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RECONNAISSANCE GEOLOGY OF THE JABAL AL HAJRAH 7 1/2-MINUTE QUADRANGLE, KINGDOM OF SAUDI ARABIA

by

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RECONNAISSANCE GEOLOGY OF THE JABAL AL HAJRAH 7 1/2-MINUTE QUADRANGLE, KINGDOM OF SAUDI ARABIA

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ABSTRACT

The Jabal al Hajrah 7 1/2-minute quadrangle, bounded by lats 18°52'30" and 19°00'00"N. and longs 43°37'30" and 43°45'00"E., is underlain by Precambrian serpentinite and layered metasedimentary and metavolcanic rocks that are intruded by plutons and dikes of ultramafic to granitic composition.

Layered rocks are divided into four general map units: quartz-biotite schist, hornblende schist, carbonaceous schist, and chlorite-epidote schist. They are metamorphosed mostly to amphibolite facies but retrograded near faults. The layered rocks are in broad flexural folds.

Igneous rocks, which intrude serpentinite and layered rocks, are diorite-gabbro, mafic to ultramafic dikes, and granite-monzogranite-granodiorite. The diorite-gabbro is part of a larger, north-trending body and is made up of several intrusive phases. The granite-monzogranite-granodiorite occurs in several irregularly shaped plutons and numerous pods and dikes.

Known mineralization is hydrothermal gold and minor base-metal sulfides, either localized along the contact between overlying serpentinite and underlying hornblende schist, or along bedding and layering in altered quartz-biotite schist and granite dikes. Mapping, geochemical sampling, and diamond drilling indicate that, although gold metallization is widespread, it is generally low grade.

INTRODUCTION

The Jabal al Hajrah quadrangle is in the southeastern part of the Precambrian Shield in the Asir Province, Kingdom of Saudi Arabia. Boundaries of the quadrangle are lat 18°52'30" and 19°00'00"N. and long 43°37'30" and 43°45'00"E. (fig. 1). There are no permanent settlements within the quadrangle; the closest is the Emirate of Al Amwah, approximately 15 km south of the southwest corner. Access roads are unimproved desert tracks. The main road from

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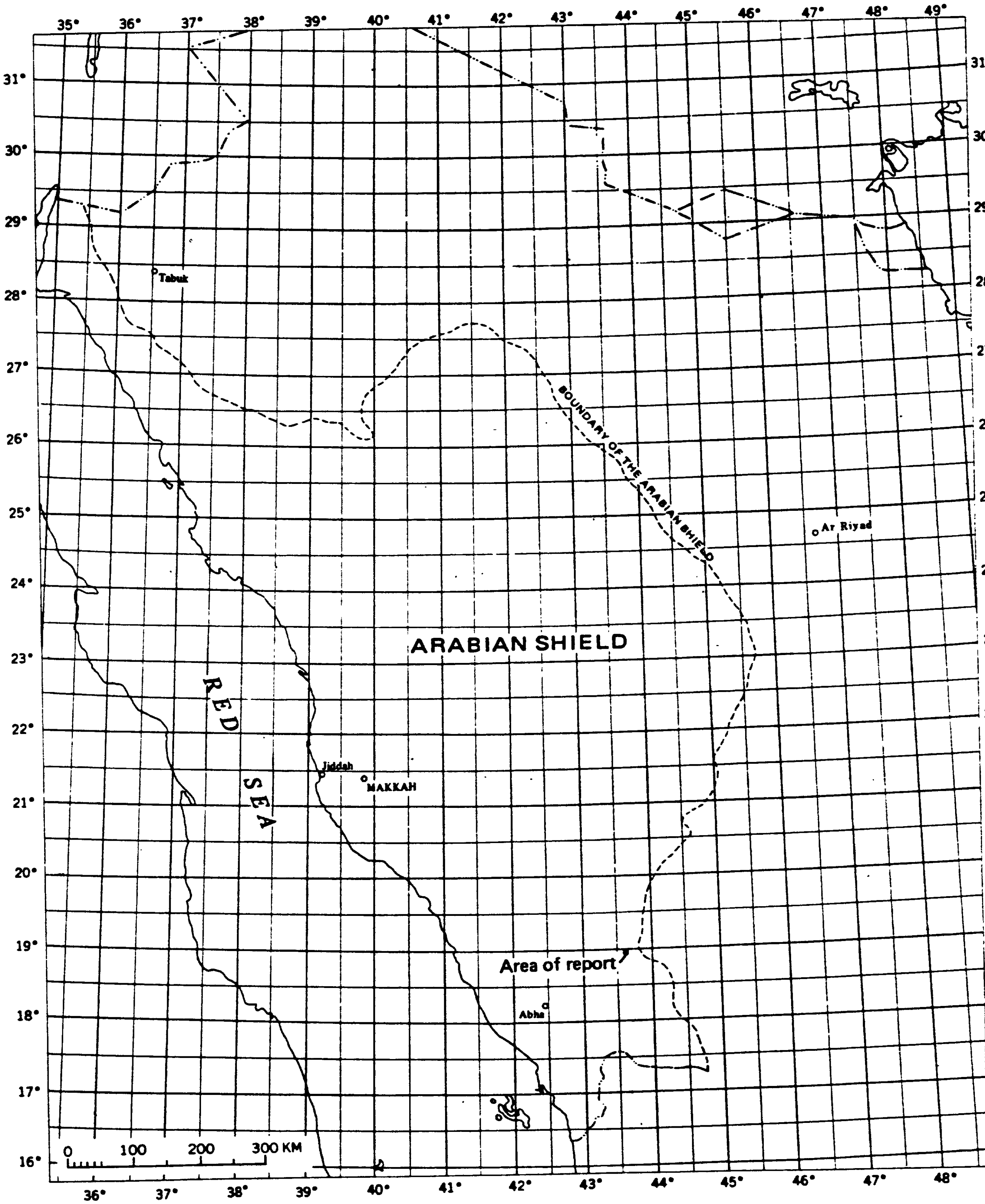

Figure 1.—Index map showing location of the Jabal al Hajrah 7 1/2-minute quadrangle, Kingdom of Saudi Arabia.

Oathlith south to Najran extends through the north-central and southeastern parts of the quadrangle. The road to Khamis Mushayt leaves the quadrangle in the northern part of the west boundary (pl. 1).

The major drainage for this part of the Arabian Shield, Wadi Tathlith, is an intermittent stream that flows northward through the western part of the quadrangle. The other wadis draining the quadrangle are tributaries of Wadi Tathlith. Water sources within the quadrangle are limited to Bir al Hamdan in the southwestern part of the quadrangle and intermittent pools and springs along Wadi Tathlith, most of which are east of Jabal Jiayfirah. Wells in Wadi al Khama and Wadi Atwayah are just outside the north and east boundaries, respectively. The lowest and highest altitudes, respectively, are approximately 1305 m where Wadi Tathlith leaves the northwest corner of the quadrangle and 1650 m at the top of Jabal Ghirban. Topography consists of isolated masses of granite standing above flat pediment plains, subdued, rounded hills of serpentinite, and steep, rugged hills of layered metamorphic rocks.

The Jabal al Hajrah quadrangle was mapped as part of an investigation of the Hajrah-Hamdah group of ancient gold mines: the Hajr, Jabal al Hajrah, Hajr Gharb, and Bir al Hamdan mines (pl. 1). The ancient mines and recent geochemical and diamond drilling exploration programs are described in another report (Helaby and Worl, 1981). An evaluation of serpentinites in the Hamdah area, some of which are exposed in this quadrangle, also appears in a separate report (Worl and Elsass, 1981). The quadrangle is covered by 1:500,000-scale (Brown and Jackson, 1959) and 1:100,000-scale (Warden, 1969) geologic maps. Directly north is the Hamdah quadrangle mapped at a scale of 1:100,000 (Overstreet, 1978). The purpose in mapping was to provide a base for future exploration and to delineate rock types and structures that are spatially related to gold metallization in the ancient mine area, namely felsic dikes and the footwall contact of the serpentinite bodies. Approximately 20 days during the period June 1976 through September 1977 were spent mapping by means of ground vehicles.

The rock units as shown on the map (pl. 1) result from field observations, augmented by some thin section and X-ray diffraction studies. Igneous rock names used follow the classification of the International Union of Geological Sciences (1973) and are based upon visual estimates of the volume percent of various minerals in thin section. Names of layered rock units indicate the dominant rock type present and are based upon field determination of mineralogy. Assay values are in grams per short ton.

This work was performed in accordance with a work agreement between the U.S. Geological Survey (USGS) and the Ministry of Petroleum and Mineral Resources of the Saudi Arabian government.

SERPENTINITE

Serpentinite exposures in the Jabal al Hajrah quadrangle are part of a series of large, flat-lying, sheetlike bodies and smaller, irregular lenses and pods in an area 20 km by 40 km (Worl and Elsass, 1981). In the Jabal al Hajrah quadrangle, the serpentinites overlie the hornblende schist, quartz-biotite schist, and carbonaceous schist units, but underlie the chlorite-epidote schist unit. The contact between serpentinite and the underlying hornblende schist unit is conformable to foliation and layering in the hornblende schist, but the nature of contact relationships with the carbonaceous schist unit is uncertain because of the contoured nature of the carbonaceous schist. The irregular outcrop pattern of serpentinite and hornblende schist, especially near the Hajr mine, is a consequence of folding and erosion. Serpentinite pods are common in hornblende schist and carbonaceous schist, but pods of hornblende schist and carbonaceous schist are not found in serpentinite. The contact between serpentinite and hornblende schist is commonly altered and in many places intruded by aplite and quartz stringer zones. The contact between serpentinite and the chlorite-epidote schist unit is complex. Most of the contact is altered, sheared, and filled with mafic dikes, and the contact seems to transect structure in the layered rocks.

In outcrop, the serpentinized rocks are various shades of brown, yellow, green, and gray, the result of differences in original constituents and the effects of hydrothermal alteration, shearing, and metamorphism. The original ultramafic rocks were of two types: metamorphic peridotite and a cumulate complex composed of peridotite and minor pyroxenite. Serpentinization was pervasive, but original textures are well preserved and include olivine and pyroxene relicts and mesh textures that are sufficient to define the original rock types (Worl and Elsass, 1981). Chrysotile and lizardite are the serpentine minerals; antigorite was not found. Associated minerals are talc, calcite, chlorite, and amphibole, mostly as alteration products of the original olivine and pyroxenes or serpentine minerals. Chromite, magnetite, and spinel are common constituents, of which chromite constitutes less than 1 percent of the rock and magnetite as much as 25 percent of some altered zones.

The serpentinites are intruded by diorite-gabbro, mafic and ultramafic dikes, and granite-monzogranite-granodiorite plutons and related dikes. Alteration of serpentinite by diorite and the mafic dikes was minor, being mainly the formation of talc and carbonates as narrow zones. Hydrothermal alteration related to the felsic intrusives is widespread at their contacts and along fractures throughout the serpentinite bodies. Alteration was of two types: formation of a reddish-tan, carbonate-rich rock and silicification, usually of previously formed carbonate-rich altered zones. Although sheared, the serpentinites are not foliated. Shearing in the serpentinite is accentuated by trains of magnetite in millimeter-thick bands along the shear planes. Regularly shaped polyhedrons ranging from 0.5 to several centimeters in diameter were produced by shearing.

LAYERED ROCKS

Layered rocks in the Jabal al Hajrah quadrangle are metamorphosed volcanic and volcaniclastic rocks of mafic to intermediate composition and related metasedimentary rocks. They are shown as four general map units (pl. 1): quartz-biotite schist, hornblende schist, carbonaceous schist, and chlorite-epidote schist. Rocks of the quartz-biotite schist, hornblende schist, and carbonaceous schist units are intergradational and intercalated on a macroscopic scale. Mineral species are similar throughout these three units, but abundances vary. The chlorite-epidote schist unit includes undifferentiated diorite, gabbro, and mafic dikes. The unit, outcropping only at Jabal Ghirban, is part of a rock section that regionally seems to overlie the sheetlike bodies of serpentinite, whereas the quartz-biotite schist, hornblende schist, and carbonaceous schist units are part of a rock section that seems to underlie the serpentinite (Worl and Elsass, 1981).

Regional metamorphism produced amphibolite-facies rocks that were retrograded to greenschist facies along the major fault zones. Mineral assemblages in the chlorite-epidote schist are more typical of albite-epidote-amphibolite regional metamorphic facies. The highest degree of metamorphism was to amphibolite facies in the hornblende schist map unit, in the extreme southeastern part of the quadrangle. This area is just north of a zone of granulite facies rocks reported by Warden (1969).

Quartz-biotite schist

The quartz-biotite schist map unit is thought to be the oldest rock exposed in the quadrangle. This map unit is mostly light-tan to light-gray, quartz-biotite schist, which is variable in grain size and outcrop appearance. Most rocks in the unit are schistose and have two, and in some localities three, surfaces that show a major schistosity and one or two surfaces that show poorly defined foliations. All surfaces are defined by oriented biotite and lithologic layering. The dominant schistosity is parallel to intercalated lenses of other lithologies and to relict bedding in these lenses. Pods and stringers of quartz are common along schistosity and foliations, and minor lit-par-lit intrusions of felsic dike material are common along the foliations.

Mineral assemblages include quartz-biotite, quartz-biotite-epidote, biotite-quartz-hornblende, and quartz-epidote, with or without muscovite, plagioclase, potassium feldspar, chlorite, actinolite, magnetite, calcite, and accessory minerals. The mineralogy is dominantly a mosaic of polygonal quartz grains and a scattering of dark-brown biotite in a granoblastic texture. Layers of green hornblende, actinolite, or coarse epidote a few millimeters to a few centimeters thick are common. Fine-grained, irregularly shaped masses of epidote occur throughout as do minor apatite and zircon. Large grains and aggregates of plagioclase and quartz are generally rimmed by a mosaic of small quartz grains in a mortar texture. Muscovite as large, irregularly shaped poikilitic grains is locally common. Hematite after pyrite cubes is rare, but disseminated dusty to granular magnetite is common. Comminuted quartz, quartz with wavy extinction, bent biotite lamellae, and ribbon structure ranging to mylonite are common in local zones. Silicification next to the large felsic dikes in the vicinity of the Hajr Gharb ancient mines is prominent.

Interbedded and intergradational with the quartz-biotite schist are lenses as much as 100 m thick of hornblende schist, chlorite schist, carbonaceous schist, phyllite, phyllitic quartzite, black marble, quartz porphyry, and dacitic metavolcanic rock.

The phyllite and phyllitic quartzite are light-brown to brownish-gray, fine-grained to aphanitic rocks. They are composed of quartz, sericite, and chlorite, with opaque minerals and some calcite. Phyllite is mostly massive, but phyllitic quartzite commonly shows lithologic layering that is probably relict bedding. Lenses approximately 1 m thick and a few tens of meters long of finely laminated, dark-blue-black crystalline marble, light-tannish-gray marble, and very fine grained tan phyllite are numerous. Quartz porphyry contains approximately 25 percent quartz phenocrysts set in a fine-grained groundmass of quartz, plagioclase, and chlorite. The dacitic metavolcanic rocks are greenschists that have relict fragmental textures and coarse to fine lithologic layering.

Hornblende schist

Most of the hornblende schist unit is fine- to medium-grained, pale to dark, brownish-green hornblende schist that has a black desert patina on the surface. The more massive rocks are mottled and contain irregularly shaped, pale-green, epidote-rich zones and dark-green, hornblende-rich zones. There is generally only one foliation, defined by mineral alignment, which is parallel to relict bedding and lithologic contacts. The more massive rocks have a rodded texture, which may reflect an original depositional texture.

The main mineral assemblages are hornblende and plagioclase (An_{28-50}), with or without epidote, actinolite, and chlorite, any of which may locally be the main mineral constituent, and generally minor biotite, quartz, diopside, and chlorite. Plagioclase, and quartz where present, are in a granoblastic groundmass; plagioclase is generally untwinned and unaltered. Pleochroic green-blue hornblende occurs as lathlike, oriented grains in the groundmass and as irregularly shaped aggregates or large grains in mafic clasts and relic lapilli. Epidote is scattered throughout as small, irregularly shaped grains. Biotite is found only with relatively abundant quartz. Actinolite forms layers of felty masses, commonly radiating from centers and replacing hornblende. Two types of relict depositional textures are common: clastic bedding, in places poorly graded, and fragmental textures with lapilli, broken feldspar crystals, and volcanic rock fragments. The more massive rocks have relict amygdules filled with quartz, epidote, and calcite, and in thin section, trachytic textures were observed. The original rocks that formed hornblende schist were probably mostly andesitic pyroclastic rocks and graywackes and subordinately massive andesitic flow rocks. Cataclastic textures, including mylonite, are common along the thrust fault zones at Jabal al Hajrah.

Intercalated with hornblende schist are intergradational lenses generally less than 10 m thick of massive amphibolite, hornblende gneiss, quartz-biotite schist, and bluish-black marble. Zones of chlorite and chlorite-sericite schist are along the major north-trending fault zones.

Carbonaceous schist

The carbonaceous schist unit is composed of intercalated lenses of carbonaceous chlorite schist, carbonaceous sericite schist, carbonaceous phyllite, quartz-sericite schist, thinly bedded dark-gray marble, well-layered hornblende schist, and quartz-biotite schist. Quartz is a major constituent, and pyrite locally makes up a few percent of the rock. Where exposed, the schist is highly foliated and has tight folds, contorted structures and wisps, and thin bands and layers of carbonaceous material. X-ray studies by Mohammad Naqvi and John Matzko, USGS, show no evidence of graphite. The dark-gray material thought to be carbonaceous turned to buff-colored ash after being heated 20 minutes at 1200°C. Heating in closed and open tubes did not give off sublimate or flammable fumes. These rocks are physically and mineralogically similar to carbonaceous schist in the Wadi Bidah district. There, the carbonaceous material was interpreted to be of algal origin in shallow seas (Kiilsgaard and others, 1978, p. 72).

Chlorite-epidote schist

The chlorite-epidote schist unit is exposed only at Jabal Ghirban and is part of a rock section that is thought to overlie the sheetlike serpentinite bodies. These rocks are structurally and lithologically complex, and just east of the Jabal al Hajrah quadrangle, a great diversity of lithologies, including serpentinite, are in chaotic juxtaposition. Numerous mafic and ultramafic dikes cut this rock section and are locally dominant, so that the layered rocks occur as screens between the dikes. Most exposures of the chlorite-epidote schist are massive, featureless greenstones and fine- to medium-grained greenschists. Foliation, as defined by aligned materials, is parallel to the mafic dikes or, in the vicinity of the larger serpentinite bodies, to the contact with serpentinite. Relict textures are few; they include pillow structures and amygdules in the massive greenstone and lapilli and fragmental crystals in the greenschist. Definitive relict bedding was not recognized. Much of the greenschist in hand specimen seems to be foliated and metamorphosed diorite and gabbro. Mineral assemblages are dominantly chlorite and epidote and, subordinately, actinolite, green hornblende, plagioclase, potassium feldspar, and quartz.

INTRUSIVE ROCKS

Three types of intrusive rocks cut serpentinite and all layered rocks exposed in the Jabal al Hajrah quadrangle. They are, in the order of decreasing age, diorite-gabbro, mafic to ultramafic dikes, and granite-monzogranite-granodiorite. The diorite-gabbro group includes a few associated dikes and irregularly shaped pods, whereas the granite-monzogranite-granodiorite group has a very extensive associated dike system.

Diorite-gabbro

The diorite-gabbro group as mapped is part of a larger, north-trending body that extends 10 km north of the quadrangle. Several intrusive phases of similar composition are present. These are not differentiated on the map except for one of the later phases, which forms dike swarms within the main body (pl. 1).

Subangular inclusions of mafic layered rocks and rounded inclusions of serpentinite are common within the diorite-gabbro. Plagioclase and hornblende are the major minerals, with subordinate biotite, pyroxene, and quartz. Plagioclase is andesine; quartz content of the rock is generally less than 10 percent. Biotite is in part a replacement of the hornblende. Most rocks are medium grained and contain subhedral plagioclase and tabular green hornblende; hornblende defines a foliation along with compositional layering. Potassium metasomatism in narrow zones along later monzogranite plugs and dikes is evidenced by replacement of plagioclase by potassium feldspar. Much of the diorite has been metamorphosed to greenschist facies; hornblende is deformed to chlorite and epidote, and plagioclase is saussuritized. A sheared and altered greenschist in the chlorite-epidote unit at Jabal Ghirban is thought to be altered diorite. This rock is cut by dikes of diorite related to the larger body and is considered to be part of the metamorphic rock unit that overlies the serpentinites.

Meladiorites exposed south of Wadi Lahu, in the southeastern part of the quadrangle, may not be related to diorite-gabbro north of the wadi. The rocks to the south are coarser grained and contain as much as 40 percent orthopyroxene altered to brown amphibole; plagioclase is andesine as it is to the north. Pyroxene-rich zones elsewhere form a small percentage of the exposures.

Mafic and ultramafic dikes

Mafic dikes of several types cut all layered rocks and serpentinite but are cut by monzogranite and related dikes. Most are individual dikes, except at Jabal Ghirban, in the east-central part of the quadrangle, where they are in a swarm that constitutes 40 to 90 percent of the exposures, the remaining exposures being rocks of the chlorite-epidote schist unit. Most of the dikes in serpentinite and many in the layered rocks are pulled apart into elliptical rounded boudins, and some are schistose along the edges. In the dike swarms at Jabal Ghirban, dikes include pyroxenite, peridotite, gabbro, diorite, andesite, and dacite. The dikes elsewhere in the quadrangle are mainly fine- to very fine grained andesite, with minor amounts of diorite and dacite. The large dikes or sills in the northwestern part of the quadrangle are medium-grained amphibolite and may have formed as volcanic flows. In detail, however, they seem to cut layering in the quartz-biotite schist and hornblende schist units.

Granite, monzogranite, and granodiorite

Granite, monzogranite, and granodiorite occur as several irregularly shaped bodies and numerous pods and dikes that cut diorite, serpentinite, and all layered rocks. Composition and texture vary considerably. The intrusive phases are coarse-grained, reddish-tan granodiorite as parts of the larger bodies; coarse-grained, gray biotite-monzogranite as most of the larger bodies and a few dikes; and light-gray biotite granite as most of the dikes and parts of some of the larger bodies. An arcuate zone of potassium-metasomatized rocks is also associated with these intrusives and is discussed below.

The slightly foliated granodiorite and monzogranite in the larger bodies are coarse grained and porphyritic. Grain size ranges from 0.2 to 2 cm, but the rock seems coarser in some areas because rounded to elliptical aggregates of quartz and plagioclase give the rock a cumulophyritic texture. Gray quartz is in rounded to elliptical phenocrysts as much as 0.5 cm in diameter, although most are less than 0.1 cm in diameter; anhedral quartz grains in the groundmass in some zones impart a mortar texture around larger grains. Sutured boundaries are common, and most of the quartz has undulatory extinction and is broken and healed. Plagioclase (An_{20-30}) is as subhedral laths and as individual phenocrysts as much as 2 cm across. Much of the plagioclase is zoned and has highly altered cores. In zones containing abundant potassium feldspar, the plagioclase is corroded, and where next to large grains of potassium feldspar it is myrmekitic. The larger plagioclase grains are commonly broken and healed by quartz and have bent twinning lamellae. Brown biotite generally lacks pleochroic halos and is present as short stubby laths in the groundmass. The biotite is generally fresh but is locally altered to blue chlorite and magnetite or epidote. Muscovite is rare. If less than one-third of the total feldspar, the potassium feldspar generally occurs as very small interstitial grains and stringers in the groundmass. If more than one-half of the total feldspar, the potassium feldspar is present as small interstitial grains, as large (as much as 2 cm in diameter) phenocrysts, and as partial replacement of plagioclase. The phenocrysts are very poikilitic and contain inclusions of highly altered plagioclase and rounded quartz. Euhedral green hornblende, partially altered to epidote, is a minor constituent. Subhedral red garnet is also a minor constituent and is found in all varieties of felsic rocks, including dikes, and in quartz veins associated with dikes.

Biotite granite is medium grained and equigranular in the larger bodies and medium to fine grained in the dikes. Granite dikes are the most abundant but many grade along strike to graphic granite, pegmatite, aplite, and rhyolite. The pegmatites are simple, composed of pink orthoclase, white quartz, and minor muscovite. Aplite is common along the contact between overlying serpentinite and underlying hornblende schist, especially in the Hajr mine area (pl. 1). The rhyolite dikes are fine to extremely fine grained and are composed of potassium feldspar and in some places quartz phenocrysts and roughly 10 percent biotite. The rhyolite may be the result of deuteric alteration, recrystallization, and potassium metasomatism of granite dikes.

Mineralogy of the dikes is similar to that of the larger bodies, except that stress figures, broken crystals, and textures due to recrystallization and cataclasis are more common. Accessory minerals found in the dike rocks but not in the larger bodies include magnetite and disseminated pyrite in some of the fine-grained varieties. Dikes in the Hajr mine area are syntectonic; the older dikes are cut off by thrust faults, but younger dikes crosscut the faults where they are shattered but not displaced by the faults.

The zone of potassium metasomatism (pl. 1) includes mylonite zones, potassium feldspar-bearing recrystallized mafic dikes, and rhyolite dikes. Boundaries of this zone are diffuse, and the degree of metasomatism ranges from partial replacement of plagioclase by potassium feldspar, to partial recrystallization of the rock and formation of biotite sheaves and small euhedral phenocrysts of potassium feldspar. The zone generally dips east. Much of the feldspathization is associated with rhyolite dikes.

QUATERNARY DEPOSITS

Alluvium

Quaternary alluvium blankets the broad, open wadis that are the dominant land form for much of this quadrangle. Wadi material consists of unconsolidated detritus ranging from fine-grained sand to gravel that is poorly sorted but locally well stratified. In the vicinity of plutonic rocks, the wadi material grades into pediment deposits of coarse- to fine-grained grus derived from the plutonic rocks.

Much of the area shown as alluvium north, south, and west of Jabal al Hajrah (pl. 1) is underlain by a section of tan to light-gray silt 50 cm to 10 m thick. Numerous lenses and pods of pebbles and cobbles of Precambrian rock types are within the silt. Major wadis that cross the silt deposits are floored by a thin veneer of gravel. The silt deposits are being studied by G. O. Bachman, who suggests that they are mostly eolian material that has been reworked by water (G. O. Bachman, written commun., 1978).

Pediment regolith

The pediment regolith covers relatively uniform, low-dipping surfaces that are 1 to several meters above the present wadi levels. The surfaces are covered by rounded, black pebbles 2 to 20 cm in diameter, which are coated by desert varnish. The major rock type is fine-grained andesite; hornblende schist is common. The andesite came from mafic dikes, which are common in the surrounding hills. The pebbles and cobbles rest on, and partially in, a grus derived from the underlying bedrock. The mantle of grus and desert-varnished pebbles and cobbles is thin, generally less than 50 cm, and minor water channels across the pediment expose bedrock in many places.

STRUCTURE

Regional structural trends in the southern part of the Arabian Shield are mostly north. In general, this part of the Shield is made up of arcuate, north-trending greenstone belts and parallel belts of gneiss domes, diorite batholiths, and gabbro to granite plutons. Major fault systems bound, and are within, the greenstone belts. The Jabal Ishmas-Wadi Tathlith fault zone and greenstone belt are a few kilometers west of the quadrangle (Worl, 1980). Structures within the greenstone belts are generally parallel to major faults and to bounding intrusive bodies; they are north trending and steeply dipping. The Hamdah serpentinites and associated greenstones are at variance to this regional pattern (Worl and Elsass, 1981) and crop out in a northeast-to east-trending, elongated, wedge-shaped area bounded on the west by the Jabal Ishmas-Wadi Tathlith fault zone and greenstone belt. On the east, they are covered by the Paleozoic Wajid Sandstone. Hamdah serpentinites and greenstones are bounded on the north and south by generally continuous, north-trending zones of gneiss domes, diorite batholiths, and plutons of gabbroic to granitic composition. The Jabal al Hajrah quadrangle is in the approximate center of the serpentinite zone. Directly south of the quadrangle is a major structural intersection of north, northeast, and northwest trends. In this area, Warden (1969) has mapped granulite-facies rocks.

Faults

Three major structural trends are evidenced by faults and dike patterns; azimuths are north, N.50°E. to N.70°E., and N.40°W. to N.30°W. The major faults trend north and seem to be the oldest set, because many are cut by northwest- and northeast-trending faults. These north-trending faults are sheared zones 10 to several tens of meters wide, whereas those of northeast and northwest trends are expressed as single, narrow fractures. Most of the northwest-trending faults and many of the northeast-trending faults are filled with felsic and mafic dikes. Numerous northeast-trending faults with minor left-lateral displacement seem to be the youngest set. The structural pattern in the southeast quarter of the quadrangle, as shown by dikes and faults, strikes N.70°E.. This zone does not extend southwest beyond the quadrangle but is continuous northeast for approximately 15 km, where it is covered by the Paleozoic Wajid Sandstone. Thrust faults exposed in the Hajr mine area dip east and northeast. Their significance is unknown, but they generally parallel the contact between hornblende schist and serpentinite and may represent major regional structures related to the "emplacement" of the serpentinites. The zone of shearing, brecciation, and alteration along the thrust faults is about 10 m wide, and several parallel but discontinuous zones of alteration and shearing in the footwall extend for a considerable distance below the main fault.

Folds

Rocks of the quartz-biotite schist and hornblende schist units are folded into broad open folds. The carbonaceous schist in general parallels these structures but in detail is highly contorted, especially near the contact with serpentinite. The folding is defined by relict bedding, best preserved in the more quartzitic layers in the quartz-biotite schist and the coarser grained layers in the hornblende schist, where it commonly is poorly graded. The minor structural features include open, flexural minor folds, similar to the large-scale folds, rodding, and boudins of the more competent beds, and mineral lineations. Only the attitude of bedding and axis of minor folds was measured systematically. The later foliations and mineral lineations probably reflect shearing related to the major fault zones. In most areas there is no field evidence for repeated or superimposed folding or for isoclinal passive shear folds, which are common through most of the Precambrian Shield.

Poles to bedding define three structurally homogeneous subareas (I, II, and III on pl. 1). The lower-hemisphere equal-area net plot of poles to bedding of subarea I define a great circle around an axis that strikes N.22°E. and plunges 30°. Definition of the great circle is fair but has a moderate amount of scatter, the nature of which suggests slight refolding around an east-trending axis. Poles to bedding in subarea II define a great circle around an axis that strikes N.45°W. and plunges 20°. The points do spread away from the great circle somewhat, especially for attitudes measured in the southwestern part of the subarea. In subarea III the poles to bedding define a great circle around an axis that strikes N.35°W. and plunges 25°. Scatter of points away from the great circle is minimal. Minor fold axes from subareas I, II, and III fall on the same great circle as the axes of rotation of bedding. The axes of rotation from subareas I and II define the limits of distribution between the N.45°W. and N.22°E. azimuths.

The structure in subarea IV (pl. 1) is not homogeneous at the map scale. All structural elements and especially the attitude of the contact between serpentinite and hornblende schist show a random distribution when plotted on an equal-area net. Small areas away from the contact are homogeneous and show patterns similar to those of subareas I, II, or III. The degree of inhomogeneity increases toward the serpentinite contact, where doubly and triply plunging, warped folds are common (Helaby and Worl, 1981). The style of folding seems to be the same on both hanging and footwall sides of the thrust faults in this subarea.

The structure of the chlorite-epidote schist unit seems to be controlled by the dike systems. The layered rocks, which make up less than one-half of the outcrop, occur as screens between the dikes. Relict bedding was not recognized. Poles to foliation plotted on an equal-area net defined a point maximum, with some rotation around a nearly vertical axis. The point maximum defines a plane that is parallel to the mafic dike swarms.

Foliation in the diorite strikes generally north to northeast and dips east or southeast 10° to 60°. Poles to the foliation define a great circle, with little scatter, around an axis that strikes N.82°W. and plunges 20°. The sheeted dike zones within the diorite are generally parallel to the foliation and define a similar structure.

ECONOMIC GEOLOGY

Mineral deposits

The Hajrah-Hamdah group of ancient gold mines is in the Jabal al Hajrah quadrangle and includes the Hajr, Jabal Hajr, Hajr Gharb, and Bir al Hamdan ancient mines, and several lesser occurrences (pl. 1). The Hajr mine has the most extensive ancient workings in southern Saudi Arabia (Worl, 1979). The workings at all of the mines consist of pits, trenches, inclined shafts, and vertical shafts. The pits and trenches are sand and rubble filled, 1 to 3 m wide, 1 to 2 (?) m deep, and as much as 160 m long. The vertical and inclined shafts are found mostly in the Hajr mine and Hajr Gharb areas and are as much as 20 m deep. A very extensive ancient village adjoins the Hajr mine on the southeast corner of the mine.

Mineralization is simple and consists of gold disseminated along selvages of granite or aplite dikes, in or along quartz-carbonate veinlets, in altered serpentinite, commonly with associated magnetite, and in silicifed quartz-biotite schist. Sulfides are not common; the occurrences include minor arsenopyrite at the Hajr mine and locally abundant sphalerite, chalcopyrite, pyrite, and galena in a quartz vein on the footwall of a granite dike at Jabal Hajr. Mineralization is in two geologic settings, both related to granite or aplite dikes. At the Hajr mine, mineralization is along the contact between the overlying serpentinite and underlying hornblende schist. The contact was invaded by aplite dikes and related quartz-carbonate veinlets, and the rocks were hydrothermally altered by solutions related to the dikes. Gold mineralization is related to the aplite dikes, related veinlets, and alteration (Helaby and Worl, 1981). At the Jabal Hajr, Hajr Gharb, and Bir al Hamdan ancient mines, gold mineralization is along bedding or layering in silicified quartz-biotite schist, along or near granite dikes. The granite dikes and aplite dikes are related and are late phases of the granite-monzogranite-granodiorite intrusives.

Exploration

The ancient gold mines were evaluated by geologic mapping, an extensive geochemical sampling program, and diamond drilling (Helaby and Worl, 1981). Twelve vertical, shallow diamond drill holes tested the contact zone at the Hajr mine, one tested an altered zone near a dike at Hajr Gharb, and one tested an altered zone in the southeastern part of the quadrangle. The results of the geochemical sampling and diamond drilling at the Hajr mine indicate widespread, low-grade (1 to 5 grams gold per ton) mineralization along the contact zone. The zone of mineralization is locally as much as 10 m thick. Drilling and geochemical sampling at Hajr Gharb indicated widespread, low-grade mineralization within 50 m of several granite dikes. Local zones as much as 1 m wide contain significant gold. Diamond drilling at the alteration zone (Hr-14, pl. 1) detected only trace amounts of gold. The evaluation program of the Hajrah-Hamdah group of ancient mines did not indicate any currently economic ore bodies, but does suggest that further limited exploration in selected areas is warranted (Helaby and Worl, 1981).

A separate program (Worl and Elsass, 1981) evaluated the metal potential in the country rocks of the Hamdah serpentinite area, part of which is covered by the Jabal al Hajrah quadrangle. The results of the study indicate that gold associated with the granite and aplite dikes is the best target for exploration, although disseminated gold deposits in layered rocks enclosing the serpentinites have some potential. One zone of particular interest is along the eastern boundary of the Jabal al Hajrah quadrangle, sample traverse line 117776 to 117801 (pl. 2), where anomalous gold was detected in and along a silicified breccia and quartz-stringer zone.

Samples collected by the USGS in the Jabal al Hajrah quadrangle are shown on plate 2. The analytical values and descriptions are stored in the computerized RASS system in the Saudi Arabian Directorate General of Mineral Resources computer in Jiddah. Most of the samples and analytical results are summarized and discussed in Helaby and Worl (1981) and Worl and Elsass (1981). Those samples that are not discussed in the above are listed, with description and gold content, in the appendix of this report. These are spot chip samples of specific rock types collected during mapping. All contain less than 1 gram gold per ton. Serpentinites in the Hajr mine area have recently been investigated for their asbestos potential (Rooney and Al-Koulak, 1979). Although a few exposures of chrysotile-bearing serpentinite are impressive, that is, zones 40 cm thick containing more than 50 percent chrysotile, the potential is judged poor to fair. The quality of the asbestos is high enough to warrant further study, but the occurrence is not nearly large enough to support a commercial enterprise (Rooney and Al-Koulak, 1979, p. 16).

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Appendix--*List of geochemical samples, descriptions, and gold analytical results*

[N = less than .04 ppm. Samples for determination of gold by atomic absorption were prepared by digesting a 10-g sample split, first in HCl, then in HNO_3; adding HBr and methyl iso buthyl ketone (M.I.B.K.) to the washed and centrifuged solution; washing the resultant organic layer in a weak HCl, HBr, and water solution to remove interfering elements; and collecting the organic layer in a test tube sealed with a polyethylene stopper (Joe Curry, written commun., 1978)]

Sample Number	Description	Gold (grams/ton)
110565	gray monzogranite	N
110764	hornblende schist	N
117016	black marble	0.12
031	granite dike, N.40°W. trend	N
033	granite dike, N.45°E. trend	N
037	quartz lens in quartz-biotite schist	N
038	hornblende schist	N
040	granite dike, N.40°W. trend	.47
100	granite dike, east trend	.05
102	mafic dike, N.10°W. trend	.05
103	granite dike, N.40°E. trend	.05
109	quartz lens next to granite dike	.06
110	granite dike, N.50°W. trend	.05
112	gossan along fault	.05
113	granite dike, N.35°E. trend	N
114	granite dike, N.70°E. trend	N
115	gossan	N
116	talus gravels	.16
117	talus gravels	.16
118	carbonate-altered hornblende schist	.16
120	quartz stringers	.05
126	sheared rock on serpentinite contact	N
131	altered serpentinite	N
132	altered rock from serpentinite contact	N
138	hornblende schist near serpentinite contact	N

Appendix--*List of geochemical samples, descriptions, and gold analytical results* [continued]

Sample Number	Description	Gold (grams/ton)
117139	sheared rock on serpentinite contact	N
141	hornblende schist near serpentinite contact	N
142	quartz prophyry	N
127000	monzogranite	0.07
004	mafic dike with red jasper	.08
005	K-feldspathized granodiorite	.08
007	alkali-feldspar granite dike, fine-grained	.07
008	biotite monzogranite	.07
009	alkali-feldspar granite dike, fine-grained	N
010	K-feldspathized granodiorite	.07
012	mafic dike	.20
017	granite dike, N.65°E. trend	.12
019	alkali-feldspar granite dike, fine-grained	.10
020	granite dike	.12
026	diorite	.05
032	diorite	.07
039	sheared rock on serpentinite contact	.08
042	alkali-feldspar granite dike, fine-grained	.10
054	alkali-feldspar granite dike, fine-grained	N
062	diorite dike, N.5°W. trend	.08
072	granite dike, N.80°E. trend	.08
079	mafic dike	.07
084	diorite dike	.05
094	granite	.08
115	hornblende schist	.10
130	granodiorite	.08
145	granite dike, N.40°W. trend	.10
154	diorite dike	.05
171	massive hornblende schist	.07
177	quartz-diorite schist	.08
180	dacite tuff	.10
187	dacite tuff	.07
188	dacite tuff	.07
190	dacite tuff	.08
197	granite dike	.08

Appendix--*List of geochemical samples, descriptions, and gold analytical results* [continued]

Sample Number	Description	Gold (grams/ton)
127224	quartzite	0.10
229	granite dike	.12
231	gray limestone	.07
263	gabbro dike	.08
269	diorite dike, N.30°W. trend	.10
270	granite dike	.08
297	granite dike	.08
315	granodiorite	.07
324	diorite dike	.10
336	carbonate-altered diorite	.08
474	quartz-biotite schist	.12