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RECONNAISSANCE GEOLOGY OF THE JABAL 'AFAF QUADRANGLE, SHEET 20/40 D, KINGDOM OF SAUDI ARABIA

by

Donald G. Hadley and Robert J. Fleck

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The work on which this report is based was performed in accordance with a cooperative agreement between the U. S. Geological Survey and the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia.

This report is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

CONTENTS

ILLUSTRATIONS

RECONNAISSANCE GEOLOGY OF THE JABAL 'AFAF QUADRANGLE, SHEET 20/40 D, KINGDOM OF SAUDI ARABIA

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Donald G. Hadley and Robert J. Fleck[1/]

ABSTRACT

The Jabal 'Afaf quadrangle (sheet 20/40 D) encompasses an area of about 2,900 km^2 along the boundary of the Red Sea coastal plain and the Red Sea escarpment between lats 20°00' and 20°30'N. and longs 40°30' and 41°00'E. The quadrangle is located about 170 km southeast of Jiddah and 100 km northwest of Al Qunfudhah.

About 75 percent of the northern and eastern parts of the area is underlain by metavolcanic and metasedimentary rocks of the Baish, Bahah, and Ablah groups and by a large variety of intrusive rocks ranging in age from pre-Ablah to Tertiary. The layered rocks are intensely deformed along north-trending axes and are metamorphosed to the greenschist and amphibolite facies. Tertiary gabbro dikes form a northwest-trending discontinuous swarm in part of the area. A variety of Quaternary deposits are found in the southwestern part of the quadrangle and in all wadis. They include pediment, alluvial, and eolian sand and gravel.

Marble and a kyanite quartzite unit were examined in several places, but have no appreciable economic potential. No metallic mineral deposits or mineralized areas were seen in the quadrangle.

[1/]U.S. Geological Survey, Menlo Park, CA

INTRODUCTION

The Jabal 'Afaf quadrangle (sheet 20/40 D) encompasses an area of about 2,900 km^2 along the boundary of the Red Sea coastal plain and the Red Sea escarpment between lats 20°00' and 20°30'N. and longs 40°30' and 41°00'E. (fig. 1). The quadrangle is located about 170 km southeast of Jiddah and 100 km northwest of Al Qunfudhah; at its closest point, it is 3 km from the Red Sea coastline. Most of the area is underlain by Precambrian and Tertiary rocks except for part of the southwestern corner, which is covered by pediment and plain deposits and eolian sand.

There are several small villages in the area. A number of unpaved roads crisscross the quadrangle, two of which are coastal-plain routes that connect Jiddah and Jizan. One of the roads extends to the headwaters of Wadi Ilyab and serves the rugged mountainous terrain at the base of the escarpment. The road that extends into the quadrangle from Ghumayqah is being paved and will serve as the principal artery of the coastal plain. Three major wadis - Wadi Iyar, Wadi ash Shaqah ash Shamiyah, and Wadi ash Shaqah al Yamaniyah - and their tributaries drain the area. Water occasionally reaches the Red Sea in these wadis during periods of particularly heavy rainfall along the rim of the escarpment and over some of the rugged outlying jabals such as Al Alonsa and Hatha. Elevations in the quadrangle range from about 15 m in the southwest to as much as 1,554 m in the extremely rugged mountainous terrain that covers most of the area. A hot spring is found in a tributary of Wadi Miraj; its source may be deep water rising along one of the Tertiary gabbro dikes.

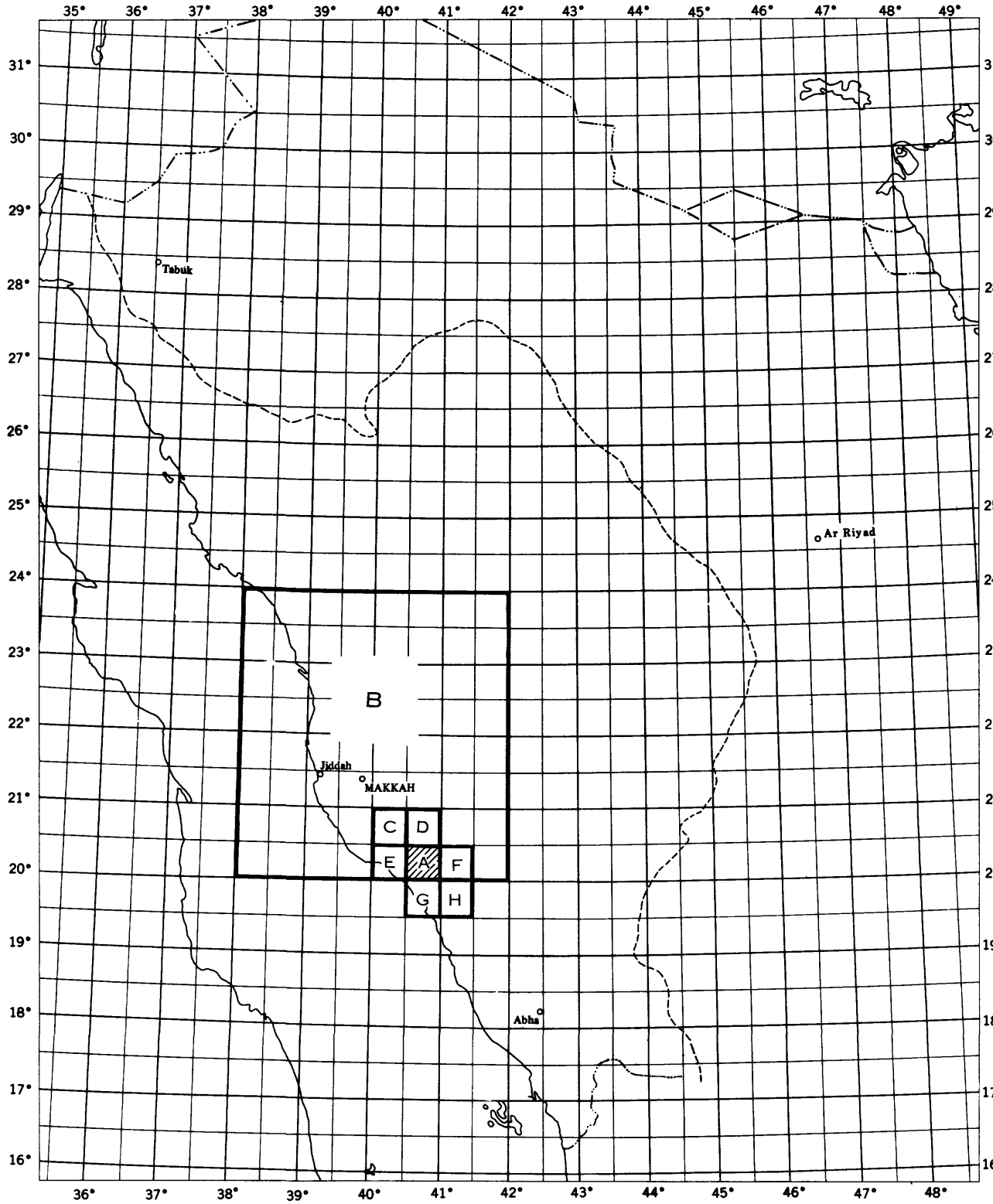

Figure 1.--Index map showing location of the Jabal 'Afaf quadrangle, A, and nearby quadrangles referred to in this report: B, Southern Hijaz; C, Wadi Sadiyah; D, Wadi Salibah; E, Al Lith; F, Jabal Ibrahim; G, Musaylim; and H, Jabal Shada.

Geologic studies in the area were first conducted by Brown and others (1963) during mapping of the Southern Hijaz quadrangle. In a later study, Gaskill (1970) evaluated kyanite and marble deposits in the quadrangle, but did only local mapping. Detailed mapping in the area was started in the early 1970's at a scale of 1:100,000 and was concluded in reports on the following quadrangles: Jabal Shada (Greenwood, 1975a); Jabal Ibrahim (Greenwood, 1975b); Wadi Salibah (Cater, 1977); and Wadi Sadiyah (Wier and Hadley, 1975). The present study was done during October 1973, in conjunction with the mapping of two other quadrangles in the area, the Al Lith quadrangle (Hadley and Fleck, 1979) and Musaylim quadrangle (Hadley, 1979).

The Precambrian layered rocks include amphibolite, volcanic rocks of the Baish group, and metasedimentary rocks of the Bahah and Ablah groups. Most of the quadrangle is underlain by intrusive rocks that have a broad range of compositions and ages. The rocks were folded twice, and probably a third time; plutonism accompanied the periods of deformation. The layered rocks are metamorphosed to the greenschist and amphibolite facies, and kyanite, garnet, staurolite, hornblende, and biotite are common metamorphic minerals. Tertiary gabbro dikes extend across much of the quadrangle except where they have been removed by erosion and covered by several types of Quaternary alluvial and eolian deposits.

Field work for this report was done by helicopter during October, 1973. Logistical and personnel support were generously

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PRECAMBRIAN ROCKS

Four sequences of Precambrian layered rocks crop out in the quadrangle. They include amphibolite and the Baish, Bahah, and Ablah groups. Most of the quadrangle is underlain by a wide variety of plutonic rocks that range in composition from gabbro to granite.

Layered rocks

Amphibolite

Two small areas of amphibolite are in the mapped area; one is near the south end of the tonalite and quartz diorite batholith and the other consists of two linear belts surrounded by the granite and quartz monzonite at Jabal Harmah. The amphibolite is dark gray to black, massive to moderately foliated, and consists of 50-60 percent subhedral to euhedral hornblende, 10-20 percent undulose quartz, 20-30 percent andesine, 1-3 percent biotite, and 2-5 percent magnetite, apatite, epidote, and sphene.

The amphibolite is indicated as being the oldest layered rock in the quadrangle, but its relative age is uncertain. Other than the amphibolite, no substantial amount of rock in

the area is thought to be older than the Baish group and inasmuch as rocks of the Baish are exposed closeby, it is probable that the amphibolite is metamorphosed Baish volcanic rocks.

Baish group

The Baish group consists of basaltic and andesitic flow rocks and genetically related volcaniclastic rocks. It comprises two units, described in lithostratigraphic terms in this report, that are correlative with the two oldest Baish units in the Al Lith quadrangle (Hadley and Fleck, 1979). The units are divided on the basis of gross lithology. The oldest is composed of basalt, andesite, and related volcaniclastic rocks, and the youngest is composed of volcaniclastic rocks and subordinate basalt and andesite.

Basalt, andesite, and subordinate interbedded volcaniclastic rocks.--The lowermost unit of the Baish group is exposed in two north-trending belts separated by the uppermost Baish unit in the west-central part of the quadrangle. It crops out in the extreme northeast corner of the mapped area and is found in the southeast corner of the area. In each area the unit dips from 35° to vertical.

Basalt and andesite are the principal rock types of the unit, interbedded with which are subordinate volcaniclastic beds of similar composition. As a rule, the rocks are strongly sheared and have been regionally metamorphosed to the greenschist facies and locally to the amphibolite facies. Original textures, bedding, and flow features are recognizable at many exposures.

The flowrocks range from 2 to 10 m thick. They are dark to medium green, fine to medium grained, and commonly porphyritic and amygdaloidal. Plagioclase phenocrysts are typically smeared out in the plane of schistosity, but where nonsheared they range from 0.3 to 2 cm in length. Glomeroporphyritic texture may be seen at some outcrops. Amygdules may be filled singly or in any combination by quartz, chalcedony, epidote, chlorite, or calcite.

Volcaniclastic beds are subordinate to the flowrocks in the lower unit. They include agglomerate and several types of tuff, are various shades of green and gray, and are intensely sheared between the more competent flow units. Measurable bedding was rarely seen, but where observed, beds range from 5 to 10 cm in thickness. A blotched and mottled appearance, resulting from sheared feldspar and lapilli fragments, is characteristic of the coarser-grained tuffs.

Volcaniclastic rocks and subordinate interbedded basalt and andesite.--The upper unit of the Baish group crops out in the western part of the quadrangle between the two belts of lower Baish rocks, and is also exposed as a narrow 0.3-0.7 km-wide fault slice sandwiched between the tonalite and granodiorite and the quartz diorite and diorite intrusions in the northwest corner of the quadrangle.

Compositionally, the rocks differ little from the lower unit except for the proportion of volcaniclastic rocks, which is substantially greater than that of flowrocks. Lithic, crystal, and ashfall tuffs and agglomerate constitute an estimated 60-70

percent of the unit. Tuff beds range from 5 to 15 cm in thickness, are various shades of green and gray, and may be traced continuously for as much as 20 m or more. A spotted appearance, due to the shearing of feldspar, is typical of this unit and most other textural features and stratification are obliterated because of shearing.

Flowrocks of the unit consist of basalt and andesite. Individual flows are difficult to recognize, but some flows are marked by concentrations of amygdules at their tops, and others are separated by interstratified pyroclastic material.

The upper unit is strongly foliated, and its structural habit is difficult to determine. The outcrop pattern of the entire Baish in the area suggests that the upper unit is the core of a syncline whose axis strikes mostly north.

Bāhah group

The Bahah group consists of two metasedimentary units, a lower unit of biotite schist and an upper unit of hornblende schist. They are defined in lithostratigraphic terms in this report and are not assigned formational rank.

Biotite schist

The lower unit of the Bahah group crops out in the south-central part of the quadrangle as the outer limbs of a northeast-plunging syncline. The lower and upper units along the southeast margin of the syncline are bounded by a wrench fault of undetermined displacement.

The unit consists of relatively well-bedded medium- to dark-brown fine-grained biotite schist. The rock is well recrystallized

because of amphibolite-grade metamorphism but relict bedding is preserved at many outcrops. Some beds are much more siliceous than others and probably are recrystallized quartzose beds. Most samples contain quartz, plagioclase, biotite, epidote, opaque minerals, and sphene. The relative quantity of any of these minerals generally varies from outcrop to outcrop.

Hornblende schist.--The upper unit of the Bahah group forms the core of the syncline in the southern part of the quadrangle, extending from the south side of Jabal al Aswadayn to an area north of Jabal al Aswadayn and west of Jabal Hatha; it also crops out in a much smaller belt on the east side of Jabal Hatha.

The unit is composed of metasedimentary rock similar to the underlying unit. It is medium to dark gray, well bedded in places but generally schistose, and is recrystallized to fine to medium grained. As in the biotite schist unit, thin-bedded quartzose beds are common. Mineralogically, the unit consists of anhedral to euhedral (mostly subhedral) quartz, plagioclase, hornblende, biotite, sphene, epidote, and magnetite..

Ablah group

The Ablah group is the youngest Precambrian layered sequence in the quadrangle. In this area the Ablah group is in fault contact with the older tonalite and quartz diorite batholith that crops out from near Wadi Malah to Wadi Athum. A very careful re-examination of the contact area, however, might disclose an unconformity and a basal boulder conglomerate similar to that at the base of the Ablah group in the Biljurshi quadrangle (Greenwood, 1975c). The Ablah group crops out in three areas. The largest

of these is in the central part of the quadrangle in a north-trending linear belt that ranges from 1 to 5 km in width and extends from Jabal al Aswadayn to the northern edge of the quadrangle. The other two areas are a lobate belt in the vicinity of Wadi Hagog near the northern boundary of the quadrangle and an irregular area in the west-central part of the quadrangle near the village of Nakhl Shahbah. In the northern part of the quadrangle, the Ablah group strikes into and is correlative with high-grade metamorphic rocks comprising quartzite, schist, amphibolite, marble, and gneiss mapped by Cater (1977) as being older than Baish group. The assumption was probably made by Cater that the metamorphic sequence was equivalent to the Hali schist mapped elsewhere and believed at the time to be one of the oldest units of the Arabian Shield (Schmidt and others, 1973). Lithologically, the sequence is identical to the Ablah group in the Aqiq (Greenwood, 1975d), Biljurshi (Greenwood and others, 1975c), Wadi Yiba (Bayley, 1972), and Wadi Hali (Hadley, 1975) quadrangles. A re-examination of the Ablah group in its type area in 1974, however, showed that it was younger than initially proposed by Brown and Jackson (1959) and Schmidt and others (1973) and younger than the Baish group (Greenwood, 1975c, d; Hadley, 1975).

In each of the three outcrop areas, the Ablah group is either intruded by the granodiorite and granite batholith or crops out within 1 km of it. As a result, it is metamorphosed to the amphibolite facies and contains an abundant assemblage of high-grade metamorphic minerals.

The Ablah group in the Jabal Afaf quadrangle consists of amphibolite, kyanite quartzite, marble, and graphite, staurolite, hornblende, garnet, and biotite schist. The rocks are thoroughly sheared and recrystallized. Primary sedimentary features are mostly obliterated, but are preserved in some instances, particularly in the marble. The schists are fine to medium grained, are light to medium gray, tan, and brown, and are texturally mylonitic, granoblastic, and porphyroblastic. In addition to the metamorphic minerals mentioned above, the minerals contained in the rock include quartz, plagioclase, epidote, sphene, a little zircon, and iron ore minerals.

Kyanite quartzite crops out along the east side of Wadi al Ajr directly east of Jabal Al Alonsa (Gaskill, 1970). It consists of a bed 7-20 m thick and can be traced along strike for about 400 m. This is the only place in the quadrangle where kyanite quartzite was seen but it also occurs in several areas in the Wadi Salibah quadrangle (Cater, 1977). The quartzite consists of intergrown blades and masses of pure kyanite in massively structured beds 0.5-1 m thick; single kyanite crystals are as much as 4 cm long. The rock is light tan to bluish gray.

Marble in the Ablah group is found near the west side of the northwestern belt. It is in a folded and strongly sheared bed that strikes mostly north, dips from 60 degrees to vertical, and measures 100-300 m in width and 4 km in length. The rock is light to dark gray, pink, tan, and green; the colors are commonly intricately interwoven because of the shearing of one color band into another. Bedding is mostly obscured, but appears to range from a few centimeters to 0.5 m in thickness. Petrographically,

the marble consists of a mosaic of coarsely crystalline calcite, and 10-20 percent quartz, plagioclase, phlogopite, and opaque minerals.

Intrusive rocks

Precambrian plutonic rocks dominate the Jabal Afaf quadrangle. They have a broad compositional range from mafic intrusive rocks (several varieties of gabbro and diorite) to granitic intrusions including quartz monzonite, granite, and monzonite, and were emplaced during three episodes. Characterization of the intrusive bodies in this report follows the scheme used in the Al Lith quadrangle, in which the intrusion is identified according to its most important one or two intrusive phases (Hadley and Fleck, 1979). For example, tonalite and quartz diorite are the two most important intrusive phases in the oldest pluton in the quadrangle.

Pre-Ablah intrusive rocks

The pre-Ablah intrusive rocks include five plutons, or bodies, of batholithic size: tonalite and quartz diorite, quartz diorite and diorite, two hornblende diorites, and biotite diorite.

Tonalite and quartz diorite.--The oldest of the pre-Ablah intrusive rocks is the tonalite and quartz diorite batholith that forms an irregular and somewhat semi-circular outcrop in the east-central part of the quadrangle. It is fine to medium grained, light to medium gray, and contains abundant mafic inclusions that were probably derived from stoped mafic volcanic rock. It is composed mainly of plagioclase, quartz, and biotite. The plagioclase is porphyritic throughout the bulk of the intrusion,

and phenocrysts are 1 to 2 cm in length. Accessory minerals include epidote, apatite, magnetite, chlorite, sphene, and a little zircon.

Quartz diorite and diorite.--The quartz diorite and diorite intrusion crops out in the northwestern corner of the mapped area and is part of a body that is also exposed in the northeastern corner of the Al Lith quadrangle (Hadley and Fleck, 1979). The rock is medium to dark gray, is coarse grained with strong prophyritic texture, and has abundant moderately to strongly saussuritized plagioclase phenocrysts as much as 1.5 cm long. Quartz is moderately to strongly undulose. Mafic and accessory minerals include 15-25 percent hornblende, 2-4 percent biotite, and 3-7 percent epidote, opaque minerals, apatite, and chlorite. The intrusion reaches elevations of as much as 700 m in the Jabal Afaf quadrangle, but is eroded to a surface of low relief in the Al Lith area. It is intruded by abundant dikes in the Al Lith quadrangle but the dikes were rarely seen in the Jabal Afaf area.

Northern hornblende diorite.--The northern hornblende diorite is the oldest of the two pre-Ablah intrusions of this composition. It crops out in a semi-circular belt surrounding Jabal Harmah in the northeastern part of the quadrangle. Its semi-circular pattern has been defined by later intrusion of the Jabal Harmah granite and quartz monzonite.

The rock is dark gray, medium grained, and protoclastic to hypidiomorphic granular. It contains less than 10 percent undulose quartz, 70-80 percent moderately to strongly saussuritized laths

of andesine, 15-25 percent chloritized hornblende, and a few percent sphene, magnetite, epidote, apatite, and calcite.

Southern hornblende diorite.--Another diorite crops out in two areas in the southeastern part of the mapped area, one about 1 km north of Wadi Ilyab and the other in the southeastern corner of the quadrangle. Compositionally, the rock is identical to the northern diorite except for minor variations in the mineral assemblage.

Biotite diorite.--Biotite diorite crops out in the south-central part of the quadrangle directly south of the village of Al Habgah. It is not well exposed and is mostly eroded down to a low-relief surface. It is dark gray, medium grained, and protoclastic, and is composed of less than 10 percent quartz, 60-80 percent saussuritized andesine, 10-20 percent biotite, and a few percent accessory minerals.

Syn-to post-Ablah intrusive rocks

The syn-to post-Ablah intrusive rocks consist of metagabbro, batholithic granodiorite and granite, hornblende diorite, and tonalite and granodiorite.

Metagabbro.--Metagabbro crops out on either side of Wadi Minsah in the northwestern part of the quadrangle and underlies Jabal Thalah near the northern border. It is composed of 70-80 percent poikilitic clinopyroxene in 1-4 cm crystals, 20-30 percent plagioclase, and 2-4 percent biotite.

Granodiorite and granite.--The granodiorite and granite intrusion is one of the largest in the area. It crops out in two areas in the quadrangle: one, in the southeastern corner of the quadrangle where the intrusion extends from Jabal Hatha

southeastward to the Musaylim quadrangle and thence into the Jabal Shada quadrangle; and two, in the north-central and western parts of the quadrangle where it crops out from Jabal Afaf to the northern border of the quadrangle. Throughout the pluton's area of outcrop, the terrain is extremely rugged; relief differs as much as 1,000 m within 2-3 km in some of the deeply incised canyons.

In addition to the main rock types, the intrusion contains tonalite, quartz monzonite, and quartz monzodiorite intrusive phases. It is light to medium gray, fine to medium grained, and porphyritic. Biotite is the main mafic mineral, making up 5-10 percent of the rock, followed by minor hornblende and chlorite. The rock is strongly foliated and schistose, largely due to cataclasis and recrystallization that resulted during syntectonic domal emplacement, but in part due to the numerous faults that cut it. It has all the tectonic and compositional characteristics of the Jabal Baqaratayn orthogneiss in the Wadi Hali and Aya quadrangles (Hadley, 1975; Prinz, 1975) and the g^1 batholithic metatonalite of the Wadi Yiba quadrangle (Bayley, 1972).

Hornblende diorite.--Hornblende diorite crops out in an elongate belt on the east side of the main belt of the Ablah group in the central part of the quadrangle. It is medium grained, dark gray, and is protoclastic to mylonitic. It contains 2-5 percent undulose interstitial quartz, 60-70 percent laths of moderately to strongly saussuritized plagioclase, 25-35 percent chloritized hornblende prisms, and less than 5 percent accessory minerals.

Tonalite and granodiorite.--A tonalite and granodiorite intrusion crops out in a narrow fault-bounded linear belt in the northwest corner of the mapped area. It contains a subordinate quartz monzodiorite phase and is continuous with extensions of the pluton in the Al Lith quadrangle (Hadley and Fleck, 1979). The rock is light pink and strongly porphyritic, and contains microcline phenocrysts as much as 3 cm long set in a medium-grained, strongly foliated, and cataclastic groundmass. The groundmass is stippled by 5-8 percent chloritized biotite and includes accessory epidote, apatite, magnetite, and sphene. The rock is especially mylonitic and cataclastic along the fault borders.

Late Precambrian intrusive rocks

Late Precambrian intrusive rocks include several types of igneous plutonic suites ranging in composition from gabbro to granite.

Metadiorite.--Metadiorite crops out in the northwestern part of the quadrangle between Wadi Minsah and Wadi al Faj. It is fault-bounded on three sides except for a stubby lobe that intrudes the Baish group, and is intruded on its northwest side by granite. Primary minerals in the rock consist of 2-3 percent interstitial quartz, 40-60 percent saussuritized andesine-labradorite, 30-40 percent hornblende, and 2-9 percent combined biotite, magnetite, apatite, and epidote. The primary minerals are conspicuously altered to chlorite, clinozoisite, sphene, and leucoxene.

Gabbro.--A roughly circular gabbro pluton underlies Jabal al Aswadayn directly northeast of Al Habgah. The rock is medium to coarse grained, is very dark gray, and has holocrystalline hypidiomorphic texture. It shows practically no deformational or alteration features. Primary minerals include 70-80 percent augite, 20-30 percent labradorite, and 5-10 percent combined magnetite, apatite, calcite, and sphene.

Granodiorite.--A 6 km by 14 km oval pluton of granodiorite underlies Jabal Hatha in the east-central part of the area. It includes subordinate granite and quartz monzonite phases and is probably equivalent in age to the intrusion at Jabal Harmah. The rock is light gray, medium grained, and contains strongly porphyritic plagioclase and microcline phenocrysts 1-2 cm long set in a finer-grained groundmass. It is composed of 10-25 percent weakly to moderately undulose quartz, 10-25 percent weakly kaolinized microcline and orthoclase, and 45-60 percent weakly saussuritized obligoclase. Secondary minerals include 4-8 percent biotite, about 1 percent hornblende, and 1-4 percent combined muscovite, chlorite, sphene, magnetite, calcite, and apatite. It is intruded by numerous west-trending mafic dikes and, because of its elevation, constitutes one of the most prominent physiographic features in the area.

Granite and quartz monzonite.--Granite and quartz monzonite underlie Jabal Harmah in the northeast quadrant of the quadrangle; like Jabal Hatha, this is one of the highest and most imposing mountains in the area. The rock makes up a circular intrusion 10 km in diameter that intrudes the tonalite

and quartz diorite and the northern pre-Ablah hornblende diorite. The intrusion contains subordinate quartz monzodiorite and quartz diorite phases. Except for the minor differences in intrusive phases, the rock is compositionally and texturally identical to that at Jabal Hatha.

Granite.--A granite intrusion crops out in the northwestern part of the mapped area from Wadi al Faj to the northern edge of the quadrangle near Jabal Hayanah. Subordinate intrusive phases found in the intrusion are tonalite, quartz diorite, and quartz monzonite. It intrudes several older plutonic units along its eastern side as well as the lower unit of the Baish group. A fault terminates the western side of the granite against the tonalite and granodiorite. The rock is medium grained, light pink to orange, and slightly porphyritic. Feldspar makes up about 75 percent of the essential minerals, of which about 65 percent is kaolinized microcline and the rest is saussuritized oligoclase. From 20 to 25 percent of the rock is quartz. Accessory minerals include 1-3 percent hornblende, 2-5 percent biotite, and 1-3 percent combined apatite, chlorite, magnetite, epidote, sphene, and a trace of zircon.

Quartz monzonite.--A small pluton of quartz monzonite intrudes the Bahah group along the east-central border of the quadrangle about 1-2 km east of Jabal Hatha. The rock is light gray to pink, fine to medium grained, and strongly cataclastic and mylonitic. It consists of roughly equal proportions of microcline and oligoclase (65-75 percent of the rock), 15-25 percent cataclastic undulose quartz, 5-10 biotite, and a few percent of accessory minerals.

Granite and quartz monzonite.--Granite and quartz monzonite crop out as separated low-lying hills in a deeply eroded intrusion on the plain in the southwestern part of the quadrangle, and as a small isolated outcrop about 5 km west of the main area. The rock is fine grained, light orange, strongly foliated, and cataclastic. It contains roughly equal proportions of quartz, oligoclase, and potassium feldspar--which form about 90 percent of the rock--2-5 percent biotite, and a few percent accessory minerals.

Dikes

Mafic dikes.--Mafic dikes intrude rocks in the east-central part of the quadrangle. They form a closely spaced west-trending swarm in the tonalite and quartz diorite. The dikes consist of basalt, diabase, and andesite. Some can be traced as far as 15 km. They are 0.5-2 m wide, have chilled borders, and in a few cases have porphyritic centers. Some of the dikes appear to be injected into fault zones, as indicated by shearing of the surrounding rock and offsets along the zones.

Granite dikes.--A few granite dikes intrude the tonalite and quartz diorite and the granodiorite of Jabal Hatha and have the same trend as the mafic dikes. Some intrude the biotite diorite near Al Habgah. They are fine grained, light pink to orange, and 0.5-1.5 m wide. The dikes contain sparse biotite and are mostly unaltered.

TERTIARY ROCKS

Miocene gabbro dikes

Miocene gabbro dikes intrude the Precambrian rocks in several areas of the quadrangle. An anastomosing network of several dikes extends from Wadi Miraj to the northwest corner of the quadrangle. The dikes there are parallel to subparallel, but commonly bifurcate and intersect one another. The dikes that crop out in the south-central part of the quadrangle south of Al Habgah are clearly extensions of those described above. A large dike is exposed continuously from the vicinity of Jabal Thalah to Wadi Kassab. Separate dikes are found in the southeast corner and in the west-central part of the quadrangle, south of the Ghumayqah-Al Qunfudhah road.

The dikes are mainly gabbro, but are composed of quartz monzonite in some places (Blank, 1978). They are 50-200 m in width, medium to dark gray, and fine to very coarse grained. Borders of the dikes are chilled and very fine grained, and form resistant ridges.

Textures are diabasic, gabbroic, and ophitic. Poikilitic augite crystals, as much as 2 cm long, make up 40-60 percent of the rock, with 30-40 percent labradorite, 2-5 percent serpentinized olivine, 3-7 percent magnetite, 2-6 percent chlorite, and a little sphene.

The dikes range in age from 19 to 27 million years (m.y.) (Brown, 1972) and average about 22 m.y.; these dates were obtained by potassium-argon whole-rock methods. The dikes are part of the

Red Sea dike swarm that extends from Ad Darb to the Gulf of Aqaba (Brown, 1972; Blank, 1978; Coleman and others, 1979).

QUATERNARY DEPOSITS

Pediment and plains, sand, gravel, and silt deposits

Most of the southwest one-fourth of the quadrangle and an area between Wadi ash Shaqah al Yamaniyah and the granodiorite and granite intrusion in the southeastern part of the quadrangle are underlain by sand, gravel, and silt on pediments and plains. The sand is very fine to medium grained and is intermixed with silt. Gravel is found mainly near outcrop areas but lag gravel sheets are occasionally found elsewhere. The area underlain by these deposits has no appreciable relief. It slopes away from the outcrop areas in most places at a rate of about 10-20 m for the first kilometer and substantially less thereafter. The sediment is dissected by the major and minor wadis of the area and is covered by several large fields of eolian sand. The area is hummocky where sand is mounded around desert shrubs and is sparsely dotted by acacia trees.

Escarpment boulder and gravel deposits

Gravel and boulder deposits are found east of Jabal Harmah in the northeastern part of the quadrangle. They are located within 10-15 km of the Red Sea escarpment and are derived by recent active denudation of the escarpment. The deposits are not consolidated and consist of clasts ranging in size from pebbles to boulders as much as 0.5 m in diameter; they include most rock types found in the escarpment headwater area. They are older than

the present wadi system and consequently are dissected, exposing material as much as 10 m thick. The detritus is stratified and commonly contains lenticular sand and pebble channels.

Alluvial sand and gravel

Alluvial sand and gravel is found in all of the wadis in the area. It is composed of tan to brown sand, gravel, minor silt, and cobbles and is poorly to well stratified. Channels and crossbedding are commonly found in erosional faces. The sediment is from 1 to 3 m thick.

Wadi flood-plain silt deposits

Within and adjacent to the major wadis are extensive flood-plain silt deposits. They consist of silt and minor fine-grained sand and clay. The sediment is light brown, is massive and well stratified, and is as much as 3 m thick in areas where wadis have been dammed or diverted for agricultural purposes. In addition to older deposits, new material is presently being deposited during periods of intermittent flooding in the low-energy overbank environment of high ground within the wadis and marginal to the main channels.

Eolian sand dune fields

Large areas containing eolian sand dunes are found in several parts of the quadrangle. The largest of these is in the central to southern part of the area; it extends continuously from the vicinity of Al Habgah northwestward to Wadi Miraj. This field alone is more than 30 km long and is as much as 6 km wide. Other fields include four found in the southwest corner

of the quadrangle and another in the southeastern part of the quadrangle banked against the granodiorite and granite batholith. Linear sand ridges are situated atop the dune fields that butt against the granodiorite and granite batholiths.

The deposits consist of tan, fine- to medium-grained sand and range from continuous sand hills to areas covered by closely associated but isolated dunes separated by barren wind-deflated ground. The dunes are as much as 5 m high.

The location of the largest dune fields is not fortuitous. The fields lie along the southwest sides of prominent topographic features because these features confine the northeastward transport of the sand.

Linear eolian sand ridges

Linear eolian sand ridges are found mostly overlying the eolian sand dune fields, but some overlie the pediment and plain deposits. The ridges consist of fine- to medium-grained sand and are 20-100 m wide by 0.4-5.5 km long. The ridges are concentrated on the dune fields because these provide a constant source of sand. Bimodal wind directions determine and maintain the shape of the ridges. The primary wind direction is from the southwest (Red Sea) throughout the year, but these winds are augmented by wind from the southeasterly monsoon.

STRUCTURE

Structural trends in the quadrangle are dominantly northerly. Rocks of the Baish, Bahah, and Ablah groups are all folded about north-trending axes. The Baish and Bahah rocks were deformed,

intruded by the mafic to intermediate plutonic rocks, and were metamorphosed to the greenschist facies, and locally to the amphibolite facies, during the pre-Ablah orogenic episode, the Tihama orogeny (Schmidt and others, 1973; Hadley and Fleck, 1979). A second period of deformation followed deposition of the Ablah group, which may lie unconformably on the older rocks (Bayley, 1972; Greenwood, 1975c), and was accompanied by intense shearing, east-west compression, amphibolite facies metamorphism (garnet, hornblende, and kyanite schists in the Ablah), and syntectonic emplacement of some plutons, especially the granodiorite and granite pluton. The type of tectonism and grade of metamorphism accompanying this period of tectonism are basically identical to those recorded in the Wadi Yiba and Hali quadrangles during domal injection of the g^1 tonalite and the Wadi Baqarah orthogneiss (Bayley, 1972; Hadley, 1975). The northwest-trending fault network may have developed, in part, during this orogenic period, but was reactivated later, as evidenced by offset of the faults crosscutting the Jabal Hatha pluton. Several plutons were intruded during one or more later intrusive-orogenic cycles. They are mainly of granitic composition, except for the gabbro of Jabal al Aswadayn. Three of the later intrusions, the Jabal al Aswadayn gabbro and the granitic plutons of Jabal Hatha and Harmah, are post-tectonic and show neither metamorphism nor appreciable deformation, except small-scale faulting.

METAMORPHISM

The Baish and Bahah group rocks are regionally metamorphosed to the greenschist facies and in broad areas to the amphibolite facies. The only area where they are metamorphosed only to the greenschist facies is in the southwestern part of the quadrangle. The Ablah group is everywhere metamorphosed to the amphibolite facies. Most of the plutonic rocks are similarly metamorphosed, except for the three post-tectonic intrusions noted above. Greenschist facies mineral assemblages include chlorite, actinolite, albite, sphene, epidote, and calcite, and the amphibolite-facies mineral suites are hornblende, quartz, biotite, andesine, staurolite, kyanite, garnet, epidote, sphene, and apatite. Metamorphic textures are protoclastic, granoblastic, poikiloblastic, xenoblastic, and nematoblastic.

ECONOMIC GEOLOGY

No areas that appeared to have significant economic potential or that warranted special study or sampling were seen in the quadrangle. The kyanite quartzite near Jabal al Alonsa was re-examined, but as Gaskill (1970) noted, it does not appear to have any potential for development at the present time. Marble in the area is likewise unexploitable at the present time because it is too far from a suitable market and is much too difficult of access.

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