of molybdenum-enriched magnetites to granitic plutons of the peralkalic magma series in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Name of pluton	Rock unit in the peralkalic magma series	Molybdenum in magnetite: Threshold (Sample no.)	Molybdenum in magnetite: Anomalous (Sample no.)
Duthur as Salam quadrangle (plate 3)			
Jabal El Adg	Peralkalic biotite granite	-----	22777
-do-	-do-	-----	22778
-do-	-do-	22779	-----
-do-	-do-	22788	-----
Jabal Ar Rubut	-do-	-----	22797
-do-	-do-	22803	-----
Pluton south	-do-	22736	-----
of Kitmah	-do-	22738	-----
Jabal Thiran	-do-	22691	-----

from the mafic rocks of the series, three from the calc-alkalic granite, six from granite gneiss and granodiorite gneiss, and three from layered gneiss. Thus, the general geochemical affinities of both barium and strontium are with the granitic rocks of the area.

Barium and strontium are associated in only eight samples, mostly granites and gneisses. Most barium-enriched samples are barren of other enriched metals; where present the other enriched metals tend to be strontium or zirconium. Only three barium-enriched samples contain associated lead or zinc. The samples enriched in strontium also are seldom associated with other metals except barium. Lead and zinc are present in only one strontium-enriched sample. Anomalous or threshold barium and strontium do not appear to be indicators of mineralization in the area.

Boron and vanadium

Anomalous sample (22451) and more than half of the sand samples with threshold values for boron, are from the Wadi Haraman quadrangle (plate 2). They come from sample sites dominantly in the eastern and central parts of the quadrangle where wind-borne sand covers much of the pediment surface on the Precambrian rocks. Most of these boron-enriched samples lack other metals except two samples (22460 and 22462) near the openings of the ancient Avala mine, where threshold lead is present. The remainder of the samples of sand with threshold boron are from the Hamdah quadrangle (plate 4) except one sample (22804) from the Duthur as Salam quadrangle (plate 3). The seven samples from the Hamdah quadrangle have one or more metals associated with the boron, more or less reflecting the diverse lithologic environments from which the samples were taken.

The preferential distribution of the boron-enriched samples on pediment surfaces in the northeastern part of the area is interpreted to mean that the source of the boron is most likely to have been wind-borne borate salts, possibly brought in from the Rub' al-Khali. This possible source for the boron-enriched samples is supported by the general lack of other enriched metals with the boron, or, where other metals are enriched, they seem to reflect the source rocks but the boron appears to be superimposed on them. No economic source for boron is indicated.

Vanadium-bearing samples of wadi sand in the area are preferentially derived from the volcanic rocks of the volcanic-sedimentary sequence and the mafic plutonic rocks of the peralkalic magma series. Four samples have anomalous amounts of vanadium: one is sand from hornblende schist and three are sand from gabbro of the peralkalic magma series. Of the 28 samples with threshold vanadium derived from the volcanic units of the volcanic-sedimentary sequence, ten came from andesite, two from pyritized andesite, one from chlorite-sericite schist, and 15 from hornblende schist.

The 22 samples of sand with threshold vanadium that were derived from the mafic rocks of the peralkalic magma series are distributed as follows: gabbro (11), gabbro and pyroxenite (5), gabbro and diorite (3), diorite (2), and diorite grading into granodiorite (1). The plutonic rocks of the volcanic-sedimentary sequence were the source of four samples of sand with threshold vanadium, of which three samples were from serpentinite, and one from amphibolite. Rocks of the volcanic-sedimentary sequence were the source of eight samples of sand with threshold vanadium: sericite-chlorite schist (2), biotite schist (2), and layered gneiss (4). The granitic rocks in the area were poor sources for sand with threshold quantities of vanadium, and where they were the source, the rocks of intermediate composition instead of the more silicic rocks were the more common. Thus, nine samples are from the granodiorite gneiss, one from the granite gneiss, and four each from the calc-alkalic granite and the peralkalic granite.

Thirty-two of the vanadium-enriched samples are also enriched in titanium and 27 are enriched in scandium, the dominant source rocks for both being the mafic units of the peralkalic magma series, hornblende schist, and the various granitic rocks. The distribution of the vanadium appears to be related to inherent geochemical characteristics of the rocks and is not connected with mineralization. No deposits of vanadium are indicated by these data.

MINERAL RESOURCES AND INDUSTRIAL ROCKS

The presently known distribution of mineral resources and industrial rocks, including mineral occurrences for which no economic use can be seen, is shown on plates 1-4. The major known mineral deposit in the area is the Ash Sha'ib ancient zinc-copper-silver mine (plate 4), which has been estimated to contain $40 million in sulfide ores with half that value in ores worth more than $25 per ton (Allcott, 1970, p. 36). The most important potential mineral resource in the area of the quadrangle is the possible chrysotile asbestos associated with anthophyllite near Hamdah (plate 4) and Tathlith (plate 2). Several varieties of minerals and industrial rocks are present that might have some economic use under more favorable conditions of access and utilization, but cannot now be exploited. The field data are interpreted to indicate several targets for future detailed examination for possible mineral deposits.

Syngenetic mineral resources

Magnetic deposits

Allanite.--Scattered small grains of allanite were discovered at two stations (22209 and 22230) in the Hamdah quadrangle (plate 4), but neither is as large as the allanite occurrence near Hamdah described by Brown (1968). At station 22209 sparse, small grains of accessory allanite are in pink granite porphyry intrusive into granite gneiss. The allanite at station 22230 forms crystals up to 1 cm across with dark reddish-brown halos as large as 3 cm. It is an accessory mineral in dikes of massive pink granite intrusive into granite gneiss.

The allanite described by Brown (1968) is in a granitic area 12 km northwest of Hamdah (plate 4) where gray granite intruded by a swarm of west-northwest trending mafic dikes is exposed on pediment surfaces and in low rounded domes. A few veins of quartz-orthoclase pegmatite are in the western part of the granite, and these contain accessory magnetite and allanite. Fragments of allanite are scattered in the lag gravels of the pediment. The allanite was examined mineralogically by Jerome Stone and spectrochemically by K. E. Valentine of the United States Geological Survey, Washington, D.C. Stone reported that the mineral is black, has a conchoidal fracture, and that small fragments of the crushed sample are green or, rarely, red (Brown, 1968, p. 1). The mineral is pale green and isotropic in plane polarized light, and has an index of refraction of 1.70 ± 0.05. It is metamict; hence it did not yield an X-ray pattern before heating. After heating it gave an X-ray pattern that was interpreted to show the presence of cerium oxide and iron oxide. The results of a semiquantitative spectrographic analysis by K. E. Valentine disclosed (Brown, 1968, p. 2):

Element	Range in percentage
Fe, Si	+10
Ce, Al	5-10
Ca, Mn, Nd, Th	1-5
Pr, Y, Ti	0.5-1
Y, Mg, Cd, Dy	0.1-0.5

Allanite has not been used commercially as a source for the rare earth elements or thorium, and at the places where it has been observed in the area, it is not sufficiently abundant to be minable.

Chromite.--Chromite is present as an accessory mineral in serpentinite replacing dunite or hornblende schist in the Hamdah asbestos district (stations 22237, 22273, 22274, and 22300, plate 4) and as scattered detrital grains in a wadi draining serpentinite east of Tathlith (22520, plate 2). Pods of serpentinite up to 500 m long and 100 m thick exposed about 19 km south of Jaash in the Duthur as Salam quadrangle (plate 3) have up to 10 percent of chromite in disseminated grains generally 2-3 mm in maximum size, but no large masses of chromite are present. Throughout the area chromite is probably a relict mineral from old ultramafic rocks associated with the volcanic-sedimentary sequence. None of the displays of chromite is more than would ordinarily be expected in an average dunite, with the possible exception of the chromite at station 22749 in the east-central part of the Duthur as Salam quadrangle. At station 22237 the chromite forms rare specks in the serpentinite and at 22300 it is a minor accessory mineral in serpentinite. Larger and more abundant grains of chromite were seen at 22273 where masses of chromite up to 8x20x70 cm make up an estimated 6 percent of a body of serpentinite 7 m wide, 3 m high, and 4 m long. At station 22520 in the Wadi Haraman quadrangle, a few pieces of detrital chromite were found.

Geochemical anomalies for chromium, described above, were noted at stations 22750, 22783, and 22795 in the Duthur as Salam quadrangle (plate 3), stations 22259, 22262, and 22337 in the Hamdah quadrangle (plate 4), and station 22520 in the Wadi Haraman quadrangle (plate 2).

If detailed field work were to be undertaken on the asbestos in the Hamdah and Tathlith areas, then a study of the chromite would be proper, but an independent survey of the chromite is not warranted.

Ilmenite.--Ilmenite is present in the area as an accessory mineral in selvages of massive anorthosite that formed as magmatic differentiates from massive gabbro (22218, plate 4; 22430, plate 2), and as detrital material in wadi sand derived from serpentinite (22520, plate 2).

The richest observed concentration is only 1.5 percent of ilmenite disseminated in the body of anorthosite covering 4-6 sq km at station 22430 in the Wadi Haraman quadrangle (plate 2). Rutile is not present. Small anorthosite dikes up to 5 cm thick and 10 m long at station 22218 in the Hamdah quadrangle (plate 4) intrude gabbro dikes in amphibolite and contain from 0.1 to 0.25 percent of accessory ilmenite, but they also lack rutile. Elsewhere in the Hamdah quadrangle selvages of anorthosite associated with gabbro lack accessory ilmenite. Even if the titanium mineral in these bodies of anorthosite had been rutile instead of ilmenite, at least 4 percent of rutile would be needed to make the anorthosite an ore. Far more ilmenite than rutile is needed to permit the mining of anorthosite for ilmenite in a favorably situated mining district.

The detrital ilmenite in wadi sand at station 22520 in the Wadi Haraman quadrangle (plate 2) is associated with detrital chromite and magnetite, probably derived from erosion of serpentinite, a product of the original ultramafic rock. This locality does not afford an exploitable source for ilmenite. It is also unlikely that exploitable ilmenite or rutile is available at the other occurrences because all the anomalies have identical low percentage of titanium (2 percent).

Magnetite.--Most rocks in the area contain accessory magnetite, as is evident from the 544 samples of wadi sand that yielded detrital magnetite out of the 566 samples taken. Magnetite as an accessory mineral was noted at two stations (22237 and 22344) in the Hamdah quadrangle (plate 4), but at neither locality is it of economic importance. At station 22237 thick dikes of garnetiferous and magnetite-bearing felsite intrude hornblende schist and serpentinite. Weathering of the accessory magnetite gives the dikes a brown color although the magnetite makes up less than 1 percent of the felsite. Scattered magnetite crystals up to 1x2x1 cm are in the wadi sand at station 22344, where gabbro intrudes granite gneiss and both rocks are intruded by pink, massive biotite granite. The source rock for the detrital magnetite was not identified.

Pyrite.--Disseminated pyrite was seen at 16 localities in the area, but no massive body of pyrite was observed. Seven (table 4) of the occurrences of pyrite originated from magmatic crystallization and five are from quartz veins that may be extreme magmatic differentiation products. Only four are associated with metamorphic rocks. The pyrite of magmatic origin is found as an accessory mineral in volcanic rocks like andesite, dacite, and rhyolite, and in late-stage granitic dikes and felsite. Hydrothermal pyrite in white quartz veins is probably the commonest mode of occurrence in the area. Large syngenetic massive pyrite bodies like those at Wadi Wassat (Overstreet and Rossman, 1970, p. 50-58) were not found in the Tathlith one-degree quadrangle.

Scheelite and powellite.--Detrital scheelite was identified in wadi sand from 24 stations in the area and detrital powellite was observed in sand from four stations (plates 1-4). No scheelite-bearing sample contained powellite. At no station where scheelite or powellite were determined by ultraviolet light were determinable quantities of tungsten identified by spectrographic analysis of the sand. Two of the samples of sand with scheelite (22396, plate 4; 22437, plate 2) had threshold and anomalous amounts of molybdenum, but none of the samples with powellite showed detectable molybdenum. The source rocks of the scheelite- and powellite-bearing samples of sand, and the relative abundance of scheelite and powellite in standard samples of 100 grams weight, are listed in table 5.

Detrital powellite is much less common compared to scheelite in the wadi sand than it is in the scheelite belt leading northward from Khamis Mushyat across the western part of the Asir quadrangle (Overstreet, 1968). In that area about 25 percent of the scheelite-bearing samples contain powellite, and the number of powellite-bearing samples is about 60 percent of the total number of scheelite-bearing samples.

Table 4. Host rocks for pyrite in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

Station number	Location	Description
		Igneous host rocks
22679	Duthur as Salam quadrangle (plate 3)	Sheared, fine-grained pink biotite granite has slight gossan and red iron stain thought to indicate possible trace of pyrite.
22725	-do-	Massive dacite with extensive thin gossan developed from fine-grained disseminated pyrite and possible pyrrhotite. Sulfide minerals make up 1-8 percent of the rock. Joints thoroughly coated with goethite and limonite, but secondary copper minerals are absent.
22726	-do-	Disseminated cubes of pyrite ranging in size from dust-like particles to grains 1 mm across make up 0.5-3 percent of host andesite. Limonite and goethite stain is common.
22727	-do-	Pyrite-bearing andesite porphyry, patches of gossan and rusty-colored surface alteration on the andesite.
22745	-do-	Unaltered, gray rhyolite dikes intrude massive, slightly epidotized and chloritized andesite. The rhyolite contains 0.1 percent of disseminated fine-grained pyrite that gives a thin yellowish-brown limonite stain to joint surfaces.
22428	Wadi Haraman quadrangle (plate 2)	Gray to pink granite dikes with less than 0.1 percent of pyrite intrude biotite diorite.
22540	-do-	White felsite dike with 0.1 percent pyrite intrudes gabbro.

Table 4. Host rocks for pyrite in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Station number	Location	Description
	Quartz veins (exclusive of the ancient mines)	
22324	Hamdah quadrangle (plate 4)	White quartz stringers with as much as 5 percent pyrite in cubes up to 4 cm across.
22343	-do-	Scattered grains of pyrite in white quartz vein 2 to 4 m thick and 700 m long, striking north.
22389	-do-	Trace of pyrite in white quartz stringers in red granite.
22437	Wadi Haraman quadrangle (plate 2)	Gabbro and red granite cut by en echelon white quartz veins with 1 to 3 percent of pink microcline and less than 1 percent of pyrite.
22539	-do-	Interlayered biotite quartzite and meta-andesite intruded by gabbro, red granite, and pink felsite in which sparse white quartz veins up to 30 cm thick and 50 m long contain less than 0.5 percent pyrite. The veins are most common in and near felsite and granite.
		Metamorphic rocks
22724	Duthur as Salam quadrangle (plate 3)	Thin-bedded, black, pyritiferous, fine-grained conchoidally fracturing marble with seams of siderite 1 to 2 m thick. Marble contains less than 1 percent of pyrite, unfossiliferous.
22225	Hamdah quadrangle (plate 4)	Faintly pyritiferous quartzite.

Table 4. Host rocks for pyrite in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Station number	Location	Description
		Metamorphic rocks (cont'd.)
22373	Hamdah quadrangle (plate 4)	Hornblende schist with 0.5 to 1 percent of disseminated pyrite in cubes up to 0.5 mm across, and white quartz veins with about 1 percent of pyrite in cubes up to 6 mm across.
22378	-do-	Black, dustlike pyrite in marble. Less than 0.5 percent of the rock is pyrite.

Table 5. Relative abundance of detrital scheelite and powellite in 100-gram samples of wadi sand, and source rocks for the sand, in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

(Determined by E. F. Overstreet in 1965 from fluorescent colors under ultraviolet light.)

Station number	Location	Grains in standard sample		Description
		Scheelite	Powellite	
		Igneous source rocks		
22825	Al Hassir quadrangle (plate 1)	3	---	Pink, fine-grained, porphyritic biotite granite with primary flow banding defined by orthoclase phenocrysts.
22676	Duthur as Salam quadrangle (plate 3)	5	---	Massive gabbro intruded by gray to pink biotite granite and short thick dikes of simple eutectic pegmatite.

Table 5. Relative abundance of detrital scheelite and powellite in 100-gram samples of wadi sand, and source rocks for the sand, in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Station number	Location	Grains in standard sample: Scheelite	Grains in standard sample: Powellite	Description
		Igneous source rocks (cont'd.)		
22686	Duthur as Salam quadrangle (plate 3)	---	5	Medium- to coarse-grained, pink, biotite granite.
22688	-do-	3	---	Massive, very fine-grained, red, biotite granite intrusive into interlayered biotite schist and hornblende schist.
22689	-do-	1	---	Coarse-grained massive gabbro intruded by pyroxenite.
22713	-do	---	1?	Massive gabbro and pyroxenite intrusive into nonlayered biotite granite gneiss and these rocks intruded by dikes of fine-grained gray massive granite.
22793	-do-	1	---	Contact between large inclusion of strongly chloritized and epidotized gabbro and pyroxenite and biotite-hornblende granodiorite gneiss.
22807	-do-	2	---	Massive, medium-grained, pink, biotite granite.
22207	Hamdah quadrangle (plate 4)	3?	---	Gray granite gneiss intruded by dikes of gabbro and red granite.

Table 5. Relative abundance of detrital scheelite and powellite in 100-gram samples of wadi sand, and source rocks for the sand, in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Station number	Location	Grains in standard sample: Scheel-ite	Grains in standard sample: Powel-lite	Description
		Igneous source rocks (cont'd.)		
22210	Hamdah quadrangle (plate 4)	---	2	Biotite granite gneiss intruded by hornblende-biotite felsite.
22223	-do-	1?	---	Biotite granite gneiss intruded by dikes of andesite and pink biotite granite.
22374	-do-	1	---	Metagabbro impregnated with dikes and stringers of pink biotite granite; metagabbro is an inclusion in granite.
22376	-do	1	---	Gabbro threaded with stringers of pink granite and pink pegmatite.
22389	-do-	3	---	Gabbro intruded by dikes of andesite and massive red biotite granite; sparse small white quartz veins with a little pyrite.
22406	-do-	1	---	Massive gabbro intruded by dikes of massive fine-grained, pink, biotite granite.
22435	Wadi Haraman quadrangle (plate 2)	1	---	Gneissic biotite granodiorite intruded by massive, pink biotite granite.

Table 5. Relative abundance of detrital scheelite and powellite in 100-gram samples of wadi sand, and source rocks for the sand, in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Station	Location	Grains in standard sample: Scheel-ite	Grains in standard sample: Powel-lite	Description
		Igneous source rocks (cont'd.)		
22437	Wadi Haraman quadrangle (plate 2)	6	---	Fine-grained gabbro intruded by dikes of pink to red granite; both rocks are broken by northerly-trending faults containing white quartz veins with 1-3 percent pink microcline and less than 1 percent pyrite.
		Metamorphic rocks intruded by granites		
22796	Duthur as Salam quadrangle (plate 3)	4	---	Epidotized massive andesite intruded by dikes of massive, fine-grained epidotized diorite.
22245	Hamdah quadrangle (plate 4)	2	---	Interlayered hornblende schist and biotite schist intruded in sequence by massive gabbro, andesite porphyry, and massive pink granite.
22262	-do-	1?	---	Contact between serpentinite and intrusive massive biotite granite.
22272	-do-	1	---	Biotite schist intruded by massive gray biotite granite and pink felsite.
22396	-do-	1	---	Interlayered hornblende gneiss and biotite gneiss intruded by massive gabbro and pink biotite granite.

Table 5. Relative abundance of detrital scheelite and powellite in 100-gram samples of wadi sand, and source rocks for the sand, in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Station number	Location	Grains in standard sample: Scheelite	Grains in standard sample: Powellite	Description
	Metamorphic rocks intruded by granites (cont'd.)			
22467	Wadi Haraman quadrangle (plate 2)	1	---	Mylonitic sericite-chlorite schist with porphyroclasts of biotite, possibly derived cataclastically from coarse-grained biotite granite gneiss.
22492	-do-	---	3?	Biotite-quartz schist intruded by dikes of fine-grained gray to pink biotite granite; cut by thin, limonite-coated shear zone.
22523	-do-	1	---	Meta-andesite and meta-andesite porphyry.
22528	-do-	4	---	Contact zone between marble and intrusive monzonite.
	Quartz veins			
22732	Duthur as Salam quadrangle (plate 3)	10	---	Large milky white quartz knobs which yield a coalescing scree on diorite and gabbro.
22373	Hamdah quadrangle (plate 4)	27	---	Hornblende schist with 0.5 to 1 percent of disseminated pyrite; cut by small, milky quartz veins containing pyrite and siderite.

? Determination doubtful.

Most of the detrital scheelite in the Tathlith one-degree quadrangle was found in drainage basins underlain by gabbroic rocks, hornblende schist, serpentinite, or andesite intruded by dikes of gray, pink, or red biotite granite. Granite, granite gneiss, or granodiorite gneiss were the source rocks for about 25 percent of the scheelite-bearing samples. Quartz veins in diorite, gabbro, and hornblende schist were the source for the two most scheelite-rich samples in the group. The beds of marble in the area were the source for only one sample of scheelite-bearing sand (22528, plate 2); it came from the contact of monzonite intrusive into fine- to coarse-grained white, gray, and blue marble. The detrital powellite was found in sands derived from granite, gabbro, and biotite-quartz schist intruded by granite. Thus, the sources of the two minerals are much the same.

None of the presently known scheelite-bearing localities appears to offer the prospect of an exploitable scheelite deposit. However, the open net of samples should not be regarded as foreclosing the possibility for the future discovery of a scheelite deposit in the area, particularly a skarn deposit along the contacts of the peralkalic granitic rocks with calcareous graywacke, marble, calc-silicate rocks, or hornblende gneiss and schist. The area in the north-central part of the Hamdah quadrangle (plate 4) may be a favorable starting place for further investigations for scheelite, with these investigations extending northward into the south-central part of the Wadi Haraman quadrangle (plate 2).

Pegmatitic deposits

Pegmatites in the area tend to be small dikes or veins along strike from dikes of granite, graphic granite, and felsite. They are generally simple eutectic, or near eutectic, mixtures of quartz and orthoclase. Accessory minerals are rare, and zoned pegmatites are most uncommon. These simple pegmatites appear to be genetically related to the plutons of peralkalic granitic rocks; a few scarce pegmatite masses are syenitic and are probably genetically related to the mafic rocks of the peralkalic magma series. Dikes of pegmatite that may be genetically related to the granite gneiss and granodiorite gneiss units tend to be sheared and are remarkably uncommon in the area.

Minerals associated with the pegmatites are cited below. All are only mineralogic occurrences.

Allanite.--Allanite was observed in pegmatites of the peralkalic magma series exposed on granite pediments to the northwest of Hamdah (Brown, 1968), as noted previously.

Amazon stone.--Two interior pegmatite dikes at the northern end of the zoned granitic pluton of the peralkalic magma series at Jabal Al Hassir contain small amounts of microcline of a quality referred to as amazon stone (plate 1). At station 22833 in pink, coarse-grained, biotite-pyroxene granite a pegmatite dike 8 cm thick and 2 m long contains scattered grains of amazon stone up to 6 mm thick and 1 cm long accompanied by crystals of clear, terminated quartz. The amazon stone from station 22837 consists of detrital crystal fragments about 2x2x3 cm derived from pegmatite in pink, coarse-grained, quartz-rich, pyroxene granite.

Axinite.--Axinite forms brown sheafs 4-5 cm long in dikes of pink granite and pegmatite of the peralkalic magma series intrusive into diorite and gabbro at station 22309 in the Hamdah quadrangle (plate 4). The dikes are sheared and recrystallized. Biotite forms long clusters on the foliation planes in the granite and pegmatite, and brown euhedral crystals of andradite garnet cut across the foliation planes. The sheafs of axinite are also undeformed. They were found in debris from the pegmatite but were not seen in place.

Magnetite.--Magnetite was identified by Brown (1968) as an accessory mineral in allanite-bearing pegmatite dikes northwest of Hamdah (plate 4), and he described how the grains of magnetite and allanite accumulated in pediment gravels. At two other localities (22327 and 22344) in the Hamdah quadrangle coarse crystals and crystal fragments of magnetite, up to 2 cm in size but generally nearer 1 cm across, were observed in wadi sand. The sources for the detrital magnetite were not found, but at both localities granite and granite dikes are present. The magnetite may have come from pegmatites associated with the granite.

Muscovite and feldspar.--Minor amounts of generally small sized, badly reeved book muscovite were found in a few pegmatite dikes in the area. At station 22217 in the Hamdah quadrangle (plate 4), rare books of colorless, strongly reeved muscovite up to 3x4 cm are present in the alaskite pegmatite core of a zoned plug of biotite granite. Strongly reeved book muscovite up to 1x2 cm makes up 6 percent of a perthitic pegmatite grading into a felsite dike at station 22299 in the Hamdah quadrangle (plate 4). The maximum width of the pegmatitic part of the dike is 3 m, and the length is probably less than 20 m.

Feldspar in the pegmatite dikes in the area is generally too intimately intergrown with quartz to permit a simple recovery by hand cobbing.

Quartz.--Massive white quartz of apparent high chemical purity is present at a number of places in the area. Much of this quartz may be suitable for ceramic purposes, but analyses of individual deposits of quartz were not made. The most visible and largest concentrations of quartz are in plutons of diorite and gabbro of the peralkalic magma series. Debris from the quartz bodies form white splays and alluvial fans on the dark mafic rocks. Many of these bodies of quartz in diorite and gabbro are shown on the geologic maps of the Duthur as Salam (plate 3), Hamdah (plate 4), and Wadi Haraman (plate 2) quadrangles. Prominent localities in the Duthur as Salam quadrangle include the area south of station 22691 and in the diorite and gabbro mass at stations 22731 and 22732. White quartz is common around stations 22307 and 22309 in diorite and gabbro in the Hamdah quadrangle. In the Wadi Haraman quadrangle similar quartz is present in a gabbro pluton near stations 22503, 22504, 22505, and 22507.

White quartz is also present at station 22708 in the Duthur as Salam quadrangle along a major west-northwest trending dike of granite and felsite.

The fault zone and contacts at station 22515 in the Wadi Haraman quadrangle lead northwestward for 20 km to Wadi Thafin and are marked by many thick white quartz veins.

Metamorphic deposits

Anthophyllite and chrysotile.--Deposits of anthophyllite and chrysotile asbestos are found near Hamdah (plate 4) and rocks favorable for these minerals are present east of Tathlith (plate 2) and south of Jaash (plate 3). Of the 21 samples of asbestiform minerals collected in these regions, 17 came from the Hamdah district (plate 4), and four were collected near the Higera mine about 15 km southeast of Hamdah. However, the deposits near Higera are in a geologic extension of the ultramafic rocks near Hamdah, and in any detailed exploration program for asbestos deposits, the Higera and Hamdah areas would have to be considered together. At the present reconnaissance stage of investigation, the only known sample of chrysotile in the collection is from the Higera area (sample 22297 from 18°56'N.; 43°41'E.). As early as 1957 the presence of chrysotile at Higera mine was known to the Ministry of Petroleum and Mineral Resources (Schaffner, 1957), and correspondence from that period between Schaffner and the Johns Manville Corporation shows that only one of several samples submitted by Schaffner to the company for examination was chrysotile, and that was too weathered to be commercially acceptable. The possibilities for deposits of marketable asbestos in the Hamdah and Tathlith areas were discussed by Kareh, Keller, and Kahr (1962).

Associated with the anthophyllite and chrysotile in the Hamdah and Higera areas are many of the ancient gold mines, small amounts of chromite, and locally a little soapstone, talc, and clear calcite, but none of these materials is known in present commercial quality or quantity. Thus, if a detailed study of the asbestiform minerals is made, by-product information could be developed on the other commodities. Because chrysotile can be beneficiated by air separation, it would make an ideal mineral commodity for mining under local conditions. Short-fiber asbestos would be usable by a domestic asbestos-cement water-pipe industry and long-fiber asbestos commands a high price in the international minerals market. The potentially favorable areas located near Higera, Hamdah, Tathlith, and Jaash need detailed investigation for minable chrysotile asbestos.

Cross-fiber asbestiform minerals fill veins in serpentinite in the Hamdah ultramafic belt. In the Higera and Hamdah areas the serpentinite most probably was derived from olivine-bearing ultramafic rocks like peridotite and dunite, because magnesite is a common by-product of the serpentinization. In the serpentinite east of Tathlith, magnesite is uncommon, and calcite and dolomite veins are present. Possibly the serpentinite in that area is derived mainly from olivine-free pyroxenite and gabbro. At some places andesite and hornblende schist are altered to serpentinite. Brown calcareous crusts are forming in the present erosion cycle at some places over the serpentinite. These crusts impart a distinctive color to the serpentinite.

Locations and descriptions of the sampled asbestiform minerals are given in tables 6 and 7, which show that anthophyllite is more common than chrysotile.

The anthophyllite in the Hamdah area and the chrysotile in the Higera area occupy fractures and replacement zones in the serpentinite, or locally in hornblende schist. These zones are clearly older than the calc-alkalic and peralkalic granitic rocks and related felsite and pegmatite, because many dikes of granite, felsite, and pegmatite intrude the anthophyllite veins. Also, the amount of anthophyllite in the serpentinite bears no relation to the presence or absence of intrusive masses of granite. Partial alteration of the anthophyllite to talc may have been caused by the intrusion of these dikes.

Special studies of the asbestiform minerals were made. Nine samples were sent to A. F. Shride, U. S. Geological Survey, Denver, Colorado, an expert on asbestiform minerals, for X-ray examination, comment on possible industrial uses, and recommendations for exploration. A summary of his report (Shride, A. F., written commun., Feb. 15, 1966) follows:

> The asbestiform mineral in 8 of the 9 samples forwarded is anthophyllite that almost certainly has no industrial use. One sample (22297, table 6) contains chrysotile of good industrial quality. If this sample is representative of a volume of rock large enough to be exploited by small-scale open pit or block caving methods, additional examination is warranted. The anthophyllite and chrysotile are wholly different commodities; thus, the

Table 6. Asbestiform minerals near the Higera mine, 15 km southeast of Hamdah, Kingdom of Saudi Arabia

Sample number	Location		Description
	North latitude	East longitude	
22122	18°55'	43°40'	Minor cross-fiber asbestiform mineral in serpentinite associated with hornblende schist and marble.
22123	18°55'	43°40'	Cross-fiber asbestiform mineral up to 7 cm long, generally 0.5 to 2 cm long, in veins dipping 20°S. in serpentinite and silicified marble.
No number	18°58'	43°41'	Radial aggregates of asbestiform mineral 2 cm to 15 cm across in small lenticular masses of serpentinite 0.5 to 4 m long in amphibolite at ruins called Um El-Fager; very little, probably anthophyllite.
22297	18°56'	43°41'	Cross-fiber chrysotile asbestos 0.5 to 8 mm thick in shear zones up to 15 cm thick in serpentinite; chrysotile makes up 8-15 percent of the shear zone. No movement has taken place after the formation of the asbestos, which has very straight fibers. At many places in this area cross-fiber asbestos not exceeding 1 cm in length is in veins up to 40 m long which dip 30°S. and locally make up 20 percent of the exposed serpentinite. In a report by A. F. Shride (written commun., February 15, 1966), U.S. Geological Survey, sample 22297 was positively identified as cross-fiber chrysotile in narrow sharp-walled veins in serpentinite. Fiber lengths are mostly less than 2.4 mm (paper stock grade), but some is as long as 11.1 mm (short textile length). Tensile strength and flexibility (softness) is excellent. The weathering "harshness" common to surface exposures of chrysotile is almost absent. Much magnetite is along the walls of the veinlets and partings in the fiber. Fiber content of the larger lumps in sample averages 25 percent.

Table 7. Anthophyllite and asbestiform minerals near Hamdah, Kingdom of Saudi Arabia

(Identification of asbestiform minerals in 8 samples as anthophyllite reported by A. F. Shride, U. S. Geological Survey, February 15, 1966.)

Sample number (see plate 4)	Description
22237	Cross-fiber asbestiform mineral 1-2 mm long in veins 20 cm wide and 200 m long dipping 80°E. in serpentinite in hornblende schist.
22240	Tiny seams of short cross-fiber asbestiform mineral, not exceeding 0.5 mm and commonly 0.25 mm across, make up less than 0.1 percent of serpentinite mass 4,000 sq m in area.
22243	Cross-fiber asbestiform mineral in veins up to 1 mm wide in serpentinite; distribution masked by talus.
22248	Cross-fiber asbestiform mineral in veins up to 2 mm thick constitute up to 8 percent of the volume of the serpentinite in which they occur. They average at least 0.5 percent of the volume of serpentinite in 40,000 sq m, but are intruded by dikes of diorite and pink aplite.
22249	Cross-fiber asbestiform mineral 0.5 to 1 mm thick in scarce veinlets dipping 70°N. in serpentinite.
22252	Trace of asbestiform mineral in serpentinite.
22255	Cross-fiber asbestiform mineral up to 6 mm across replaces serpentinite in gabbro and diorite; it makes up 0.5-1.5 percent of serpentinite with area of 3000 sq m.
22270	Badly weathered cross-fiber anthophyllite up to 20 cm long in veins dipping 65°N. in serpentinite in hornblende schist. Fibers are broken by fractures subparallel to the wall of the vein into lengths of 2-3 cm. Locality is poorly exposed. Anthophyllite sample was described as essentially monomineralic, soft, punky, very weak, pearly lustered fiber; part is slip fiber, otherwise fibers are parellel and up to 7.5 cm long. Fibers are thoroughly impregnated with iron oxides.

Table 7. Anthophyllite and asbestiform minerals near Hamdah, Kingdom of Saudi Arabia (cont'd.)

Sample number (see plate 4)	Description
22275	Slip-fiber asbestiform mineral in fault dipping 60°N., 10-30 cm wide, vertical height of exposure is 2 m. Badly weathered.
22279	Anthophyllite from veins in serpentinite intrusive into hornblende schist. The anthophyllite was described as hard, woody material with somewhat platy parting. Megascopically the material resembles amphibole, but X-ray analysis shows that talc is considerably more abundant than anthophyllite. One mineral component (serpentine-like) was not identified.
22286	Lenticular masses of cross-fiber asbestiform mineral up to 20 cm wide and 3 m long dipping 40°N. in serpentinite. Fractures sub-parallel to the walls cut the mineral into fibers 2-3 cm long. Slip-fiber asbestiform mineral is developed parallel to slickensides in serpentinite where it covers surfaces 5 cm thick and up to 1 m long. The lenticular masses are intruded by dikes of gray granite and perthitic pegmatite. Asbestiform mineral is sparse.
22290	Cross-fiber anthophyllite with fibers up to 30 cm long in veins up to 5 m in length in serpentinite in hornblende schist. The veins strike E. and dip 60°S. They thicken and thin along strike from 5 cm to 30 cm. Anthophyllite veins replace 15 to 30 percent of serpentinite in an exposure at least 150 m long, 60 m wide, and 30 m thick. The anthophyllite-bearing vein system may persist several kilometers along strike, but individual veins are short. The anthophyllite was described as similar to sample 22270, but weaker, not as deformed, and with apparent fiber lengths up to 15 cm. Identical short-fiber--another generation(?)--is matted in random orientation on the principal joint planes.

Table 7. Anthophyllite and asbestiform minerals near Hamdah, Kingdom of Saudi Arabia (cont'd.)

Sample number (see plate 4)	Description
22291	Cross-fiber anthophyllite up to about 10 cm long in vertical veins up to 20 m long is in serpentinite in hornblende schist. The serpentinite forms lenticular masses from 0.75 m wide and 1.5 m long to 20 m wide and 300 m long in the foliation of the schist. From 0.1 to 0.5 percent of the volume of the serpentinite is anthophyllite. Outcrops of serpentinite occupy at least 10,000 sq m. The anthophyllite was described as mostly soft fiber very similar to 22270 with a similar X-ray pattern, but the specimens also include poorly fibrous woody parts comparable to 22294. A gray-green micaceous mineral (identification not made) is conspicuous along cleavage planes and as knots within fiber.
22294	Cross-fiber anthophyllite in fibers up to 10 cm long is in veins with random orientation in serpentinite masses that conform to the layering of hornblende schist and quartzite that strikes N.65°W. and dips 75°N. The veins of anthophyllite are individually short and tapering, up to 6 m long. In aggregate the veins make up less than 1 percent of the serpentinite. The anthophyllite was described as hard slip(?) fiber as much as 15 cm long. The anthophyllite resembles petrified wood. Most of the sample is anthophyllite, but the best cleaned material included an appreciable amount of talc and small amounts of a serpentine(?) mineral.
22295	Cross-fiber anthophyllite veins up to 8 cm wide are in serpentinite in hornblende schist striking N.70°E. and dipping 65°N. The serpentinite makes up about 20 percent of the exposed rock and forms lenticular masses a few meters to a few tens of meters thick by a few meters to a few hundred meters long. From 0.5 to 2 percent of the serpentinite is replaced by anthophyllite. All the anthophyllite veins are sheared so that the longest fibers are only 2-3 cm long although the veins are 5-8 cm thick. Slip-fiber anthophyllite is almost as common as cross-fiber anthophyllite. The anthophyllite was described as hard slip (?) fiber as much as 7.5 cm long with fibers that do not separate readily. X-ray data were interpreted to show that a trace of talc (?) is included.

Table 7. Anthophyllite and asbestiform minerals near Hamdah, Kingdom of Saudi Arabia (cont'd.)

Sample number (see plate 4)	Description
22300	Cross-fiber and slip-fiber anthophyllite are formed in vertical fractures in dunite and serpentinite in hornblende schist. The maximum length of the cross-fiber anthophyllite is 4 cm, but the exposure is crossed by myriads of thin veinlets of cross-fiber anthophyllite up to 5 mm wide which make up as much as 8 percent of the serpentinite in areas up to 2,000 sq m. The slip-fiber anthophyllite occurs in lenticular pods up to 25 cm thick and 1.5 m long. The anthophyllite was described as having fiber as much as 7.5 cm long. It is similar to 22270. Data from an X-ray examination were interpreted to show that small amounts of a serpentine mineral are included in the best cleaned material.
22304	Cross-fiber anthophyllite is exposed for only 1-2 m in veins that attain a thickness of 12 cm but are fractured sub-parallel to their walls so that the actual lengths of the fibers are less than the width between the walls. Among the wide veins there are many thin veins of anthophyllite up to 2 mm across. In total the veins make up about 1 percent of the volume of serpentinite bodies that are hundreds of meters thick and at least several thousand meters long. The anthophyllite was described as slip (?) fiber up to 3.8 cm long and similar to 22270. It is much contaminated by weathering products. The texture was interpreted to show that the anthophyllite had been thoroughly wetted and mashed in a near-surface environment--i.e., movement (fault or creep) after the woody material was available in the weathering zone may have aided in the development of the fibrous character. X-ray analysis indicated a moderate content of talc.

potentials of the two materials should be considered exclusive of one another. Presence of the two types of minerals in one ultramafic belt is wholly congruous, but differentiation of the types in the field is a necessity.

Anthophyllitic masses of the sort apparently represented here commonly exist below the zone of weathering as woodlike materials that cleave, at best, as splinters rather than fibers. Suitable leaching in the zone of weathering (or in some hydrothermal zones where the product is ordinarily insignificant in volume) enhances the fibrous character of such deposits. Possibly rock physically similar to samples 22286 and 22294 (table 7) is the original material that assumed a more fibrous form when exposed to weathering. However, these particular samples may be less fibrous than the others because they have been partly altered to talc prior to weathering. Samples 22270 and 22304 (table 7) perhaps represent the range of ultimate fibrous forms that can be expected. Probably these samples represent material more asbestiform than can be uncovered at even shallow depth. The exceptional better material might be an occasional small pocket of fiber that escaped infiltration by limonite and surface salts, and for that reason would be superior in quality to the surface samples.

If the above seems to be too subjective a basis for rejecting the anthophyllite, the lack of its general use in industry seems to be an adequate reason for rejection.

Ordinarily the best of anthophyllite fibers are not flexible enough for any of the textile uses. Anthophyllite fibers lack tensile strength, or powder too readily, to be processed as binder or filler fibers in asbestos cement or molded products, or to be used in loose insulation packings. Anthophyllite is superior to the other varieties of asbestos only in being chemically the most inert. For this reason, small amounts of the purest forms of anthophyllite are used as filters in laboratories or in small-scale industrial plants that employ strong acids or alkalis. Rarely, exceptionally flexible anthophyllite of moderate strength enters trade as a substitute for one of the more flexible varieties of asbestos.

Anthophyllite suitable for filters or the lesser applications is rare, but the quantity used is so small that the occasional lucky find is apparently quite adequate for all demands, and it is not a commodity given priority in trade. Thus, even if the Hamdah material proved to be of this high quality, the anthophyllite would be difficult to market.

Rock with chrysotile in the amount and lengths seen in specimen 22297 (table 6) is the ore that furnishes at least 70 percent of all asbestos used. The fiber of this sample is soft, that is, flexible, silky, and with good fatigue resistance on repeated flexing. This fiber also has very good tensile strength. It is of the quality, therefore, that could be used in textiles, when long enough, or in the many products in which abrasive handling is part of the manufacturing process. The range of myriad uses might be:

(1) Longest fibers (Group 3--mill fibers of spinning length): woven textiles, yarn-type and loose packings, high-value molded products such as clutch and brake facings, laminated binder with resins for custom-shaped products.

(2) Intermediate fibers (Groups 4 and 5): asbestos-cement products (shingles, sheets, mill-board, and pipe), papers, pipe covering, gaskets, and industrial filters.

(3) Shortest fibers: uses similar to (2) plus use in putties, paints, asphalt coatings (including such heavy duty uses as road surfacing), filter or binder in floor tile and similar plastics.

The value of soft chrysotile asbestos of adequate strength depends mainly on length. Most of the fiber in sample 22297 is less than 2.4 mm in length. In the cleanly separated state this fiber, which is designated paper stock or short single fiber, is worth $100-$150 per ton. Some of the fiber is as long as 11.1 mm, which would be worth perhaps $600 per ton if separated in lengths mostly greater than 9.5 mm. In lengths greater than 19 mm such fiber sells for as much as $1600 per ton. Obviously, the proportions of the different lengths--the fibers of various ores separate differently on milling--extrapolated back to the recoverable fiber content of the rock, determine the value of the ore.

No harsh fiber (fiber that flexes like broomstraw and breaks more readily on repeated flexing than soft fiber) was seen in sample 22297 (table 6). If the deposit is extensive, sooner or later harsh fiber probably will be found. It would need to be appraised separately for different use. Harsh fiber is of less value than soft, and its prices are not so closely tied to length. Harsh fiber is not detrimental to a worthwhile discovery. Indeed, unless the fiber is harsh to the point of being brittle, harshness can be an asset in establishing an asbestos-cement industry, because certain problems of curing and quality control are alleviated, if the use of slime-producing soft fibers can be minimized.

Some experience in assessing harshness is required because there is (1) a true harshness inherent as an essentially original feature, (2) a brittleness that occurs in areas of hydrothermal alteration or adjacent to a post-fiber intrusion, and (3) a rotting or "drying out" caused by weathering. The original harshness or softness of chrysotile asbestos is a characteristic generally consistent through a considerable part of a deposit. There are no deposits in which a vein is soft and an adjacent vein is harsh. The secondary brittleness tends to be patchy in distribution, and it can be recognized by geometric relation to the alteration of the host rock, if exposures are adequate. The weathering alteration is superficial. Soft fiber that has weathered to stiff and weak fiber may retain the characteristic of separating in cobwebby filaments when pulled apart. With a little experience gained by watching fiber characteristics as a deposit is exposed, the various aspects will become apparent.

The fibrosity of chrysotile is not a weathering phenomenon. The chrysotile specimen (22297) exhibits very little of the usual weathering effects. On exposure of only a few years chrysotile loses translucency, whitens, becomes relatively dull in luster, and may accumulate iron stains. The most bleached fibers may powder readily on rubbing between the fingers. The fibers in sample 22297 retain the luster, color, and texture that can be expected at depth. Because chrysotile is not particularly resistant, chemical weathering can be detrimental, especially if the ore zone bottoms at shallow depths. This is a factor for geologic appraisal from knowledge of the depth of leaching along fracture systems.

Slip fiber, where used to describe chrysotile, generally means cross fiber that has been displaced along fault planes to the extent that it is mixed with gouge and is, therefore, difficult to separate by milling. Areas prone to slip should be apprised separately if possible.

Specimen 22297 of chrysotile contains considerable magnetite, which is detrimental for use in electrical insulation and filters. However, magnetite does not seriously affect most uses and should be of little concern, especially as it may be an aid to exploration (see below). Most of the magnetite in sample 22297 borders the veinlets or is loose along partings within the veins rather than infiltrated along fibers as the spindle-like blebs that are abundant in some ores. If all the magnetite has the same habit as that in specimen 22297, the fiber would probably mill fairly free of magnetite.

Sample 22297 as submitted is millrock, in contrast to bonanza ore that might be handcobbed. Millrock requires for treatment a somewhat sophisticated and, therefore, expensive plant that can be used for some time. The scale of operations of mine and mill is not dictated simply by the rate of amortization. There seems to be a lower limit of plant size below which the control of the grade of the product is not easily standardized. In part, this reflects the problems of producing enough of the various lengths of fibers so that blends can be made that are suitable for at least the minimum range of products that will use all the recovered fiber. It is estimated that appropriate mining and milling procedures might require a deposit that could furnish 1,000 tons of ore per day for 10-20 years, to give an order of magnitude to the size of target that should be sought.

Chrysotile asbestos that occurs in massive serpentinites commonly is localized in shear zones tens to hundreds of feet in width. These zones in one instance may be dominated by simple parallel sheeting and in another may display conjugate fracturing and veining of considerable complexity. The shear zones may be in positions determined, at least partly, by the relative competence of various rock facies in the ultramafic belt. Perhaps more often than not the zones of favorable fracturing are along one wall of the ultramafic body or at a deflection from the usual trend of the host body. The attitude of the fiber-bearing zone must be determined, and whether it is well defined or made up of subzones interleaved with relatively unmineralized rock needs to be worked out. Though delineation of the kinds of rocks and the type and density of fractures can be an aid, the lack of considerable familiarity with the local terrane can make reasonable assessment of these features impracticable; also, exposures in these kinds of rocks commonly are inadequate. Fortunately, the systems of asbestos veins are also the loci for concentrations of magnetite. Once suitable asbestos fiber is known to be present in an area, magnetic anomalies can outline the targets for exploration. The speculative anomalies first defined by airborne surveys are commonly surveyed in detail by ground magnetic methods in the exploration of chrysotile. Preliminary airborne geophysical surveys have been made of the Hamdah and Higera areas (CAMS, 1967) but results were not available to the writer.

Diamond drilling is the preferred method of sampling at depth, because it gives a better statistical coverage of the zone than exploration adits or shafts. Conventional techniques of drilling require slight modification when exploring for chrysotile, and a driller with the experience to cope with problems peculiar to the coring of fibrous materials. Fiber cut by the drill may ravel for some distance; thus, the veined part of the core may be destroyed, return water may be plugged off or channeled to escape elsewhere, or at minimum an excessive "salting" of the sludge may occur. Even if cleanly cut, chrysotile fiber fluffs excessively and causes the evaluation of sludges to be tricky. Therefore, high core recovery is very desirable.

In badly fractured ground, or in zones with much slip fiber, large cores (BX or NX) are usually cut, and even these may not be satisfactory. Ideally, drilling is done perpendicular to the dominant direction of the veining of the asbestos. Some trenching commonly precedes drilling in order to assess attitudes and other geologic aspects of a given deposit. At many deposits the potential ore zones are fractured to such a degree that ripping and trenching by tractor, with little or no blasting, is feasible. If the zones are suitably disposed a considerable part of the exploration can be trenching.

The evaluation of samples is done mainly by painstaking logging of cleaned faces or of drill core, primarily to estimate the proportions of various lengths of chrysotile fiber and the quality. Mere determination of total fiber content is not especially useful without the data on length; total fiber content may be determined as a supplemental step by mechanical separation. A summary of the method of evaluation is given by Jenkins (1960, p. 38-40), but it should not be assumed from the description that the application is simple. Evaluation is complicated by such problems as how to allow for the partings common in veins, how to estimate lengths where cross fibers are disposed at acute angles to the walls of veins, and estimating the makeup of slip fiber or of mixed veins with harsh and soft fiber. Laboratory simulation of grinding in mills has not been satisfactory. Before the results of logging can be used for precise estimates of the value of the ore, a correction factor is applied. This factor is based on some sort of experience, usually the full scale grading in the mill of bulk samples, or at the least, an analogy with a nearby tested deposit. This correction is commonly a value factor on the order of 2 to 3; that is, the total yield of fiber based on visual estimates could be in error by 50 percent and the length (value) estimates could be in error by 100 percent to give a factor of 3. In Canada the final appraisal is commonly based on several bulk samples of several thousand tons each in size.

Talc.--Small amounts of talc were detected in some of the asbestiform mineral deposits mentioned above, but talc was not observed as a major constituent in any of the rocks. At station 22275 in the Hamdah quadrangle (plate 4) talc is in a fault zone in serpentinite (table 7), and at station 22298 in the same quadrangle talc schist is associated with gold-bearing quartz veins in serpentinite. Neither is a minable source for talc.

Magnesite.--Magnesite in thin joint fillings, small veins, and irregular masses was found at eight localities in the Hamdah quadrangle (plate 4) and three in the Wadi Haraman quadrangle (plate 2). All the magnesite is in serpentinite except at station 22283 (table 8), where magnesite veins originating in serpentinite follow joints out of the serpentinite into biotite-muscovite schist. The magnesite is thought to have resulted from the alteration of peridotite and dunite to serpentinite with surplus magnesium releasted as magnesite. None of the deposits is an economic source for magnesite.

Garnet.--Garnet is rare in the metamorphic rocks. Biotite granite gneiss at stations 22709 and 22710 in the Duthur as Salam quadrangle (plate 3) contains 0.2-1 percent of fractured spessartite garnets up to 4 mm across. They are of no economic value. Gneissic gabbro intruded by massive red biotite granite at station 22761 in the Duthur as Salam quadrangle has joints filled by veins of epidote and quartz with thin selvages of brown garnet and quartz. The garnets are less than 0.5 mm across and are of no value.

Graphite.--Graphitic phyllite or graphite schist are known at station 22243 in the Hamdah quadrangle (plate 4) and at stations 22486 and 22512 in the Wadi Haraman quadrangle (plate 2), but graphite is not concentrated in minable amounts at any of these localities. At station 22243 graphite schist is interlayered with biotite schist and intruded by serpentinite and quartz porphyry, but crystalline graphite has not formed at the intrusive contacts. Graphitic chloritoid schist is interlayered with quartzite and metamorphosed lithic tuff and this sequence is intruded by gabbro at station 22486. Silicified marble and graphitic phyllite are interlayered at station 22512.

Ilmenite.--White, gray, and blue, fine-to coarse-grained marble at station 22527 in the Wadi Haraman quadrangle (plate 2) has about 0.1 percent of a platy, dark gray to black, metallic mineral at contacts with intrusive monzonite. The mineral may be ilmenite.

Magnetite.--Layered biotite-hornblende gneiss, magnetite quartzite, and magnetite-biotite schist at station 22317 in the Hamdah quadrangle (plate 4) has the richest concentration of magnetite observed in any rocks in the area; however, the magnetite-bearing layers are thin and the area of exposure is small. The magnetite-rich quartzite and schist contain 20 to

Table 8. Magnesite in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

Sample number	Description
	Hamdah quadrangle (plate 4)
22204	Sparse detrital magnesite in wadi gravel, and thin fillings of magnesite in joints in serpentinite 2.5 km to the southwest.
22262	Rare thin films of magnesite along joints in serpentinite.
22264	Rare thin films of magnesite in joints in serpentinite.
22281	Joint in serpentinite occupied by filling of magnesite 1 cm thick and 60 cm long.
22282	Sparse thin films of magnesite in joints in serpentinite.
22283	Magnesite veins occupy joints in serpentinite and extend out of serpentinite into biotite-muscovite schist; veins anastomose and attain a maximum thickness of 50 cm, contain many inclusions of host rock, and occupy about 15 percent of the rock mass underlying an area of 500 sq m.
22284	Sparse veinlets of magnesite up to 2 cm thick in serpentinite.
22291	Scattered veins of magnesite up to 2 cm thick and 4 m long in serpentinite.
	Wadi Haraman quadrangle (plate 2)
22520	Sparse, thin seams of mixed magnesite and calcite fill scattered joints in serpentinite.
22521	Major joints in serpentinite filled with magnesite up to 2 cm thick.
22522	Trace of magnesite filling small fractures in serpentinite; calcite veins are more common than magnesite.

40 percent of magnetite in grains less than 0.5 mm across intimately intergrown with quartz or quartz and biotite. The magnetite-rich, quartzose layers are 2-3 cm thick and alternate with feldspathic layers 2-4 cm thick which lack magnetite. These rocks are interstratified in units up to 75 cm thick with the biotite-hornblende gneiss. The length along strike of the magnetite-bearing layers is about 50 m. Doubtless the magnetite quartzite and magnetite-quartz schist persist for greater distances, but the exposures are covered by scree. The exposed magnetite-rich layers are only a mineralogical curiosity, but the area itself has been covered by regional airborne magnetic surveys, not available to the writer, which should be examined for possible magnetic anomalies that might disclose other and larger deposits.

Pyrite and siderite.--Thin-bedded, black, conchoidally-fracturing marble at station 22724 in the Duthur as Salam quadrangle (plate 3) contains less than 1 percent of fine-grained, disseminated pyrite, and has beds of siderite 1-2 m thick. The marble is interbedded to the west and east with meta-andesite. Poor graded bedding was interpreted to show that the marble, which strikes N.20^{o}E. and dips 25^{o}NW. is right side up. The siderite is too thin for any economic use.

Sedimentary and residual deposits

Iron in the Wajid Sandstone.--Hematite and limonite are variably present as cement near the base of the Wajid Sandstone (Overstreet, 1966a, p. 55), particularly in the lower 30 m of the exposed basal part of the section in the western part of its outcrop area. The cement is not an iron ore, but locally it makes up as much as 10 or 12 percent of the rock, although the average is only about 0.2 percent. Locally, the Wajid Sandstone has been replaced along bedding planes by nearly pure hematite, but these replacement masses are only 3 or 4 cm thick. Parts of the Wajid Sandstone contain many spheroidal concretions of limonite where the rock is otherwise free of ferruginous layers or cement. Where circulating ground water has re-deposited iron in joints, massive fillings of limonite and hematite up to a few centimeters thick are found. Some of these little deposits have been prospected in the Wadi Idimah area about 85 km south of the Tathlith one-degree quadrangle, but none of the ferruginous material in the Wajid Sandstone is minable commercially.

Placers.--Placer concentrations of black sand have been seen in the Wajid Sandstone (Overstreet, 1966a, p. 50-55) at several places south of the Tathlith one-degree quadrangle, but none seemed to offer minable concentrations of economic minerals. The observed black sand deposits consist mainly of ilmenite and epidote with locally variable amounts of magnetite, amphibole, pyroxene, and traces of zircon and garnet. The layers of black sand are up to 70 cm thick and are flatly lenticular, reaching several hundred meters in length. Locally they contain white quartz pebbles. They interfinger with well-sorted quartz sand and have a heavy ferruginous cement. No commercial use was seen for these small placer deposits.

Owing to the local presence of chromite, ilmenite, magnetite, and allanite in the crystalline rocks of the mapped area (plates 1-4), and to the exposure of layered norite and gabbro that might be a source for platinum, perhaps some additional attention should be given to an evaluation of the lenticles of black sand in the Wajid Sandstone. The discovery of detrital monazite in the Lower Paleozoic Siq Sandstone in northwestern Arabia (Brown, G. F., written commun., Nov. 18, 1967) also raises the question if this mineral might be present in the Wajid.

Source rocks for chromite, ilmenite, and magnetite, and potential source rocks for platinum, are present in the Hamdah ultramafic belt immediately west of the present western margin of the Wajid Sandstone in the Hamdah and Wadi Haraman quadrangles. It is probable that the Wajid extended farther west than its present western margin, and parts of it may have directly overlain the source rocks for chromite, ilmenite, magnetite, and possible platinum. Until they were buried by the Wajid, however these heavy minerals could have been transported east and southeast into the basin of deposition of the Wajid Sandstone. Platinum, if present, is unlikely to have been transported very far, but chromite, ilmenite, and magnetite are capable of being moved for considerable distances. The lower beds of the Wajid Sandstone would be the most favorable sites for the concentration of these minerals, and the westernmost exposures would be more likely to have them than exposures farther to the east.

Ordinarily, placers rich in ilmenite have a different geomorphic history from the magnetite placers, and this history leads to the TiO_2-enriched ilmenites wanted by industry. Ilmenite theoretically contains 52.7 percent TiO_2. Under conditions of secular weathering, ilmenite loses iron, and the residual grain is enriched in TiO_2. Thus, the placers that enjoy greatest commercial success contain weathered ilmenite with 58-60 percent TiO_2. The TiO_2-enriched ilmenites have a complex geomorphic history. They are not delivered directly to the sedimentary basin in which they are ultimately concentrated as placers. Their transport is protracted through several cycles of intermediate deposition, weathering, erosion, and further transport until they arrive at the final site, depleted in iron and enriched in titanium. Magnetite is vulnerable to destruction by weathering and transport; therefore, its principal placer deposits accumulate rather close to the original source rocks. From these considerations, it might be predicted that the ilmenite in the Wajid Sandstone would be closer in TiO_2 content to theoretical ilmenite than to weathered ilmenite. Obviously, chemical analyses of detrital ilmenite from the Wajid Sandstone are needed to determine its tenor in iron and titanium. The Wajid might be a reasonably good place for the accumulation of magnetite placers, but the sparsity of magnetite in the observed black sands, and the rusty coatings and encrustations on them, suggest that the magnetite has been depleted by intrastratal solution.

The granitic rocks of the peralkalic magma series are locally enriched in allanite in the area, but monazite is very sparse. An antipathetic relation exists between allanite and monazite in both granitic rocks and metamorphosed pelitic sediments such that monazite is rarely present, or sparsely present, where allanite is common (Overstreet, 1967, p. 13-26). Few volcanic rocks contain monazite, whereas some rhyolites are notably enriched in allanite. Allanite is most common in metamorphic rocks of the greenschist facies to the lower subfacies of the amphibolite facies, whereas monazite is most common as an accessory mineral in metamorphic rocks of the upper subfacies of the amphibolite facies and the granulite facies. Among the source rocks for monazite, the sillimanite-microcline gneisses are particularly important. Thus, the best-known placers for monazite, like the best for rutile, show a connection with Precambrian shield areas with high-grade metamorphic rocks.

The Precambrian shield area in the mapped area lacks the high-grade metamorphic rocks that are the chief source for placer monazite. The area has the low-grade metamorphic rocks and rhyolite in which allanite is found in other regions, and it has granitic rocks known to contain allanite. Thus, it can be regarded as a potential source for allanite, but not for monazite.

Good detrital concentrations of monazite require deep weathering of the source rocks, winnowing of the heavy minerals during stream transport to some intermediate host--generally Cretaceous, Tertiary, or Pleistocene coastal plain deposits--further weathering in the intermediate host, followed by erosion of the host along a strand line and redeposition of the heavy minerals under the influence of waves and currents. These processes generally remove the less stable heavy minerals like garnet, epidote, amphiboles, and pyroxenes. Inasmuch as these unstable minerals have been noted in the black sands of the Wajid Sandstone, the indication is for an unfavorable geomorphic history for the formation of monazite placers, even if monazite was present in the source rocks.

Basal conglomerates of some sedimentary rocks have been reported to be remarkably rich in detrital monazite where an unusual source was nearby (Vickers, 1956), but this condition is not likely to apply to the Wajid in the mapped area.

Continental sedimentary rocks in arid regions seem most unfavorable as possible hosts for major concentrations of monazite for the reasons given above. However, an alternative possibility is that in appropriate arid environments large placers of allanite might form, particularly in coalescing alluvial fans. Large placers of allanite are unknown in most tropical areas--an interesting exception has recently been reported from the Philippine Islands (MacDonald, 1971, p. 81-83)--because in the warm, humid environment allanite weathers to a soft pulverent material that is destroyed during erosion. In arid regions, however, allanite is relatively stable and could be concentrated in placers. This is particularly interesting because allanite tends to be at least 10 to 100 times as abundant in its typical source rocks as monazite is in its favored sources. Thus, the quantity of allanite available for concentration from a given volume of eroded Precambrian rock would be far larger than it is for monazite. The lower specific gravity of allanite would make for less effective placer concentration than monazite. Alluvial fans are less efficient for winnowing than beaches, but there might be some allanite concentrated in continental deposits, or shallow-water deposits like the Wajid Sandstone. In alluvial fan deposits, the heavy minerals tend to be concentrated in fine-grained channel fillings (McGowen and Groat, 1971, p. 47-52).

Gold placers were recognized in 1966 (Overstreet, 1968a, p. 70) as a geologic possibility in the area of the Wadi Al Habajiyah ancient mining center (described below) east of Hamdah, and a recommendation for exploration to evaluate the possibility was made.

A discussion of the preliminary results of prospecting for diamonds and other heavy minerals in the alluvium of the Arabian shield was recently presented by Motti (1969). Two or more terrace deposits were recognized by Motti in the region south of Wadi ad Dawasir, and he noted that the terraces along the approaches to Wadi Tathlith are covered with wind-blown sand. Terrace deposits rather than alluvial fans or pediments were thought to present the most favorable possibilities for the concentration of heavy minerals. The marine terraces on the northern Red Sea coast were thought to be more favorable than the alluvial terraces in the interior of the shield.

Possible nickel in marble.--A mass of marble at station 22902 in Al Hassir quadrangle (plate 1) is white, green, grayish green, and brown, thinly laminated with green to white chert, and intensely squeezed into the noses of folds in hornblende schist. The mass is 8-40 m thick and 150 m long. Because of the green color, an analysis should be made to see if the marble is enriched in nickel; however, wadi sand in the area has only background quantities of nickel. Other green marble needing similar investigation is exposed at 22756 in the Duthur as Salam quadrangle (plate 3) and 22212 in the Hamdah quadrangle (plate 4).

Silt and clay.--The sedimentary deposits of silt shown on plates 2-4 and described previously, have local economic importance as construction materials and for cultivation. The extent to which they can be developed agriculturally is mainly dependent on available water, which has been decreasing in recent centuries.

New sources of water are needed, together with improved agricultural practices, to develop the full agricultural potential of the silts.

Scattered small exposures of residual clay and saprolite, and of lenticles of sedimentary clay in the Wajid Sandstone, are present in the area. None could supply more than a few cubic meters of kaolinite or other clay after digging, washing, and decanting. The thin sedimentary clays associated with the deposits of silt are of probable montmorillonitic type that have no ceramic use.

Epigenetic deposits

Gold

Al Lugatah ancient mine.--The Al Lugatah ancient gold mine in Al Hassir quadrangle (plate 1) is also known as the Farrash mine from the prominent mountain to the west named Jabal al Farrash (Brown and Jackson, 1959). The mine consists of a series of openings that extend northward for about 450 m along a lode of white quartz in sheared red quartz porphyry. The porphyry is a tectonic slice caught up in chlorite schist in the major north-trending fault zone along Wadi Thafin about 15 km northwest of Tathlith (Overstreet, 1966b, p. 24-25; Overstreet, Bahijri, and Shararahly, 1969, table 6). The lode strikes north and dips 55°W. The largest veins are about 2.5 m thick. Three groups of shafts and open cuts are spaced along the lode. All openings are small and the stopes are narrow, being confined to the veins.

The remains of six rectangular houses around which fragments of grindstones are clustered lie immediately to the west of the central part of the lode. No slag is present, but small piles of crushed white quartz are near the buildings; thus, it is inferred that free gold was the product. Absence of sulfide minerals or secondary copper minerals at the lode, and low percentages of copper, lead, and zinc in quartz from the lode (table 9), further support the inference that gold was the product. Judging from the size of the dumps (about 5,000 tons of rock) and the limited extent of the workings, it is inferred that only a small amount of gold was produced at the Al Lugatah mine.

The southern and most extensively worked part of the Al Lugatah lode was reached through two vertical shafts, three inclined shafts, and two trenches in an area about 10x40 m where no vein thicker than 0.7 m is exposed. The length of the underground workings is not known, but it seems probable that the shafts are connected underground. About 4,000 tons of quartz is on the dumps around the southern workings.

Table 9. Assays and analyses of ores and rocks from the Al Luqatah ancient mine in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

(Assays for gold and silver in samples P-2036 through P-2046 by D. F. Schaffner (1956b); assays for gold and silver in samples 22883 and 22885 by S. M. Bahijri, Directorate General of Mineral Resources, 1966; chemical analyses for copper, lead, and zinc by A. H. Shararahly, Directorate General of Mineral Resources, 1966.)

Sample number	Material sampled	Troy oz/ton		Percent		
		Gold	Silver	Copper	Lead	Zinc
	North working					
P-2036	.58 m schist with quartz stringers on south wall of entrance to north stope.	0.03	0.17	n.d.	n.d.	n.d.
P-2037	Grab sample of quartz at north stope.	0.11	0.26	n.d.	n.d.	n.d.
P-2038	.27 m composite of 4 quartz stringers in east side of shaft, 1.07 m down.	0.03	tr	n.d.	n.d.	n.d.
P-2039	.49 m massive quartz in bottom of shaft, 1.22-1.68 m down.	0.02	tr	n.d.	n.d.	n.d.
	South working, large stope					
P-2040	.62 m quartz, south face of stope.	0.15	0.17	n.d.	n.d.	n.d.
P-2041	.68 m quartz, north face of stope.	0.23	0.14	n.d.	n.d.	n.d.
P-2042	.37 m quartz, pillar in stope.	0.02	tr	n.d.	n.d.	n.d.

Table 9. Assays and analyses of ores and rocks from the Al Lugatah ancient mine in the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Material sampled	Troy oz/ton		Percent		
		Gold	Silver	Copper	Lead	Zinc
	South working, small stope					
P-2043	.18 m quartz, north face	0.03	0.12	n.d.	n.d.	n.d.
P-2044	.15 m quartz, south face	0.08	tr	n.d.	n.d.	n.d.
	Tailings in village ruins area					
P-2045	#1 test hole, .30 m deep	0.22	0.45	n.d.	n.d.	n.d.
P-2046	#2 test hole, .30 m deep	0.15	0.25	n.d.	n.d.	n.d.
	Al Lugatah mine					
22883	Lode quartz	0.01	0.18	0.03	0.15	0.8
22885	Lode quartz	nil	nil	0.1	0.5	1.5

n.d. = no data

tr = trace

Along the lode 130 m north of the southern workings are the central group of openings at the Al Lugatah mine. This group consists of two open cuts, each about 15 m long and 1.5 m wide, on a massive white quartz vein 1.8 m thick. The northern open cut is 16 m north of the southern trench. Both cuts are shallow and filled with sand.

Ninety-six meters north of the north end of the central workings is the southernmost of the northern openings. It is a cut 22 m long, 3 m wide, and up to 1.8 m deep in white brecciated quartz and quartz veinlets in sericitized and silicified quartz porphyry. To the north 34 m from the northern end of this cut, a second open cut grades northward into a small stope in a white quartz vein up to 2.5 m thick. The combined length of the open cut and stope is 18 m, and the maximum width and depth of the cut are 0.9 and 4 m. Drifted sand covers the floor, but the dumps are very small, and the observed depth is probably close to the true depth. A square pit 1x1 m and 2 m deep explored the lode 4 m north of the combined open cut and stope. Fifteen meters to the east of the pit, two small trenches also explored the lode. A crosscut trench entering into an inclined stope 24 m north of the small square shaft is the largest opening in the northern workings. The inclined stope strikes N.60°W., is inclined 40°S., and is at least 12 m deep, 1-2 m high, and 7 m long. Two small trenches are located 30 m north of the crosscut trench.

The Al Lugatah mine is smaller and less worthy of further exploration than the mines in the Hamdah region to the southeast.

Wadi al Habajiyah ancient mining center.--Five small, ancient and abandoned gold mines are situated along the east wall of Wadi al Habajiyah and the north wall of an eastern tributary about 15 km upstream from the confluence of Wadi al Habajiyah with Wadi Tathlith and 8 km east of Hamdah in the Hamdah quadrangle (plate 4). The area has been called the Wadi al Habajiyah ancient mining center (Overstreet, 1968a, p. 58-63). The mines can be reached by driving up Wadi al Habajiyah, leaving the main road from Qal'at Bishah to Najran near Bi'r Umm az Ziba'. They can also be reached by driving cross-country from Hamdah.

The names of the mines used in the following account are the ones given by a local resident of Hamdah. They are described from south to north.

El Hlamiya south consists of nine open pits at least two of which lead into shallow stopes, and two trenches, one of which opens into stopes at least 14 m deep. All workings are oriented north along the north end of a low, north-trending ridge. On the wadi floor north of the mine are the ruins of 22 stone houses up to 4x5 m in plan. Slag is absent; therefore, the mine is assumed to have been worked for free gold. The sparsity of base metals shown in analyses of ores, tailings, and pillars at El Hlamiya south and the other mines in the Wadi al Habajiyah ancient mining center(table 10) is further evidence that these mines produced free gold.

The principal working of El Hlamiya south mine is an eastern trench which leads into a stope. Other workings are an immediately-adjacent trench to the west, which is 65 m long, 2-3 m wide, and 0.5-1.5 m deep which possibly led into stopes now filled, and a pit about 4 m deep and 40 m off the west end of the 65 m trench. These openings are in a shear zone in hornblende schist which is intruded in sequence by serpentinite, granite, felsite, and andesite. Following the last intrusion the rocks were strongly sheared by a fault striking north and dipping 60°W. The fault is at the contact between the schist and the serpentinite. Later this fault was cut by a cross fault striking N.70°W. and dipping vertically. Schist and serpentinite along the northerly fault are silicified, and a granular, white to greenish-colored quartz vein was emplaced in the north-trending fault. The vein is 0.3-1.8 m thick and of unknown length. It is followed by the stope in the eastern trench and seems to have been followed by the 65 m trench, but the relations of the other openings to the vein are unclear. The pit 40 m off the west end of the 65 m trench enters a small stope in a brown altered zone in the hornblende schist. Elongation of the stope is N.40°E., and it is inclined 80°N. From the debris around the pit it is not possible to tell what was actually mined, but a mixture of silicified and rusty hornblende schist and serpentinite may have been taken out. No quartz from veins was seen.

The ancient and abandoned Jabal Ibn Hassun mine is in a shear zone in serpentinite hills leading southward to Wadi al Habajiyah. The ruins of three small, square, stone houses are on the flat between the wadi and the mine, and at the mine are ruins of two other stone houses. These houses are about 2x2 m to 3x4 m in plan. The mine consists of three main open pits, all of which lead into stopes, and one trench, with subsidiary test pits on the same hill and on adjacent hills. The dumps consist of leached and limonite-stained, sericitized serpentinite, bluish white quartz, and white felsite. There is no slag, but the analyses of tailings and lode quartz at the Jabal Ibn Hassun mine and the Jabal Ibn Hassun extension show that these workings yielded ore richer in zinc than the El Hlamiya group (table 10). A few fragments of grindstones are about. From these observations it is inferred that free gold was recovered at the Jabal Ibn Hassun mine. Crushed tailings were estimated to have a volume of 2,000 cu m.

The trench at the Jabal Ibn Hassun mine is oriented N.10°E. and is inclined 80°W. along the west side of a white felsite dike. It is 20 m long, 1-3 m wide, and 1.5-4 m deep in sheared and limonite-stained serpentinite. From the present appearance of the trench it is not clear what was taken out. Perhaps the ore was chloritized hornblende schist forming a septum in the serpentinite.

Table 10. Assays and analyses of ores, tailings, and pillars from mines in the Wadi al Habajiyah ancient mining center

(Assays for gold and silver by S. M. Bahijri, Directorate General of Mineral Resources, 1966; chemical analyses for copper, lead, and zinc, by A. H. Shararahly, Directorate General of Mineral Resources, 1966).

Sample number	Material and mine	Troy oz/ton		Percent		
		Gold	Silver	Copper	Lead	Zinc
22289	Tailings, Jabal Ibn Hassun mine	0.11	0.21	0.1	0.2	1.2
22292	Pit sample, El Hlamiya north mine	0.05	0.12	tr	0.15	0.2
22293	Quartz, El Hlamiya south mine	0.06	0.20	tr	0.12	0.1
22298	Lode, Jabal Ibn Hassun extension	tr	0.20	tr	0.2	0.9
22299	Pillars, Riah mine	0.04	0.15	tr	0.16	0.8

tr = trace

The three main open pits are approximately aligned at N.55°E., but the long direction of each is N.10°E. to N.20°W.; thus, they are subparallel to the trench. They are in strongly sheared rock consisting of brecciated, chloritized, and sericitized hornblende schist, serpentinite, and felsite. The northern pit is about 5 m long, 3-4 m wide, and 3-5 m deep inclined steeply westward. The central pit consists of two intersecting trenches of which the larger is 12 m long, 3 m wide, and 4 m deep oriented N.50°E. The smaller is 8 m long, 3 m deep, and 3 m wide oriented N.40°W. Both are in serpentinite, but the one striking northwestward follows the wall of a felsite dike. At the southern pit the strike of the opening is N.10°E., the length is 22 m, and the width and length are 1-4 m and 8 m. The opening leads into a shallow stope at its northern end. The rocks are sericitized and chloritized hornblende schist, serpentinite, and felsite. It is not certain what was taken as ore from these pits. Probably it was altered metamorphic rocks containing gray and white mottled quartz.

The Jabal Ibn Hassun extension is about 1.5 km east-southeast of the Jabal Ibn Hassun mine, but the extension deposit has no apparent geologic connection with the Jabal Ibn Hassun mine. The workings, however, are characterized by greater amounts of zinc (table 10) than the El Hlamiya mines. The ancient workings of the Jabal Ibn Hassun extension are in closely folded, sheared, and altered hornblende schist and serpentinite intruded by white felsite. The axes of tight folds in the metamorphic rocks strike north and plunge 55°S. Chlorite replaces hornblende and talc replaces serpentine in the schist and serpentinite. Little stringers of gray to white quartz impregnate the chloritic and talcose rocks. These stringers make up narrow lodes about 20-40 cm wide. Several such lodes are present in a face 3 m wide in a little pit or caved shaft about 2 m deep at the northern end of the Jabal Ibn Hassun extension, where they were mined.

About 40 m to the southeast, three small trenches 2-3 m long, 1-1.5 m wide, and 0.5 m deep explore minor alteration zones in hornblende schist near the crest of a little hill.

El Hlamiya north mine is very small. No houses are associated with it, nor are slag piles present. It is a cluster of shallow trenches arranged in four groups to explore gray, granular quartz veins in hornblende schist and serpentinite. The most northerly working is a trench 12 m long, 2.5 m wide, and 0.5-1 m deep on a narrow quartz lode parallel to the foliation in hornblende schist striking N.10°W. and dipping 80°W. Windblown sand fills the trench, but it was probably little deeper than 1 m, because the dump is small.

Forty meters south of the trench are three small open pits arranged in a semicircle on the southern crest of a low serpentinite hill capped with heavily limonite-stained serpentinite intruded by an irregular mass of sugary gray quartz. Each of the little pits is about 2 m long, 1.5 m wide, and 0.5 m deep. They explored little masses of quartz in serpentinite that strike about N.10°E. and dip 80°W. Practically no waste is present around the pits; therefore, most of what was extracted was removed, possibly for hand-cobbing at another site. Probably mainly quartz was removed. It is very lean in base metals (table 10).

On a ridge about 60 m south of the above-mentioned pits, a group of three small pits, of which the largest is 4 m in diameter and 1.5 m deep, are located on a shear zone in hornblende schist. The shear strikes N.50°E. and dips vertically. The west wall of the largest pit is sharply defined by the east side of a sill of gray felsite, which does not appear in the other pits. Along the shear the hornblende schist is altered to chlorite schist, which is by far the most common rock in the little dumps. Whether the ore was the quartz or the chlorite schist was not determined.

The largest opening at El Hlamiya north mine is 50 m south of the three pits in the chloritized shear zone in hornblende schist. This opening is a trench 15 m long, 2.5 m wide, and 4.5 m deep oriented N.5°E. and inclined 85°W. on sheared and chloritized serpentinite with traces of relict anthophyllite. No quartz was seen. Chloritic gouge along the fault apparently was the mineralized material.

The Riah ancient and abandoned mine consists of pits and underground workings that appear to have followed the footwall contact of a white, muscovite-biotite felsite dike with selvages of pegmatite in serpentinite and hornblende schist. Riah mine is situated on the north bank of an eastern tributary to Wadi al Habajiyah. No houses are present. Probably free gold was obtained, because slag is absent, but the pillars are richer in zinc than material at El Hlamiya mines.

The major working of the Riah mine is a stope about 30 m deep on a 20° incline opening from a pit 7 m in diameter and 2.5 m deep. To judge from the pillars left standing the ore was a lode of quartz stringers 0.6-1.2 m thick in biotite-rich schist, possibly biotitized hornblende schist, along the footwall of the flat-lying felsite and pegmatite dike. Locally, the lode gives way to white or gray vein quartz, vuggy and rusty, which reaches the full width of the mined face.

At least three other pits were sunk on fractured dikes of felsite and pegmatite in biotitized and chloritized hornblende schist. These dikes are also flat lying and are either part of or subparallel to the dike under which the stope was opened. Fracture zones striking N.20°E. and dipping vertically through the felsite and pegmatite, were excavated along with biotite-rich schist under the dikes. At the northernmost pit the biotitized hornblende schist of the footwall was removed to a depth of 1.2 m from the bottom of the pegmatite over a face more than 5 m wide. The pegmatite is 2-3 m thick. It consists principally of perthite with about 6 percent of muscovite and also platy green biotite mimicing the form of hornblende crystals up to 1.5 cm long.

A quarry on the northwest side of the Riah workings explored an L-shaped face of pegmatite in serpentinite. Each limb of the L is about 8 m long and 2.5 m high. Apparently, the pegmatite was mined for gold. The pegmatite is a differentiate from the felsite and contains inclusions of felsite. At least nine other small test pits and quarries explore the pegmatite, but only one is in felsite.

Twenty meters south of the openings in the pegmatite, a trench 20 m long, 2-4 m wide, and 2 m deep was opened in a rusty, pyritized zone in hornblende schist. The pyritized zone strikes N.35°E. and dips vertically. Dumps associated with this trench are much smaller than those around the pegmatite.

Possibly 2,000-4,000 tons of rock was mined at Riah, but the amount that was milled cannot be estimated. Possibly a high percentage of the rock that was removed was ore.

Wadi Al Mushel ancient prospect.--The Wadi Al Mushel ancient prospect was visited on October 28, 1966 (Overstreet, Bahijri, and Shararahly, 1969, p. 11-12). It is about 8 km southwest of the Ash Sha'ib mine and 1.5 km east of the main road from Qal'at Bishah to Najran at a point about 25 km north of Hamdah (plate 4). The prospect is a shallow, sand-filled pit oriented N.15°E. on a vein of milky quartz in fine-grained biotite-hornblende granodiorite gneiss with foliation striking N.40°E. and dipping 40°S. The gneiss is intruded by many small, simple eutectic pegmatite dikes with pink microcline and poorly developed ptygmatic folds. The pit is about 40 m long and 8 m wide, but it is less than 0.5 m deep. It is ringed by little dumps of quartz and gneiss totaling 5-10 tons. None of this quartz is crushed to fine sizes. The quartz is white to transparent, granular, fractured, and locally vuggy with traces of pyrite weathered to limonite, extremely rare copper stain, and a little chlorite. A grab sample of this quartz contained a little gold and 3.6 percent zinc (table 11).

Piles of quartz and shallow test pits extend intermittently about 200 m northward along the probable strike of the vein as indicated by the direction of elongation of the pit. Between these piles, quartz float is continuous on the pediment surface. Perhaps a continuous quartz vein of irregular width strikes northward for about 200 m, and it seemingly has been opened at its wider parts by test pits. The area is a sand plain with few outcrops.

Table 11 Assay and analysis of a grab sample of quartz from the Wadi Al Mushel ancient prospect

(Assay for gold and silver by S. M. Bahijri, Directorate General of Mineral Resources, 1966; analyses for copper, lead, and zinc by A. H. Shararahly, Directorate General of Mineral Resources, 1966).

Sample number	Troy oz/ton		Percent		
	Gold	Silver	Copper	Lead	Zinc
30151	0.22	nil	tr	0.2	3.6

tr = trace

A small pile of white quartz, possibly marking a test pit, is about 190 m south of the principal opening. The area between is covered by sand.

The Wadi Al Mushel prospect is 18 km north-northwest of the Wadi Al Habajiyah ancient gold mining center (plate 4). The vein at the Wadi Al Mushel prospect resembles those at the Wadi Al Habajiyah center in orientation, mineralogy, and tenor, except that the quartz at Wadi Al Mushel prospect is much richer in zinc (tables 10 and 11). The possibility exists that similar small ancient mines or prospects and undiscovered deposits lie between the Wadi Al Mushel prospect and the mines along Wadi Al Habajiyah, and also in the direction of the Ash Sha'ib mine to the north.

Avala ancient mining center.--The Avala ancient gold mining center in the Wadi Haraman quadrangle (plate 2) consists of the Avala mine and an unnamed prospect about 23 km northeast of Tathlith and the road between Qal'at Bishah and Najran. Milling operations at Avala mine were supported by a quarry where grindstones were made at station 22417 on the north end of Jabal Al Kilab about 16 km southeast of the Avala mine. Fragments of grindstone found at Avala are made of the same porphyritic biotite granite quarried at Jabal Al Kilab.

The Avala mine is on the southeast side of Jabal Bani Adla where the ancient workings extend northward for 1.2 km as a series of pits, trenches, shafts, and quarries. The white quartz of the ancient dumps can be clearly seen on aerial photographs of the region. At the south end of the workings, and reaching southward for 0.2 km are the ruins of the village associated with the mine. These ruins comprise at least 70 stone buildings, most of which have grindstones and tailings strewn about them. A little slag is present, but the quartz from the dumps is lean in base metals (table 12); therefore, it is inferred that the main product was free gold (Schaffner, 1956a; Overstreet, 1966a, p. 64-65; Overstreet, Bahijri, and Shararahly, 1969, tables 5 and 6). Total tailings may be about 30,000 cu m.

The workings of Avala mine appear to be located along two intersecting fault zones. The southern workings are along a fault parallel to the cleavage in a sequence of meta-andesite, graywacke, and marble intruded by gabbro. This fault strikes N.25°E. and dips vertically. The northern workings are along a fault trending N.15°W. and dipping vertically in dominant gabbro. In extent the southern group of workings is about 400 m long and the northern group is 700 m long.

Gabbro in the fault zone is chloritized and silicified by brown chert, but meta-andesite in the fault zone is only slightly altered. Through these chloritized and silicified rocks, and parallel to the fault zone, passes a lode of thin, brecciated, and cemented white quartz stringers. Apparently the brecciated quartz and chert were the ore; at least they are the principal pulverized rocks at the grinding sites. Massive white quartz forming a late vein up to 1 m thick in the central part of the workings was left unmined.

An unnamed prospect consists of a small open trench oriented N.35°E. in a brecciated zone in gabbro intruded by gray massive granite at station 22466 in the Wadi Haraman quadrangle (plate 2) about 3 km northeast of the Avala mine (Overstreet, 1966a, p. 65). Both the gabbro and the granite are brecciated, and the breccia is cemented with white quartz which is also brecciated. The brecciated quartz is healed by white quartz. The trench is about 20 m long, 3 m wide, and 1 m deep. Probably the trench was originally nearly 2 m deep, because the dump is somewhat large for the opening. No sulfide minerals are present, and the breccia may not extend beyond the ends of the trench.

Reported ancient mines and prospects.--Ancient mines and prospects reported to the writer by Bedouin in the field, and not actually examined, are listed here under the section on gold because most of the known ancient mines are inferred to have been worked primarily for that metal.

The locations of three ancient mines in the area were described by Bedouin, but none of the three was found by the writer.

Table 12. Assays and analyses of ores, slag, and rocks from the Avala ancient mine

(Assays for gold and silver in samples P-2047 through P-2058 by D. F. Schaffner (1956a); assays for gold and silver in samples 22453 through 22459 by S. M. Bahijri, Directorate General of Mineral Resources, 1966; analyses for copper, lead, and zinc by A. H. Shararahly, Directorate General of Mineral Resources, 1966.)

Sample number	Material sampled	Troy oz/ton		Percent		
		Gold	Silver	Copper	Lead	Zinc
P-2047	Grab sample of quartz on dumps	0.47	0.15	n.d.	n.d.	n.d.
P-2048	-do	0.23	0.27	n.d.	n.d.	n.d.
P-2049	-do-	0.20	0.15	n.d.	n.d.	n.d.
P-2050	-do-	0.05	tr	n.d.	n.d.	n.d.
P-2051	#1 test hole, .93 m deep in tailings	0.27	0.10	n.d.	n.d.	n.d.
P-2052	#2 test hole, .77 m deep in tailings	0.22	tr	n.d.	n.d.	n.d.
P-2053	#3 test hole, .62 m deep in tailings	0.26	0.14	n.d.	n.d.	n.d.
P-2054	#4 test hole, .52 m deep in tailings	0.30	0.12	n.d.	n.d.	n.d.
P-2055	.46 m quartz on hanging wall of workings at bottom of shaft	tr	tr	n.d.	n.d.	n.d.
P-2056	.37 m of rhyolite dike with much quartz in shaft	tr	tr	n.d.	n.d.	n.d.

Table 12. Assays and analyses of ores, slag, and rocks from the Avala ancient mine (cont'd.)

Sample number	Material sampled	Troy oz/ton		Percent		
		Gold	Silver	Copper	Lead	Zinc
P-2057	.15 m of quartz on footwall of northeast face	0.05	tr	n.d.	n.d.	n.d.
P-2058	Grab sample of yellowish quartz on dumps in valley 46 m southeast of mine	tr	tr	n.d.	n.d.	n.d.
22453	Quartz from dump	0.04	0.06	0.1	0.17	0.2
22453A	Slag	0.01	0.30	0.4	0.3	1.0
22456	Quartz from dump	0.12	nil	0.03	0.1	0.2
22457	-do-	tr	0.06	0.15	0.2	1.2
22459	Lode material from dump	0.02	0.06	0.12	0.22	1.3

n.d. = no data

tr = trace

A large mine was said to be on the east flank of Jabal Mufta, east of station 22801 in the Duthur as Salam quadrangle (plate 3), but a search failed to reveal it or to disclose any evidence of mineralization in the epidotized and brecciated andesite and rhyolite forming Jabal Mufta.

Two ancient mines were said to be in the vicinity of the Ash Sha'ib mine in the Hamdah quadrangle (plate 4), but neither was found (Overstreet, 1968a, p. 65-66). A large mine was reported to be on the hill north of station 22236 (plate 4), but the specific locality was not known to the Bedouin who made the report, and a search failed to reveal it. The hill consists of mafic rocks intruded by granite dikes and is 10.5 km east-southeast of the Ash Sah'ib mine.

A mine with ruined houses and grindstones was reported to be about 4 km east of the Ash Sha'ib mine, but a search with two guides failed to disclose the mine although several stone tumuli were found at the approximate site. The tumuli are more antique than the ruins associated with mines in the area.

Base metals

Ash Sha'ib ancient mine.--The Ash Sha'ib ancient mine is the only known base metal deposit in the area. It consists of several openings, scattered small piles of slag, the ruins of 14 stone houses, three smeltering sites, and a mosque, and is about 8 km east of the main road between Qal'at Bishah and Najran 25 km north-northeast of Hamdah (plate 4). A fragment of building stone in the ruins of the mosque had a partial inscription thought to be in Kufic script. Thus, the ancient mine may have been operated about 1,200 years ago.

The ancient mine and ruins were visited by the writer on June 7, 1965, and descriptions and recommendations for further geologic, geochemical, and geophysical examination to be followed with exploration by diamond drilling were made (Overstreet, 1966a, p. 63-64, 70; Overstreet, Bahijri, and Shararahly, 1969, p. 9-17).

Geophysical surveys were begun in November 1966 by W. E. Davis and Hisham Kazzaz, and geochemical invesitgations were started at about the same time by G. H. Allcott. The geophysical work included an electromagnetic dip angle survey, electromagnetic horizontal coil survey, natural potential survey, resistivity measurements, and a magnetic study (Davis and Kazzaz, 1970). Further geophysical investigations at Ash Sha'ib included a Turam electromagnetic survey in 1967 by Mohammed Akrass and Hisham Kazzaz of the Directorate General of Mineral Resources, an airborne electromagnetic survey using the INPUT system in 1967 by Canadian Aero Mineral Survey Limited (CAMS, 1967), and helicopter airborne electromagnetic and magnetic surveys in 1968 by Sander Geophysics Limited (1968).

Surface geochemical sampling was done by Allcott (1969, p. 21; 1970, p. 17-22) using a 20 by 50 m grid pattern over the mineralized area, where the sample media was rock in place or weathered debris transported less than 100 m. The sample net was extended into wadis around the deposit, where minus 80-mesh fractions of alluvium were collected. Allcott reported (1970, p. 17 and table 3) that the alluvium did not contain the anomalous metals present in the gossan; an observation harmonious with the results of all our geochemical orientation surveys in Saudi Arabia during 1964-66, which clearly demonstrated the necessity of using plus 80-mesh alluvium, not minus 80-mesh material, for sampling. Some geobotanical investigations were made by Allcott (1970, p. 20) using as sample media ash from grass, Acacia twigs, and the twigs of another shrub. The results suggested that molybdenum values in plant ash may be useful in arid-region geochemical exploration as an indicator element for base metal deposits, particularly copper.

A plane table survey of the geology of the area of the Ash Sha'ib mine was made in 1968 by Kiilsgaard and Tompkins (Kiilsgaard, T. H., and Tompkins, F. V., written commun., 1968), and that map was used by Allcott in his appraisal of the deposit (Allcott, 1970, fig. 2).

Six diamond drill holes were sunk between April 2, 1967, and June 7, 1968, to explore the deposit (Allcott, 1970, p. 27-31).

The brief review of the geology and ore deposit at the Ash Sha'ib ancient mine given below is summarized from Allcott's reports (Allcott, 1969; 1970).

> The Ash Sha'ib ancient mine is in an east-trending septum of metamorphosed sedimentary rocks between a pluton of granite on the north and a pluton of gabbro on the south. Dikes of diabase, granite, pegmatite, and aplite intrude the metasedimentary rocks. The granite is intruded by dikes of pegmatite and aplite, and the gabbro is intruded by dikes of granite. A pegmatite dike cut by a mineralized fault contains anomalous amounts of zinc, barium, and gallium. Zinc and barium are elements associated with the mineralization. Gallium may be associated with the epidotization of the pegmatite or with the sulfide mineralization, because both epidote and the massive sulfides are rich in gallium. The metasedimentary rocks consist of dominant hornfels with some dolomitic marble, tremolite schist, and skarn. The folding of the metasedimentary rocks is probably related to the intrusion of the pluton of granite, because the strike of the rocks is

parallel to the contact, and they dip away from the granite. A number of faults identifiable in two sets were mapped, mainly from interpretation of the data acquired by the combined helicopter-borne electromagnetic and magnetic survey (Sander Geophysical Limited, 1968). The faults terminate against or are parallel to the contact between the metasedimentary rocks and the granite. The two sets of faults may be the result of compressional forces from a northwesterly direction. The attitudes of the fault planes are consistent with a stress model in which the granitic pluton was the source of the compressional force.

Localization of the mineral deposit is the result of the filling of fissure veins and the replacement of dolomitic marble. The main replacement is along fissures that intersect the dolomitic marble where the fissures divide into many stringers to form enlarged replacement zones. In the hypogene zone the ore minerals are sphalerite, chalcopyrite, and minor amounts of galena accompanied by a gangue of pyrite, barite, quartz and fluorite(?). A zone of oxidation extends 30-40 m below the present land surface. It contains secondary carbonate, oxide, silicate, and sulfate ore minerals and gangue minerals of which the major ore minerals are malachite and smithsonite. Minor amounts of azurite, chrysocolla, hydrozincite, and hemimorphite(?) are also present. Limonite, manganese oxides, and barite are common among the supergene gangue minerals.

The sequence of thermal events interpreted for the development of the ore deposit began with the intrusion of the gabbro into the metasedimentary rocks. Hornfels was formed adjacent to the contact of the gabbro. Subsequently, granite was emplaced, and the metasedimentary rocks again may have been altered. Pegmatite dikes were introduced during the late stages of the intrusion of the granite, and subsequently some were displaced by recurrent faulting. The final stage of intrusion brought hydrothermal solutions along the fault planes, from which solutions the sulfide minerals were deposited.

The mineralogy and the data from analyses for trace elements are compatible with the thermal history of an ore deposit formed during the cooling of a granitic pluton. The presence of cordierite in the hornfels indicates a temperature of 400^{o}-600^{o}C. during contact metamorphism. This mineral was subsequently altered at lower temperature by hydrothermal activity to sericite. Moderately high concentrations of gallium and germanium in the sphalerite indicates intermediate to low temperatures during the deposition of the sphalerite (Rankama and Sahama, 1950, p. 726, 733). Further evidence (Bateman, 1950) for a low temperature of formation is the tentative identification of small amounts of purple fluorite in the ore. The fluorite must have been deposited at a low temperature, because it loses its color above 175^{o}C.

The correlated mineralized intervals intersected by the diamond drill holes form an easterly striking, southerly dipping, approximately tabular body of mineralized rock with variable thickness on the order of 3.5 to 6.0 m, a strike length of about 650 m, and a downdip length of at least 170 m based on the deepest intersection of the vein by drilling. Actual length downdip has not been determined. The weight of ore estimated for the deposit to a depth of 170 m is 2,170,000 tons having a gross estimated value of $40 million based on metals priced at: zinc, $0.14 per pound; copper, $0.42 per pound; and silver, $2.45 per troy ounce. Using a cutoff for minable ore of $25 per ton, the gross value of the Ash Sha'ib minable ore was estimated to be $20 million. This was regarded as too low for successful economic development; particularly in view of problems in the extractive metallurgy of zinc sulfide and zinc oxide ores, zinc being a major potential product.

Estimates of the past production of the mine were made on a basis of the size of the ancient workings and the amount of slag. About 1,200 tons of ore and waste rock were removed from pits, trenches, shafts, and stopes. The ratio of ore to waste rock is 1. About 500 tons of slag was produced in the reduction of the ore. This slag contains 2 percent copper, 3 percent zinc, 0.02 percent lead, less than 0.1 ounce per ton of silver, and no gold. A crude estimate of the smelter heads, made mainly from oxidized ore in the open pit and from drill core, is 4 percent copper, 8 percent zinc, 0.2 percent lead, 2 ounces per ton of silver, and less than 0.02 ounces per ton of gold. The recovered metal is estimated to have been about 10,000 kg copper, 25,000 kg zinc, and 30 kg silver. The smelter product was probably an alloy of zinc and copper with minor amounts of lead and silver. A brass alloy may have been obtained if some zinc was fumed off during smelting.

Geochemical anomalies.--The only geochemical anomaly for copper in wadi sand is at station 22214 in the Hamdah quadrangle (plate 4) about 9 km west-southwest of the Wadi Al Mushel ancient prospect. Except for white, massive to rarely vuggy quartz veins in bc joints in the chlorite-sericite schist at the station, there is no evidence of mineralization to account for the anomaly, and the veins themselves are unmineralized. Chromium and nickel are also anomalous at the station; thus, the original pyroclastic source rock for the schist may be the source of the anomalous copper, but a similar effect is lacking elsewhere in the same source rocks.

Five of the seven samples of wadi sand with anomalous lead are from the Al Lugatah ancient mine (22881 and 22882) in Al Hassir quadrangle (plate 1)and the Avala ancient mine (22454, 22455, and 22458) in the Wadi Haraman quadrangle. Both remaining samples of anomalous lead are in Al Hassir quadrangle where one is associated with threshold gallium (22826) in the core of the Al Hassir pluton of peralkalic granite. The other (22846) may be mainly derived from felsite dikes in which is a trace of pyrite. Further study might be given station 22826 in view of the threshold gallium and large variety of other anomalous elements found in the sample.

Among the nine samples of wadi sand with anomalous zinc, only sample 22333 in the northwest corner of the Hamdah quadrangle (plate 4) near Jabal Bjat, has threshold gallium. This sample is 3.5 km west-northwest of sample 22332 which also has anomalous zinc. The sands are derived from mafic rocks, and the source areas should be reviewed for the possibility of a base-metal deposit similar to Ash Sha'ib, some 30 km to the southeast. The other samples with anomalous zinc (22761, 22766, and 22782 in plate 3; 22215 and 22241 in plate 4; and 22430 and 22433 in plate 2) have been discussed in the section on Geologic Relations of Selected Elements.

The unusual sample with anomalous bismuth (22777) in the Duthur as Salam quadrangle (plate 3) needs further evaluation.

Industrial rocks

Scant present industrial use can be seen for the rocks and minerals noted below, but they are listed to show the range of materials in the area of the Tathlith one-degree quadrangle.

Building and ornamental stone

Abundant stone is present for local needs and many sites are suitable for quarrying, but two exposures of granite and one of marble seem noteworthy.

Good stone for dressing or polishing, and free from potential iron stain, could be obtained from white to faintly pink massive, medium-grained, porphyritic to equigranular biotite granite at station 22871 in Al Hassir quadrangle (plate 1). The microcline phenocrysts are up to 0.7x1.2 cm and are set in a generally equigranular matrix with individual grains of feldspar and quartz up to about 0.6 cm and grains of biotite generally 1 mm or less in size. Quarrying of the steep face of the exposure would be technically feasible.

Red, massive, coarse-grained biotite granite with practically no inclusions and free from dikes is exposed at station 22793 in the Duthur as Salam quadrangle (plate 3). The rock may be a little too coarse grained to make excellent ornamental stone, and a little magnetite might cause spots of rust on polished surfaces, but the jointing, exposure, and color commend the site as a possible quarry for building stone.

Clear calcite

Clear calcite forms veins and small lenticular masses up to a few centimeters in thickness and 1 m in length in serpentinite and pyroxenite at station 22282 in the Hamdah area (plate 4). The veins and masses of calcite are too small to be used as a commercial source for optical-grade calcite, and a faint grayish-brown tint mars the nearly water-clear transparency of the calcite. However, the remote possibility exists that larger and more perfect veins of clear calcite may be found in the Hamdah ultrabasic belt. Perhaps the vicinity of Tathlith (plate 2) offers a better opportunity for discovery, because more calcite veins are present there than farther south around Hamdah (Overstreet, 1968a, p. 68-69).

Crushed rock

One of the best materials in the area as a source of rock for crushing for road metal is the plutons of unmetamorphosed gabbro. Many bodies of gabbro are shown on plates 1-4.

Limestone and marble

Outcrops of limestone and marble, noted at 47 stations in the area, are described in table 13 and partial chemical analyses for 18 of these deposits are given in table 14. Most of these bodies of marble were described from megascopic observations in preliminary reports (Overstreet, 1968a, p. 47, 50, table 11; 1968 , p. 18-19, table 4) before the results of chemical analyses were received. The analyses were completed in February 1966 by Jamal Sumbul at the Chemical Laboratory of the Directorate General of Mineral Resources in Jiddah (Overstreet, 1968c, p. 32, 36, table 5). They disclosed that the samples of Precambrian marble were more siliceous and argillaceous (table 14) than had been thought fromthe field estimates. None of the samples in table 14 is rich enough in CaO for use in the manufacture of Portland cement, and most samples have too much MgO for that use. At least five of the analyzed samples of marble have compositions within the range of composition of natural cement rocks to make Roman cement and quick-setting cement. These are identified in table 14.

Marble associated with amphibolite and hornblende schist is more dolomitic than the other marbles, and marble associated with graywacke, meta-graywacke, and biotite gneiss tends to be more siliceous than the other marbles.

Table 13. Summary descriptions of exposures of limestone and marble in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

Sample number	Description
	Al Hassir quadrangle (plate 1)
22896*	Blue to black, brecciated, dolomitic limestone in andesite; at least 30 m thick and 800 m long, dip possibly vertical.
22902	Green, white, gray-green, and brown marble thinly laminated with green to white chert and interlayered with hornblende schist; complexly folded and squeezed into the nose of a fold to form a mass 8-40 m thick and 150 m long. Because of the thin laminations of chert, the marble is without commercial value. It should be analyzed for nickel.
22906	Brown, contorted marble interlayered with andesite and graywacke. Three beds of marble are up to 20 m thick with outcrop lengths of 1 km, 1.8 km, and 2.4 km.

Table 13. Summary descriptions of exposures of limestone and marble in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Description
	Al Hassir quadrangle (plate 1) (cont'd.)
22912	Brown marble interbedded with agglomerate and andesite; maximum thickness 10 m, about 1 km long, dips 80°.
22914*	White to gray, platy to schistose marble exposed in a shear zone in andesite. Marble is 2-30 m thick and is intermittently exposed along strike for 4 km. Platy character would make marble unsuitable for ornamental or building stone, but it could be used as flagstone or natural cement rock.
22918	Series of layers of brown to black marble interbedded with graywacke and andesite. Thickness is unknown, but is probably not over 40 m; the total length is at least 2.6 km, dip is 40°. The quality is unknown; it may be pyritiferous.
22919*	Black, slightly pyritiferous, contorted and cleaved marble, 8-10 m thick, 2 km long, dips 80°, in thin-bedded graywacke siltstone and sandstone. No commercial value.
22934*	Gray to brown marble at least 15 m thick and 3 km long in intermittent exposures where it is interbedded with graywacke and andesite. Strong cleavage makes it unsuitable for architectural use.
22935*	Gray to brown marble at least 12 m thick and 2 km long in intermittent exposures; interbedded with graywacke and andesite. Not suitable for architectural use owing to strong cleavage.
	Duthur as Salam quadrangle (plate 3)
22693*	White, light gray, and buff marble 35 m thick, 120 m long, dips 70° in biotite schist. Insufficient quantity for quarrying, but it is suitable for ornamental stone.

Table 13. Summary descriptions of exposures of limestone and marble in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Description
	Duthur as Salam quadrangle (plate 3) (cont'd.)
22724*	Thin-bedded, black, pyritiferous, fine-grained marble with layers of siderite 1-2 m thick; outcrop width 500 m and length 2.3 km, dip 25°, beds may be repeated, hence true thickness unknown; interbedded with meta-andesite.
22728*	Blue-gray to brown marble up to 300 m in outcrop width and 2.1 km long, beds possibly repeated, nearly vertical dip in andesite and graywacke. Forms ridge called Jabal Tobruq 1.5 km east of As Subaykhah. Suitable for local use as a source for lime; also natural cement rock.
22746*	Brown and black lenticular mass of marble 40 m thick and 300 m long dipping 75° in andesite; suitable for natural cement rock.
22749	Small, lenticular masses of brown marble associated with gabbro and serpentinite. Marble is not suitable for commercial use.
22750	Small, lenticular masses of brown marble interbedded with andesite. Is not suitable for commercial use.
22753*	Brown, gray, and white marble interlayered with hornblende schist; dip vertical. Two principal layers: eastern is 60 m thick and 1.5 km long; western is 20 m thick and 1.25 km long. Both layers are too jointed and fractured for use as ornamental or building stone, and both layers are too impure for use for lime or other chemical purposes. About 1.5 km to the northeast a thin lenticular mass of marble 300 m long is exposed. It is similar to the western layer. Suitable for natural cement rock.
22756*	Bed of white marble may be 60 m thick and 0.75 km long, dips 70°, but outcrops are largely covered by sand. Marble is medium- to fine-grained and contains irregular bands of bright green serpentine, which would make it a desirable ornamental stone if it could be quarried. Contains too much magnesium for chemical use.

Table 13. Summary descriptions of exposures of limestone and marble in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Description
	Duthur as Salam quadrangle (plate 3) (cont'd.)
22763*	Saccharoidal gray to white marble has sparse tiny spots of limonite possibly derived from pyrite. Marble is interlayered with hornblende gneiss; the marble is 4 m thick and is exposed on opposite limbs of north-plunging anticline about 3 km long. The marble is intruded by red biotite granite. Suitable for natural cement rock.
22805*	White, dolomitic marble largely covered by sand, interpreted to form 2 septa dipping 40^{o} in biotite-hornblende granodiorite. Northern septum is at least 10 m thick and 3 km long; southern septum is at least 2 m thick and 1 km long. This dolomitic marble is very white and even grained; it would make good ornamental stone.
	Hamdah quadrangle (plate 4)
22212	Nearly flat-lying septum of impure white to green marble, intruded by dacite, in granite gneiss; should be analyzed for nickel.
22218	Rare, thin lenticles of impure marble in amphibolite; is of no economic value.
22262	Isolated lenticular mass of brown marble in serpentinite; mass is about 20x25x35 m; not suitable for commercial use.
22263	Ferruginous marble in serpentinite altered to gossan of limonite and jasper 4-6 m thick, 700 m in diameter; caps hill.
22266	Thin layers of marble in biotite-quartz schist and hornblende schist; not suitable for commercial use.
22279	Thin layers of marble in hornblende schist; is of no commercial value.
22314	Brown marble interlayered with hornblende schist; not suitable for commercial use.

Table 13. Summary descriptions of exposures of limestone and marble in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Description
	Hamdah quadrangle (plate 4) (cont'd.)
22337	Lenticular masses of brown, silicified marble in serpentinite; not suitable for commercial use.
22350	Brown silicified marble and metapyroxenite in layered biotite gneiss; not suitable for commercial use.
22364	Inclusions of brown marble up to 8 m thick and 40 m long in gabbro; not suitable for commercial use.
22377*	White to gray marble exposed along the northwest wall of Wadi Bayaadth, strikes N.45°E., dips vertically, about 20 m thick and 5.5 km long; has best chemical quality of marbles analyzed in the area (table 14).
22378	Two parallel layers of very coarsely crystalline white to gray marble in northwest wall of Wadi Bayaadth (station 22377); has 0.5 percent of dust-like pyrite, and is cut by veins of white quartz; eastern layer is 20 m thick, western layer is 8 m thick.
22380	Five layers of white to gray, coarse-grained marble in biotite gneiss; layers are 0.5-4 m thick, very pure; extension of marble at station 22378.
22381*	White to gray marble layers up to 1 m thick in biotite gneiss; white quartz veins common in marble; end of marble starting at 22377.
22411	Black, fine-grained, impure marble interlayered with biotite-muscovite schist and meta-andesite; is not suitable for commercial use.
	Wadi Haraman quadrangle (plate 2)
22453	Impure, silicified marble with brown chert, interlayered with meta-andesite and metagraywacke at Avala mine.
22481	Fine-grained, dark gray marble crops out over an area 0.1-0.5 km wide and 2.5 km long; interlayered with meta-andesite, intruded by gabbro; total area of outcrop is 0.75 sq km.

Table 13. Summary descriptions of exposures of limestone and marble in the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Description
	Wadi Haraman quadrangle (plate 2) (cont'd.)
22482	Gray marble extensively intruded by gabbro and granite; dips vertically; quality not equal to that of marble exposed at station 22481.
22483	Gray marble interlayered with meta-andesite and intruded by gabbro and gray granite; quality of marble not equal to that at station 22481.
22484	Lenticular layers of white to gray marble in meta-andesite; intruded by gabbro and granite.
22487*	Gray, fine-grained marble with sparse quartz stringers; outcrop forms ridge 20-60 m thick and 600 m long.
22500	Fine-grained, impure quartzose marble and hornblendic calc-silicate rock interlayered with meta-andesite and intruded by gabbro.
22512*	Beds of ferruginous, silicified red marble in graphitic phyllite; 1-2 m thick, up to 40 m long; not suitable for commercial use.
22522	Lenticular masses of brown marble in serpentinite; up to 2 m thick and 20 m long; not suitable for commercial use.
22526*	White, gray, and blue, fine- to coarse-grained marble, forms distinctive hill; intruded by monzonite; 0.1 percent of platy, black, metallic mineral, possibly ilmenite, at contact; large volume of marble present.
22529	Little lenticles of brown, silicified marble in meta-andesite; not suitable for commercial use.
22542	Dark gray marble interlayered with meta-andesite and lithic tuff; marble is about 20 m thick and 1 km long.
22543	Sparse lenticles of dark gray marble up to 4 m thick and possibly 500 m long interlayered with hornblende gneiss and intruded by rare dikes of pink felsite less than 1 m thick.

* Analysis given in table 14.

Table 14. Major elements in Precambrian marble from the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia

(Analyses by Jamal Sumbul, Directorate General of Mineral Resources, February 4, 1966.)

Sample number	Percent						
	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CO_2
Al Hassir quadrangle (plate 1)							
22896	30.0	16.4	5.5	3.1	0.5	0.8	43.7
22914*	43.0	2.8	13.8	7.6	0.51	0.68	35.1
22919	43.2	0.5	20.26	3.6	0.7	0.69	33.7
22934	24.5	16.7	6.6	1.9	0.6	0.6	43.5
22935	26.6	16.5	7.1	9.3	1.0	0.6	43.8
Duthur as Salam quadrangle (plate 3)							
22693	40.7	3.1	11.8	0.4	3.4	2.5	36.1
22724	22.1	2.7	36.7	6.1	2.2	1.95	26.8
22728*	43.5	1.3	14.6	2.7	0.5	2.5	48.2
22746*	36.4	8.1	11.2	4.4	1.1	1.03	40.4
22753*	34.4	7.4	14.6	4.9	1.07	0.5	36.2
22756	28.8	16.7	7.94	3.04	0.7	0.4	41.5
22763*	40.0	3.03	16.4	4.09	1.5	0.2	36.4
22805	27.4	15.9	12.9	3.3	0.5	0.93	32.2

Table 14. Major elements in Precambrian marble from the area of the Tathlith one-degree quadrangle, Kingdom of Saudi Arabia (cont'd.)

Sample number	Percent						
	CaO	MgO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CO_2
Hamdah quadrangle (plate 4)							
22377	48.0	3.1	2.04	1.8	0.4	0.5	41.6
22381	30.6	0.9	33.1	3.3	1.1	0.92	26.97
Wadi Haraman quadrangle (plate 2)							
22487	35.4	9.6	7.6	2.5	0.57	1.2	41.7
22512	10.2	1.9	72.4	2.4	0.5	1.97	12.8
22526	36.1	8.4	7.8	6.6	0.2	1.05	38.8

* Within the range of composition of natural cement rocks.

Soapstone

Soapstone was noted at two stations (22204 and 22261) in the Hamdah quadrangle (plate 4), but it is in small deposits of poor quality that lack industrial use (table 15). The geologic possibility exists for better, possibly exploitable, deposits of soapstone in the Hamdah ultrabasic belt.

Table 15. Descriptions of soapstone in the Hamdah quadrangle

Sample number (plate 4)	Description
22204	Lenticular masses of soapstone less than 1 m thick and 7 m long in serpentinite; soapstone is of poor quality and has no commercial use.
22261	Poor quality soapstone formed from pyroxenite along contacts of intrusive granite; is not suitable for commercial use.

Circular plutons as possible groundwater reservoirs

The shapes of the zoned circular plutons of the granitic rocks in the peralkalic magma series are interpreted to be like steep-walled inverted cones with the apex down. The contacts of these plutons appear to be tight, and locally the host rocks are converted to hornfels. The plutons tend to be strongly jointed and they are divided into segments by faults. Surface relief is variable and may be considerable on the larger plutons. This upper surface is locally smooth rock and locally mantled with gruss. In area, the larger plutons occupy hundreds of square kilometers.

To an unknown extent it is possible that the upper surfaces of the plutons have effectively caught the sparse rainfall of the area and channeled it downward through joints. At depth the maze of joints in the pluton may be serving as a reservoir of groundwater, unless the water is drained off through the faults.

The pluton at Jabal Al Hassir offers an excellent example to test for fractures that may serve as a reservoir for groundwater. An evaluation of the possible presence of groundwater at depth in the Jabal Al Hassir pluton might be made by resistivity surveys over the pluton and along possible channelways defined by faults leading out of the pluton.

SUMMARY

Geological and geochemical reconnaissance in the area of the Tathlith one-degree quadrangle disclosed several deposits of gold, base metals, and industrial minerals and rocks, only one of which, the Ash Sha'ib base metal deposit, was subsequently thoroughly evaluated (Allcott, 1970). The result of that evaluation showed a deposit having an estimated 2,170,000 tons of sulfide ore to a depth of 170 m worth $40 million for the contained zinc, copper, and silver; however, only $20 million of the ore was estimated to be worth $25 or more per ton. Thus, the Ash Sha'ib deposit to the depth explored was regarded as being too small to support a mining venture. Sparse evidence on the distribution of zinc and silver in the area, as developed in the present reconnaissance, points to the need for more detailed and comprehensive search for additional ores similar to that at Ash Sha'ib. The Higera ancient mine a few kilometers south of the southern border of the Tathlith one-degree quadrangle should be included in the area of search, and particular attention should be given to the contacts of mafic and granitic plutons of the peralkalic magma series, for possible zinc deposits.

The most important industrial mineral in the area is chrysotile asbestos; thus far only identified near the Higera mine. Very large tracts near Hamdah, however, have notable amounts of anthophyllite. Many untested veins of asbestiform

minerals are present near Hamdah, and the ultramafic area has been covered by several kinds of airborne magnetic surveys. The results of these surveys need to be compared with the bedrock geology as a means of identifying sites suitable for possible asbestos deposits. Samples of asbestiform minerals from these veins need to be studied by X-ray analysis for type and purity of the asbestiform minerals. Where chrysotile is found, an evaluation of the sizes of the deposits and the kinds of fibers should be made. The commodity is valuable, and it can be processed by methods making use of air instead of water--an obvious advantage in this area. The ultramafic rocks near Tathlith and Jaash also need to be examined for asbestos.

Chromium, nickel, and platinum are remote possibilities, of which nickel in weathered rocks and zoned complexes of gabbro and norite seems the best of the three.

The attractive possibility should be evaluated by geophysical procedures that the zoned circular plutons of the peralkalic granitic rocks may be reservoirs for groundwater at depth.

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