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RECONNAISSANCE GEOLOGY OF THE BI'R AL BADRIYAH QUADRANGLE

KINGDOM OF SAUDI ARABIA

by

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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 Also on open file in that office is a large amount of material, in the form of unpublished manuscripts, maps, field notes, drill logs, annotated aerial photographs, etc., that has resulted from other previous geologic work by Saudi Arabian government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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RECONNAISSANCE GEOLOGY OF THE BI'R AL BADRĪYAH QUADRANGLE, KINGDOM OF SAUDI ARABIA

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ABSTRACT

The Bi'r al Badrīyah quadrangle covers an area of 2843 sq km in the extreme eastern part of the Precambrian Shield in central Saudi Arabia. The Precambrian rocks in the southeastern part of the area are unconformably overlain by limestone of Permian age, which occupies only a small part of the quadrangle. Three great sequences of Precambrian rocks are recognized and called, from oldest to youngest, the Halaban Group, the Bi'r Khountina Group, and the Murdama Group. From evidence within the quadrangle itself the three groups are seen to be separated by erosional unconformities, and the Halaban and Bi'r Khountina Groups are intruded by granitic and gabbroic plutonic rocks and a wide variety of dikes. Exposures north of the quadrangle show that the Murdama Group is also intruded by granitic rocks.

The Halaban Group, consists of three formations called, from oldest to youngest, the Umm Mushraha Formation, the Jebal al Egfool Formation, and the Wadi al Jifr Formation. These rocks are variably metamorphosed, but characteristically they are at the epidote-albite amphibolite facies of regional metamorphism, are polymetamorphic, and rest unconformably on ancient granite gneiss. The Umm Mushraha Formation consists of amphibolite, schistose andesite, and greenstone associated with minor meta-agglomerate, meta-graywacke, and marble. The Jebal al Egfool Formation consists of sheared and metamorphosed volcanic rocks of intermediate composition, and the Wadi al Jifr Formation is made up of metamorphosed felsic volcanic rocks.

Rocks of the Bi'r Khountina Group are rather similar to the Halaban Group in original composition, but they are separated from the Halaban by an angular unconformity and have distinctive formations of conglomerate (the Idsas Formation), marble (the Fawara Formation), and graywacke (the Abu Sawarir Formation) at the base. Most of the Bi'r Khountina Group consists of andesitic volcanic rocks in the Badriyah Formation. Mostly, the Bi'r Khountina Group is unmetamorphosed or feebly metamorphosed to the greenschist facies. Locally, as in the aureole of intrusive rocks, the Bi'r Khountina Group reaches higher metamorphic grades.

The rocks of the Murdama Group unconformably overlie the Bi'r Khountina Group, and basal conglomerates of the Murdama contain fragments of distinctive rocks intrusive into the Bi'r Khountina. The Murdama Group is composed of the Z'reiba Formation, consisting of conglomerate and schistose conglomerate and the Abt Formation, a thick sequence of laminated, mainly fine-grained, sedimentary rocks. Metamorphism in the Murdama increases toward the north, and along the north edge of the area the Murdama Group is represented by chlorite-sericite schists.

Three major episodes of folding are recorded in the Precambrian rocks. The earliest episode folded the rocks of the Halaban Group along north-trending axes which are now truncated by the unconformity at the base of the Bi'r Khountina Group. After the rocks of the Bi'r Khountina and Murdama Groups were deposited, the three groups were folded along northwest-trending axes of regional scale. Later, possibly at a time of major faulting along a northwesterly direction, the rocks were again folded on north-trending axes.

Samples of rock materials collected at 105 localities in the quadrangle were analyzed for 27 elements. Only one anomalous value was found: a low positive anomaly for lead at the Umm Mushraha gold mine. Threshold amounts of Ag, B, Cr, Cu, La, Mn, Mo, Ni, Sc, Sn, Ti, V, and Zr were detected. The distribution of copper and molybdenum suggests that two plutons of biotite-hornblende granite in the central part of the quadrangle, and the rocks between them, should be examined for possible disseminated copper and molybdenum of the porphyry type. The distribution of scandium and detrital scheelite suggests that a zone adjacent to phyllonite in the northeastern quarter of the quadrangle be examined for tungsten associated with amphibolite.

Several small ancient gold mines, of which Umm Mushraha is the largest, were found in the quadrangle. None appears to be exploitable, but they constitute the most positive evidence for mineralization in the area. Umm Mushraha is in a mineralized zone that may extend north and north-northwesterly at least 30 km to the Umm Amal mine in the quadrangle to the west. This seems to be the most favorable area to explore for gold. Smagh mine is on a phyllonite zone which may also contain a little tungsten. Ancient and abandoned gold mines lie along the same fault structure in the quadrangle to the north. The pattern of intersection of north-trending faults by younger, northeast-striking faults, as seen at Smagh mine, is also present west of Smagh mine; the intersections were the sources of samples containing threshold copper and detrital scheelite. Such intersections and associated structures should be examined for possible gold.

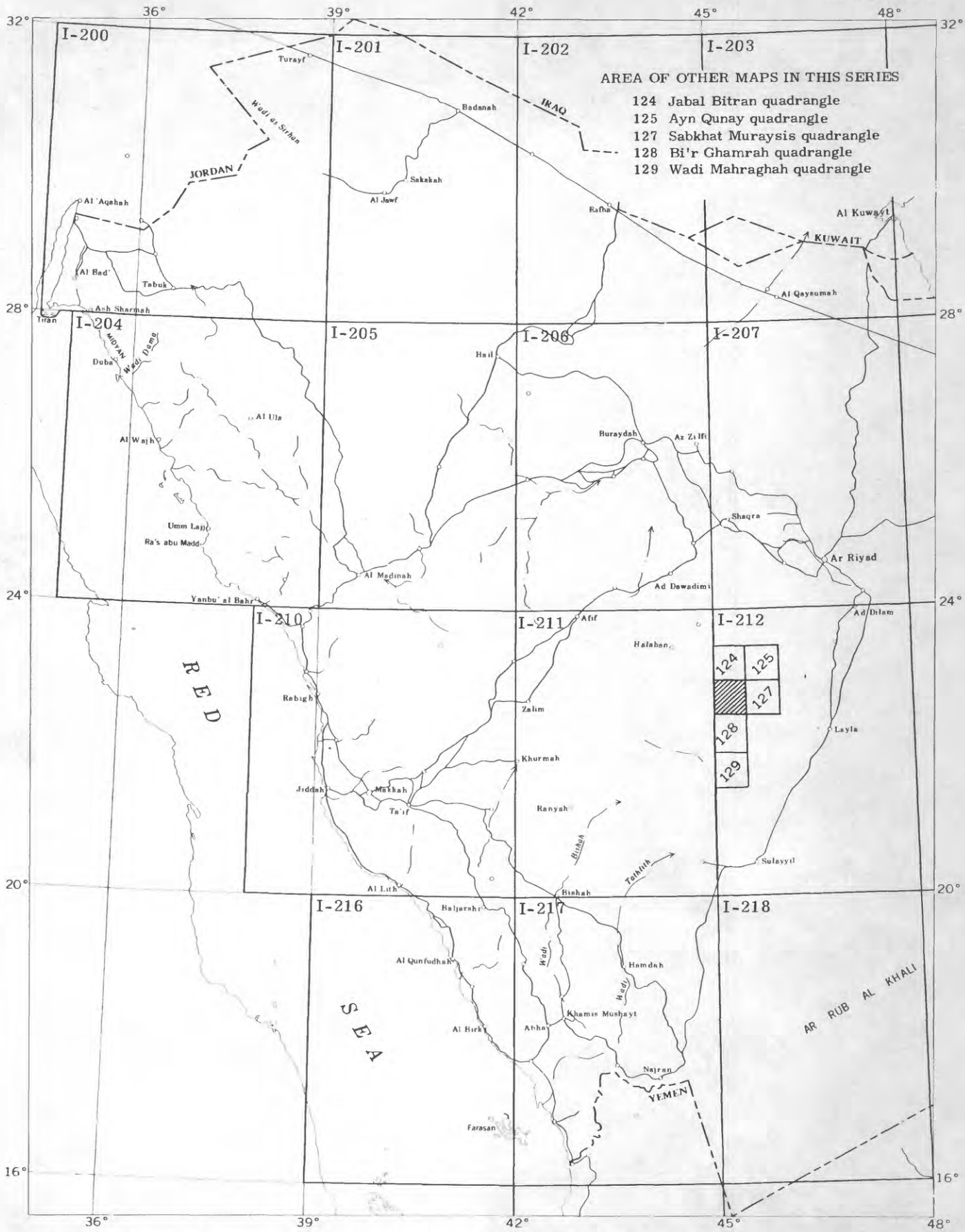

Figure 1. - Index map showing the location of the Bi'r al Badriyah quadrangle

Marble exposed at Jabal al Badr al Esswed in the south-central part of the quadrangle should be analyzed chemically. It could be readily quarried for industrial use, should the need arise, but the marble is too thin-bedded for use as building or ornamental stone.

INTRODUCTION

Location

The Bi'r al Badrīyah quadrangle, Kingdom of Saudi Arabia, covers an area of 2843 sq km in the central part of the country (fig. 1). In the extreme southeastern corner of the quadrangle the Precambrian rocks of the Arabian Shield are unconformably overlain by Permian sedimentary rocks. Altitudes of the wadi floors and hills are unknown, but it is estimated that the broad flats in the southeast are at an altitude of about 700 m above sea level and that the highest hills in the northeast are about 850 m above sea level. The principal drainage is southeastward into Wadi al Badrīyah, thence northeastward. Major unpaved roads cross the southern and northwestern quarters of the area, and tracks passable to trucks and four-wheel-drive vehicles lead between these roads and into the principal wadis. Small semipermanent encampments are around Bi'r al Badrīyah and Bi'r Mahantis near the main road in the south, but permanent settlements are absent. The water at Bi'r al Badrīyah is brackish, but that at Bi'r Mahantis is sweet.

Previous investigations

The area within the Bi'r al Badrīyah quadrangle is a small part of the western edge of the region shown on the 1:500,000-scale Southern Tuwayq quadrangle (Bramkamp, Gierhart, Brown, and Jackson, 1956). Except for the work of those authors, and a possible visit by a Ministry geologist to the Smagh mine, no previous investigations have been made of the Bi'r al Badrīyah area.

Present work and acknowledgments

The northeastern quarter of the quadrangle as far south as the fault passing northwestward from Sawda Diab was examined by V. P. Kahr, Directorate General of Mineral Resources, during two trips in October-November 1959 and June-July 1963. This same area was studied and sampled in reconnaissance fashion by Overstreet, Whitlow, and Ankary, April 6-10, 1964, (Overstreet and others, 1965), and the remainder of the area was examined by Overstreet and Whitlow between May 13 and May 19, 1164 (Overstreet and Whitlow, 1965), as partial fulfillment of the agreement reached in September 1963 by officials of the Ministry of

Petroleum and Mineral Resources, Kingdom of Saudi Arabia, and the United States Geological Survey to explore the mineral potential of the Precambrian Shield of Saudi Arabia. Throughout the work emphasis was placed on the search for ancient mines and mineralized rocks. Delineation of the regional geology was a secondary function. The final map and text was prepared by Overstreet and reflects his analysis of the geologic relations. A slightly different interpretation of the geology of the northeastern quarter of the quadrangle has been recorded by Kahr (1962).

The writers wish to thank the Ministry and the officials of the Directorate General of Mineral Resources for the support received in the conduct of this investigation.

GEOLOGY

The reconnaissance geologic map (plate 1) is based on brief field work; thus, many important concepts have not been thoroughly tested.

Rock types and stratigraphic succession

The northeastern and southwestern parts of the area covered by the Bi'r al Badrīyah quadrangle are underlain by amphibolite and other rocks of the Halaban Group. These rocks are overlain in a synclinorium in the central part of the quadrangle by unmetamorphosed to slightly metamorphosed younger Precambrian volcanic and sedimentary rocks of the Bi'r Khountina and Murdama Groups. Incompetent conglomerate and marble at the base of the Bi'r Khountina Group in the synclinorium has controlled faulting along the limbs of the synclinorium, but the Bi'r Khountina Group has more regional geologic significance than the faults, and the stratigraphic succession is not greatly altered by the faults.

Hornblende-biotite granite gneiss

The oldest rock exposed in the quadrangle is gray, nonlayered, hornblende-biotite granite gneiss. It is intimately intruded by dikes of diorite, gabbro, pyroxenite, and andesite, and it seems to have formed the land surface on which the Umm Mushraha Formation of the Halaban Group was deposited. Inclusions of biotite gneiss in the hornblende-biotite granite gneiss show that the hornblende-biotite granite gneiss itself was originally an igneous rock. Northward, beyond the limits of the Bi'r al Badrīyah quadrangle, the hornblende-biotite granite gneiss contains inclusions of ancient metamorphosed sedimentary rocks older than the Halaban Group, from which it is interpreted that there are older sedimentary rocks in this part of Saudi Arabia than any shown on plate 1. The hornblende-biotite granite

gneiss has been deformed at least two times; it is possible that it has undergone three deformations, but evidence for the third is lacking in this quadrangle.

Halaban Group

Unconformably overlying the hornblende-biotite granite gneiss is a great but unknown thickness of andesitic volcanic rocks, sparse associated graywacke, and other sedimentary rocks, now much altered by regional and contact metamorphism, to which the name Halaban Group is here given. The term is here raised to group from the original assignment of Halaban Formation (Jackson and others, 1963). In earlier work (Bramkamp and others, 1956) in the area covered by plate 1, the rocks here called Halaban Group were given several lithologic names but no formation name was assigned. From oldest to youngest those lithologic units here placed in the Halaban Group were called: amphibolite schist, amphibolite schist with mafic undifferentiated intrusive and extrusive rocks, and andesite and fine-grained dioritic rocks, flows, and intrusives. The degree of metamorphism of these rocks is variable, but in general the Halaban Group is more metamorphosed than the younger but similar-appearing Bi'r Khountina Group. Three formations, from oldest to youngest called the Umm Mushraha Formation, the Jabal al Egfool Formation, and the Wadi al Jifr Formation, are recognized in the Halaban Group. In the northeastern corner of the quadrangle, rocks of the Umm Mushraha Formation are locally converted to phyllonite along a fault.

Umm Mushraha Formation.-- The lower part of the Halaban Group consists of several more-or-less contemporaneous rocks of varying composition to which the name Umm Mushraha Formation is here given after prominent exposures on the north side of Wadi Umm Mushraha in the southwest part of the quadrangle. The Umm Mushraha Formation comprises four units: amphibolite, hornblende gneiss and schist, marble, and biotite-hornblende gneiss. Generally these rocks are of albite-epidote amphibolite and amphibolite facies in the western and southwestern parts of the quadrangle and of greenschist facies and albite-epidote amphibolite facies in the northeastern part of the quadrangle.

The amphibolite unit of the Umm Mushraha Formation consists of a wide variety of gray, green, and dark green, fine- to coarse-grained, layered and nonlayered metamorphic derivatives of what was originally andesite, andesite porphyry, agglomerate, gabbro, and sparse graywacke.

The hornblende gneiss and hornblende schist unit consists of strongly layered amphibolitic rocks the more massive of which are gneiss and the less massive are schist. The garnetiferous biotite-

hornblende gneiss unit is generally strongly layered with quartzo-feldspathic layers alternating with hornblende layers. Locally the garnetiferous biotite-hornblende gneiss is strongly lineated, and in places, as at the east end of Wadi Umm Mushraha, is nonlayered and granitic. The highest metamorphic grade reached by rocks in the Halaban Group, the lower subfacies of the amphibolite facies, is attained in the garnetiferous biotite-hornblende gneiss of the Umm Mushraha Formation.

Lenticles and pods of gray and brown marble and silicified marble are present in the hornblende gneiss and hornblende schist unit of the Umm Mushraha Formation, and somewhat smaller layers and masses are in the amphibolite unit. The marble may be more common in the upper part of the Umm Mushraha Formation than in the lower part.

Jebal al Egfool Formation.-- The Jebal al Egfool Formation in the Halaban Group, named here for prominent exposures of rocks of the formation on and around Jebal al Egfool in the eastern part of the quadrangle, consists of intermediate volcanic and hypabyssal intrusive rocks. The rocks in the formation are epidotized hornblende-quartz porphyry, and epidiorite. Gray-green sheared and epidotized quartz porphyry with blue quartz and epidotized hornblende-quartz porphyry is interpreted here to be a hypabyssal intrusive into amphibolite of the Umm Mushraha Formation, and to have been metamorphosed with the Umm Mushraha Formation. Thus, the epidotized quartz porphyry tends to grade by metamorphic change to chlorite schist and amphibolite indistinguishable from the amphibolite unit of the Umm Mushraha. The epidotized quartz porphyry is intruded by epidiorite, a dark gray to greenish gray, sheared and epidotized fine-grained diorite grading into andesite porphyry. The epidiorite seems to intrude quartz porphyry and is intruded by rhyolite porphyry dikes. The sequence of epidotized quartz porphyry, epidiorite, and rhyolite in the east-central part of the quadrangle may be a remnant of a caldera.

Wadi al Jifr Formation.-- The Wadi al Jifr Formation, named in the Sabkhat Muraysis quadrangle (Overstreet, Whitlow, and Ankary, 1972), is represented in the Bi'r al Badrīyah quadrangle by dark red to brown, massive to locally sheared rhyolite and rhyolite porphyry dikes that intrude epidiorite in the eastern part of the quadrangle. In the western part of the quadrangle similar dikes intrude amphibolite and garnetiferous biotite-hornblende gneiss of the Umm Mushraha Formation. The rhyolite dikes of the Wadi al Jifr Formation in the west are intruded by gabbro and diorite older than the Bi'r Khountina Group.

Gneissic granodiorite

The gneissic granodiorite is a complex unit of light-colored to dark green gneissic granodiorite, diorite, and associated epidotized, chloritized, and feldspathized mafic volcanic rocks. In places, particularly where the rock is most typically granodioritic, it is possibly older than the Halaban and a granodioritic phase of the hornblende-biotite granite gneiss much mixed with intrusive mafic rocks. Elsewhere it has the aspect of epidiorite and metamorphosed andesite with feldspar porphyroblasts. The rocks in the unit seem to be polymetamorphic. At many places insensible gradation exists between gneissic granodiorite and meta-andesite. The gneissic granodiorite is, however, separated from the overlying Bi'r Khountina Group by unconformity.

Gabbro and diorite unit and hornblende syenite

A unit of undivided gabbro and diorite forms gray to dark gray, fine- to coarse-grained, massive to gneissic plutons in the southwestern quarter of the quadrangle. The gabbro and diorite unit intrudes amphibolite and garnetiferous biotite-hornblende gneiss of the Umm Mushraha Formation and is intruded by swarms of andesite dikes of the Bi'r Khountina Group. Unconformably overlying the gabbro and diorite unit is conglomerate, marble, and andesite of the Bi'r Khountina Group. Doubtless the gabbro and diorite in this unit is of many ages, because many parts of the amphibolite in the Umm Mushrhaha Formation in the northeastern quarter of the quadrangle appear to have been derived from gabbro and diorite, and because unchanged cores of gabbro and diorite are preserved in schistose, gneissic, and amphibolitic envelopes. The position assigned to the unit as mapped only reflects the fact that the largest body of gabbro and diorite in the quadrangle cuts across rhyolite of the Wadi al Jifr Formation. Hornblende from a sample (number 432) of quartz dioritic gneiss from this area was reported by G. F. Brown (written commun., March 18, 1970) to have given a K/Ar age of 604 $\pm$ 12 m.y. in an analysis by Isotopes, Inc. This would appear to be a post-Bi'r Khountina Group and post-Murdama Group age.

A sill of nearly white hornblende syenite intrudes amphibolite of the Umm Mushraha Formation near the west edge of the quadrangle about 2 km north of Wadi Harehmbla. The sill is about 20 m thick, of unknown length, and is parallel to foliation in the amphibolite. The hornblende syenite is interpreted to be a magmatic differentiate from the gabbro and diorite unit.

Phyllonite

A long, narrow zone of gray and light-gray quartz-chlorite-sericite phyllonite crops out in the northeastern part of the quadrangle. Mottled surfaces of the phyllonite consist of aggregates of chlorite in a dominant matrix of quartz and sericite. The exposed length of the phyllonite is 17 km and the maximum width is about 1 km, but the fault along which it formed extends northward beyond the end of the phyllonite.

The phyllonite is inferred to have been produced by the low-grade metamorphic recrystallization of mylonite formed in a north-trending fault where cataclastic action reduced hornblende-biotite granite gneiss and amphibolite, chlorite-sericite-quartz schist, and meta-agglomerate of the Umm Mushraha Formation to mylonite. Subsequent progressive regional metamorphism caused the mylonite to recrystallize at the greenschist facies to phyllonite. Probably the recrystallization took place before deposition of the Bi'r Khountina Group, because the trend of the phyllonite is strongly athwart the strike of the unconformity and conglomerate that mark the base of the Bi'r Khountina Group. If the phyllonite formed before the Bi'r Khountina Group was deposited, then at least the northern extension of the fault along which the phyllonite occurs was reactivated in late Bi'r Khountina time, because gabbro and pyroxenite of probable late Bi'r Khountina age are cut by this fault in the extreme northern edge of the quadrangle.

Bi'r Khountina Group

The term Bi'r Khountina Group is used here for a thin sequence of unmetamorphosed to weakly metamorphosed Precambrian sedimentary and volcanic rocks that unconformably overlies the Halaban Group. The name of the group was introduced by Overstreet and Whitlow (1972a). In the area of the southern Tuwayq quadrangle (Bramkamp and others, 1956) represented here, the rocks equivalent to the Bi'r Khountina Group were called sericite and chlorite schist and amphibolite schist. Later the term Abt Schist was applied to metamorphosed parts of these rocks (U. S. Geol. Survey and Arabian American Oil Co., 1963). In the southern Najd quadrangle, equivalent rocks were shown as parts of the Halaban and Murdama Formations of Jackson and others (1963).

The Bi'r Khountina Group in the Bi'r al Badrîyah quadrangle consists of a lower, dominantly sedimentary facies overlain and intertongued by a volcanic facies. These rocks are divided into four formations called from oldest to youngest, the Idsas Formation, the Fawara Formation, the Abu Sawarir Formation, and the Badrîyah Formation. The sedimentary facies of the group is represented by the Idsas, Fawara,

and Abu Sawarir Formations, and the volcanic facies by the Badrīyah Formation. The sedimentary formations consist of a basal conglomerate (Idsas Formation), more or less continuous, overlain by discontinuous but locally thick beds of marble (Fawara Formation) above which is the main clastic sedimentary unit of the group (Abu Sawarir Formation) composed of graywacke and argillite. Rocks of the Abu Sawarir Formation are increasingly tuffaceous upward and include some andesitic tuff and flows. Overlying the Abu Sawarir are the andesitic volcanic rocks of the Badrīyah Formation.

The volcanic rocks appear to thicken northwestward into the core of the great synclinorium occupied by the Bi'r Khountina Group. The tightness of folding in this synclinorium seems to increase northward and the rocks of the Bi'r Khountina Group become progressively more metamorphosed northward. Along the northern edge of the Bi'r al Badrīyah quadrangle they have the typical greenschist facies aspect that caused them to be named Abt Schist (U.S. Geol. Survey and Arabian American Oil Co., 1963). They do not, however, occupy the ancient Precambrian position below the Halaban to which the Abt was assigned.

Idsas Formation.-- The Idsas Formation (Kahr and others, 1972) in the Bi'r al Badrīyah quadrangle consists of graywake conglomerate of variable thickness and composition that is discontinuously exposed along the northeastern flank of the synclinorium in the Bi'r Khountina Group where the conglomerate rests with sharp angular unconformity on the Umm Mushraha Formation and other rocks of the Halaban Group. The Halaban rocks, and old, north-trending structures defined by them, are overlain by the conglomerate. The conglomerate of the Idsas Formation is sheared and faulted at this contact. The faults more or less follow the unconformity because the conglomerate is less competent than the Umm Mushraha Formation below and the Badrīyah Formation above. Despite the faults the conglomerate is present along the contact, showing that the conformity is the principal geologic feature of the contact.

The graywacke conglomerate of the Idsas Formation has a chloritic matrix in which are set round pebbles, cobbles, and boulders of diorite, epidiorite, amphibolite, granite gneiss, and epidotized gneissic granodiorite, all of which crop out in the rock sequences to the east of and stratigraphically below the conglomerate. Boulders and cobbles of gray limestone and andesite are locally present. They may represent earlier-deposited rocks of the Bi'r Khountina Group reworked during relative fluctuations of sea level which exposed early Bi'r Khountina materials to erosion (Overstreet and Whitlow, 1972a). Thin, discontinuous beds of marble are intercalated with the conglomerate. The upper part of the conglomerate is fine grained and has a tuffaceous and arkosic matrix; pebbles are the largest clastic particles. The

fine-grained, tuffaceous conglomerate is overlain to the west by andesite porphyry.

Locally, as at Sawda Diab near the southeastern edge of the map, the chloritic conglomerate is strongly sheared, containing stretched cobbles and pebbles that form a lineation down the dip of the foliation and parallel to clots of chlorite in the matrix.

Intensely sheared conglomerate, possibly the Idsas Formation, is exposed in the extreme southwestern corner of the Bi'r al Badrīyah quadrangle where the conglomerate rests on gabbro and diorite and is at the base of the Badrīyah Formation. The conglomerate has a fine-grained chloritic matrix in which are set sheared pebbles and boulders of dark grayish brown marble up to 15 cm across, and pebbles of andesite Bedding in the conglomerate is obscured by two directions of cleavage, but the conglomerate seems to grade upward into weakly metamorphosed laminated tuff and argillite. All pebbles and boulders are well rounded. Where the matrix is not sheared and recrystallized it can be seen to be crystal lithic tuff of very small, sharply angular lithic fragments. This conglomerate may be as much as 300 m thick.

The conglomerate in the Idsas Formation along the northeastern flank of the synclinorium and the conglomerate near the southwest corner of the quadrangle contain detrital fragments of marble, have tuffaceous material in the matrix, and are in part overlain by andesite flows. No large bodies of marble are associated with them, but the conglomerate in the north has interbedded lenticles of marble. Similar conglomerate is absent above the large bodies of marble at Jabal al Badr al Esswed and Jabal al Badr al Hambra, and the marble grades downward into calcareous conglomerate. Similar marble and calcareous conglomerate grade downward to graywacke conglomerate with detrital marble, agglomerate, and greenstone in the Bi'r Ghamrah quadrangle (Overstreet and Whitlow, 1972a). Therefore, the conglomerate in the Bi'r al Badrīyah quadrangle is inferred to be below the thick marble unit.

It is probable that the conglomerate along the northeastern side of the synclinorium becomes progressively younger toward the north as the overlying sedimentary facies of the Bi'r Khountina Group gives way to the volcanic facies.

Fawara Formation.-- Discontinuous but locally thick beds of marble overlie the Idsas Formation and are here correlated with the Fawara Formation (Kahr and others, 1972). The largest exposures of this marble are at Jabal al Badr al Hambra and Jabal al Badr al al Esswed in the south-central part of the quadrangle on the southern limb of the

large synclinorium in the Bi'r Khountina Group. At these exposures the Fawara Formation consists of three parts which from bottom to top are: (1) gray calcareous conglomerate, (2) thin-bedded gray to black marble, and (3) brown silicified marble with stromatolitic structures. Their total thickness is not known. It changes abruptly along strike and may reach a thickness of as much as 800 m.

The gray calcareous conglomerate grades downward into bouldery graywacke conglomerate of the Idsas Formation. The gray calcareous conglomerate contains cobbles and boulders of gray, buff, and brown marble and chert, and boulders of blue and brown marble as much as 60 cm across. Locally the cobbles and boulders are stretched down-dip in the bedding planes of the marble. Fragments of igneous and metamorphic rocks are lacking.

Thin-bedded gray to black and locally red marble overlies the calcareous conglomerate with gradational contact. This marble is very pure, fine-grained calcium carbonate. Some of the best exposures are along the northern flank of Jabal al Badr al Esswed.

The brown silicified marble overlies the thin-bedded marble along contacts that are brecciated, sheared, and marked by slickensides. Possible tectonic slices of contorted, thin-bedded, nonsilicified, gray to black marble crop out in the brown silicified marble. Black to dark gray chert nodules as much as 4 cm across are present in the silicified marble, but they make up less than 1 percent of the volume of the rock. Irregularly rounded and embayed brown areas as much as 10 cm across of unreplaced calcite make up as much as 30 percent of the silicified marble. These brown calcite structures display highly variable degrees of crystallinity. Some are aphanitic and others are coarsely crystalline aggregates of rhombohedral calcite. They are interpreted to be stromatolitic structures.

Because the silicified marble contains tectonic slices of unsilicified, gray, thin-bedded marble, the silicification seemingly preceded the faulting. Possibly the silicification accompanied or soon followed the deposition of the original brown carbonate sedimentary rock.

Many features show that differential movement has taken place between the different types of marble. The stretched pebbles oriented down-dip may have been rotated into alignment. Breccia, shears, and slickensided surfaces at the contact between the silicified marble and thin-bedded marble, together with sharp folds in the thin-bedded marble which are absent from the silicified marble, show that the thin-bedded marble has been squeezed between competent overlying

silicified marble and underlying calcareous conglomerate. Along Jabal al Badr al Hambra and Jabal al Badr al Esswed the brown silicified marble appears to have been displaced toward the southwest over the gray marble and away from the main trough of the synclinorium occupied by rocks of the Bi'r Khountina Group.

Black calcite and white calcite veins commonly coat joints in both the nonsilicified and silicified marble. These veins are unmineralized.

A small mass of serpentinite is exposed with stromatolitic silicified marble on the little hill marking the extreme northwestern end of Jabal al Badr al Hambra. Possibly the serpentine was interbedded with the marble and was formed from an andesite flow when the marble was silicified.

Large individual beds of marble do not crop out along the southwestern flank of the synclinorium beyond the northwestern end of Jabal al Badr al Esswed. However, several small lenticles of silicified brown marble have been found to the northwest along the inferred contact between the Bi'r Khountina and Halaban Groups. These marbles are associated with hornblende gneiss and schist of the Umm Mushraha Formation. In the extreme northwestern corner of the mapped area, their relations are complicated by faults, by a small intrusive stock of peralkalic granite at their northern end, and by an intrusive mass of gabbro and pyroxenite on their east. These marbles are shown as part of the Halaban Group, but the real possibility exists that they are the approximate stratigraphic equivalent of the Fawara Formation at Jabal al Badr al Hambra, and that the enclosing hornblende schist is andesite of the Badriyah Formation metamorphosed to schist by the intrusive gabbro and pyroxenite.

Similar small bodies of marble (marked m on plate 1) have been identified at various places along the northeastern edge of the synclinorium in the Bi'r Khountina Group. Large bodies of marble are absent on this edge. This marble is interpreted to be interstratified lenticles not directly correlative with the thick masses at Jabal al Badr al Hambra.

Sheared boulders of dark grayish brown marble are present in conglomerate in the extreme southwestern part of the Bi'r al Badriyah quadrangle, but the marble itself was not found.

Marble was not shown by Bramkamp and others (1956) in the southern Tuwayq quadrangle. The marble at Jabal al Badr al Hambra and Jabal al Badr al Esswed was shown as amphibolite schist owing to its dark color

on aerial photographs and the resemblance of this color to the mafic rocks at Bi'r Mahantis. Very similar marble is shown on the geologic map of the southern Najd quadrangle (Jackson and others, 1963) to the west, where it is called Farida Marble. The main outcrop of Farida Marble is along the projected strike of the marble at Jabal al Badr al Esswed, but the stratigraphic position shown for the Farida Marble by Jackson and others (1963) is much higher than the position assigned here to marble of the Fawara Formation. Nevertheless, the similarities in lithology between the Farida Marble and the marble of the Fawara Formation in Jabal al Badr al Hambra, and the alignment of the two bodies along a major structure, suggest that they are part of the same formation and may be stratigraphic equivalents. The faults shown around the Farida Marble are here thought to be less important to the interpretation of the position of the Farida than the probable stratigraphic position occupied by the marble. Until the stratigraphic position of the Farida Marble is resolved in the southern Najd quadrangle no reason exists for extending the name southeastward to the marble in this quadrangle.

Abu Sawarir Formation.-- The basal conglomerate and marble of the Bi'r Khountina Group are overlain by a thick sequence of graywacke and argillite here named the Abu Sawarir Formation for prominent exposures at Jabal Abu Sawarir in the east-central part of the quadrangle. Metamorphic equivalents of these rocks are shown as chlorite-sericite schist of the Abu Sawarir Formation for those at the greenschist facies, and as biotite-muscovite schist of the Abu Sawarir Formation for rocks at the albite-epidote amphibolite facies. Metaconglomerate is also present in the formation. These sedimentary and metamorphosed sedimentary rocks are mainly exposed in the southeastern part of the northwest-plunging synclinorium in the Bi'r Khountina Group; thus, they are interpreted to be in the lower part of the group. Calcareous graywacke intertonguing with thin flows of andesite crops out in the northwestern part of the quadrangle. It has been mapped as graywacke of the Abu Sawarir Formation because of the main graywacke component. However, it probably is intercalated in massive andesite of the Badriyah Formation.

Variable amounts of volcanic material are associated with these rocks, and the quantity of tuff appears to increase upward. Agglomerate, tuffaceous andesite, tuffaceous graywacke, andesite porphyry, and thin andesite flows are the most common volcanic components of the Abu Sawarir Formation. Doubtless there is much interfingering of the sedimentary and volcanic rocks, and probably the sedimentary facies grades laterally and vertically into the volcanic facies.

Intermittently exposed and probably thin and lenticular layers of gray to brown marble are intercalated with tuffaceous argillite of the Abu Sawarir Formation north of Sawda Diab. Locally the marble is at the base of the tuffaceous argillite and rests on discontinuous lenticles of conglomerate containing pebbles and boulders of the underlying epidotized quartz porphyry of the Jebal al Egfool Formation. Where the marble and conglomerate are absent the tuffaceous argillite rests directly on rocks of the Halaban Group, which further supports the interpretation that the sedimentary facies of the Bi'r Khountina is in the lower part of the group.

The major intrusive into the Abu Sawarir Formation is biotite-hornblende granite, which has produced narrow contact metamorphic aureoles of chlorite-sericite schist and biotite-muscovite schist from graywacke and argillite and of chlorite schist from intercalated andesite.

Lenticles of graywacke conglomerate in graywacke and argillite of the Abu Sawarir Formation locally show metamorphic effects at the contact of intrusive biotite-hornblende granite. The matrix is recrystallized, and porphyroblasts of biotite and feldspar are present. This is almost certainly not conglomerate of the Idsas Formation. The graywacke metaconglomerate with porphyroblasts of biotite and microcline in the Abu Sawarir Formation contains pebbles of quartz, greenstone, and fine-grained diorite. It grades upward into gray to black argillite and dark graywacke locally metamorphosed to chlorite-sericite-quartz phyllite and schist. The metaconglomerate grades along strike into garnet-free biotite-muscovite schist which in turn grades into fine-grained chlorite-sericite schist about 230 m from the contact with intrusive biotite-hornblende granite. Locally the graywacke metaconglomerate and associated rocks are strongly sheared. Near contacts with the biotite-hornblende granite, the biotitic metaconglomerate is intruded by notably small and discontinuous dikes of the granite and small dikes and stringers of fine-grained diorite. Simple, small, quartz-microcline-biotite pegmatite is present but rare in the biotite-muscovite schist but is absent from the chlorite-sericite schist.

Badrīyah Formation.-- Overlying and partly interfingering with the sedimentary facies of the Bi'r Khountina Group is a great but unknown thickness of volcanic rocks named here the Badrīyah Formation after the excellent exposures of rocks of the formation in the central part of the Bi'r al Badrīyah quadrangle north of Wadi al Badrīyah. Where unmetamorphosed these volcanic rocks are dark green, green, dark brown and nearly black andesite, andesite porphyry, trachytic andesite, andesite lithic tuff, and agglomerate. Intercalacted with the volcanic

rocks of the Badriyah Formation are small amounts of graywacke, thin-bedded calcareous graywacke, and lenticles of marble. The volcanic rocks mainly comprise massive flows, but dikes and sills of andesite, and more rarely of dacite and rhyolite, are also present. The andesite flows are the most common part of the formation. Where the andesite is brecciated, epidotized, and altered to greenstone, schistose andesite, and actinolite schist, it has been mapped separately on plate 1. Such alteration is rather common adjacent to intrusive contacts of somewhat younger gabbro, pyroxenite, biotite-hornblende granite, and alkalic granite. Locally, the intensity of contact metamorphism was great enough to form fine-grained hornblende schist and layered amphibolite from andesite tuff. The foliation of these schists is parallel to the intrusive contact.

A bleached zone occupies a small area of andesite in the central part of the quadrangle. On aerial photographs the zone appears as somewhat lighter in color than the surrounding rocks. On the ground the bleached zone is composed of greenish-gray to pale-green andesite notably lighter in color than surrounding dark green, dark brown, and nearly black andesite. In the bleached zone the rocks occupy a depression rimmed by hills of dark andesite. The bleaching seems to have been caused by the hydrothermal alteration of a strongly brecciated part of the andesite about 1000 m long and 700 m wide. Cracks in the bleached andesite as much as 30 cm wide and 25 m in exposed length are stained with limonite; sulfide minerals, although not seen, may have been the source of the limonite. Phyllitic shear zones up to 2 m in width and 45 m in exposed length trend N. 10° E. 70° E. in the bleached area and contain hematite-stained calcite.

Gabbro, pyroxenite, serpentinite, and amphibolite

Dark gray, dark green, and nearly black, massive, fine- to coarse-grained gabbro forms subcircular to kidney-shaped intrusive massive as much as 4 km long in andesite of the Badriyah Formation. Composite plutons of gabbro, pyroxenite, and associated rocks of the same apparent age are more common than gabbro alone. These composite plutons are as much as 8 km across where they intrude rocks of the Bi'r Khountina Group, and they are larger where they intrude the Halaban Group. The largest of these composite plutons intruding the Bi'r Khountina Group is unconformably overlain by conglomerate of the Murdama Group, a relation that shows the gabbro and pyroxenite unit is younger than at least part of the andesite in the Badriyah Formation and older than the Murdama Group.

At most observed exposures gabbro is the dominant rock. It is intruded by dikes of pyroxenite. At a locality 2 km north of the

central part of Jabal al Badr al Hambra a small plug of fine- to coarse-grained, nearly black pyroxenite intrudes the Abu Sawarir Formation. Diorite and peridotite are locally associated with the gabbro, but they tend to be less common than gabbro.

Observed contacts between gabbro and pyroxenite are devoid of chromite. Megascopic olivine is absent from all these rocks except peridotite. Some of the pyroxenites contain mica which may be phlogopite. Brown garnets in the large body of gabbro and pyroxenite in the northwestern part of the mapped area are not pyrope.

Green, dark green, and brown serpentine and serpentinized pyroxenite, gabbro, diorite, and andesite, with associated veinlets and masses of magnesite, is exposed in the southern part of the quadrangle. In the northwestern part of the area the gabbro and pyroxenite unit is sheared and locally serpentinized and fractured and locally silicified. The fractured and silicified parts of the rock are sporadically filled with short vuggy veins of calcite and quartz. Copper stains and small masses of gossan are present on some of the veins, and several ancient mines were opened in them.

Locally the gabbro and pyroxenite are converted to dark coarse-grained amphibolite by contact-metamorphic effect of younger intrusive alkalic granite. Relict cores of massive gabbro and pyroxenite are in the amphibolite. Such amphibolite is difficult to distinguish from some of the older amphibolitic rocks associated with the Halaban Group.

Biotite-hornblende granite

Two plutons of biotite-hornblende granite occupy the central part of the Bi'r al Badriyah quadrangle, where they are intrusive into the Abu Sawarir and Badriyah Formations of the Bi'r Khountina Group. Similar granite forms detrital boulders and cobbles in conglomerate at the base of the Murdama Group in the northwestern part of the quadrangle. The biotite-hornblende granite produced narrow contact metamorphic aureoles in the graywacke and andesite of the Abu Sawarir and Badriyah Formations. Primary flow banding in the plutons is parallel to their contacts with these formations, and inclusions of graywacke are in the granite. Swarms of andesite and diabase dikes, with fewer rhyolite dikes, cut the biotite-hornblende granite plutons and rocks of Bi'r Khountina Group, but the dikes do not intrude rocks of the Murdama Group. Indeed, cobbles of diabase and rhyolite resembling the dikes in the granite are among the detrital components of the conglomerate in the Murdama Group. From these relations the biotite-hornblende granite is interpreted here to be younger than the lower part of the Badriyah Formation and older than the Murdama Group.

The dike swarms in the biotite-hornblende granite are interpreted to be feeders for younger parts of the Badrīyah Formation exposed northwestward down the plunge of the synclinorium in the Bi'r Khountina Group. Similar granite was not seen in the younger parts of the Badrīyah Formation to the northwest (Kahr and others, 1972). Younger volcanic rocks of the Badrīyah Formation, exposed east of the Bi'r al Badriyah quadrangle, are notably more felsitic than the andesites in this quadrangle (Overstreet and others, 1972). Seemingly, the trend toward a major felsitic component in the lavas in the upper part of the Badrīyah Formation is signalled by the rhyolite dikes associated with dikes of andesite in the biotite-hornblende granite.

The biotite-hornblende granite unit forms composite plutons of gray, medium-to coarse-grained, quartz-poor, biotite granite, biotite-hornblende granite, hornblende granodiorite, biotite-hornblende granodiorite, and biotite diorite. In general, hornblende is sparse. It is present as relicts unreplaced by biotite. Within about 250 m of their walls the plutons tend to become dioritic, and selvages of biotite-rich diorite define a crude flow banding parallel to the contacts of the plutons. However, at many places the rock is not diorite at the contact, and in some places it is pink, fine- to medium-grained granite at the contact. Where flow banding is present clots of biotite tend to form a lineation which plunges down dip in the plane of the primary flow banding. The southeast pluton has sparse unoriented inclusions of metagraywacke as much as 40 cm across which have small porphyroblasts of biotite and feldspar and resemble the contact-metamorphosed wallrocks of the Abu Sawarir Formation. No inclusions of the Badriyah Formation were seen in the biotite-hornblende granite unit.

The wallrocks around the plutons are variably affected by contact metamorphism which is more pronounced in the Abu Sawarir Formation than in the Badrīyah Formation. Graywacke and argillite of the Abu Sawarir Formation are altered to fine-grained, layered, biotite-muscovite schist which gives way to fine-grained chlorite-sericite schist about 230 m from the contact. Locally the chlorite-sericite schist is present out as far as 0.5 km from the granite. Biotite and feldspar form porphyroblasts to 1 mm across in recrystallized conglomerate and graywacke as far as 200 m from the contacts, and these same minerals are in recrystallized inclusions of graywacke in the granite and its dioritic border phases. Hornfels is very uncommon. Andesite of the Badrīyah Formation is altered to fine-grained hornblende schist with foliation parallel to the contact for a few tens of meters from the contact. A little chlorite schist and chlorite-epidote schist formed at the granite contacts from andesite intercalated with argillite in the Badrīyah Formation, but the amount is too small to show on the map.

The sparse contact alteration is interpreted to show that the biotite-hornblende granite was emplaced in a low-energy, low-volatile environment. Possibly the variable degree of contact metamorphism relates more to variations in the original amount of water in the intruded rocks than to variations in the volatiles in the granite.

Further evidence that the biotite-hornblende granite was lean in volatiles comes from the scarcity of interior and exterior pegmatites in or around the plutons and from the sparseness and small size of veins. Simple, quartz-feldspar pegmatite dikes are scarce but present in massive andesite of the Badriyah Formation near the granite contacts; pegmatite was not seen in the hornblende schist of this formation. Simple, small, quartz-microcline-biotite pegmatite dikes are present but scarce in biotite-muscovite schist of the Abu Sawarir Formation adjacent to the granite, but are absent from chlorite-sericite schist a few 100 m from the contact. Accessory minerals are extremely scarce in the pegmatites; pyrite is the only one identified. Quartz veins seem to be scarcer than pegmatites in and around the plutons. Brecciated quartz-calcite veins up to 12 cm thick and 5 m long, that have small quantities of galena and chalcopyrite, are in gray to black argillite of the Abu Sawarir Formation immediately east of the southeastern pluton. Even these veins may not be genetically related to the granite; they could be a metamorphic differentiation product from the argillite itself.

Dike swarms cut the plutons, and the dikes extend out into the wallrocks and cross the screen of andesite of the Badriyah Formation between the plutons. The trend of the dikes swerves from northwestward in the southeastern pluton to westward in the northern pluton. This change in direction is interpreted to result from folding along a north-trending axis between the plutons and parallel to axes in the Murdama Group farther to the northwest. Most of the dikes are andesite, andesite porphyry, hornblende-augite andesite, and diabase with fine-grained, chilled margins. Scarce dikes of rhyolite and pink granite are parallel or subparallel to the andesite dikes. The pink granite dikes may be a coarse-grained phase of the rhyolite. They are not shown separately on plate 1.

The biotite-hornblende granite in the northern pluton is brecciated along a north-trending fault which offsets the andesite dikes about 100 m. Relative movement is east side toward the north. No mineralization was seen along the fault.

Granite porphyry

The granite porphyry is a gray biotite-muscovite granite porphyry containing round quartz phenocrysts to 8 mm across and sparse accessory epidote and allanite. It crops out in a poorly exposed plug in the east-central part of the quadrangle. The plug is probably younger than the biotite-hornblende granite because it lacks the dike swarms characteristic of that granite, thus it may have been intruded later than the dikes. The plug of porphyry has had scant effect on its wallrock, which is thinly laminated argillite of the Abu Sawarir Formation which has a strong fracture cleavage dipping inward toward the plug. The argillite lacks other contact effects. Relations and age of the gray granite porphyry are uncertain; the plug may be genetically related to the alkalic granite.

Andesite, dacite, and rhyolite dikes

Dark green, dark brown, and dark gray to black dikes of andesite, andesite porphyry, hornblende-augite andesite, lamprophyre, and diabase are best exposed where they intruded biotite-hornblende granite in the central part of the quadrangle. They are inferred to be feeders for younger parts of the andesite in the Badrīyah Formation, and their relations have already been discussed. Also included in the unit are some andesite dikes of unknown age relations outside the granite plutons.

Light to dark gray dacite dikes and sills, thought to be related to the late andesite dike swarm in the biotite-hornblende granite, are intrusive into slightly metamorphosed basal units of the Bi'r Khountina Group but are not themselves metamorphosed. Closely associated with the dacite are dikes of gray, brown, and dark red rhyolite and rhyolite porphyry that grade locally into pink granite. These felsic dikes are thought to be part of an important felsic volcanic phase in the upper part of the Badrīyah Formation not otherwise represented in the quadrangle.

Murdama Group

In the Bi'r al Badrīyah quadrangle the Murdama Group is represented by a small synclinal mass of conglomerate of the Z'reiba Formation and graywacke of the Abt Formation probably correlative with similar graywacke in the southern part of the Bi'r Ghamrah quadrangle (Overstreet and Whitlow, 1972a) and with similar graywacke and conglomerate in the Wadi Mahraghah quadrangle (Overstreet and Whitlow, 1972b). The area underlain by the conglomerate and graywacke in the Bi'r al Badrīyah quadrangle was originally mapped by Bramkamp and others (1956) as

amphibolite schist with minor beds of quartzite, but a formation name was not given. The name Murdama Group is here extended from the Bi'r Ghamrah quadrangle, where the name was introduced (Overstreet and Whitlow, 1972a), to these rocks.

Z'reiba Formation.-- The base of the Murdama Group in the Bi'r al Badrīyah quadrangle consists of brown, gray, and greenish gray conglomerate at least 350 m thick to which the name Z'reiba Formation is here given for exposures on the northeast flank of Jabal Z'reiba. Locally the matrix of the conglomerate is graywacke sandstone metamorphosed to sericite-chlorite schist. The bulk of the conglomerate consists of well-rounded pebbles, cobbles, and boulders of rhyolite, blue marble, gray marble, andesite, granite, and diabase. Some boulders are as much as 70 cm in diameter. At the northern end of Jabal Z'reiba, the pebbles, cobbles, and boulders are conspicuously stretched in a north-trending lineation that plunges 50° S.

The components of the conglomerate appear to be derived from rocks of the underlying Bi'r Khountina Group and biotite-hornblende granite.

Abt Formation.-- The main part of the Murdama Group in the Bi'r al Badrīyah quadrangle is gray to greenish gray, medium- to coarse-grained graywacke, calcareous graywacke, and schistose graywacke of the Abt Formation which overlies the Z'reiba Formation. The Abt Formation probably grades into the conglomerate of the Z'reiba Formation because the grains increase in size toward the bottom of the Abt where pebbly conglomeratic graywacke and thin layers of quartz-pebble conglomerate with matrix of sericite-chlorite schist are present. The thickness of the Abt Formation, which was named in the Jabal Bitrān quadrangle (Kahr and others, 1972), is not known.

Alkalic granite

Gray, locally pink and red, fine-to medium grained, equigranular to porphyritic, massive to gneissic biotite granite underlies largely sand-covered areas in the southern and northeastern parts of the quadrangle. The granite is intrusive into the Halaban and Bi'r Khountina Groups in the quadrangle and outside the area this granite is also intrusive into the Murdama Group (Overstreet and Whitlow, 1972a). In the northeastern part of the Bi'r al Badrīyah quadrangle this granite is intrusive into the granite gneiss of Bramkamp and others (1956). Because of its composition, texture, and age relations, this granite is here called alkalic granite after the designation used by Jackson and others (1963) in the Southern Najd quadrangle.

Peralkalic granite

Near the center of the west edge of the quadrangle, gray to pink, quartz-poor, feldspathic biotite granite intrudes biotite-hornblende gneiss of the Umm Mushraha Formation. Except for the development of small amounts of epidote in the gneiss, the wallrocks are practically unaltered. Adjacent to the wallrocks the pluton is bordered by an intermittent zone as much as 100 m thick of coarse-grained hornblende-biotite granite. This circular pluton forms a topographic depression floored with granitic sand. No dikes were seen on the floor. This pluton resembles the peralkalic granite of Jackson and others (1963) in the Southern Najd quadrangle to the west, but a body of granite and another of porphyry a few kilometers to the north and small granitic stocks 20 to 28 km south and southeast, in many respects similar to the circular pluton, have other characteristics which cause them to resemble the biotite-hornblende granite and granite porphyry in the quadrangle. Owing to this resemblance, and to the absence of a contact between these small bodies of granite and the Murdama Group, it cannot be said with certainty that the granite is younger than the Murdama. However, a circular pluton of similar granite intrudes what is probably the metamorphosed equivalent of the Murdama in the Jabal Bitrān quadrangle (Kahr and others, 1972). Despite resemblance to the biotite-hornblende granite, these small bodies of granite along the western edge of the Bi'r al Badrīyah quadrangle most likely are stocks of the peralkalic granite that forms large intrusives in the Southern Najd quadrangle (Jackson and others, 1963). They are, therefore, called peralkalic granite here.

Gray, quartz-poor, biotite-hornblende granite porphyry, shown as peralkalic granite on plate 1, forms a poorly exposed plug about 12 km north of the main pluton of peralkalic granite in the quadrangle. It intrudes massive andesite of the Badriyah Formation.

Three small stocks of peralkalic granite intrude gabbro and diorite in the southwest corner of the quadrangle. At each of these stocks the rock is gray, locally pink, granitic porphyry resembling the stock in the northwestern part of the quadrangle. Blocky inclusions of the gabbro and diorite are common, and the hornblende in the inclusions is chloritized. The granite porphyry is cut by dikes of pink to red granite that extend out into the wallrocks for at least 200 m, and both the stocks and the granite dikes are intruded by andesitic dikes. The westernmost of the three small plugs has numerous short mineralized quartz veins, which were mined in antiquity from workings now known as Umm Mushraha mine. These quartz veins are cut by the andesite dikes in the Bi'r Khountina Group. Like the large pluton to the north, these small stocks also occupy topographic depressions.

Post-Precambrian sedimentary rocks

Four varieties of post-Precambrian sedimentary rocks are shown on plate 1. The oldest is the Khuff Formation of Permian age. The area of Khuff shown as outcrop was interpreted from aerial photographs without field check, and the description of the unit in the map explanation is taken from Bramkamp and others (1956).

Three kinds of Quaternary deposits are shown. They are classed as gravel, sand, and silt. The gravel is regarded as the oldest of these formations because of its lag characteristics. The sand and the silt are essentially synchronous, and although both have water-laid and aeolian components, the outline of the silt is clearly defined by the lowest part of the wadi floor where it was deposited mainly from flowing water. The outlines of the sand define the areas of outcropping crystalline rocks. Most of the sand was deposited from sheet wash, but it is constantly shifted by wind.

Structure

The rocks in the area of the Bi'r al Badrīyah quadrangle have been involved in at least three episodes of folding. The oldest episode, which did not affect rocks younger than the Halaban Group, is preserved in north-trending folds and foliation in the Halaban. The best preserved of these folds is a south-plunging anticline in amphibolite of the Umm Mushraha Formation which exposes hornblende-biotite granite gneiss in the core. The east limb of this old fold is greatly modified by later folding along northwest axes, and by the extensive late intrusion of gabbro and alkalic granite.

Faults, also having north trends, formed somewhat later than the early north-trending folds. One prominent zone of these faults is occupied by phyllonite. These main north-trending faults are older than the major synclinorium in the Bi'r Khountina and Murdama Groups, but faulting was reactivated along this direction in late Bi'r Khountina time.

The second major episode of folding produced the dominant structure of the Bi'r al Badrīyah quadrangle, and an important regional feature in this part of the Precambrian Shield. This is the large, northwest plunging synclinorium occupied by the Bi'r Khountina and Murdama Groups but also involving the underlying Halaban Group. Owing to the northwesterly plunge of this structure, successively younger formations enter toward the northwest. It also appears that the regional grade of metamorphism of the rocks in the Bi'r Khountina and Murdama Groups increases northwestward into the core of the

synclinorium. The axes of the structures of the second episode of folding are strongly athwart the older north-trending structures in the Halaban.

Late in the history of the northwest folding of the second main episode a series of northwest-trending faults developed at and near the base of the Bi'r Khountina Group on the flanks of the synclinorium and parallel faults formed elsewhere in the area. The original movement on these faults seems to have been related to the squeezing of the Bi'r Khountina up and out of the flanks of the main synclinorial trough. Thus, at many places, on the south side of the synclinorium particularly, linear features along the fault plunge toward the axis of the synclinorium. However, at a later period, possibly accompanying the emplacement of the alkalic granite, renewed movement took place on these northwest-trending faults. This movement seems to be at a high angle, and has moved the northeast sides of the faults relatively up and over the southwest sides. At most places the late movement has obscured the earlier movement. Along with the late movement toward the southwest, there is also a component of left-lateral slip.

The third episode is a late Precambrian(?) period of folding along north-trending axes seen in the Bi'r al Badrīyah quadrangle as the doubly plunging syncline in the Murdama Group and by the rotation of the andesite dikes between the northern and southern plutons of biotite-hornblende granite. Probably these late north-trending folds developed when motion toward the southwest, accompanied by left-lateral slip, occurred on the northwest-trending faults about the time the alkalic granite was emplaced.

No evidence was found to show that the faults recognized in the Precambrian affected the Permian rocks in this area.

GEOLOGIC RELATIONS OF SELECTED ELEMENTS

Samples of wadi sand, concentrates, and magnetite were collected at 105 localities in the area of Precambrian rocks in the Bi'r al Badrīyah quadrangle. The samples were analyzed for selected elements to gain additional data on possible mineralization. The principal results are shown on the geologic map (plate 1).

Procedure

Samples of about 10 kg weight were dug from the upper 30 cm of dominantly water-laid wadi sand and were sieved on stainless steel screens to obtain 100 g of -30+80 mesh sand. Tailings from the sieves were panned for a heavy-mineral concentrate. The concentrate was

examined under ultra-violet light for scheelite and powellite, and magnetite was separated from the concentrate. Analyses were made of the sieved fraction, concentrate, and magnetite at the Jiddah Laboratory of the Directorate General of Mineral Resources, Kingdom of Saudi Arabia. The sieved fractions of wadi sand were analyzed spectrographically by C. E. Thompson, U. S. Geological Survey, and Kamal Shahwan, Directorate General of Mineral Resources, for 27 elements, and with chemical methods by Thompson for copper, zinc, and molybdenum. The concentrate was analyzed chemically for copper, zinc, and molybdenum. The semiquantitative spectrographic analyses were performed according to modified techniques used by the U. S. Geological Survey (Theobald and Thompson, 1968, p. 2), and the wet chemical analyses were done by normal trace-elements procedures.

Results

Results of the analyses are given in histograms (fig. 2 and 3). Nineteen histograms in figure 2 show the elements present in spectrographically detectable amounts in 103 analyses of wadi sand. Eight elements were below the limits of detection: antimony, 200 ppm (parts per million); beryllium, 2 ppm; bismuth, 20 ppm; cadmium, 50 ppm; germanium, 20 ppm; niobium, 50 ppm; tungsten, 50 ppm; and zinc, 100 ppm. The abundances of the 19 detected elements were compared with the results of 321 similar samples of wadi sand collected from the Precambrian area in the Southern Tuwayq quadrangle. Thirteen elements reached threshold 1/ amounts in some samples and a small positive anomaly was identified for lead (table 1). The wet chemical analyses of wadi sand (fig. 3) confirm the results of the spectrographic analyses for copper, zinc, and molybdenum, except that by chemical procedures about twice as many threshold values were determined for copper in sand.

Metals by multiple analyses

The abundances of copper, zinc, and molybdenum were determined in three sample media (wadi sand, concentrate, and detrital magnetite) by wet chemical methods, and in wadi sand by spectrographic means also. Tungsten was determined in the concentrate only, but it was also sought spectrometrically in the sand. The results of the spectrographic analyses are shown on the geologic map (plate 1), where it can be seen that three samples of sand have threshold values for copper and

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1/ Threshold amount as here used is a quantity exceeded by about 2½ percent of the total observations (Hawkes and Webb, 1962, p. 31).

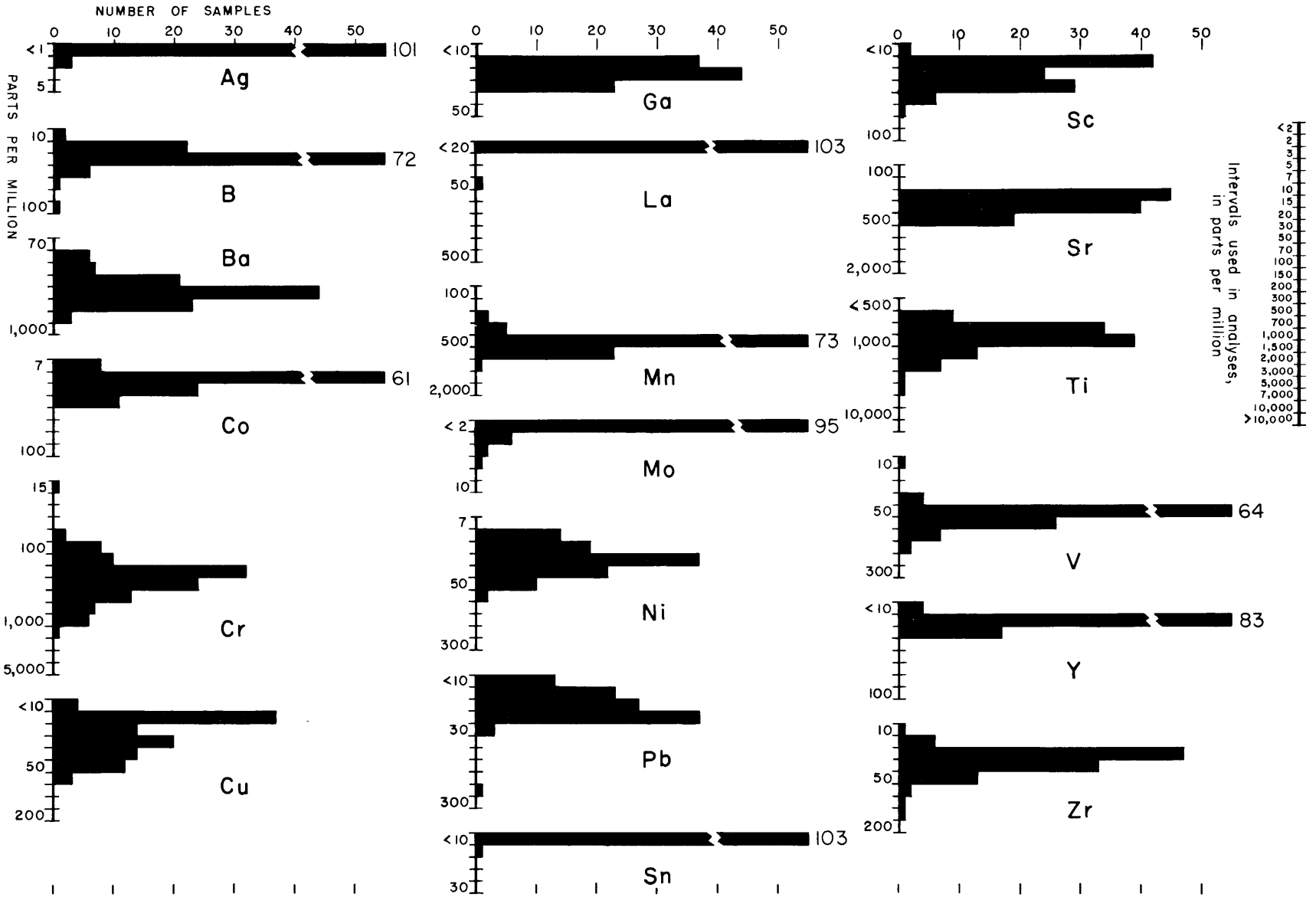

Figure 2. Histograms of 103 spectrographic analyses of wadi sand, Bi'r Al Badriyah quadrangle

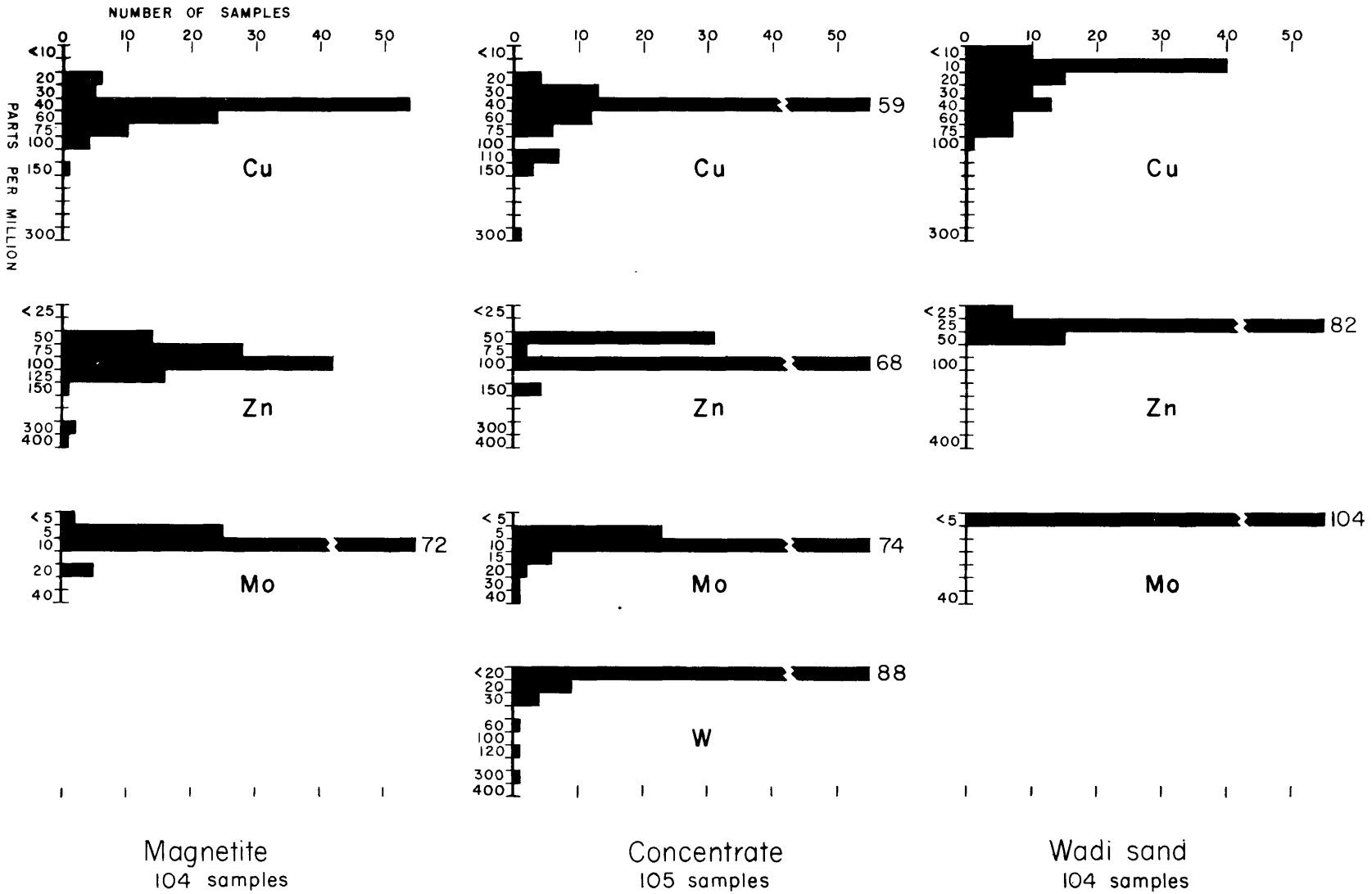

Figure 3. Histograms of wet chemical analyses of magnetite, concentrate, and wadi sand, Bi'r Al Badrīyah quadrangle

Table 1. Threshold values of selected elements in wadi sand, Bi'r al Badrīyah quadrangle, Kingdom of Saudi Arabia.

(Analyses by C. E. Thompson, U. S. Geological Survey, and Kamal Shahwan, Directorate General of Mineral Resources)

Element	Regional threshold in Southern Tuwayq quadrangle ppm	Number of samples in Bi'r al Badrīyah quadrangle at or above regional threshold value
Ag	1	3
B	50	2
Cr	1000	7
Cu	70	3
La	20	1
Mn	1000	1
Mo	3	3
Ni	70	2
Pb	50	1 (a)
Sc	30	7
Sn	10	1
Ti	3000	2
V	150	2
Zr	150	1

(a) Sample has the anomalous value of 200 ppm.

molybdenum (table 1) but zinc is below the threshold. Wet chemical analyses disclosed eight samples of sand with threshold quantities of copper, but molybdenum and zinc are below the threshold (table 2). Concentrates and magnetite disclose threshold quantities of copper, zinc, and molybdenum in small numbers of samples (table 2). The zinc in magnetite at three localities is in the lowest part of the range found elsewhere (Theobald and Thompson, 1962, p. C73) in magnetite having potential association with zinc mineralization. None of these metals, however, forms a geochemical anomaly.

Copper.-- Eighteen of the 27 threshold values detected for copper in the various media (tables 1 and 2) are in samples from rocks in the Halaban Group and associated mafic intrusive rocks; only four are from the Bi'r Khountina Group. Four samples are from the peralkalic granite, and one is from the hornblende-biotite granite gneiss.

Among the samples from the Halaban Group, the sand and concentrate from the same localities tend to have threshold values, but the few samples of magnetite containing threshold copper tend to be from other localities. These relations suggest that the source of the sparse copper is mostly heavy secondary oxide and carbonate minerals, though at most localities none was seen.

Eleven of the Halaban samples containing threshold copper are from amphibolite of the Umm Mushraha Formation and amphibolite reduced to phyllonite in the northeast quarter of the quadrangle. The north-trending phyllonite zone and immediately adjacent rocks are a notable source for threshold copper in sand and concentrates. Scheelite is commonly present in these concentrates, and the samples of sand include three of the seven samples with threshold scandium. The small ancient working called Smagh is in the phyllonite, and the working is the source of a scheelite-bearing concentrate containing threshold copper. The other seven samples from the Halaban Group and associated mafic rocks that have threshold copper are from the hornblende gneiss of the Umm Mushraha Formation and from gabbro and diorite south of the synclinorium in the Bi'r Khountina Group. The evidence of the samples shows that the rocks of the Halaban Group, particularly the Umm Mushraha Formation, being dominantly mafic in the Bi'r al Badriyah quadrangle, are slightly richer in copper than rocks of the other Groups.

The four samples derived from the Bi'r Khountina Group that have threshold copper include two samples from conglomerate of the Idsas Formation immediately above the Halaban, one sample from meta-andesite in the Badriyah Formation, and one from the contact aureole of the intrusive biotite-hornblende granite (plate 1). Sand, concentrate,

and magnetite are represented by the threshold samples, but in each instance the amount of copper is at the lower limit set for the threshold. There is no coincidence of two or more sample media having threshold copper at the same locality. Seemingly, the threshold values in the Bi'r Khountina can be attributed to detrital recycling from the Halaban in the conglomerates, and possibly to normal laboratory variation (Theobald and Thompson, 1968) in the other samples, although the sample from the contact with the biotite-hornblende granite may be slightly enriched in copper owing to metamorphic effects. Very minor chalcopyrite, not reflected in the amount of copper in the associated sample, was seen on the east side of the southern pluton of biotite-hornblende granite. The sample with threshold copper from the contact came, however, from the southeast side of the northern pluton, where copper minerals were not seen.

Table 2. Threshold values for copper, zinc, molybdenum, and tungsten by wet chemical procedures, Bi'r al Badrīyah quadrangle, Kingdom of Saudi Arabia. (Analyses by C. E. Thompson, U. S. Geological Survey, and L. Al Dugaither, Directorate General of Mineral Resources).

Element	Regional threshold in Southern Tuwayq quadrangle, ppm			Number of samples in Bi'r al Badriyah quadrangle at or above regional threshold value		
	Sand	Concentrate	Magnetite	Sand	Concentrate	Magnetite
Cu	75	100	100	8	11	5
Mo	5	20	20	-	4	5
W	-	60	-	-	3	-
Zn	75	150	150	-	4	4 (a)

(a) Includes one sample with 150 ppm; two samples with 300 ppm; and one sample with 400 ppm.

Threshold copper is associated with wadi sand and magnetite from the peralkalic granite at the Umm Mushraha mine in the southwestern corner of the quadrangle and with the small stock 9 km east-southeast of that mine.

A single sample of scheelite-bearing concentrate from the hornblende-biotite granite gneiss on the east side of the phyllonite zone in the Halaban has a low threshold amount of copper.

Zinc.-- Zinc was not detected at regional threshold abundances in wadi sand by either spectrographic or chemical procedures, but 150 ppm zinc was found in four concentrates and one sample of magnetite, and three samples of magnetite had 300-400 ppm (table 2). Zinc tends to be associated with the mafic rocks: three samples of magnetite with threshold zinc are from the amphibolite and biotite-hornblende gneiss of the Umm Mushraha Formation, one concentrate with threshold zinc is from the unit of gabbro and diorite associated with the Halaban, and two concentrates are from gabbro and pyroxenite associated with the Bi'r Khountina. Magnetite from biotite-hornblende granite has threshold zinc as does one concentrate from unmetamorphosed graywacke of the Abu Sawarir Formation in the southeastern part of the quadrangle.

Amphibolite of the Umm Mushraha Formation near the west edge of the map at Wadi El Gai Deniya was the source of the detrital magnetite with 400 ppm zinc. This magnetite also has the most copper (150 ppm) of any reported from the quadrangle, but no megascopic evidence of mineralization was seen. However, an ancient mine is about 4 km to the west and the Umm Amal mine is 12 km to the north-northwest in the Jabal al Hawshah quadrangle (Whitlow, 1968, map; Saudi Arabia Ministry of Petroleum and Mineral Resources, 1965, p. 24). Detrital magnetite with 300 ppm zinc was derived from biotite-hornblende gneiss of the Umm Mushraha Formation 6 km northeast of the Umm Mushraha mine and a scheelite-bearing concentrate from the unit of gabbro and diorite associated with the Halaban Group just east of the mine contains 300 ppm zinc. Bedouin reported the presence of ancient mines along Wadi Umm Mushraha east and northeast of the Umm Mushraha mine, but no workings were found..

Magnetite with 300 ppm zinc came from the north-trending small fault on the south side of the pluton of biotite-hornblende granite in the center of the quadrangle, but other indications of mineralization were not seen.

Molybdenum and tungsten.-- Molybdenum in threshold amounts in the three sample media and tungsten in threshold amounts in concentrates are associated dominantly with rocks of the Bi'r Khountina Group and intrusives into them. Eleven of the 15 threshold analyses (table 2) are samples from these rocks.

Commonly the contact zones between the intrusive biotite-hornblende granite and the Bi'r Khountina are slightly enriched in molybdenum. Indeed, 11 of the 14 threshold values for molybdenum in the quadrangle are concentrated in the southern and southeastern parts of the northern pluton of biotite-hornblende granite, in the northern and western parts of the southern pluton of biotite-hornblende granite, in andesite of the Badrīyah Formation between these two bodies of granite, and argillite of the Abu Sawarir Formation near the southern pluton (plate 1). Granite porphyry related to the biotite-hornblende granite yielded sand with 5 ppm molybdenum and was the source of concentrates with minor scheelite.

Copper is less than threshold in most of the molybdenum-bearing samples from the two plutons of biotite-hornblende granite; thus, a porphyry type of copper deposit is not indicated, but the area is slightly enriched in molybdenum associated with granitic rocks.

The other samples with threshold molybdenum are from scattered sources and localities. Sand from the unit of gabbro and diorite 10 km northeast of the Umm Mushraha mine has 3 ppm molybdenum, and a concentrate from amphibolite of the Umm Mushraha Formation south of Jabal al Badr al Esswed has 20 ppm molybdenum. Magnetite in metagraywacke of the Abt Formation on the east side of the doubly plunging syncline in the northwestern part of the quadrangle has 20 ppm molybdenum.

Two concentrates with 120 ppm and 300 ppm tungsten came from intrusives in the Bi'r Khountina Group. The first came from the north edge of the southern pluton of biotite-hornblende granite. The second came from the ancient working in the unit of gabbro and pyroxenite near where the unit is overlain by the Murdama Group in the northwestern part of the quadrangle. The contact at the east side of the stock of peralkalic granite to the north of Wadi El Gai Deniya was the source of a concentrate with 60 ppm tungsten. Very few of the scheelite-bearing concentrates marked on plate 1 contained enough tungsten for chemical detection.

Anomalous lead

The only sample with anomalous lead in the quadrangle is sand from a small wadi draining the unit of gabbro and diorite about 200 m east of the stock of peralkalic granite at Umm Mushraha mine. It contained 200 ppm lead. The gabbro is intruded by dikes of peralkalic granite. Rusty, sericitized and silicified shear zones in the gabbro at this locality are followed by old open trenches 1 to 2 m wide and up to 60 m in length. These shear zones apparently were mined for

thin, parallel to subparallel veins of gray to milky quartz, but lead minerals were not seen in the veins or altered wallrocks.

Threshold elements

Spectrographic analyses of wadi sand disclosed local threshold abundances of silver, boron, chromium, copper, lanthanum, manganese, molybdenum, nickel, scandium, tin, titanium, vanadium, and zirconium (table 1). The relations of copper and molybdenum have already been described.

Considerable similarity of distribution exists among certain elements. Silver and zirconium are associated in the mineralized area of the Umm Mushraha mine. Manganese, nickel, scandium, titanium, and vanadium are most common in sands from the mafic rocks associated with the Halaban Group. Lanthanum and tin were found in sand from the biotite-hornblende granite. However, no general order was found in the distribution of boron and chromium.

Silver and zirconium.--Threshold amounts of silver (1 ppm) and zirconium (150 ppm) were found in one sample of sand apiece from the Umm Mushraha mine area, and two samples of sand with similar amounts of silver were found elsewhere in the quadrangle. The sample with threshold silver from Umm Mushraha mine is the specimen that had anomalous lead. The zirconium-bearing sample is also from the eastern contact between intrusive peralkalic granite and gabbro and diorite.

One specimen of sand at the northern contact of the southern pluton of biotite-hornblende granite had 1 ppm silver which was associated with threshold tungsten and molybdenum. The third sample with 1 ppm silver in the Bi'r al Badrīyah quadrangle was from apparently unmineralized graywacke and conglomerate of the Abu Sawarir Formation at the north end of Sawda Diab. Despite the proximity of the locality to a major fault, the threshold value for silver is thought more likely to be attributable to normal laboratory variation than to local mineralization.

Manganese, nickel, scandium, titanium, and vanadium.-- Threshold amounts of these elements are dominantly identified with the older mafic rocks associated with the Halaban Group; thus, their distribution is what would be expected from the composition of the rocks. However, it is notable that none of these elements is represented at threshold abundance in the mafic parts of the Bi'r Khountina Group or mafic plutons intruded into rocks of this group, and only one element, vanadium in conglomerate, reaches threshold amounts in the Bi'r Khountina. One element, scandium, is remarkably persistent in amphibolite of the Umm Mushraha Formation, where it has a close but probably

indirect relation to scheelite.

Manganese (1000 ppm), vanadium (150 ppm), and copper (75 ppm) were found in sand from gneissic diorite and gabbro in the Umm Mushraha Formation about 4 km northwest of the Smagh mine near the northeastern edge of the quadrangle. The gneissic mafic rocks contain many slabby inclusions of layered biotite gneiss, and the area appears to be part of the contact zone between plutonic intrusive mafic rocks and older hornblende-biotite granite gneiss. No mineralization was seen.

The two occurrences of threshold nickel are in amphibolite of the Umm Mushraha Formation and in the unit of gabbro and diorite in the southwestern quarter of the quadrangle. Both samples only contained 70 ppm nickel. Sand from medium-grained hornblende gneiss of the Umm Mushraha Formation with scarce gray and glassy to milky quartz stringers with nests of hornblende crystals located 21 km northeast of the Umm Mushraha mine has threshold nickel associated with high threshold titanium (500 ppm), threshold scandium (30 ppm), and low threshold copper (70 ppm). Concentrates from this sand have a little scheelite. No mineralization was seen. To the north of the stock of peralkalic granite at Umm Mushraha mine and in the unit of gabbro and diorite associated with the Halaban Group where those rocks are intruded by north-trending andesite dikes and a small circular mass of pyroxenite, a sample of sand had 70 ppm nickel but lacked threshold amounts of other elements. No chromite or olivine was seen. The gold mineralization at Umm Mushraha mine was in no way reflected by the trace elements in this sand, which came from unmineralized rocks.

Scandium in wadi sands displays the greatest geochemical coherence of any minor element studied in the Bi'r al Badrīyah quadrangle. Six samples contained 30 ppm scandium and one had 50 ppm. Three of the samples with 30 ppm scandium are from the central part of the phyllonite in the northeastern quarter of the quadrangle. Two samples with 30 ppm scandium are from the eastern parts of the amphibolite in the Umm Mushraha Formation in the southwestern quarter of the quadrangle, and one sample apiece with 30 ppm and 50 ppm are from the biotite-hornblende gneiss of the Umm Mushraha Formation in the southwestern quarter of the quadrangle. All samples with threshold scandium except the most northerly in the phyllonite are from sand that yielded scheelite-bearing concentrates. By no means all scheelite-bearing sand in the quadrangle contains threshold scandium. It is thought that scandium is a dispersed element in abundances below the threshold in ferro-magnesian amphiboles of the amphibolite and biotite-hornblende gneiss in the Halaban Group. Scandium may become somewhat concentrated along zones of local thermal rise, as in the phyllonite in the north

and the contact zone of the alkalic granite in the south. The replacement by scandium of iron and manganese in wolframite is well known in the literature (Rankama and Sahama, 1950, p. 514-515), but scandium is not known to replace calcium in scheelite. The common association of scandium and scheelite in samples from the same localities possibly means that some wolframite is also present. If it is, then the total amount must be very small, because none of the sands with threshold scandium is also the source of a concentrate in which threshold amounts of tungsten were found.

Of the two samples with threshold titanium, one with 5000 ppm titanium was described with nickel. The other sample has 3000 ppm titanium. It is from gabbro and epidotized diorite at a point 3 km southwest of the Umm Mushraha mine. No megascopic evidence of mineralization was seen, and the amount of titanium in the sand is expectable from a mafic source.

Vanadium (150 ppm) in sand from amphibolite of the Umm Mushraha Formation was discussed with manganese. Vanadium in the same threshold amount was also found in the Idsas Formation in the southwest corner of the quadrangle where conglomerate of the formation overlies mafic rocks of the Halaban Group. Possibly the source of the small quantity of vanadium in the Idsas Formation was detrital material from the Halaban. It may also be in some secondary mineral that was not identified in the conglomerate.

Lanthanum and tin.--The low threshold amounts of 50 ppm lanthanum and 10 ppm tin were found in one sample of sand each. The lanthanum-bearing sample came from the northwest part of the northern pluton of biotite-hornblende granite, and the tin-bearing sample was taken in hornblende schist of the Badriyah Formation on the southeast side of the same pluton. Threshold molybdenum and a little scheelite were found in concentrates from the sand having threshold tin, but there is no megascopic evidence of tin mineralization in the schist in the contact aureole of the biotite-hornblende granite.

Boron.--The low threshold value of 50 ppm boron was detected in sand from the Idsas Formation north of Sawda Diab at the southeastern edge of the quadrangle, and 100 ppm boron was found in sand from the Umm Mushraha Formation on a northeast-trending fault near the north edge of the quadrangle about 7 km west-northwest of Smagh mine. Although the Idsas Formation is strongly sheared at the sample locality, it is unmineralized. Possibly the boron, and also the threshold copper at this locality, is related to late rhyolite dikes which intrude the Bi'r Khountina Group in the area of Sawda Diab, but the actual association is not known. To the north where threshold boron is in sand

from a fault zone in amphibolite of the Umm Mushraha Formation, a concentrate from the sand contained sparse scheelite. Scarce, thin, quartz-chlorite-calcite veins with a trace of copper stain are in the amphibolite, and the rocks are widely epidotized. Short, thin dikes of massive pink granite, possibly related to the alkalic granite, intrude the amphibolite. The fault projects northeastward. A possible extension of it near an intersection with a north-trending fault is the site of samples with threshold copper, manganese, and vanadium (plate 1). Inasmuch as the Smagh mine is on a similar intersection of faults, the area between the boron-bearing sample and the manganese-bearing sample might have more extensive mineralization than was seen at either sample locality.

Chromium.-- The low threshold of 1000 ppm chromium was found in six samples of sand in a variety of geologic environments mostly related to rocks of the Bi'r Khountina Group. One sample with 1500 ppm chromium came from biotite-hornblende granite in the southern part of the northern pluton. Swarms of andesite dikes with chilled margins are in the granite at that locality, but no ultramafic rocks were seen. The source of the chromium in the sand from the pluton is not known; however, it may be from the andesite dikes because sand from andesite in the Badriyah Formation off the north edge of this pluton and sand from greenstone in the Badriyah Formation at the south edge of the quadrangle had 1000 ppm chromium. At both andesite localities, concentrates from the sand contained scheelite, and the northern occurrence had scarce thin, white, granular quartz veins with chlorite, calcite, pyrite, and sparse copper stains.

The other localities of threshold chromium (1000 ppm) in sand include sources in conglomerate in the Abu Sawarir Formation in the central part of the north edge of the synclinorium, graywacke with intercalated andesite in the Abu Sawarir Formation exposed to the southwest of Jabal Z'reiba, amphibolite of the Umm Mushraha Formation just south of Wadi El Gai Deniya, and hornblende gneiss of the Umm Mushraha Formation at the east edge of the stock of peralkalic granite north of Wadi El Gai Deniya. No special relations to ultramafic rocks are known for any of these concentrations. These threshold values for chromium also seem to relate to normal distribution in mafic rocks like andesite, amphibolite, and hornblende gneiss.

MINERAL DEPOSITS

Several small mineral deposits were formerly exploited in the area of the Bi'r al Badriyah quadrangle. All appear to have been worked for free gold. The ancient workings include the Smagh mine, Umm Mushraha mine and adjoining workings, and two old workings in the

northwestern part of the area. Other ancient mines are said by the Bedouin to be present. Slight indications of copper, lead, molybdenum, and magnesite were found, and a large resource of high-calcium marble is present. Remote possibilities for diamond and sperrylite (platinum arsenide) exist.

Gold

Free gold in quartz veins and lodes is inferred to be the commodity sought in former times in the several ancient and abandoned workings found in the area. The inference is based on the observation that grindstones and finely ground quartz tailings are at the principal workings, but slag, which is found where complex sulfide ores were mined, is absent. Open veins lacking extensive alteration of the walls were exploited in the younger granitic rocks, and veins with serpentinized and silicified walls or lodes, were opened in mafic rocks and phyllonite. All the observed openings are small; the largest of the known mines is Umm Mushraha.

Veins in younger intrusive rocks

The Umm Mushraha mine is the only gold mine in quartz veins in a younger intrusive rock presently known in the quadrangle.

Umm Mushraha mine.-- The area of scattered ancient openings called the Umm Mushraha mine is spatially related to the walls and core of a circular stock of peralkalic granite porphyry which intrudes gneissic diorite, gabbro, and local pyroxenite intrusive into the Halaban Group. The stock occupies a topographic depression surrounded by hills of mafic rocks. The ancient openings, mostly shallow trenches, are in both the stock and its wall rocks. These openings surround the stock, which is about 1 km in diameter, and extend out into the mafic rocks up to 500 m from its western edge, 600 m from its eastern edge, and up to 200 m from the north and south edges. Thus, the mineralized area at Umm Mushraha mine is about 2000 m long from east to west and 1400 m wide from north to south. The greatest concentration of openings is in the mafic rocks on the eastern and northeastern flank of the stock out to a maximum distance of 400 m from the stock. Within the stock itself most of the openings are short trenches oriented about north and extending on an axis of N. 85° E. across granite into the mafic rocks. Many of the openings are filled with windblown sand.

Grinding of the ore was done at two principal points. One was near the west end of the axis of trenches in the granite, and the other was at the east end of the axis. Tailing piles in the western grinding

area, together with scattered small tailing piles outside the main grinding area, contain at least 10,000 cu m of cobbed and crushed white to gray quartz. The eastern pile has at least 5,000 cu m of crushed quartz. Fragments of grindstones are present, but slag is absent. Copper stains and copper minerals are absent, and samples from the tailing piles contain less than threshold amounts of copper, zinc, and lead, although one sample of sand from the eastern part of the Umm Mushraha working had 200 ppm lead. Owing to the absence of slag, to the lack of base-metal sulfides in the tailings, and to background abundances of the base metals it is inferred that the mine was operated for free gold in quartz.

The quartz forms numerous short, podlike masses, and short veins in the granite and adjacent mafic rocks. None of the veins is more than 100 m long and 2 m thick. Most are half that size. In the granite as well as the wall rocks, the veins occupy fractures oriented in several directions, but the main vein system strikes N. 10° E. and is vertical. Quartz in these veins is milky and has limonite after pyrite. The veins in this system are more abundant in the gneissic diorite and gabbro to the east and north of the stock than they are in the stock. Other directions of veins in which openings have been made are: north, vertical dip; N. 35° E., dip unknown, albite-bearing; N. 20° W., vertical dip; milky quartz; N. 75° E., dip 30° S., milky quartz. The veins in the granite stock are cut by an andesite dike that strikes N. 5° E., and dips vertically. In the gneissic diorite and gabbro east of the stock are north-trending rusty sericitized and silicified shear zones that contained thin parallel or subparallel veins of gray to milky quartz that have been mined from trenches up to 2 m wide and 60 m long.

The close spatial connection between the veins and the granite stock is interpreted to show that the veins are genetically related to the granite. However, the principal set of veins and small lodes strikes north, a trend nearly parallel to the veins in phyllonite at the Smagh mine, and nearly parallel to possibly mineralized faults in the northeastern quarter of the quadrangle. The possibility therefore exists that the veins at the Umm Mushraha mine occupy fractures in the peralkalic granite but are not genetically related to that granite. Such late gold deposits were recognized to the south in the Bi'r Ghamrah quadrangle (Overstreet and Whitlow, 1972a), but those deposits contain more copper, lead, silver, and molybdenum than the deposit at Umm Mushraha. Despite those differences, the geologic similarities are otherwise clear, and they are probably part of the same period of mineralization, which may have taken place shortly after the peralkalic granite crystallized. Absence of beryllium in these deposits suggests that the period of mineralization at Umm Mushraha is closer in age to

the peralkalic granite than it is to a later episode of igneous activity represented in the Bi'r Ghamrah quadrangle by the Shammar Rhyolite, because beryllium is one of the characteristic trace elements of the Shammar (Overstreet and Whitlow, 1972a).

Potential areas.-- North-trending fractures between Umm Mushraha mine and the small but similar mine in the northwestern part of the Bi'r Ghamrah quadrangle (Overstreet and Whitlow, 1972a) should be examined for possible gold deposits.

Bleached areas in the garnetiferous biotite-hornblende gneiss of the Umm Mushraha Formation about 6 km northeast of Umm Mushraha mine, which were the source of sand samples containing threshold scandium and concentrates containing threshold copper and zinc, are potential sites.

North-trending veins in the sand-covered floor of the circular pluton of peralkalic granite, and its walls, near the west-central edge of the quadrangle, and veins associated with the small stock of peralkalic granite 8 km north-northwest of the pluton are also potential areas of gold mineralization. The ancient Umm Amal gold mine is on the western contact of that small stock (Whitlow, 1968).

Veins in mafic rocks

Several small gold mines and reported mines explored veins in mafic rocks in the Bi'r al Badrīyah quadrangle.

Reported mines in Wadi Umm Mushraha.-- Local bedouin reported to the writers in 1964 the presence of several ancient workings in the dioritic and gabbroic hills along the south side of Wadi Umm Mushraha to the east of the Umm Mushraha mine. Possibly one of these reported mines is the small working shown (plate 1) a little over 1 km north of Umm Mushraha mine. This is a shallow trench on small parallel quartz stringers in mafic rock. It resembles individual openings on the east side of the stock at Umm Mushraha. Mines farther to the east were not found, but doubtless similar workings are present.

Smagh mine.-- The Smagh mine consists of an abandoned opening 1.5-2 m wide, 15 m long, and a maximum of 3 m deep on a set of glassy gray quartz veins that strike No. 15° W. and dip 85° W. parallel to the foliation of phyllonite. A strong lineation plunges down-dip in the phyllonite, and the walls of the small exposed parts of the vein are similarly striated. As no ruins of buildings, grinding stones, nor piles of crushed quartz are at this ancient working, the ore may have been transported northward to a group of ancient workings in the area of the Jabal Bitrān quadrangle (Kahr and others, 1972).

The veins at Smagh mine are albite-bearing and much spotted by weathered pyrite. Limonite stains are common on the adjacent wall rocks. The veins are seldom more than 20 cm thick. They appear to be short and discontinuous along strike and down dip. Extremely sparse copper stain was found, and concentrates from the mine area had the threshold amount of 150 ppm copper. A few grains of scheelite were in the concentrate.

The foliation of the phyllonite zone provided the channels for the veins, but it is thought that the veins were emplaced during later movement on an old fault long after the phyllonite was formed. Evidence for this is given in the discussion of the phyllonite. A strong possibility exists that the control of the Smagh veins is the intersection of a younger fault that strikes N. 50° E. into the phyllonite zone at the site of the mine.

Smagh mine is little more than a prospect. It has small veins in wallrocks that are little altered, and anomalous trace elements are absent. Probably the veins were opened for gold in connection with larger mining operations conducted farther north, but not enough gold was found in the surface parts of the veins to encourage further development. Smagh mine itself does not justify further exploration except that it is on a major regional structure, the phyllonite zone, which extends northward to other mines. Thus, that structure deserves further attention.

Openings west of the Murdama.--Two small ancient workings were found in mafic rocks about 4 km west of the Murdama Group at Jabal Z'reiba in the northwestern quarter of the quadrangle (plate 1). The southerly of the two openings consists of a trench about 1.5 m wide and 12 m long filled with windblown sand. The trench is oriented N. 40° W. parallel to the foliation of partly serpentinized pyroxenite. Parts of the walls, and extensions of the rock in the direction of strike beyond the ends of the trench, are covered with quartz-calcite-limonite gossan. The quartz in the gossan is quite vuggy and milky. Several such alteration zones are in the vicinity of the trench, but all are smaller than the trench. About 5 cu m of waste rock is on the dump. Mixed with the serpentinized pyroxenite waste is a little jasper and greasy gray quartz. Probably the opening was made to obtain the vuggy, milky quartz from the gossan for free gold. Whatever ore was recovered must have been hand cobbed and transported from the opening without processing, because pulverized quartz is absent. Analyses disclosed no threshold or anomalous elements in samples from the dump.

The northern opening is a prospect trench about 10 m long on a quartz-calcite vein that extends N. 70° W. with vertical dip in sheared

and locally serpentinized diorite, gabbro, and pyroxenite. The vein is about 40 cm thick, and was probably opened for gold. Quartz in it is milky and vuggy. Other similar small veins are present in the area, but they were not mined. Sparse copper stain is present, but copper is below threshold values (table 1) in the samples. Scheelite was present in the concentrate, which also had the high threshold value of 300 ppm tungsten. Lamped samples of rock, including garnetiferous gabbro, however, lacked scheelite.

The northern and southern openings are small, thus the tenor of the ore in gold was probably low. The presence of scheelite in the northern working, and the presence of small masses of brown gossan and silicified zones due south of the northern opening and 3 km east of the southern opening (see below) suggest that this area of gabbro and pyroxenite be examined further.

Potential areas.-- Six areas in mafic rocks near ancient workings, or on features resembling those at ancient workings, are areas of potential gold mineralization in the Bi'r al Badriyah quadrangle.

Three areas are in the northwestern quarter of the quadrangle. Two of these are brown silicified zones 3.4 km and 4.4 km due south of the previously described northern working west of Jabal Z'reiba. The brown silicified rocks form pods up to 30 cm thick and 35 m long in a zone 80 m wide extending N. 5° E. up a valley toward the northern working. These two silicified zones and the northern working may define a north-trending mineralized fault with surface expression of the mineralization only at the northern working. Samples from the two silicified zones contained no anomalous elements, and the concentrates lacked scheelite.

The third potentially mineralized area in the northwestern quarter of the quadrangle is 11 km northwest of the small northern working previously described. At this locality, andesite of the Badriyah Formation is thoroughly brecciated, chloritized, and sericitized with its color bleached to yellowish green and sage green. Small veins and pods of calcite and gray, greasy-appearing quartz are present in the breccia. Samples have no anomalous metals, and concentrates lack scheelite.

At the west-central edge of the quadrangle, a tributary that leads north into Wadi El Gai Deniya was the source of sand and concentrates with threshold copper, zinc, and chromium (plate 1). This is in the line of gold-bearing, north-trending mineralization seen at Umm Mushraha mine to the south and Umm Amal mine to the north-northwest (Whitlow, 1968).

In the region near Smagh mine two areas of potential gold mineralization warrant further study. Both are associated with intersections of north-trending and northeast-trending faults in amphibolite, and in that respect resemble the probable structural control at Smagh. One of these areas is on the southwestward extension of the northeast-trending fault at Smagh where the fault may intersect north-trending and northwest-trending faults 8 km southwest of Smagh (plate 1). Samples from this area had no unusual abundances of minor elements although a little scheelite was in a concentrate. The other potential area is along the northeast-trending fault which intersects north-trending faults 8 km west and 5.4 km west-northwest of Smagh (plate 1). Samples and concentrates had threshold amounts of copper, boron, vanadium, and manganese, and one concentrate contained a little scheelite.

An area of intersections of an east-northeast trending fault with at least two north-trending faults in chlorite-sericite schist at the east-central edge of the quadrangle 16 km southeast of Smagh mine has threshold copper in concentrate. A bedouin reported that there are many ancient workings in quartz veins to the north and south of this locality, but precise descriptions and distances were not given. Ancient writing was said to be present on the rocks near the workings, and at a numberof places piles of crushed ore remain. The locality at the intersection of the faults appeared to be barren of minerals, but the association of faults and reported workings suggests that further examination should be made in this area.

Copper, lead, and molybdenum

No megascopic or chemical data indicate the presence of minable deposits of copper or molybdenum in the Bi'r al Badrīyah quadrangle. One chemical analysis disclosed anomalous lead at the old Umm Mushraha mine. Several small outcrops of copper and lead sulfides of no commercial importance were seen near the contacts of the biotite-hornblende granite and alkalic granite and the remote possibility exists for copper and molybdenum in the biotite-hornblende granite.

Quartz-calcite veins.-- Quartz-calcite veins with some chlorite, probably formed mainly during contact metamorphism of andesite and argillite of the Bi'r Khountina Group, locally contain traces of copper and lead, but they are of no economic importance. On the east side of the southern pluton of biotite-hornblende granite, argillite is brecciated and the breccia is cemented with quartz-calcite veins up to 12 cm thick and 5 m long. Rare grains of galena and chalcopyrite are present. Concentrates from the area contain a little scheelite, but neither copper nor lead reached threshold values.

Andesite of the Badrīyah Formation exposed at a point 1.8 km off the northwest side of the northern pluton of biotite-hornblende granite contains rare thin veins of white granular quartz with calcite marginal selvages. The veins strike N. 35° W., are vertical, short, and seldom wider than 20 cm. Chlorite and oxidized pyrite are in the veins, and a trace of copper stain is present. The only threshold element noted was chromium in sand from the area. Concentrates had a little scheelite. These veins are zoned, alpine-type low-temperature assemblage with quartz core and carbonate wall zones. Lead is absent and there is practically no copper.

Malachite stains coat some joints but are not common in greenstone of the Badrīyah Formation near the eastern edge of the large body of alkalic granite at a point 3.4 km west of Bi'r Mahantis at the southern edge of the quadrangle.

Quartz-chlorite veins with specks of galena were observed 7 km north of Sawda Diab where graywacke and argillite of the Abu Sawarir Formation changes to chlorite-sericite schist.

Possible copper and molybdenum in granite.--Minor amounts of copper and molybdenum were detected in samples from the two plutons of biotite-hornblende granite in the central part of the quadrangle, and a bleached area in the Badrīyah Formation east of the northern pluton was the source of a concentrate with threshold molybdenum. None of the analyses gave anomalous values, but the persistence of threshold values in the southern part of the northern pluton, the northern part of the southern pluton, and the area between, suggests that further study should be made to define the possibility of a porphyry-type disseminated deposit of copper or molybdenum.

Magnesite and marble

Short, thin pods of white magnesite are locally present on N. 45° W. joints in serpentinite 6 km northwest of Bi'r Mahantis, but no large deposits are exposed. Similar but more extensive deposits occur south of Bi'r Mahantis in the Bi'r Ghamrah quadrangle (Overstreet and Whitlow, 1972a). Inasmuch as the intervening area is largely sand covered, there is probably more magnesite, but the area to the south is better than the area to the north of Bi'r Mahantis.

Blue to black, seemingly very pure marble makes up all of Jabal al Badr al Esswed. Bedding is thin and contorted, and on the average dips steeply to the north. No megascopic evidence of dolomite, silica, or other impurities was found, but analyses of the rock have not been made. Analyses should be made to determine its quality as a source for $CaCO_3$, because the marble could be easily quarried. Among the

possible uses would be manufacture of Portland cement by blanding with nearby andesite, and for use in smelting magnetite and Jabal Idsas to the north in the Jabal Bitrān quadrangle (Kahr and others, 1972) if that magnetite deposit were exploited.

Doubtful mineral localities

Doubtful, or remotely possible, localities for tungsten, uranium, sperrylite, and diamond were noted during the reconnaissance. All should be reviewed again, but none deserves a very high priority in the mineral exploration program.

Tungsten.-- The presence of small amounts of scheelite at a number of places in the quadrangle is shown by symbol on plate 1, but only four areas justify further work. The most important of the four is the region around the phyllonite zone in the northeastern quarter of the quadrangle. The rocks for 4 km on the east and west sides of the phyllonite should be examined for scheelite and wolframite for the full length of the zone because of the frequency with which scheelite occured in concentrates, and because the threshold scandium may possibly indicate wolframite.

The second possible area is the east side of the body of gabbro and pyroxenite west of Jabal Z'reiba in the northwestern quarter of the quadrangle. The places to be examined first are the northern working and the probable south trending fault mentioned under Gold. Should scheelite be found, then conglomerate of the Z'reiba Formation immediately to the east should be tested for possible detrital scheelite.

The third possible tungsten area is the garnetiferous biotite-hornblende gneiss of the Umm Mushraha Formation in the vicinity of the large circular stock of peralkalic granite in the extreme west-central part of the quadrangle.

The fourth possible tungsten area is the scheelite-bearing locality in the northwestern corner of the quadrangle near silicified marble and a plug of gabbro and pyroxenite. Brown silicified marble is associated with hornblende schist and gneiss of the Umm Mushraha Formation immediately west of the west contact of the gabbro and pyroxenite (plate 1). The northern end of the marble is intruded by peralkalic granite. Concentrates from sand to the northwest of the granite are scheelite-bearing.

Uranium.-- The presence of threshold amounts of vanadium in the Idsas Formation in the southwest corner of the quadrangle may indicate

that a little uranium is present, possibly in complex secondary minerals. The conglomerate at this locality certainly, and possibly elsewhere in the quadrangle if the southwestern area is uraniferous, should be checked for uranium.

Sperrylite.-- Extremely fine grained, hairlike veinlets of a hard, silvery mineral are associated with thin plates of shiny black chromite in a kidney-shaped intrusive of pyroxenite and serpentinite 24 km northwest of Sawda Diab. The mineral is quite rare in the rock, and no microscopic or chemical study was made of it. Because of the remote possibility that the mineral may be sperrylite (platinum arsenide), further examination of the sample (specimen 7298) should be made.

Diamond.-- Diamond was not observed in the Bi'r al Badrīyah quadrangle, nor were pyrope-bearing kimberlites seen, but dark garnetiferous gabbro occurs at the ancient gold working west of Jabal Z'reiba and in the northern part of the unit of gabbro and pyroxenite. The remote possibility exists that kimberlite may be present, or be under the Z'reiba Formation. Therefore, when the mafic rocks and conglomerate are examined for possible scheelite, as recommended above, concentrates from the conglomerate should be examined for pyrope, olivine, perofskite, and nickel-rich pyroxenes typically associated with diamond in kimberlite.

RECOMMENDATIONS

Possible gold deposits along the west edge of the quadrangle from the Umm Mushraha mine northward for 30 km to the Umm Amal mine (Whitlow, 1968) provide the greatest possibility for the discovery of an exploitable mineral deposit. This work should be done in connection with exploration proposed for the Umm Amal area (Whitlow, 1968).

Possible gold and tungsten mineralization in the vicinity of the phyllonite zone in the northeastern quarter of the map should be sought by geologic mapping and geochemical surveys.

The two plutons of biotite-hornblende granite in the central part of the quadrangle should be geologically mapped and studied geochemically for possible disseminated copper and molybdenum of the porphyry type. Combined airborne radiometric and magnetometer survey might be useful in this connection.

Chemical analyses are needed of the marble at Jabal al Badr al Esswed to determine its purity and of the gabbro and pyroxenite unit 24 km northwest of Sawda Diab to determine whether there is platinum in the rock.

Heavy minerals in the Z'reiba Formation at the base of the Murdama Group in the northwestern part of the quadrangle should be examined for detrital gold, scheelite, and the indicator minerals for diamond.

REFERENCES CITED

Bramkamp, R. A., Gierhart, R. D., Brown, G. F., and Jackson, R. O., 1956, Geologic map of the southern Tuwayq quadrangle, Kingdom of Saudi Arabia: U. S. Geol. Survey Misc. Inv. Map I-212A.

Hawkes, H. E., and Webb, J. S., 1962, Geochemistry in mineral exploration: New York, Harper and Row, pp. 415.

Jackson, R. O., Bogue, R. G., Brown, G. F., and Gierhart, R. D., 1963, Geologic map of the southern Najd quadrangle, Kingdom of Saudi Arabia: U. S. Geol. Survey Misc. Geol. Inv. Map I-211A.

Kahr, V. P., 1962, Jebel Idsas area, geology and mineralization: Saudi Arabian Dir. Gen. Mineral Resources open-file rept. 158, 31 p.

Kahr, V. P., Overstreet, W. C., Whitlow, J. W., and Ankary, A. O., 1972, Reconnaissance geology of the Jabal Bitrān quadrangle, Kingdom of Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-124, 70 p., 4 figs., 1 pl., 2 tables.

Overstreet, W. C., and Whitlow, J. W., 1970, Summary of trip May-June 1964 to the southern Tuwayq quadrangle, Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-17, 5 p.

Overstreet, W. C., and Whitlow, J. W., 1972a, Reconnaissange geology of the Precambrian rocks in the Bi'r Ghamrah quadrangle, Kingdom of Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-128, 33 p., 3 figs., 1 pl., 1 table.

_____, 1972b, Reconnaissance geology of the Precambrian rocks in the Wadi Mahraghah quadrangle, Kingdom of Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-129, 30 p., 3 figs., 1 pl.

Overstreet, W. C., Whitlow, J. W., and Ankary, A. O., 1970, Summary of field trip March-April 1964 to the southern Tuwayq quadrangle, Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-16, 8 p.

_____, 1972, Reconnaissance geology of the Precambrian rocks in the Sabkhat Muraysis quadrangle, Kingdom of Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-127, 23 p., 3 figs., 1 pl.,

Rankama, Kalervo, and Sahama, T. G., 1950, Geochemistry: Chicago, Univ. of Chicago Press, p. 912.

Saudi Arabia Ministry of Petroleum and Mineral Resources, 1965, Mineral resources of Saudi Arabia, A guide for investment and development: Saudi Arabian Dir. Gen. Mineral Resources Bull. 1, 73 p.

Theobald, P. K., Jr., and Thompson, C. E., 1962, Zinc in magnetite from alluvium and from igneous rocks associated with ore deposits: Art. 84 in U. S. Geol. Survey Prof. Paper 450-C, p. C72-C73.

_____, 1968, Experimental error in sample preparation and spectrographic analysis in the Jiddah Laboratory, Saudi Arabia: U. S. Geol. Survey open file rept. (IR) SA-26, 5 p.

U. S. Geological Survey and Arabian American Oil Company, 1963, Geologic map of the Arabian Peninsula: U. S. Geol. Survey Misc. Geol. Inv. Map I-270A.

Whitlow, J. W., 1968, Geology and geochemical reconnaissance of the Jabal al Hawshah quadrangle, southern Najd, Kingdom of Saudi Arabia: Saudi Arabian Dir. Gen. Mineral Resources Mineral Investigations Map MI-16.