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RECONNAISSANCE GEOLOGY OF THE WADI WASSAT QUADRANGLE

KINGDOM OF SAUDI ARABIA

by

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and

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PREFACE

In 1963, in response to a request from the Ministry of Petroleum and Mineral Resources, the Saudi Arabian Government and the U. S. Geological Survey, U. S. Department of the Interior, with the approval of the U. S. Department of State, undertook a joint and cooperative effort to map and evaluate the mineral potential of central and western Saudi Arabia. The results of this program are being released in USGS open files in the United States and are also available in the Library of the Ministry of Petroleum and Mineral Resources. Also on open file in that office is a large amount of material, in the form of unpublished manuscripts, maps, field notes, drill logs, annotated aerial photographs, etc., that has resulted from other previous geologic work by Saudi Arabian government agencies. The Government of Saudi Arabia makes this information available to interested persons, and has set up a liberal mining code which is included in "Mineral Resources of Saudi Arabia, a Guide for Investment and Development," published in 1965 as Bulletin 1 of the Ministry of Petroleum and Mineral Resources, Directorate General of Mineral Resources, Jiddah, Saudi Arabia.

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William C. Overstreet and Darwin L. Rossman

ABSTRACT

The Wadi Wassat quadrangle covers an area of 2926 sq km in the southwestern part of the Kingdom of Saudi Arabia. The west half of the quadrangle is underlain by crystalline rocks of the Arabian Shield, but in the eastern half of the quadrangle the Precambrian rocks are covered by Permian or older sandstone which is succeeded farther east by aeolian sands of Ar Rub' al Khālī.

The Shield consists of a sequence of unmetamorphosed to metamorphosed interlayered volcanic and sedimentary rocks intruded by igneous rocks ranging in composition from gabbro to syenite and in age from Precambrian to Cambrian(?). The volcanic rocks range in composition from andesite to rhyolite and in texture from agglomerate to thick, massive flows and lithic tuff. They are interlayered with conglomerate, fine-grained graywacke sandstone, calcareous graywacke, siltstone, tuffaceous laminated shale, pyritiferous sediment, carbonaceous shale, limestone, and dolomite. Most clastic debris is derived from andesite. In places the rocks are polymetamorphosed; elsewhere they are unmetamorphosed. The rocks on which this volcano-sedimentary eugeosynclinal sequence was deposited are not exposed in the area of the quadrangle.

Regional dynamothermal metamorphism was the dominant process affecting the volcanic-sedimentary rocks in the western part of the quadrangle. In the eastern part of the Precambrian area the chief metamorphic effect results from contact action along the walls of intrusive plutons.

The oldest igneous rock to intrude the volcanic-sedimentary sequence, after the dikes and sills of the sequence itself, is granite gneiss and gneissic granodiorite. The gneiss is sparsely present in the quadrangle, but northwest of the quadrangle it forms an immense batholith which is one of the major geologic features of southwestern Arabia. However, the most common intrusive rocks of the quadrangle are a magmatic differentiation sequence that ranges in composition from gabbro and diorite to granite, rhyolite, and syenite. The siliceous members of the differentiation sequence commonly contain aluminous pyroxene or amphibole, and to the sequence the name peralkalic magma series has been given. Plutonic rocks of the series are widely intruded by hypabyssal rocks of the series. In most places, the older hypabyssal rocks tend to form interior dikes in the plutonic rocks, and the younger hypabyssal rocks commonly form the exterior dike swarms outside the plutonic rocks of the magma series. Many exterior dike swarms are concentrated in roof pendants of volcano-sedimentary rocks over the plutonic members of the magma series. Isotopic ages of rocks in the peralkalic magma series range from

598±24 m.y. to 509±15 m.y. by K/Ar and Rb/Sr methods.

A profound angular unconformity exists between the Precambrian and Cambrian(?) crystalline rocks and the Permian or older sandstone which laps onto the Shield from the east and south. This sandstone, called Wajid Sandstone, is reddish-brown, yellow, tan, and white crossbedded sandstone with ferruginous cement and concretions in some layers. Locally, the rocks underlying the Wajid Sandstone are deeply weathered.

Poorly sorted alluvial sand and gravel mantle the wadi floors. In the northeastern and southwestern parts of the quadrangle well-sorted aeolian sand is common.

The volcanic and sedimentary rocks of the quadrangle are part of the east limb of an immense synclinorium(?) that closes southwestward around a batholitic core of gneissic granite and granodiorite. These layered rocks were isoclinally folded along northerly and north-northeasterly trending axes prior to the intrusion of the peralkalic magma series. During intrusion, the layered rocks were again folded as they were pushed aside, and major old regional northerly faults were reactivated with persistent left-lateral displacement.

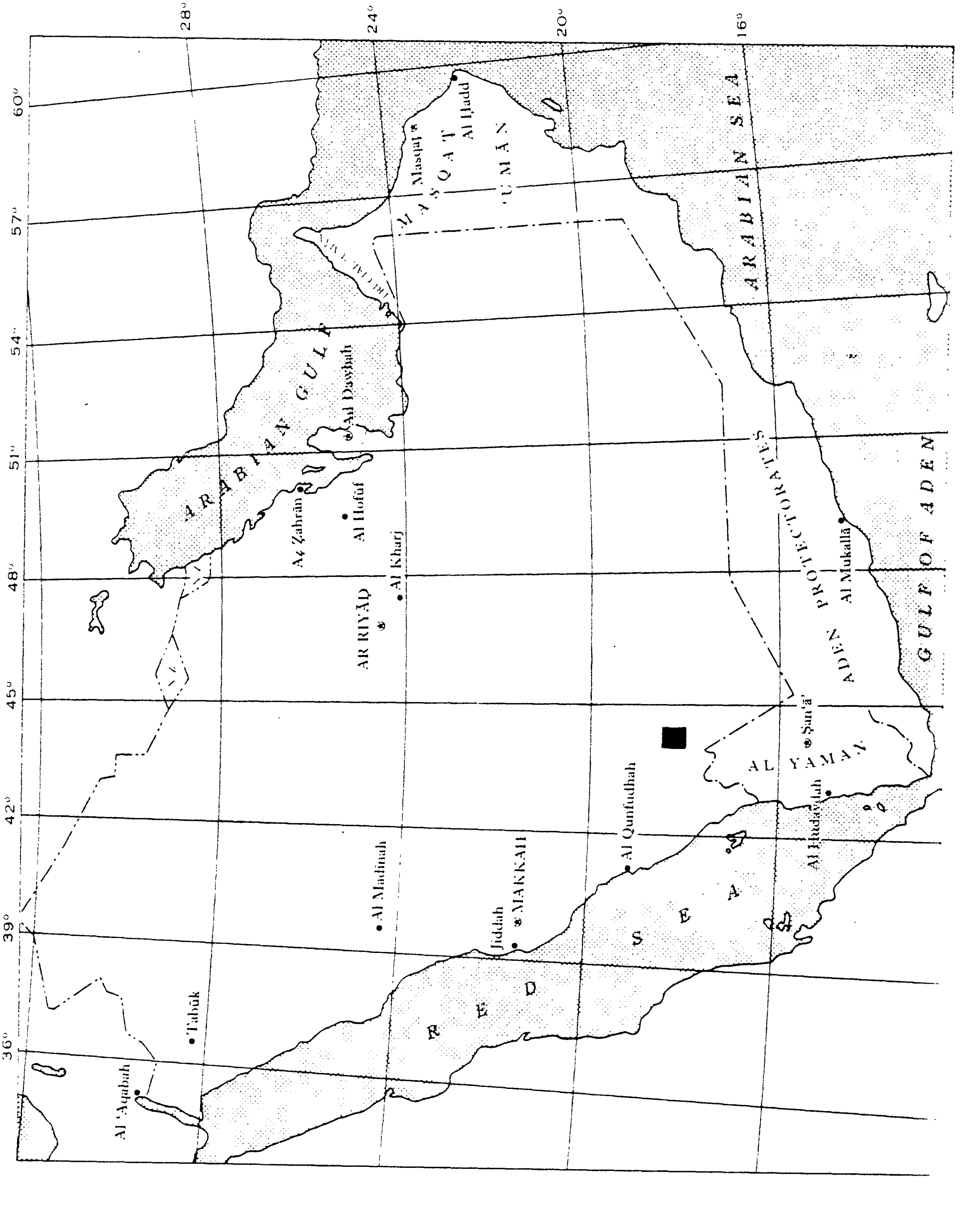
Reconnaissance geochemical sampling disclosed several notable groupings of threshold and anomalous elements with specific rock units, of which the strongest is the association of Be, La, Nb, Pb, Sn, Y, and Zr with granitic rocks of the peralkalic magma series. Other associations are: Co, Cr, Ni, Mn, Ti, and Sc with the andesite unit and mafic intrusives; and Cu, Mo, and Zn with diorite, gabbro, and the andesite unit, particularly where the andesite unit is richly pyritiferous. None of these elements is known to be concentrated in exploitable amounts in the Wadi Wassat quadrangle.

The largest observed mineral deposit in the area of the quadrangle are massive pyrite at Wadi Wassat and Wadi Adhbat. These sulfide deposits are an immense resource in sulfur and iron -- possibly as much as 8.2 million tons of pyrite per meter of depth in the two areas -- but base and precious metals have thus far not been discovered in minable quantity in the sulfide-rich rocks. Several small ancient mines, probably worked for gold, are in the southwestern part of the quadrangle, but they are too small for present-day mining. Granite suitable for quarrying is present. A possibility exists for scheelite.

INTRODUCTION

Location

The Wadi Wassat quadrangle covers an area of 2,926 sq km in the southwestern part of the Kingdom of Saudi Arabia (fig. 1). The quadrangle is at the eastern edge of the Arabian Shield. In the eastern half of the quadrangle the rocks of the Shield are covered by sandstone and farther east by aeolian sands of Ar Rub' al Khali. The central part of the quadrangle (pl. 1) is a drainage divide separating



28°
24°
20°
16°
60°
57°
54°
51°
48°
45°
42°
39°
36°
ARABIAN GULF
Al Dawhah
Az Zahrān
Al Hofuf
Al Kharj
AR RIYĀḌ
Masqaṭ
Al Ḥadd
MASQAT
'UMĀN
ARABIAN SEA
ADEN PROTECTORATES
Al Mukallā
GULF OF ADEN
Ṣan'ā'
AL YAMAN
Al Ḥudaydah
Al Qunfudhah
MAKKAH
Jiddah
Al Madinah
RED SEA
Tabuk
Al 'Aqabah

south- and southeast-flowing wadis on the south from north- and northeast-flowing wadis on the north. Elevations in the flat areas in the northeast are around 1,180 m, but near the head of Wadi Wassat they reach 1,400 m above sea level (Brown and Jackson, 1959). High hills in the southwestern corner of the quadrangle are 1,688 m above sea level.

A major unpaved road crosses the area leading northward to Bishah and southward to Najran at the border between Saudi Arabia and Yemen. A number of small roads reach the wells in the area. Permanent settlements are absent except for a family located on Bi'r Adhbat and another family at Bi'r Ihnasehriyah. Immediately to the north of the quadrangle the large wells at Bi'r Idimah serve as a center for commerce and traffic, but not for a settlement. The large well at Al Husayniyah, about 25 km south of the quadrangle, also supports a dominantly migratory population, but has in addition a few buildings and permanent residents.

Previous work

The Wadi Wassat quadrangle is a small part of the east edge of the Asir quadrangle of 1:500,000 scale previously mapped by Brown and Jackson (1959). No other geologic work had been done in the area of the quadrangle prior to the work described here except for some mineral exploration during 1964 by Mr. Hatim Khalidi.

Present investigation

The investigations leading to this report were undertaken in parts of November 1964, May and October 1965, and February-March 1966 by W. C. Overstreet (Overstreet, 1968a; 1968b; 1968c; 1968d; Overstreet, Bahijri, Fourati, and Gonzalez, 1966; Overstreet, Bahijri, and Shararahly, 1966; Overstreet, Gonzalez, Thompson, Fourati, and Sharah, 1967; and Overstreet, Raisanen, Fourati, Shahwan, and Baradja, 1969), and February through May 1967 by D. L. Rossman as part of the work performed for the Ministry of Petroleum and Mineral Resources, Directorate General of Mineral Resources, Kingdom of Saudi Arabia, by the U.S. Geological Survey. During later stages of the investigation, selected areas were examined by electromagnetic ground geophysical methods by W. E. Davis and R. V. Allen, U.S. Geological Survey, and M. N. Akhrass and Hisham Gazzaz of the Directorate General of Mineral Resources (Allen and Davis, 1969a, 1969b; Davis, Akhrass, and Gazzaz, 1969). Diamond drilling of massive pyrite deposits was undertaken by Louis Ganzalez and Eino Raisanen of the U.S. Geological Survey. Subsequent to the field work on which this report is based, the area was visited briefly by A. E. Weissenborn and R. L. Earhart (1969) of the U.S. Geological Survey and studied in 1968-69 by Conrad Martin, U.S. Geological Survey. The results reported here are those of Overstreet and Rossman based on the pioneering work of Brown and Jackson.

Acknowledgments

The writers wish to acknowledge the support they received from officials of the Directorate General of Mineral Resources, Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia. The surveys described below are part of the broad program of mineral exploration being conducted by the Directorate for the Royal Government. The findings are in partial fulfillment of an agreement made in September 1963 between the Ministry and the United States Geological Survey.

GEOLOGY

Rock units

Rock units exposed in the Wadi Wassat quadrangle (pl.1) are a Precambrian sequence of unmetamorphosed to metamorphosed interlayered volcanic and sedimentary rocks intruded by igneous rocks ranging in composition from diorite and gabbro to granite and syenite, and ranging in age from Precambrian to Cambrian(?). In the eastern part of the quadrangle these rocks are overlain unconformably by sandstone of Permian or older age. Throughout the quadrangle the older rocks are locally mantled by aeolian and alluvial sand.

Metamorphosed interlayered volcanic and sedimentary rocks

Volcanic rocks ranging in composition from andesite to rhyolite and in texture from agglomerate to thick, massive flows and lithic tuff are interlayered with sedimentary rocks. In considerable part the clastic debris forming the sedimentary rocks is derived from andesite. These sedimentary rocks include conglomerate, fine-grained graywacke sandstone, calcareous graywacke, siltstone, tuffaceous laminated shale, bedded volcanic wacke, extremely fine-grained pyritiferous sediment of andesitic composition, carbonaceous shale, limestone, and dolomite. In places the rocks are polymetamorphosed; elsewhere they are even unmetamorphosed. Locally they are silicified. Regional dynamothermal metamorphism was the dominant process affecting these rocks in the western part of the quadrangle. In the eastern part of the Precambrian area the chief metamorphic effect was caused by contact action along the walls of intrusive mafic and felsic plutons. Locally this effect is also noticeable in the west-central part of the area.

Andesite, greenstone, and hornblende schist:-- The mafic volcanic rocks in the sequence are dominantly andesite. They include massive andesite, bedded andesite, vesicular andesite, andesite porphyry, trachytic andesite, fine- to medium-grained andesitic agglomerate, lapilli tuff, brecciated massive andesite, brecciated laminated andesite, and flow-banded porphyry. The bedded andesite commonly contains pyrite. Coarse-grained porphyritic varieties of the andesite grade into microdiorite and biotite diorite (pl.1) that is older than the biotite diorite associated with the peralkalic granite (Overstreet and others, 1969, p.41). Possibly the increase in grain size is in part caused by the contact metamorphic effect of intrusive granite.

Metamorphism of these mafic rocks produced variations that range in lithology from chloritized and epidotized andesite and diorite to greenstone, vesicular greenstone, chlorite schist, actinolite schist, hornblende schist, hornblende-biotite schist, and hornfels. Pyroxenite dikes in the greenstone are chloritized to metapyroxenite.

Felsic metavolcanic rocks:-- Rhyolite flows and rhyolitic ash are interlayered with andesite, carbonaceous shale, slate, and felsite. Some of the thinly laminated sedimentary rocks may originally have contained rhyolitic ash. At many places, particularly where the mafic volcanic rocks and sediments have not been metamorphosed and the rhyolite is in sills, it is difficult to separate old rhyolite of the volcanic-sedimentary sequence from younger rhyolite of the intrusive cycle related to the peralkalic granite (pl.1). Also, where exposures are weathered and leached, it is difficult to separate rhyolite from the fine-grained pyritic sediment. However, rhyolite porphyry, rhyolite agglomerate, and conformably layered rhyolite in the volcanic-sedimentary sequence is locally and variably metamorphosed to the same grade as associated sediments and andesite. Commonly this rhyolite is partly altered to sericite schist which is interlayered with graphitic sericite schist and sericite-chlorite schist. These schists are intruded by unaltered dikes of rhyolite genetically related to the peralkaline granite. The possibility exists that the upper part of the volcanic-sedimentary sequence has more rhyolite than the lower part.

Graywacke, sericite-chlorite schist, pyritic sediment, and marble:--The sedimentary units in the volcanic-sedimentary sequence seem to be more common in the upper part than in the lower part of the sequence, but they are interlayered throughout the sequence. In the upper part of the sequence the sedimentary rocks are intruded by far fewer mafic dikes than are the sediments in the lower part of the sequence. The most common sedimentary rocks are fine-grained graywacke sandstone, calcareous graywacke, siltstone, gray-green laminated tuffaceous shale, carbonaceous shale, and massive to laminated microcrystalline pyritiferous rock. Limestone, dolomite, and conglomerate are present. Where affected by metamorphism the rocks were changed mainly to slate, graphitic slate, sericite schist, and sericite-chlorite schist, but locally they formed contorted chlorite schist, biotite schist, biotite-muscovite schist, pyritic graphite schist, graphite-chloritoid-muscovite schist, hornfels, quartzite, marble, and biotite-almandine skarn.

The principal sulfide-bearing rock of the quadrangle, and the host of the pyrite-pyrrhotite deposits at Wadi Wassat and Wadi Adhbat, is a very fine-grained sedimentary rock of andesitic composition (pl.1), possibly water-laid crystal tuff, and bedded volcanic wacke. Where studied, the unit is about 300 m thick and lies between thick masses of andesite (D.L. Rossman, written commun., 1967). The sulfide-rich rock ranges in thickness of lamination from thin beds less than 2 mm thick to beds as much as several meters across. Graded bedding, slump features, crossbedding, ripple markes, and intercalated calcareous layers attest to its sedimentary origin. Locally the sedimentary phases contain lapilli of andesite, and some of the fine-grained rock is trachytic; thus, it has a close spatial and genetic association with, and gradation to, volcanic extrusive rocks and water-laid ash. Most of the rock consists of fine-grained pieces of andesine a few tens of microns across, with randomly oriented sparse amphibole crystals, and rare quartz. From 1 to 10 percent of the rock is pyrite, and locally it is nearly all pyrite. The rock commonly weathers red to buff, in which condition it resembles weathered rhyolite.

The largest bodies of the pyritic rock were affected by a thermal rise associated with the intrusion of diorite and granite (Overstreet and others, 1969, p.45-52). The original sedimentary-volcanic pyrite was mobilized by the termal rise. Extensive recrystallization of the pyrite took place, variable amounts of pyrrhotite and gypsum were formed, and extensive epigenetic replacement relations developed between the mobilized sulfide and the host rocks. The metamorphosed sulfide-bearing bedded pyroclastic rocks mostly retain their original textures despite the growth of metamorphic quartz, plagioclase, colorless amphibole, chlorite, calcite, garnet, pyrite, and pyrrhotite.

These metamorphic minerals are interpreted to show that the grade of metamorphism is middle greenschist facies (R.G. Coleman, written commun., 1968).

Lenticles of marble are present at many places (pl.1), but all seem to be impure. Black to dark-brown marble, possibly manganiferous, is interlayered with greenstone. Gray to brown, thin-layered, ferruginous marble up to 8 m thick is exposed intermittently along strike for 3 km in sericite-chlorite schist, and thin lenticles of brown, silicified marble are also present in sericite-chlorite schist. Lenticles of gray and brown marble up to at least 3 m thick are interlayered with chloritic andesite and sericite-chlorite schist. Some outcrops of marble are strongly limonitic, and some silicified marble originally may have been siliceous dolomite.

Granite gneiss

Light-gray to gray, rarely reddish-gray, coarse-grained, locally porphyritic, biotite granite gneiss and hornblende-biotite granite gneiss is exposed mainly in the southern part of the quadrangle (pl.1). Locally the rock grades into granodiorite. From relations observed to the northwest of the quadrangle, and from descriptions by Brown and Jackson (1959) the granite gneiss unit is known to intrude the sequence of metamorphosed interlayered volcanic and sedimentary rocks, but intrusive contacts were not seen in the Wadi Wassat quadrangle. The granite gneiss is widely intruded by various units of the peralkalic magma series. Where the intrusive relations between gabbro and diorite of the peralkalic magma series and the granite gneiss, or between the granite gneiss and amphibolite of the metamorphosed volcanic rocks, are particularly complex, a mixed rock unit is shown on plate 1. The granite gneiss probably belong to an older intrusive sequence than the peralkalic magma series.

Peralkalic magma series

The term peralkalic magma series is used to identify a probable differentiation sequence of igneous rocks that ranges in composition from gabbro and diorite to granite, rhyolite, and syenite, the silicic members of which commonly have aluminous pyroxene and amphibole. The plutonic rocks of the series are widely intruded by hypabyssal rocks of the series. Generally, the older hypabyssal rocks tend to form interior dikes in the plutonic rocks, but the younger hypabyssal rocks commonly are dike swarms outside the plutonic rocks of the peralkalic magma series. Many dike swarms are concentrated in roof pendants of andesite and metasediments over the plutonic members of the magma series.

Diorite and gabbro:-- The oldest rocks of the peralkalic magma series are masses and plutons of gray to nearly black, fine- to coarse-grained diorite grading into medium- to coarse-grained gabbro (pl.1) It also grades into hornblende granodiorite. Much of the diorite is biotite-bearing, some is biotite-hornblende diorite, and some is quartz diorite.

The diorite and gabbro intrude the sequences of metamorphosed interlayered volcanic and sedimentary rocks and the granite gneiss unit. Inclusions of volcanic and sedimentary rocks are common in the diorite near its contacts; generally the inclusions show effects of contact metamorphism. At some places where the diorite and gabbro intrude schistose phases of the sequence of volcanic and sedimentary rocks, the schists are raised in metamorphic rank for 20-30 m adjacent to the contact, and carbonaceous slates are converted to black hornfels. Very locally the zone of contact metamorphism is wide enough to show at the map scale. At a few places, schistose rocks intruded by the diorite and gabbro were brecciated and silicifed at the time of or after emplacement of the mafic intrusives, but before the intrusion of the late-stage units of the peralkalic magma series. Siliceous zones also are locally in the diorite at contacts between diorite and intrusive pink biotite granite.

The diorite and gabbro are intruded by all other rock units of the peralkalic magma series. The gabbro is generally cut by sharp-walled dikes of the younger units, as is the diorite. Locally, however, the diorite is fractured into megabreccia, in which the interstices are filled with medium-grained gray granite. Most contacts in the megabreccia are sharp, but some tend to be gradational. Some blocks of diorite and, especially, quartz-diorite, tend to have nebulitic contacts with the intrusive granite.

Most of the diorite and gabbro is plutonic, but several apparently shallow intrusive masses of diorite and diorite porphyry are in the north-central part of the area, and several mafic plugs, possibly younger than the magma series, are exposed near Bi'r Adhbat. Perhaps related to the hypabyssal intrusive masses of diorite and diorite porphyry are dikes of fine-grained diorite and andesite porphyry (pl.1) which form satellitic swarms in and around small masses of diorite in the north-central part of the quadrangle. These dikes are older than most dikes in the magma series, because they are intruded by the silicic rocks of the series. However, they trend toward the west-northwest, which is also the strike of the youngest dikes known in the quadrangle, suggesting that this direction was repeatedly opened for intrusion.

Biotite granite:-- Pink to red, locally gray, medium- to coarse-grained, commonly porphyritic biotite granite forms large plutons in the southwestern, west-central, and north-central parts of the quadrangle (pl.1). These intrusives are part of a more extensive batholith shown by Brown and Jackson (1959) to extend at least 65 km farther northwestward. As mapped on the Wadi Wassat quadrangle the biotite granite unit includes the batholitic parts of the peralkalic granite of Brown and Jackson (1959) but excludes the somewhat younger pyroxene-bearing granites found in circular plutons. The biotite granite of the Wadi Wassat quadrangle (pl.1) also includes the calc-alkalic granite of Brown and Jackson (1959), thus confirming their interpretation that a unit of porphyritic, biotite-bearing granite, commonly with bluish quartz, is older than the unit of pyroxene granite and associated syenite.

The biotite granite unit (pl.1) is the earliest plutonic silicic rock in the magma series. Owing to the general large size of the masses of biotite granite, contact metamorphic effects are more common beyond its walls than around other units in the series.

Most dark minerals in the rock are biotite, but locally hornblende or pyroxene are present. Blue quartz is especially abundant at the northern end of the large pluton in the southwestern part of the quadrangle, but it is sparse elsewhere. Microcline phenocrysts locally and feebly display a preferred orientation which marks a faint planar structure in the granite. However, it is not certain the orientation of the feldspar was formed by primary flow banding. At a number of places the feldspar crystals grow across the contact between inclusions of andesite or diorite and the granite. Such undisturbed crystals may have grown in the solid state after the granite had crystallized. If this is so, then the crystals oriented in planar structures acquired their orientation by preferred growth in a previously developed structure.

Rhyolite:-- Dikes, sills, and masses of rhyolite appear to be the hypabyssal equivalent of the biotite granite and of other silicic rocks in the series (pl.1). From the intrusive relations among these rocks it seems likely that the earliest rhyolite in the series is younger than the diorite and about contemporaneous with the biotite granite. Most of the rhyolite dikes are younger than the biotite granite but are older than the granites and syenite in the composite circular pluton at Jabal Ashirah. A few rhyolite dikes are younger than the granites and syenite of the circular pluton at Jabal Ashirah. A swarm of pyroxene rhyolite dikes is interpreted here to be the next to the youngest igneous rock in the quadrangle.

For mapping purposes all rhyolite dikes, sills, and masses thought to be related to the peralkalic magma series and ranging in age from penecontemporaneous with the biotite granite to penecontemporaneous with felsite and granite dikes related to the end stage granite porphyry of the magma series are called rhyolite (pl.1). Pyroxene rhyolite dikes seem to be somewhat younger than the other rhyolite dikes.

The rhyolite is light to dark gray, buff, pink, red, and reddish brown. Locally it has small phenocrysts of quartz, biotite, and spessartite. Pyrite is variably present but locally may make up as much as 12 percent of a dike. Mainly the rhyolite dikes are massive, but locally they have strong flow banding parallel to their walls. Generally the rhyolite is unaltered, but locally it may be slightly chloritized, epidotized, or sheared. Thin dikes are flint-hard and break with conchoidal fracture. Thick dikes tend to grade inward into felsite and fine-grained granite; thus, it is inferred that many of the felsite and granite dikes were emplaced under about the same conditions of temperature and pressure and at about the same time as the rhyolite.

Granite, pegmatite, and felsite:-- Massive, pink to white dikes of biotite granite, graphic granite, pegmatite, and felsite, all are combined into one unit on plate 1, and are here interpreted to be apophyses and differentiates of the biotite granite, contemporaneous with to older than the rhyolite. The three dike rocks are intergradational along strike, and the granite and felsite dikes resemble the cores of thick rhyolite dikes.

Pyroxene granite, syenite, and quartz porphyry:-- Late tectonic to post-tectonic differentiates of the peralkalic magma series include pyroxene granite, syenite, quartz porphyry, and other rocks in stocks, dikes, and composite circular plutons (pl.1). These intrusive rocks are generally massive, but locally they have primary flow banding marked by aligned mineral grains. Grain size and composition are commonly variable. This variation is greatest in the zoned circular pluton at Jabal Ashirah where six variants are found: (1) coarse-grained, generally porphyritic pyroxene granite that grades through decrease in quartz into (2) coarse-grained quartz syenite and syenite, (3) fine-grained pyroxene granite, (4) fine- to medium-grained, quartz-rich biotite granite, (5) massive, medium grained, pink to red quartz porphyry which grades into dike swarms of (6) granite porphyry around the periphery of the pluton.

At Jabal Ashirah the walls of the pluton in contact with earlier rocks of the peralkalic magma series, generally the west side of the pluton, are coarse grained, whereas the walls in contact with much older rocks, generally the east side, are fine grained. Possibly the much older granite gneiss east of the pluton had a cooling effect on the composite pluton resulting in a chilled margin to the east. Also, the walls of the pluton appear to be older than the core, and inclusions of the wall parts are in the core. Thus, the coarse-grained pyroxene granite, the equivalent fine-grained pyroxene granite, and syenite are slightly older than the quartz-rich biotite granite, quartz porphyry, and granite porphyry. The older coarse-grained rocks tend to have primary flow banding, but the younger rocks lack flow banding.

The pyroxene is commonly altered to hornblende or biotite, and less commonly to epidote. Finer-grained phases of the rocks tend to be richer in quartz than the coarse-grained phases. Among all phases the textures commonly are inequigranular with prophyritic feldspars in the coarser rocks and phenocrysts of pyroxene, biotite or quartz in the finer rocks. Sub-spherical inclusions, possibly cognate, of fine-grained diorite and felsite are most common in the fine-grained biotite granite unit; inclusions of biotite schist are in the coarse-grained pyroxene granite.

Felsite and porphyritic granite dikes, quartz veins:-- Gray to red felsite dikes grading into dikes of porphyritic granite, granite porphyry, quartz porphyry, and graphic granite are somewhat younger than the pyroxene granites and fine-grained biotite granite (pl.1). They seem to be penecontemporaneous with, and possibly are related to, the quartz porphyry unit. Scarce, thin, muscovite-bearing aplite dikes may be of about the same age as these felsites and porphyries.

Barren, massive white quartz veins and irregular masses of quartz are present but very scarce in the Wadi Wassat quadrangle. The largest observed vein is about 0.4 km west of the south end of the main gossan on Wadi Wassat at diamond drill hole 8. The quartz vein strikes east-northeast. It may be genetically related to the graphic granite and quartz prophyry dikes.

Dacite, diabase, and basalt dikes:-- A group of dark dikes younger than the main units of igneous rocks in the magma series are called dacite and dacite porphyry and diabase and basalt (pl.1). The dacite dikes are generally older than the diabase and basalt dikes. It is probable that this group of dark dikes, except for some possibly much younger basalt, are penecontemporaneous. They are most abundant in diorite, biotite granite, pyroxene granite, and quartz porphyry in the north-central part of the quadrangle and in diorite, hornblende schist, and sericite-chlorite schist in the west-central part of the area. The dark dikes with ophitic texture and pyroxene are called diabase, and those with biotite, orthoclase, and plagioclase are called dacite. No plutonic rock in the magma series has been related to these dark hypabyssal dikes. They preceded in time the emplacement of the pyroxene rhyolite dikes and syenite porphyry dikes which are closely related to the end stage of the magma series; therefore, the dacite and diabase presumably are a part of it. They may, in fact, contain lamprophyres.

Some basalt dikes may be younger even than the Wajid Sandstone (see below), and by comparison equivalent to the Tertiary basalt in the As Sarat Mountains (Brown and Jackson, 1959), but none of them apparently intrude the Wajid. Several small mafic plugs in the southwestern part of the quadrangle resemble Tertiary basalt of the As Sarat (Brown and Jackson, 1959).

Pyroxene rhyolite dikes:-- Pyroxene rhyolite forms swarms of light-gray to dark-red dikes trending N.20°W.--N.30°W. in the north-central part of the quadrangle (pl.1). In many of them, pyroxene is replaced by pseudomorphic elongate aggregates of biotite, and magnetite phenocrysts are present. Thick dikes may have felsitic cores, and some dikes grade into pyroxene- or biotite-bearing felsite dikes. The pyroxene rhyolite dikes cut every variety of igneous or metamorphic rock in the quadrangle except the basalt of possibly Tertiary age, and syenite porphyry dikes. Most pyroxene rhyolite dikes are in parallel swarms near stocks of granite porphyry and pyroxene granite. From these relations it is inferred that the pyroxene rhyolite dikes are hypabyssal or extrusive late phases of the granite porphyry and pyroxene granite.

Syenite porphyry dikes:-- The syenite porphyry is the youngest dike rock in the quadrangle with the possible exception of the basalt dikes that may be Tertiary. Contacts between the syenite porphyry and basalt were not seen. The syenite porphyry dikes form a distinctive swarm that strikes N. 70°W. across the northern part of the gossan at Wadi Wassat. The main trend of the dikes is N.70°W., although some are along fractures that strike N.20°W. The dike swarm extends about 12 km in an east-southeasterly direction to disappear beneath the Wajid Sandstone to the east and against diorite to the west.

The dikes in the swarm include syenite porphyry, trachyte, latite, and dacite. Three specimens examined in thin section are reported to be hypabyssal dikes belonging to the latite-trachyte group (R. G. Colemen, written commun., 1968). Blocky euhedral phenocrysts of sodic plagioclase and potassium feldspar are set in a fine-grained groundmass of potassium feldspar, biotite, minor quartz, and brown hornblende. Differences among the dikes in mineral assemblage, texture, and color are great. These facts, and the complex crosscutting relations among the dikes, infer that the dikes show differentiation and intrusion over a considerable span of time.

Plutonic syenite is not exposed around Wadi Wassat, but it is present farther south near Jabal Ashirah. The syenite porphyry dikes are here thought possibly to be the hypabyssal equivalent of the plutonic syenite.

The syenite porphyry is unmetamorphosed whereas the older dark dikes are locally chloritized and the older rhyolite dikes are sericitized in places. The syenite porphyry tends to be fresh and unaltered even where it crosses bodies of massive sulfide which are deeply weathered to gossan. Syenite porphyry in the gossan is essentially unweathered.

Permian and later sedimentary rocks and residuum

A profound angular unconformity exists between the crystalline rocks of the quadrangle and overlying sedimentary rocks (Brown and Jackson, 1959) and residuum. The sedimentary rocks are the Wajid Sandstone of Permian or older age, and Recent alluvial and aeolian sand (pl.1). The residuum consists of gossan on layers of massive and disseminated sulfides. The age of the gossan is complex.

Wajid Sandstone:-- The Wajid Sandstone as mapped by Brown and Jackson (1959) of Permian or older age is a reddish-brown, yellow, tan, and white cross-bedded sandstone with ferruginous cement and concretions in some layers (pl.1). Thin conglomerate layers and lenticular beds of clay are present. Locally the Wajid Sandstone overlies deeply weathered Precambrian rocks. Apparently the Permian or older erosion surface on which the Wajid was deposited was weathered and the weathering products, though in part deposited in the sandstone as lenticles of clay, where not everywhere removed, and relict saprolite was preserved under the sandstone. These relations have important implications in an estimate of the age of the gossan at Wadi Wassat.

Gossan:-- Symbols on the geologic map (pl.1) show the distribution of known masses of gossan, and are about the length and width of the outcrops of gossan; however, they do not represent the actual lengths and widths of the bodies of massive pyrite and pyritized rocks from which the gossan was derived. In general the gossan occupies a larger surface area than the actual outcrop area of the source rock owing to a spreading of the gossan materials.

The best developed gossan is at Wadi Wassat, but somewhat less well-developed gossan is near Bi'r Adhbat to the northwest of Jabal Ashirah (Overstreet, 1968a, p. 7-9; 1968b, p. 27; 1968c, p. 31-45; 1968d, p.11-15; Overstreet, Bahijri, Fourati, and Gonzalez, 1967; Overstreet, Bahijri, and Shararahly, 1969; Overstreet, Gonzalez, Thompson, Fourati, Sharah, and Sumbul, 1967; Overstreet, Raisanen, Fourati, Shahwan, and Baradja, 1969; and Weissenborn and Earhart, 1969).

The gossan at Wadi Wassat consists of buff, brown, and maroon, scoriaceous to delicately banded, pulverent to hard and brittle mixtures of hematite, limonite, goethite, jaspar, chalcedony, kaolinite, calcite, and gypsum with variable, often large, quantities of relict leached pyritic host rock. It is developed on and from pyrite-bearing tuff, pyritic sediment, and pyrite-bearing argillite, andesite, diorite, granite, and rhyolite, and from massive pyrite through the oxidation of the pyrite in the zone of weathering. The oxidation was caused by the circulation of ground water. Soluble sulfates of iron and other elements were brought to the surface in the water and there precipitated as insoluble oxides and sulfates. At many places the oxides are unmoved residue from which the soluble compounds have been dissolved. Data from drilling indicate the gossan are up to 28m deep. There may be places where it is deeper.

Much of the area of the gossan is not underlain by pyrite-bearing rocks. Iron oxides have precipitated from groundwater and surface run-off, spread both by gravity and capillarity, well beyond the limits of the pyrite-bearing rocks; thus, gossan can be found on all the rocks including wadi sand, gravel, and evaporites (Overstreet, 1965, p.4).

Megascopic evidence for copper, lead, or zinc minerals in the gossan is lacking. The scarcity of these metals, and the sparseness of gold and silver, is confirmed by the results of hundreds of analyses of samples from the surface and from drill holes in gossan at Wadi Wassat and Wadi Adhbat.

<u>Alluvial and aeolian sand</u>:-- Poorly sorted alluvial sand, gravel, and sporadic small encrustations of calcium carbonate, gypsum,

melanterite, and iron oxides of Quaternary age mantle wadi floors throughout the quadrangle. Sand derived from the Wajid Sandstone is notably redder than the other sands. Well-sorted aeolian sand with small dunes is common in the northeastern and southwestern parts of the quadrangle.

Isotopic ages of selected rocks

The relative ages of the rock units are shown by their positions in the stratigraphic sequence. Isotopic ages of 14 samples of rocks from the quadrangle are also available (table 1), but only a narrow segment of the local geologic section is represented by the analyses. Most analyses are of younger units in the peralkalic magma series. In a general way the K/Ar and Rb/Sr ages of the samples fit the probable order in the intrusive sequence with diorite oldest and syenite porphyry dikes youngest. One reported age, microcline from pegmatite intrusive into granite porphyry, appears to be too great. The K/Ar whole-rock ages of the samples of the andesite unit from diamond drill hole number 2 at Wadi Adhbat and the sample of massive andesite (30052D) from the north-central part of the quadrangle are too young for the geologic relations of the andesite. It is here thought that the K/Ar whole-rock ages of the andesite are apparent ages caused by loss of argon during a thermal rise in and recrystallization of the andesite attributable to intrusion of the peralkalic magma series. The Rb/Sr age of one sample (30057A) from the andesite unit also appears to

Table 1.-- Summary of isotopic age data for rocks in the Wadi Wassat quadrangle, Kingdom of Saudi Arabia.

	Map unit	Sample number 3/	Rock type	Apparent isotopic age (million years)	Analytical method 1/	Source of analysis 2/
Peralkalic magma series	p	30024A	Latite dike of the syenite porphyry dike unit	534±15	K/Ar	Geochron
	p	30052C	Trachyte dike of the syenite porphyry dike unit	509±15	do	do
	pr	30055A	Pyroxene-biotite rhyolite dike	564±15	do	do
	pr	30071	Pyroxene-biotite felsite dike intrusive into granite porphyry (30069).	554±16	do	do
	fg	30070	Microcline from pegmatite intrusive into granite porphyry (30069).	598±24	Rb/Sr	U.S.G.S.
	grp	30069	Granite porphyry intrusive into biotite diorite (30068)	562±28	do	do
	di	30068	Biotite diorite	588±24	K/Ar	Geochron
Andesite	a	30052D	Massive andesite	567±22	K/Ar	Geochron
	a	30057A	Chloritized and epidotized andesite intruded by massive rhyolite.	599±42	Rb/Sr	U.S.G.S
		Samples from drill hole A2, interval in feet				
	a	259.5-260	Bedded andesite tuff with lapilli and fine-grained porphyritic andesite.	577±17	K/Ar	
	a	312-313	Massive andesite and andesite porphyry	566±16	do	
	a	340.75-341.6	Coarse-grained andesite	562±15	do	
	a	396.1-396.5	Coarse-grained andesite	559±15	do	
	a	398-398.5	Coarse-grained andesite	583	do	

1/ K/Ar whole rock and Rb/Sr whole rock age except 30070, which is Rb/Sr age of microcline crystal.

2/ Geochron = Geochron Laboratories, Inc., Mass., U.S.A.; U.S.G.S. = Carl E. Hedge, Branch of Isotope Geology, U.S. Geological Survey, Denver, Colorado.

3/ Arranged in order of increasing age from field relations; brace shows similar inferred age.

reflect an apparent age related to metamorphic effects from intrusion. The real age of the andesite unit is not shown by these analyses.

The isotopic ages show that emplacement of the rocks of the peralkalic magma series began late in Precambrian time and continued until Late Cambrian time.

Structure

The general structural setting of the area is well shown on the map by Brown and Jackson (1959) where metamorphosed interlayered volcanic and sedimentary rocks of the Wadi Wassat quadrangle are part of the east limb of an immense synclinorium(?) that closes southward around a batholitic core of gneissic granite. The layered rocks were tightly, even isoclinally, folded along northerly and north-northeasterly trending axes prior to the intrusion of the peralkalic magma series. Major regional faults along the same trend show persistent left-lateral displacement. These old faults, in part at least, were reactivated along the same trend after intrusion of the magma series. During intrusion of the magma series, the already folded layered rocks were again folded as they were pushed aside for the entry of diorite, biotite granite, and other plutonic rocks of the series. Axes of folds thus formed commonly trend northwesterly, and major north-northwest, northwest, west-northwest, and westerly faults and fractures opened at this time. All movements are of pre-Permian age, because evidence for them is absent in the Wajid Sandstone. South of the quadrangle, between Jabal 'Ashirah and Najran, the Wajid Sandstone is downthrown as much as 100 m along numerous vertical faults. Doubtless such faults are in the Precambrian rocks in the Wadi Wassat quadrangle, but they were not identified.

The composite circular pluton at Jabal 'Ashirah has imperfect flow structures interpreted here to indicate that the walls of the pluton dip steeply inward, and that the body has the shape of an inverted tear-drop.

Rock weathering

The main evidences of rock weathering in the area of the Wadi Wassat quadrangle are the presence of saprolite and gossan, both of which are produced by chemical disintegration of original rock materials. Saprolite is soft enough to dig with pick and shovel, and the residual rock particles are unmoved with respect to each other. Because the particles are unmoved, the textures and structures of the original rock are preserved. Saprolite is largely quartz, clay, weathered mica, pyroxene and amphibole, and residual fragments of feldspar. Gossan may be either soft or flint-hard, and it is partly residual and partly transported.

Most discussions of rock weathering show that heavy rainfall is needed for the chemical solution leading to the formation of saprolite. If the saprolite in the Wadi Wassat area formed under conditions of greater rainfall than presently obtain (about 5 cm per year), it is most uncertain that heavy rainfall was needed. The gossan is still forming under conditions of sparse rainfall.

Pre-Permian chemical weathering

The flat erosion surface on which the Permian or older Wajid Sandstone is deposited is evidence of long exposure and erosion of the crystalline rocks prior to the deposition of the Wajid. Locally the Wajid Sandstone overlies deep saprolite of the crystalline rocks. Apparently the Permian or older erosion surface on which the Wajid was deposited was weathered, and the weathering products, though in general eroded and deposited in the sandstone as lenticles of clay, were not everywhere removed, and relict saprolite was preserved locally under the sandstone. These relations are of importance in a consideration of the age of the gossan at Wadi Wassat.

Post-Permian chemical weathering

Presence of saprolite under the Wajid Sandstone is strong indirect evidence that a gossan was also present over the pyritic rocks at Wadi Wassat prior to the deposition of the Wajid. After this probable gossan was covered by Wajid Sandstone it is likely that the unconformable interface between the Precambrian rocks and the Wajid Sandstone was a surface on which ground water continued to move. The water would have filtered into the pre-existing gossan and continued the leaching and oxidation of the pyrite, thereby extending the gossan to greater depth.

Eocene(?) lateritic weathering, which reached as deep as 130 m in the As Sarat mountains (Brown and Jackson, 1959) only 110 km west-southwest of Wadi Wassat, seems not to have affected the rocks presently exposed in the Wadi Wassat area; therefore, the Wajid Sandstone probably covered the Precambrian rocks in Eocene(?) time. However, if the Eocene(?) climate was notably wet, it is possible that deep oxidation proceeded then under the Wajid at the gossan on Wadi Wassat. Unroofing of the gossan in post-Eocene(?) time brought to the surface once more a weathering product of great antiquity. Continued weathering and erosion into Recent time formed the present exposures.

Thus, the gossan is believed to have formed over a long time interval, but none of the presently exposed gossan is likely to be as old as the pre-Wajid erosion surface. This old surface forms the top of the ridge of andesite 2 km west of the gossan, and it stands at about 1350 m above sea level. The top of the present gossan-covered hills is about 1280 m, and marks the level of an intermediate surface. A third surface at about 1250 m is forming today at the level of the present wadi drainage. Formation of the presently-exposed gossan thus dates back to the time of the intermediate level. The age of this surface is not known, but it probably is mid-Tertiary and younger than the Eocene(?) laterite of the As Sarat, because the present base level is already well developed at the level of Wadi Wassat which doubtless has required a considerable length of time to accomplish

Quaternary alluvium cemented with iron oxides adjacent to gossan is proof that the process of solution and oxidation is continuing at the gossan. Inasmuch as chemical weathering tends to bring diverse materials toward a uniform chemical composition, the postulated long continued weathering at Wadi Wassat would help explain the slight variation in the distribution of minor elements in the gossan.

Saprolite has also continued to form on crystalline rocks exposed in wadis developed since the removal of the Wajid Sandstone, because thin saprolitic rinds are locally on rock outcrops at the wadi floors.

Geologic relations of selected elements

Samples of -30 mesh +80 mesh wadi sand weighing about 100 g and smaller samples of detrital magnetite were collected at 142 localities in the Wadi Wassat quadrangle and analyzed spectrographically and 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. More than 1000 samples of gossan, drill core, and rock chips were taken for analysis in investigations of massive pyrite at Wadi Wassat and Wadi Adhbat, but the results of this work, summarized in the section on mineral deposits, are shown on the plate 2.

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 L. Aldugaither and Ibrahim Baradja. Methods of spectrographic analysis (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.2 and 3) and map (pl.2), where it can be seen that 21 of the 27 elements were detected in the spectrographic analyses. Elements sought but not found, and their limits of detection, are: silver, 1 ppm (parts per million); bismuth, 20 ppm; cadmium, 50 ppm; germanium, 20 ppm; antimony, 200 ppm; and tungsten, 50 ppm. When the abundances of the 21 detected elements are compared with regional abundances found for 1787 samples of wadi sand in the area of the Asir quadrangle, it is seen that 20 of the 21 elements reach threshold abundance and 15 reach anomalous abundance (table 2). The values for threshold and anomalous abundances were determined by inspection of histograms of the 1787 samples from the Asir quadrangle, which tended 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 anomalous values may be somewhat low.

The values for copper, zinc, and molybdenum in detrital magnetite from the area of the Wadi Wassat quadrangle (fig.3) were compared with

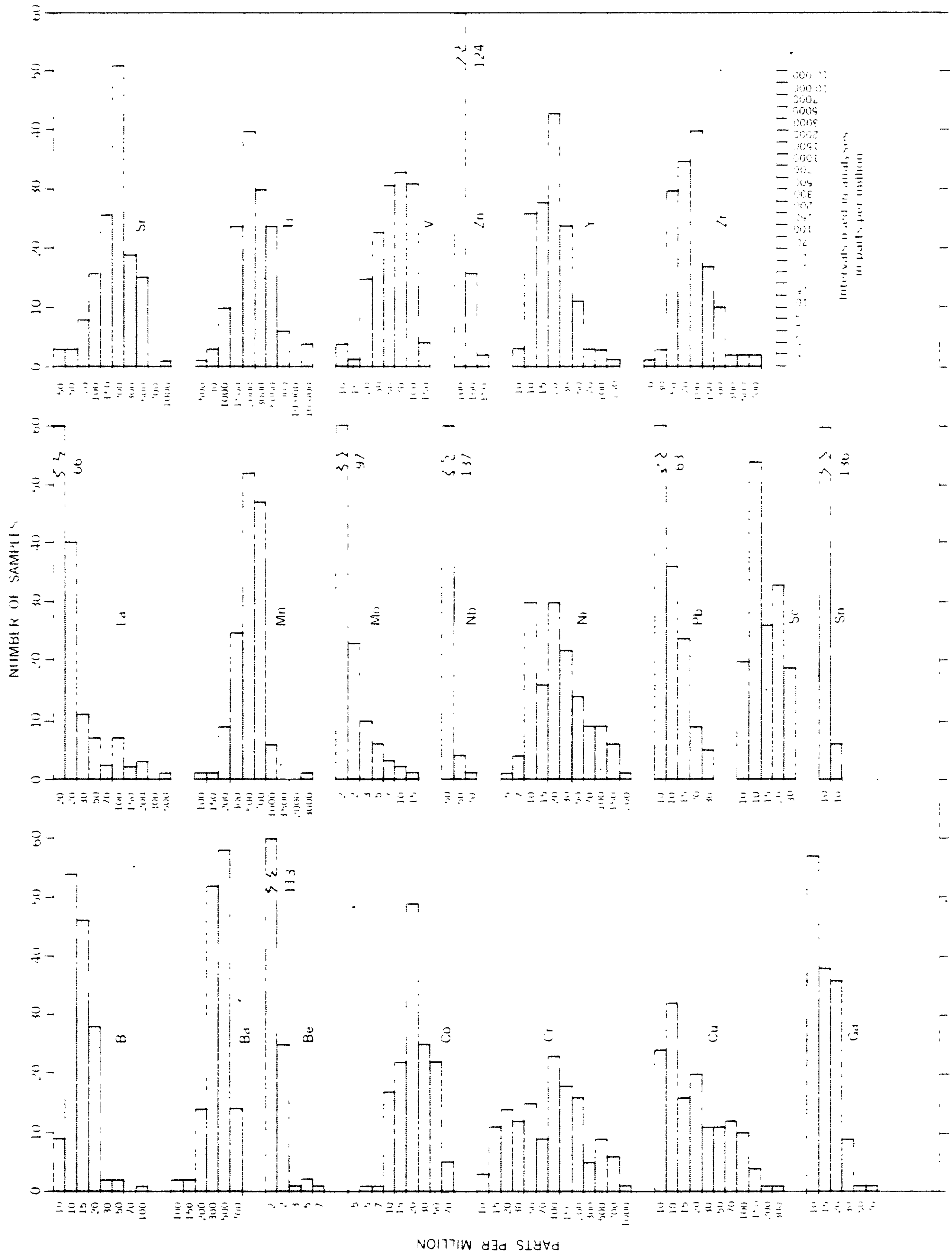


Figure 2. Histograms of 142 spectrographic analyses of wadi sand Wadi Wassat quadrangle

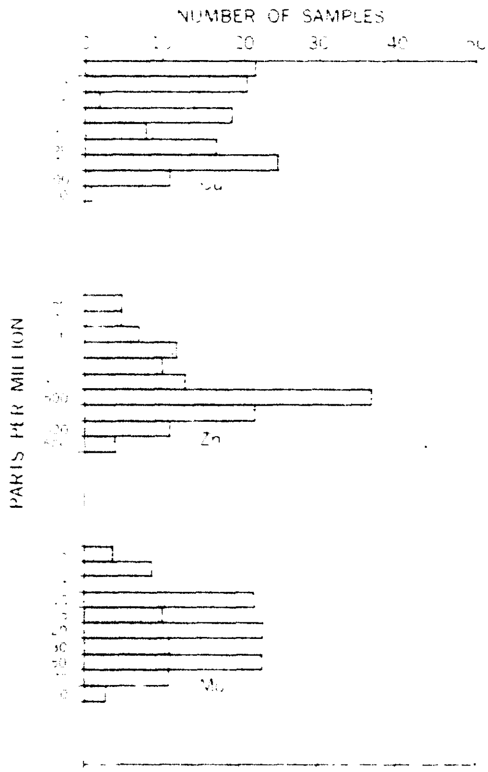


Figure 3.—Histograms of 125 [illegible] analyses
[illegible] magnetite [illegible]

Table 2.--Threshold and anomalous values for selected elements in wadi sand and magnetite, Wadi Wassat quadrangle, Kingdom of Saudi Arabia.

Element	Regional values from Asir quadrangle, ppm		Number of samples in Wadi Wassat quadrangle at or above regional values	
	Threshold	Anomalous	Threshold	Anomalous
Wadi sand				
Boron	30-50	70+	4	1
Barium	700-1,000	1,500+	14	--
Beryllium	2	3+	25	4
Cobalt	50	70+	22	5
Chromium	300-500	700+	14	7
Copper	70-100	150+	22	6
Gallium	30-50	70+	10	1
Lanthanum	50	70+	7	15
Manganese	1,000	1,500+	6	1
Molybdenum	3-5	7+	16	6
Niobium	50	70+	4	1
Nickel	150	200+	6	1
Lead	20-30	50+	14	--
Scandium	30	50+	19	--
Tin	10-15	20+	6	--
Strontium	700	1,000+	--	1
Titanium	7,000-10,000	>10,000	6	4
Vanadium	150-200	300+	4	--
Zinc	100	150+	16	2
Yttrium	50	70+	11	7
Zirconium	150	200+	17	18
Detrital magnetite				
Copper	100	150+	11	1
Zinc	700	1,000+	22	4
Molybdenum	30-50	70+	34	14

results of analyses of 1633 samples of magnetite from the Asir quadrangle, and the number of threshold and anomalous values are shown on plate 2 and in table 2. In table 2 the threshold and anomalous values in detrital magnetite are about one order of magnitude higher than in wadi sand.

Several notable groupings of threshold and anomalous trace elements are associated with specific rock units (pls. 1 and 2). The most obvious of these is the association Be, La, Nb, Pb, Sn, Y, and Zr with granitic rocks of the peralkalic magma series. Other associations are: Co, Cr, Ni, Mn, Ti, and Sc with the andesite unit and mafic intrusives; Cu, Mo, Zn with diorite, gabbro, and the andesite unit, particularly where the andesite unit has massive sulfides.

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

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 are characteristic of sands from granites in the peralkalic magma series.

Beryllium, lanthanum, yttrium, and zirconium are commonly but not invariably enriched in the same sample, and the association lanthanum-yttrium-zirconium is in greater amounts than that of the four elements. Niobium-enriched samples are invariably rich also in beryllium, lanthanum, yttrium, and zirconium, but the reverse is not true: niobium is the least common element in the full suite. Rise in abundance of yttrium is paralleled by strong rises in beryllium, lanthanum, and zirconium, and the sporadic entry of niobium, lead, and, very locally, titanium. Threshold and anomalous values for zirconium are more numerous than those for any other element in the Wadi Wassat area; thus, threshold amounts of zirconium are rarely accompanied by threshold or greater amounts of the other elements in the association.

Threshold and anomalous gallium is generally associated with beryllium, lanthanum, lead, and zirconium in the younger red granitic rocks, particularly the pyroxene-bearing granites, of the peralkalic magma suits. Gallium is also enriched in one sample each of sand from gabbro and biotite-almandine skarn.

No anomalous lead was detected. Threshold lead is in two associations: a common association with threshold and anomalous beryllium, gallium, lanthanum, yttrium, and zirconium, or restricted suites of these elements, where beryllium is the most common associate; and three occurrences in which threshold lead in wadi sand is unaccompanied by other trace elements at threshold or anomalous abundances. These three occurrences probably represent extreme examples of restricted suites in the peralkalic magma series: Two localities are in biotite granite and one is in porphyritic biotite granite. Also, all wadi sand samples with threshold lead are the sources of detrital magnetite enriched in molybdenum and zinc--an assemblage in magnetite characteristic of sources in granites of the peralkalic magma series.

Generally, lead tends to be associated with the lower anomalous and threshold values for yttrium.

No anomalous tin was detected. Threshold tin is in six samples possibly representing two sources: three in the restricted or full suite of beryllium, lanthanum, yttrium, and zirconium of which two are associated with lead and all are from biotite granite; and three in suites free of those elements. These samples are from mixed rocks at contacts between biotite granite, diorite, and andesite, including gossan. Thus, it is not certain if the contact area of the biotite granite is the source of the tin, but it probably is and is otherwise free of the general association of beryllium and the other elements.

Zirconium in threshold and anomalous abundances is associated with the early mafic rocks of the magma series--gabbro and diorite--and persists through the full sequence to reach highly anomalous abundances in the youngest parts of the zoned granitic pluton at Jabal 'Ashirah. Lead appears to be preferentially associated with the oldest granitic rocks of the peralkalic magma series, and in them it is present in a uniquely restricted suite lacking other trace elements in threshold or anomalous abundance, as for example in the biotite granite in the southwestern quarter of the quadrangle. Tin is also associated with the older granitic rocks of the series. Threshold beryllium is in granites of probable intermediate age in the peralkalic magma series, like the major pluton in the north-central part of the quadrangle. Beryllium persists through the series to the youngest units of the zoned pluton at Jabal 'Ashirah, where beryllium commonly reaches anomalous levels. Niobium has a strong tendency to be associated with the younger rocks of the peralkalic magma series: three of the four threshold values and the only anomalous value for niobium are in the young intrusive rocks of the pluton at Jabal 'Ashirah. Lanthanum and yttrium are common in the younger granitic rocks of the magma series and rare in the older granitic rocks.

None of these threshold or anomalous metals is known to be sufficiently concentrated to be exploitable, but the pattern of distribution indicates the preferred associations of these elements. If minable concentrations of beryllium, the rare earths, niobium, or zirconium are in this area, then they are mostly likely to be associated with the youngest rocks of the peralkalic magma series. Anomalous lead and tin are absent; however, if anomalous concentrations are found, they are likely to be associated with the older granitic rocks of the magma series.

Cobalt, chromium, and nickel

Threshold and anomalous cobalt and chromium are associated in only 9 of the many samples in which the individual elements have been enriched. However, threshold and anomalous nickel is invariably accompanied by threshold and anomalous cobalt and copper, and in 6 out of 7 samples threshold and anomalous nickel is accompanied by threshold chromium. Cobalt is more commonly found at threshold and anomalous values than chromium or nickel, and nickel is the least common of the three. Nickel in threshold or anomalous amount is found only in andesite or metamorphosed andesite, but cobalt and chromium are also commonly associated with gabbro and diorite. Cobalt and nickel, particularly, but also chromium, commonly are with threshold or anomalous copper in areas of andesitic rocks containing massive sulfides at Wadi Wassat and Wadi Adhbat. Indeed, on a regional scale, the andesite sequences with interlayered massive sulfides are characterized by greater amounts of cobalt, chromium, nickel, copper, molybdenum, and zinc than sulfide-free sequences of andesite.

At none of the localities represented by these threshold and anomalous values has any evidence of minable concentrations of these elements been found. Their presence, however, focuses further attention on the massive sulfide bodies.

Manganese, titanium, and scandium

The sample with anomalous manganese and three of the six samples with threshold manganese accompany the four anomalous values for titanium. However, threshold titanium is not associated with threshold or anomalous manganese, and titanium at both threshold and anomalous concentrations is not accompanied by threshold or anomalous copper. A strong association exists between threshold and anomalous manganese and threshold zinc: five of the seven manganese-enriched samples have threshold or greater amounts of zinc. Cobalt and scandium are commonly but not invariably associated with the manganese but both these elements are far more commonly represented among anomalous or threshold samples in the Wadi Wassat area than is manganese. Manganese-enriched samples, like titanium-enriched samples, tend to come from andesite, gabbro, and diorite, but the manganese-enriched samples have a tendency for association with volcanic rocks and the titanium-enriched samples mostly from plutonic rocks, gabbro and diorite being the commonest sources. A clear antipathetic relation exists between titanium-enriched samples and samples enriched in chromium or copper such that no threshold or anomalous values for titanium are associated with those for chromium or copper. This mainly appears to be caused by the association of above-background chromium and copper with mafic volcanic rocks and titanium with plutonic rocks.

Scandium is most commonly, but not invariably, associated with cobalt, chromium and manganese in areas underlain by mafic volcanic rocks. However, scandium is in three of the four samples anomalously rich in titanium, which are also enriched in cobalt and manganese and are from biotite diorite and biotite-hornblende diorite. Scandium thus is only enriched in samples from areas underlain by basic rocks, but in these areas scandium tends to be mostly near contacts where the mafic rocks, commonly diorite or gabbro, are intruded by granitic rocks of the peralkalic magma series.

Minable concentrations of manganese or titanium were not observed in the quadrangle. Scandium is in concentrations not more than 30 ppm.

Copper, molybdenum, and zinc in wadi sand

Copper and zinc are strongly differentiated in the samples of wadi sand. Copper is largely associated with samples from the andesite unit, particularly in massive sulfides. Several threshold samples of zinc are from areas underlain by syenite and pyroxene or hornblende granite grading into syenite, but the most common associations of the zinc-enriched samples are with diorite and gabbro of the peralkalic magma series, diorite of the andesite unit, and gossan on massive-sulfide-bearing parts of the andesite sequence. Threshold and anomalous zinc occurrences bear a strong antipathetic relation to copper-enriched samples. Only 3 out of the 18 zinc-rich samples are with copper: one is derived from gossan and two are from andesite. A similar but not as strong tendency separates threshold or anomalous zinc from molybdenum. Only seven of the 22 molybdenum-enriched samples are associated with zinc. Of the three elements, molybdenum is the only one enriched along fault zones in the granitic rocks of the peralkalic magma series.

Copper is commonly accompanied by cobalt, but cobalt is rather uncommon in association with zinc-enriched and molybdenum-enriched samples. This association relates to the tendency for copper and cobalt to be enriched in the andesite unit where there are massive sulfides.

Exploitable copper, molybdenum, and zinc were not observed in the areas of threshold or anomalous samples, but the distribution of copper and zinc, particularly, bears a close relation to the known large bodies of massive sulfide. Although the massive sulfide bodies are not presently known to have copper or zinc ore, genetically similar deposits should be sought in adjacent areas for these ores.

Copper, molybdenum, and zinc in detrital magnetite

Notable differences are present between the total number of magnetites with threshold and anomalous copper, molybdenum, and zinc and the total of wadi sand samples enriched in these elements (table 2). Only 12 magnetites are enriched in copper whereas 28 samples of wadi sand are so enriched. Molybdenum is far more common at threshold and anomalous abundances in magnetite (48 samples) than in wadi sand (22). Zinc is enriched in 26 magnetites and 18 sands. Half of the copper-enriched magnetites are from localities where the wadi sand is also enriched in copper, but only 20 percent of the molybdenum-enriched magnetites and 10 percent of the zinc-enriched magnetites are from localities where wadi sand is similarly enriched.

Only one of the magnetites with threshold or anomalous copper is also enriched in molybdenum, and none with copper is enriched in zinc. This partition of trace elements in the magnetites relates to the source rocks of the magnetite. Magnetite with threshold or anomalous copper is derived mainly from graphitic slates, carbonaceous shale, marble, and schistose pyroclastic rocks in the andesite unit or its metamorphic equivalents. Molybdenum and zinc are preferentially enriched in magnetites from the younger plutonic granitic and syenitic rocks of the peralkalic magma series. Copper in magnetite is commonly accompanied by threshold or anomalous cobalt in wadi sand.

Seven of the 12 copper-enriched magnetites are from the general area of the massive sulfide deposits at Wadi Wassat; however, they are dominantly from parts of the andesite unit intruded by north-trending rhyolite dikes east of the sulfides. The other copper-bearing magnetites are mainly from localities in sericite-chlorite schist and andesite associated with the Wadi Adhbat sulfides.

Molybdenum and zinc in magnetite are among the commonest trace elements disclosed by the analyses. Molybdenum is closely associated with zinc: only three samples of threshold or anomalous zinc out of the 26 are unaccompanied by molybdenum. Wadi sand from the same localities as the molybdenum- and zinc-enriched magnetites typically contain threshold or anomalous beryllium, lanthanum, lead, yttrium, and zirconium--elements characteristic of sand from the peralkalic magma series. Even the zinc-bearing magnetites lacking molybdenum are in sand with restricted suites of trace elements common to the peralkalic magma series. The youngest plutonic granites of the magma series, for example, the pluton at Jabal 'Ashirah, mostly yield magnetite enriched in molybdenum and zinc. Diorite and older granites in the series tend to have magnetite with above-background amounts of copper and molybdenum.

No evidence for minable enrichments of copper, molybdenum, or zinc was found.

Barium and strontium

Barium and strontium in wadi sand have weak associations with rocks of the peralkalic magma series. In half its occurrences, threshold barium is associated with gabbro, diorite, granodiorite, biotite-hornblende granite, and syenite of the magma series. Where barium is enriched in sand from granite of the magma series, the barium tends to be unassociated with other threshold or anomalous elements; rarely beryllium and lead may be present. Barium is associated with zirconium in sand from syenite, with strontium in sand from granodiorite, and with cobalt in sand from gabbro. The other occurrences of threshold barium are with sand from schists, andesite, and biotite-almandine skarn. Chromium is a common element in sand from hornblende schist and sericite-chlorite schist. Gallium, yttrium, and zirconium are enriched with barium in sand from the skarn. Barium-enriched sand from andesite and schist tends to lack associated trace elements.

Variations in the quantity of barium in the samples reported here show no relation to the massive sulfide bodies in the andesite unit. However, detailed analyses of drill core from the massive sulfide bodies show good inverse correlation between the massive sulfide and the amount of barium (Overstreet, Raisanen, and others, 1969, p.68).

The only analyzed sand in the Wadi Wassat quadrangle with anomalous strontium is from granodiorite. Threshold barium is also present.

Neither barium nor strontium was found in exploitable abundance in the samples.

Boron and vanadium

Boron in threshold and anomalous amounts is sparsely with other enriched elements, generally copper, cobalt, molybdenum, and scandium, which are the commonest trace elements in the sand samples. Boron is more common in sand from sedimentary parts of the andesite unit than from volcanic parts; thus, boron is in sand from slate, marble, and argillite in addition to andesite.

Three of the four threshold vanadium values are with threshold scandium, and two contain threshold copper and cobalt. All samples with vanadium are from andesite, chlorite schist, or gossan developed on massive sulfide in the andesite unit. Anomalous vanadium is absent.

Neither boron nor vanadium was found in exploitable abundance in the sampled areas.

Tungsten in scheelite

No sample of wadi sand had enough tungsten to be detected by spectrographic methods. However, examination of the wadi sand by ultraviolet light revealed eight samples to have scheelite. Five of them are from granites of the peralkalic magma series. One, on the north rim of the Jabal 'Ashirah pluton, has nearly the full suite of trace elements characteristic of the magma series. The other scheelite-bearing samples from the magma series have restricted suites of trace elements characterized by beryllium and one other element at threshold level, or no other threshold element than beryllium. The three other scheelite-bearing sands are from sericite-chlorite schist and greenschist in which threshold to anomalous cobalt and chromium are present. Magnetite with anomalous molybdenum and zinc was found at two scheelite-bearing localities in pyroxene granite.

MINERAL RESOURCES

The largest known mineral deposits in the area of the Wadi Wassat quadrangle are massive sulfides in Wadi Wassat and about 30 km to the southwest along Wadi Adhbat. Several small ancient mines, probably worked for gold or gold and base metals, are in the area of the quadrangle, and low-grade occurrences of graphite have been observed. Some of the younger biotite granite has favorable characteristics for quarrying for use as building and ornamental stone.

Massive sulfide deposits

Wadi Wassat

Deposits of massive sulfide crop out over a strike length of 17 km, crossing Wadi Wassat at a point about 125 km by road north of Najran, a community on the border of Saudi Arabia and Yemen. The closest settlement to the sulfide deposits on Wadi Wassat centers around the great ancient wells at Bi'r Idimah on the main route from Najran to Bishah about 20 km north of Wadi Wassat. Small wells are at Bi'r Ihnasehriyah, within 2 km of the southern end of the deposit, and Bi'r El Hashraj, about 5 km east of the northern end of the deposit.

A conspicuous but locally discontinuous belt of gossan has developed to depths of 10 to 28 m over the massive sulfide deposits. Although the gossan has attracted the attention of contemporary geologists from the early 1950's onward, there is no physical evidence that early occupants of the region mined the sulfide deposits. Presently, Bedouin leach medicinal salts from sand adjacent to parts of the gossan. The deposits have been studied in the 1960's through geologic mapping, geochemical and geophysical surveys, and the drilling of nine holes, one of which was not completed. The results of these investigations have been described in a number of preliminary reports (Overstreet, 1968a; 1968b; 1968c; 1968d; Overstreet, Bahijri, Fourati, and Gonzales, and others, 1967; Overstreet, Raisanen, and others, 1969; Allen and Davis, 1969a; 1969b; and Weissenborn and Earhart, 1969).

The sulfide deposit at Wadi Wassat was originally thought by

Overstreet (1968d) to be of hydrothermal origin, and many textural relations reflecting this interpretation were discussed in 1966. The results of diamond core drilling and chemical analyses led to a reinterpretation of the possible mode of origin (Overstreet and others, 1969), and the concept of a metamorphosed syngenetic deposit consisting of very fine-grained massive and disseminated sulfides lying in and partly replacing a thin- to thick-bedded sequence of tuffaceous sedimentary rocks of andesitic composition and associated bedded volcanic rocks in the andesite sequence. Sulfides are also present in granite and diorite adjacent to the gossan, and in fault zones that cross the strike of the main sulfide-bearing layered rocks. Thus, the sulfides are not restricted to one stratigraphic unit, although the largest bodies are in bedded rocks.

Massive sulfide consisting of 80-95 percent of pyrite with some pyrrhotite forms beds 2.8 m to 24.5 m thick averaging 12 m in thickness as revealed by diamond drilling. Chemical analyses show up to 46.22 percent S with an additional 3.57 percent SO_3 in the massive pyrite (L. E. Reichen, written commun., 1967). Disseminated sulfide beds contain 35-80 percent pyrite with some pyrrhotite, range in true thickness from 2.1 to 16 m, and averages 6.3 m thick. If the sulfide deposits are part of a sequence of bedded rocks, as is here inferred, then the sulfides may extend to considerable depths. These bedded rocks form a septum between plutons of granite and diorite, and the sulfide deposits terminate to the north and south against intrusive granite.

Variable amounts of pyrrhotite are with the pyrite, and much younger pyrite and marcasite are in the gossan. Thus, pyrite at Wadi Wassat is in three major generations with several habits in each generation. The relationship between the pyrite and pyrrhotite is not exactly clear as of this writing, and more work needs to be done. One generation each of pyrrhotite and marcasite are present, and these sulfides are in several mineral associations. The three generations of sulfides are: (1) original syngenetic pyrite deposited contemporaneously with the host rock, (2) second generation porphyroblastic pyrite and first generation pyrrhotite formed from original syngenetic pyrite during a thermal rise associated with the intrusion of the plutons, and (3) third generation pyrite associated with first generation marcasite formed during weathering. Results of fire assay of 77 samples of core from massive and disseminated sulfides are mainly nil in gold. The greatest values for copper, lead, and zinc in core are respectively 115 ppm, 75 ppm, and 500 ppm. The highest values are in the core from the northern end of the gossan. Cobalt is in pyrite from core in a narrow range of values between 15 and 50 ppm, a tenor reported to be characteristic of sedimentary pyrite (Fleischer, 1955). In 46 analyzed samples, selenium tends to be undetectable at the level of 3 ppm (Irving May, written commun., 1967). Low abundances of nickel, manganese, selenium, and molybdenum (Wright, 1965, p.1013, 1016) support a thesis of original sedimentary origin for the pyrite.

Some of the most striking megascopic features of the deposit were produced by epigenetic replacement processes, but certain relict textures appear to be of syngenetic sedimentary of sedimentary-volcanic origin; the abundances of precious metals, base metals, and other minor elements are similar to abundances reported for pyrite of sedimentary origin. Thus, the Wadi Wassat deposit is probably polygenetic. Original syngenetic sulfide is thought to have mobilized during the thermal rise caused by igneous intrusions into the sulfide-bearing strata. New sulfide phases were generated and a strong migration of sulfer took place. Probably little or no sulfides or metallic elements were added. Thus, the chemical composition of the sulfides recrystallized or formed during the thermal rise and replacement stage have the same trace-element composition as the sulfides of original syngenetic origin. For example, it extensive bodies of pyrrhotite were produced by metamorphism of syngenetic pyrite lean in gold, silver, cobalt, and nickel, then the pyrrhotite would be lean in these elements.

The facts that small differences in chemical composition of samples exist between northern and southern parts of the deposit, and that analyses of surface samples representing the whole area of the gossan have not been completed suggests that more marked differences may be found on closer study. Many syngenetic deposits of massive sulfides locally contain these metals. Considering the immense size of the deposit at Wadi Wassat and the fact that massive sulfide bodies were unexplored in Saudi Arabia prior to the discovery of this deposit, further exploration for base metals is recommended, because there is the remote possibility that valuable metals in addition to iron and sulfur may be in some unexplored areas under the gossan. From present views of the origin of the sulfides it is here thought that the deposit will not contain ores of gold, silver, cobalt, or nickel. It is principally a potentially source for sulfur and iron; the possibility for the exploitation of the deposit for pyrite has not been appraised.

Tonnage estimates for the Wadi Wassat deposit as a whole are tentatively inferred as 4.2 million tons of 80 to 95 percent pyritic material per meter of depth, basing this inference on a ratio between surface area of gossan and thicknesses of pyrite measured in drill core. This estimate appears to be a maximum order of magnitude. Estimating material with 80 to 95 percent of pyrite in the areas of influence of the eight drill holes, Weissenborn and Earhart, (1969, p.14-15) arrived at 125 million tons of pyrite with at least an equal amount of lower grade material with 35 to 80 percent pyrite. However, the prism of gossan above the sulfides is thought be unsuited for use as an iron ore owing to large percentages of undesirable oxides. Ten samples contained 24.5 to 31.9 percent iron with about equal amounts of silica and 3.8 to nearly 11 percent of sulfur. Alumina, lime, and phosphorus are also high.

Wadi Adhbat

The Wadi Adhbat mineralized area is about 30 km southwest of the massive sulfide deposits at Wadi Wassat and appears to be in the same sequence of rocks, or part of the same sequence, explored at Wadi Wassat (Overstreet, 1968a; 1968b ; Davis and others, 1969 ; D.L. Rossman, written commun., 1967; and Weissenborn and Earhart, 1968). The Wadi Adhbat deposits are mainly along and adjacent to Wadi Adhbat and its northern tributary, Wadi Garruther, centering around Bi'r El Adhbat 20 km north-west of Jabal 'Ashirah and 32 km west of the road from Najran to Bishah. Several small wells are in the Wadi Adhbat basin, but the water supply is scanty and the only fixed settlement is a family at Bi'r El Adhbat.

The Wadi Adhbat area is underlain by highly folded but slightly metamorphosed massive andesitic rocks interbedded with the sulfide-bearing rocks (pl.1). These pyroclastic rocks and sedimentary rocks form a roof pendant in a differentiated sequence of igneous rocks consisting mainly of plutons of diorite and granite, which locally contain small amounts of sulfide. The plutons separate the sulfide-bearing rocks at Wadi Adhbat from those at Wadi Wassat. Dikes and plugs of granite, rhyolite, andesite, and diabase intrude the andesite sequence.

The three largest gossans in the Wadi Adhbat area were called by Weissenborn and Earhart (1969, p.17): (1) Nahaum gossan in the north-eastern part of the area; (2) the Al Harr gossan exposed 1 km west of the Nahaum; and (3) the Simlal gossan in the western part of the area. Nahaum gossan is the largest and the only one tested by diamond drilling. Results of exploration on it show that it strikes north, dips steeply east, and crops out continuously over a width of 10 to 200 m for a length of 1500 m on the west side of a tributary to Wadi Garruther. The gossan thins and terminates to the north but is cut off by a fault to the south. Unmetamorphosed siliceous pyroclastic rocks are thought by Weissenborn and Earhart (1969, p.18) to be the host for the massive sulfides at Nahaum. On the hanging wall side the massive sulfides grades into disseminated sulfides in siliceous rhyolite, but on the footwall they terminate sharply at a contact with rhyodacite. The massive sulfide zone, consisting of 80-95 percent pyrite with some pyrrhotite, is 47 m in true thickness where drilled, and is estimated by Weissenborn and Earhart (1969, p.20) to decrease to about 10 m in thickness and have an average thickness of 28.5 m. Inasmuch as a continuous electromagnetic conductor was reported by Davis and others (1969) to extend for 1400 m under the gossan, the massive sulfide body at Nahaum was estimated by Weissenborn and Earhart (1969, p.20) to have this length, and the amount of massive sulfide to a depth of 100 m was estimated to be 11.67 million tons. Analyses of core from the Nahaum massive sulfide deposit disclosed no gold, no more than 0.44 oz/ton silver, and maxima of 30 ppm copper, 50 ppm zinc, and 10 ppm molybdenum. The exception low values for base and precious metals in the core indicate that economic deposits of these metals are highly improbable in the massive sulfide deposit (Weissenborn and Earhart, 1969, p.19).

The Al Harr and Simlal gossans are thought to resemble Nahaum gossan in geologic relations and composition. All are strata-bound syngenetic pyrite deposits with a fine-banded to colloform texture. The bands are commonly less than 1 mm thick and consist of dark gray, fine-grained, siliceous material. Extremely fine grained quartz is commonly in the massive pyrite zones, but is estimated by Weissenborn and Earhart (1969, p.19) to make up no more than 10 percent of the rock mass. Where associated siliceous volcanic rocks contain less than 15 percent of pyrite, the rock is unoxidized and gossan is lacking. Above 15 percent of pyrite the rock oxidizes, and small, weak gossan form parallel to the main gossan over massive pyrite (Weissenborn and Earhart, 1969, p.18).

Weathering has produced a platy exfoliation mimicking thin bedding in the rocks on which the gossan occurs (Martin, Conrad, written commun., May 3, 1969). This pseudo-bedding adds to the impression of stratigraphic control; however, the platy exfoliation lies roughly parallel to the slopes, draping, as it were, the ridges of gossan.

Very minor but real regional differences in the amount of copper associated with the sulfide-bearing rocks were found at four localities, but the anomalous amounts, generally 100-400 ppm, are thought to be too low to indicate possible deposits of economic value. In many of the areas sampled, the rock contains some of the original sulfides; thus, if copper were present in economic grade and size at the sampled localities, it is unlikely to have gone undetected. The four anomalous localities are: (1) the En Nugger Pass area where a small ancient mine is situated; (2) mineralized rock associated with a small intrusive plug 2.5 km northwest of Bi'r Adhbat where a small quartz vein contains specks of chalcopyrite and the wall rock to a distance of 1 m from the vein contains up to 1200 ppm copper; (3) sulfide-bearing rocks in the andesite sequence at lat 18°07'N.; long 44°05.5'E. contain 100 to 200 ppm copper;

and (4) the area 1.5 to 2 km due south of the previous locality, where analyses of sulfide-bearing rocks several hundred meters north of a granitic intrusive disclosed an increase in copper toward the granite to more than 200 ppm.

For the whole of the Wadi Adhbat massive sulfide area, inferred resources are tentatively estimated on the order of 5 million metric tons of sulfide per meter of depth. Available evidence shows that the deposits may be essentially barren of exploitable precious or base metals; thus, they are a potential resource for iron and sulfur. Should the pyrite deposits at Wadi Wassat prove to be of commercial interest, then the massive sulfides at Wadi Adhbat should be investigated further.

Gold and base metals

Quartz veins are not common in the Wadi Wassat quadrangle. They are particularly sparse in rocks of the andesite unit, but their number in this unit increase toward the contact of intrusive bodies of granite. Most veins consist of dense, massive, nearly barren white quartz that in places contains sparse carbonate and pyrite.

Large north-trending and northwest trending faults are in the quadrangle, and locally the north-trending faults are mineralized mainly in pyrite without copper-- but the northwest-trending faults are essentially void of mineralization.

The only evidence found for gold in the area of the Wadi Wassat quadrangle are a few small ancient and abandoned mines in the southwest part of the quadrangle in the general area of Wadi Adhbat. From the grindstones and other archeological evidence at the mines, it is here interpreted that the metal sought was gold. Assays and analyses of a few samples from these small openings disclosed low tenors in gold and small amounts of copper, but nothing of present economic grade and size. All the veins are small and do not appear to deserve further exploration.

Indirect evidence of the distribution of copper, lead, and zinc was given above in the section on geologic relations of selected elements, where it was shown that no positive anomaly for lead was found, and that the low positive anomalies for copper and zinc, though frequently associated with the same rock units, are strikingly antipathetic and seem to be too low to indicate the possible presence of ores of copper and zinc.

El Ergun mine

The abandoned ancient working or prospect trench know as El Ergun mine is 8 km west of the center of Jabal 'Ashirah. In its present condition El Ergun mine consists of an open trench, 2 to 4 wide and 20 m long, and 0.5 m deep, on a vein of white quartz striking N.30°E. and possibly 0.3 m thick and 20 m long (Overstreet, 1968a, p.13). Nearby are the remains of two or three ancient houses, but slag piles are absent. Very little ore appears to have been taken from the trench: only about 0.75 tons of quartz tailings are present, and waste rock on the dump, estimated at 30 to 40 tons, accounts for most of the rock removed.

Wall rock is coarse-grained biotite granite gneiss with foliation striking N.30°E., vertical. A phonolite sill intrudes the gneiss, and for a few meters forms the northeastern wall of the vein. The phonolite is chloritized and limonitized for 6 m at the northern end of the vein, but the alteration is not intense. The southern end of the quartz vein closes against a dike of andesite porphyry which strikes N.60°E., vertical, and is cut by the phonolite. The vein lies in the northwest quadrant formed by the dike and sill, and is subparallel to the phonolite sill. The vein consists of white massive quartz with sparse scattered pyrite crystals altered to limonite. Some joints and fractures are thinly stained by limonite, but the quartz is not heavily stained. The vein does not contain other sulfide minerals. Gold probably was the metal south.

About 0.5 km northeast of El Ergun mine a steeply dipping quartz vein strikes N.50°W. for 500 meters. Evidence of some prospecting in antiquity is present.

Another ancient working similar in size to El Ergun mine was reported by a local guide to lie 7 km to the north of El Ergun, but it could not be found.

Mine southwest of Bi'r El Adhbat

A quartz vein exposed 3 km southwest of Bi'r El Adhbat was worked formerly for gold. The site, marked by the remains of several stone buildings and by grind stones and other artifacts for crushing and milling quartz, lies between two small ravines in schistose rocks of the andesite unit. The rocks strike N.45°E. and dip 20°W. Although the quartz vein is no longer exposed, it appears from the shape of the workings to strike parallel to the schist for about 30 m and to dip gently southwestward. Distinctive gray-blue, dense, lustrous quartz is abundant in the dumps and around the ruins. Sparse galena and pyrite are in the quartz, and small grains of free gold were found in crushed quartz around the old grindstones.

A large quartz vein 5 to 7 m thick and several hundred meters long strikes northeastward and dips 20° to 30° W. on a ridge about 1 km southwest of the ancient mine and 4.4 km southwest of Bi'r El Adhbat. The vein appears to have been prospected in ancient times, but no mine workings are present. Small veins extend westward from the main vein. A few sparse grains of pyrite are near the footwall of the vein, but otherwise the vein seems to be barren.

Mine south-southwest of Wadi En Nugger

A quartz vein about 10 cm wide strikes north and dips 70° W. in schist of the same attitude about 3 km south-southwest of the mouth of Wadi En Nugger. Shallow workings extend along the vein for about 15 m, but the dump is small and other evidence of exploitation, like piles of crushed and ground quartz, are lacking.

En Nugger mine

The En Nugger ancient mine is an open trench 1.5 to 4 m wide, 2 to 5 m deep, and 44 m long in the saddle at the heads of Wadi En Nugger and Wadi Ghrutha. The ancient mine forms the pass between the two wadis. Rubble covers the floor of the trench. The trench is oriented N.20°E. in sheared andesite and argillite along the contact between siliceous gossan on the west and sheared, iron-stained andesite on the east (Overstreet, Bahijri, and Shararahly, 1969). Irregular surface workings consisting of shallow-pits and dug faces extend into red gossan for about 25 m west of the trench. No buildings, slag, or grind stones are present.

The rocks around En Nugger mine are hydrothermally altered and sheared argillite, rhyolite, and andesite which strike north and dip 35° E. These rocks are impregnated with pyrite, the weathering of which has imparted brilliant red stains which are a conspicuous feature at the head of Wadi En Nugger. The material excavated from the opening was hydrothermally altered rock and gossan. Quartz veins were not seen. Cutting the hydrothermally altered rocks of the northerly trending shear zone are unaltered, unfaulted, diabase dikes that strike N.70°W. and dip vertically. Mineralization at the head of Wadi En Nugger was before the intrusion of the diabase. No secondary copper minerals were seen in the area. Four grab samples of gossan, pyritized andesite, and pyritized carbonaceous argillite were analyzed by S. M. Bahijri and A. H. Shararahly and found to contain traces of gold and copper, up to 0.32 oz/ton silver, 0.15 to 0.25 percent lead, and 0.8 to 1.8 percent zinc. Pyrite and pyrrhotite were identified in core from diamond drill hole A3 sunk to a depth of 119.5 feet to explore mineralization under the gossan. Pyrrhotite increases in abundance with depth, and pyrrhotite and pyrite together make up 10 to 15 percent of the volume of the rock. The material drilled is of no economic value.

A quartz vein exposed about 1.8 km south of En Nugger pass contains widely scattered grains of chalcopyrite. The vein strikes northeastward and dips 20° to 40° northwest. It pinches and swells along strike, reaching a maximum thickness of 60 cm and locally pinching out. A hydrothermal alteration zone consisting of introduced iron carbonate extends outward from the vein for several meters into sedimentary rocks.

A quartz vein 4.9 km northwest of En Nugger pass is 5 to 7 m thick and has a strike length of about 500 m toward the northeast. The vein dips 20° to 30° S.E., and like the vein south of the pass, the hanging wall of this vein forms the present surface of a north-trending ridge. In general the quartz is white and almost barren of sulfides.

Other materials

The area of the Wadi Wassat quadrangle contains several notably fine exposures of pink to red, massive, medium-grained to locally porphyritic biotite granite suitable for quarrying and for use as ashlar dimension stone, and ornamental stone. However, at present the distances to using centers prohibit development. Among the best potential quarry sites are: (1) isolated exposures of pink massive, quartz-rich biotite granite suitable for ashlar, located 9 km west-northwest of Bi'r El Hashraj; (2) porphyritic, medium-grained biotite granite suitable for dimension stone, exposed 7.6 km southwest of Bi'r Ihnasehriyah; and (3) medium-grained granite suitable for dimension and ornamental stone in the southwestern promontory, on the western side, and at the southern end of the embayment on the north side of Jabal 'Ashirah.

A number of exposures of dark, impure, ferruginous, siliceous, or dolomitic marble are shown on plate 1 of which the largest beds are west of the head of Wadi Mahal. None of this material is suitable for industrial, agricultural, or architectural use; although some could be burned locally for crude lime. Outside the area of the quadrangle some impure marble beds have the composition of natural cement rocks (Overstreet, 1968d, p.37). Locally, where the metamorphic grade of the marble and its host rocks is in the amphibolite facies, almandine-bearing skarn layers are formed from the calcareous rocks. The possibility exists that some skarn may be scheelite-bearing. Perhaps where skarn is associated with the younger granites of the peralkalic magma series the most favorable conditions obtain.

Such skarn, in older units of the magma series, was found 4 km southeast of El Ain Welgereen in the south-central part of the quadrangle, but scheelite was not detected there.

Graphitic schist is exposed in the western part of the quadrangle, particularly along parts of Wadi Talham, Wadi Adhbat, and Wadi Senakha. Most commonly the graphitic rocks are sericite or muscovite schists associated with chlorite schist. However, the graphite is amorphous and makes up only a few percent to about 10 percent of the rock. Even where the schist is intruded by granite or diorite, as at the locality in Wadi Senakha 7.5 km southwest of Bi'r El Adhbat, and the metamorphic grade is raised to muscovite-chloritoid schist, crystalline graphite has not been formed. The graphitic schists in the quadrangle are too low grade for use as source of graphite.

SUMMARY

The most important potential ore deposits presently known in the quadrangle are the massive sulfides at Wadi Wassat and Wadi Adhbat. Feasibility studies are needed to learn if these deposits can be exploited for iron and sulfur. Favorable results of the feasibility studies would lead to the need for more detailed physical exploration of the individual deposits.

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