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EXPLANATORY NOTES TO THE GEOLOGIC MAP OF THE JABAL IBRĀHĪM QUADRANGLE, SHEET 20E, KINGDOM OF SAUDI ARABIA[1]

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CONTENTS

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Abstract.—The Jabal Ibrāhīm quadrangle lies between lat 20° and 21° N. and long 40°30′ and 42° E., close to the western margin of the Arabian Shield. It is predominantly underlain by layered and intrusive rocks of late Proterozic age. These rocks are bounded in the southwest by faults that parallel the margin of the Red Sea, and they are overlain in the northeast by Pliocene to Pleistocene lava flows.

Five principal units of Proterozoic layered rocks crop out in the quadrangle. From oldest to youngest, they include the Baish and Bahah groups, the Qirshah and Khutnah formations, and the Ablah group. Volcanic rocks of the Baish and Bahah groups are bimodal tholeiitic basalt and soda dacite-rhyolite composition; these groups, together with plutons of diorite and tonalite, constitute an intraoceanic island-arc volcanic complex that developed between about 950 and 840 Ma.

The Qirshah and Khutnah formations and a younger group of diorite and tonalite intrusive rocks also represent an island-arc complex, but the geochemical data indicate that the volcanic rocks are more mature than those of the Baish and Bahah groups. They include tholeiitic basalt and calc-alkalic andesite to rhyolite. The geochronologic data, although somewhat ambiguous, are sufficiently consistent to suggest that this arc complex developed between about 750 and 720 Ma.

The youngest layered rocks, the Ablah group, are predominantly of epiclastic origin. They were deposited unconformably upon the older two sets or arc-complex rocks after a perioed of deformation and greenschist-facies metamorphism.

During successive events in the quadrangle, the arc complexes were fully accreted to each other. They and the Ablah group were then further metamorphosed and intruded by syntectonic granite gneiss batholiths, and the area became a stabilized craton by the emplacement of late-tectonic to posttectonic granitic plutons.

Mineral occurrences are abundant in the quadrangle, and many small ancient workings are known. The older arc complex contains copper and zinc sulfide deposits, as well as gold-enriched mobilized sulfide and quartz-vein mineralization. The younger arc complex hosts similar types of mineralization. Both sets of mineral occurrences are typical of volcanogenic mineralization in island arcs and represent fundamental elements in the metallogeny of the rgion. An example of sedimentary-hosted copper mineralization occurs in the basal, transgressive part of the Ablah group. Fluorite-barite veins controlled by fault structures, and traces of molybdenite in pegmatite are believed to be of hydrothermal origin related to the intrusion of late-tectonic granitic plutons. Despite a large number of occurrences, the economic mineral potential of the quadrangle is low.

خلاصة: يقع مربع جبل ابراهيم بين خط عرض ٢٠°، ٢١° شمالا وخط طول ٤٠°٣٠′، ٤٢° شرقا بالقرب من الحافة الغربية للدرع العربى وغالبا مغطى بصخور طباقية ومتداخلة من العصر البروتيروزويك المتأخر. وتحد هذه الصخور فى الجنوب الغربى بصدوع متوازية للبحر الاحمر، ومغطاة فى الشمال الشرقى بتدفقات اللابا من عصر البليوسين الى البليستوسين وتظهر فى المربع خمسة وحدات رئيسية من الصخور الطباقية البروتيروزية وتشمل من الاقدم الى الاحدث مجموعتى بيش والباحة ومكونات قرشه وختنه ومجموعة عبلة. تتكون الصخور البركانية لمجموعتى بيش والباحة من ثيوليتك بازالت وصودا ديسايت ريولايت، وتكون هذه المجموعات مع الصخور العميقة من الديورايت والتونالايت مركب قوس جزيرة بركانى محيطى والذى تطور بين حوالى ٩٥٠، ٨٤٠ مليون سنة. مكونات قرشة وختنه ومجموعة اصغر من الديورايت والتونالايت (صخور مقتحمة) تمثل ايضا مركب قوس جزيرة بركانى، ولكن المعلومات الجيوكيميائية تدل على ان الصخور البركانية اكثر نضوجا من تلك فى مجموعتى بيش والباحة والتى تشمل ثيوليتك بازالت وكالك قلوى انديزايت الى ريولايت. معلومات تقدير العمر هى الى حد ما غامضة الا انها كافية لتدل على ان مركب القوس تطور بين ٧٥٠، ٧٢٠ مليون سنة. الصخور الطباقية الاحدث (مجموعة عبلة) تكون غالبا من اصل فوق فتاتى وقد ترسبت بغير توافق على مجموعتين من مركب قوس من الصخور الاقدم بعد فترة تهشيم وسحنة شست اخضر متحولة. خلال الاحداث المتتابعة فى المربع التحمت مركبات القوس مع بعضها وقد تحولت اكثر من مجموعة عبلة واقتحمت بواسطة الحركات المتزامنة للباثوليث من الجرانيت النايسى وأصبحت المنطقة «كراتون» ثابت وذلك باحلال الحركات المتأخرة الى الحركات المتقدمة من صخور الجرانوتويد الجوفية. المربع غنى بالمظاهر المعدنية وكثير من الاعمال القديمة الصغيرة معروفة. يحتوى مركب القوس الاقدم على رواسب كبريتيد النحاس والزنك وأيضا على الذهب الغنى فى الكبريتيد وعروق المرو. مركب القوس الاحدث يحتوى على انواع مشابهة من التمعدن. كلا المجموعتين من المظاهر المعدنية من اصل بركانى فى اقواس جزر وتمثل عناصر اساسية فى «الميتالوجى» للمنطقة مثال التمعدن فى النحاس المتجمع فى الصخور الرسوبية يظهر فى الجزء الضحل والممتد لمجموعة عبلة. سيطرت الصدوع على عروق الفلورايت والبارايت. ويعتقد ان آثار الموليبدانايت فى البغماتايت ذات اصل مائى مرتبط باقتحام الحركات المتأخرة. وعلى الرغم من كثرة المظاهر المعدنية الا ان الجدوى الاقتصادية ضئيلة.

INTRODUCTION

Location

The 1:250,000-scale geologic map of the Jabal Ibrāhīm quadrangle, sheet 20E, covers 17,150 km in southwestern Saudi Arabia between lat 20° and 21° N. long 40°30′ and 42° E. (fig. 1). The quadrangle reaches to within 1 km of the Red Sea coastline and spans the Red Sea escarpment between the Tihāmat (Red Sea coastal plain) and the gently eastward-sloping Asir plateau. The highest altitude is 2,602 m at Jabal Bayḏān on the escarpment in the northwest; the lowest point is less than 100 m above sea level, where Wādī ash Shāqqah ash Shāmīyah leaves the southwestern corner of the quadrangle, some 9 km from the coast. The quadrangle is named after Jabal Ibrāhīm, located in the central part of the quadrangle in which the mountain is located; the two quadrangles are distinguished in this report by appending the index number (20/41 C) to the 1:100,000-scale quadrangle.

Al Bāḩah, just east of the escarpment on the southern edge of the quadrangle, is the largest town in the region. It and numerous villages in the central part of the quadrangle are accessible from the At Tā'if-Abhā highway. The southwestern corner of the quarangle is traversed by the Tihāmat highway, which extends along the coastal plain from Makkah to Jizan.

Previous investigations

The geology of the Jabal Ibrāhīm quadrangle has been mapped in reconnaissance at 1:500,000 scale by Brown and others (1963) and at 1:100,000 scale by Greenwood (1975a, c), Cater (1977), Hadley and Fleck (1980), and Greene and Gonzalez (1980). The geology of selected parts of the quadrangle has been studied by Metz and others (1971), Jackaman (1972), Fujii (1979), and Zakir (1972); and regional syntheses of the geologic relations in the area have

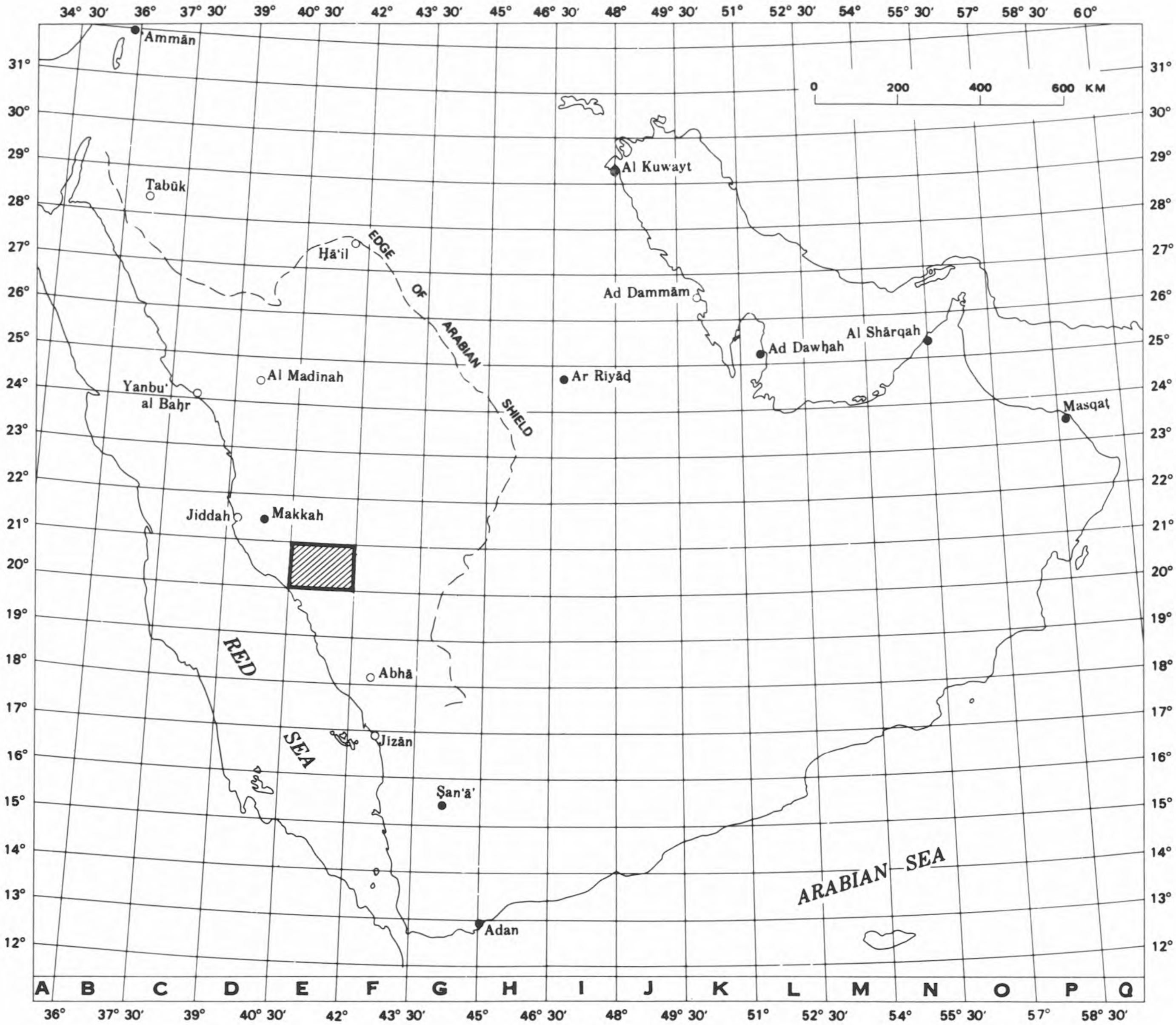

Figure 1.—Index map of the Arabian Peninsula showing the location of the Jabal Ibrāhīm quadrangle.

been undertaken by Schmidt and others (1973), Greenwood and others (1976), Jackson and Ramsay (1980), Jackson and others (1982), Greenwood and others (1982), and Johnson (1983). Potassium-argon and rubidium-strontium geochronologic data pertaining to the quadrangle have been provided by Fleck and others (1976), Aldrich (1978), Brown and others (1978), Fleck and others (1980), Bokhari and Kramers (1981), Fleck and Hadley (1982), Kroner and others (in press), Marzouki and others (1982), and D. P. F. Darbyshire and others (written commun., 1983); lead-isotope data were reported by Stacey and others (1980) and Bokhari and Kramers (1982). Petrographic geochemical analyses of samples from various parts of the quadrangle were undertaken by Ramsay and others (1981), Duyverman and others (1982), Roobol and others (1983) and Reischmann and others (in press).

Mineral occurrences, first investigated by Larken (1936), are widespread in the quadrangle and have been studied extensively. Result of early exploration were reported by Allcott (1969), Earhart (1969), and Igarashi (1969); and the quadrangle was included in assessments of the mining potential of western and southern Saudi Arabia by Goldsmith (1971), Liddicoat (1974), and Roberts and others (1975). Johnson and Vranas (1984) recently described the metallogeny of the region. Copper and zinc sulfide mineralization of the Bīdah district, in the center of the quadrangle, has been described by many authors, including Earhart and Mawad (1970), Earhart (1971), Jackaman (1972), Greenwood and others (1974), Kiilsgaard and others (1978), Hopwood (1979), Riofinex (1979), and Smith and others (1983). The potential for copper and zinc in the Shuwāş district in the southeastern part of the quadrangle was assessed by Fujii (1976), Takahashi (1976), Igarashi (1977), Igarashi and Goto (1977), and Fujii and Kato (1977), and Fujii and Kato (1979a, b). Gold exploration has been reported on by Mawad (1980), Worl (1982), and Worl and Smith (1982). Allcott (1970) and Igarashi (1975) investigated fluorite occurrences, and Worl and Flanigan (1977) discussed a sedimentary rock-hosted copper deposit. Barite mineralization occurs in the Al ʻAqīq area, located in the southeastern part of the quadrangle (Cartier, 1983). Base-metal occurrences in the southwestern part of the quadrangle were evaluated by Bowden and Morfett (1981), and marble and kyanite occurrences, by Gaskill (1970).

Present work

The 1:250,000-scale geologic map of the Jabal Ibrāhīm quadrangle is mainly a compilation based on five 1:100,000-scale geologic maps (Greenwood, 1975a, c; Cater, 1977; Greene and Gonzalez, 1980; and Hadley and Fleck, 1980). The northeastern corner of the map was compiled from photogeologic interpretation aided by the 1:500,000-scale geologic map of Brown and others (1963), as well as from unpublished map data of R. C. Greene (written commun., 1983).

Correlation of the map units used in the present compilation with those in the 1:100,000-scale source maps is given in table 1. The correlations are controlled, where possible, by the available geochronologic data. As this compilation was prepared in whole or in part from reconnaissance geologic maps that predate establishment of the Saudi Arabian Code of Lithostratigraphic Classification and Nomenclature, the naming and classification of informal rock units herein may not necessarily conform with formal usage stated in the code.

This text summarizes information from the notes accompanying the five 1:100,000-scale source maps; it is augmented by petrographic and geochemical data from the sources previously cited. Discussion of mineralization in the quadrangle is based mainly on reports by Jackaman (1972), Riofinex (1979), and Smith and others (1983) on the Bīdah district and Fujii (1976), Igarashi (1977), and Fujii and Kato (1979a) on parts of the Shuwās district lying within the quadrangle. Mineral occurrences and ancient workings are plotted on the geologic map. Details concerning these occurrences and workings are recorded in the Mineral Occurrence Documentation System (MODS) of the Saudi Arabian Deputy Ministry for Mineral Resources utilizing a four-digit code number, presently prefixed by zero (0XXXX). MODS information is available from the Office of the Technical Advisor to the Deputy Minister, Jiddah, Kingdom of Saudi Arabia.

Cater made a preliminary compilation of the geologic map and drafted this text in 1981. The map was recompiled by Johnson on a revised Landsat mosaic quadrangle map (U.S. Geological Survey, 1981), and the text was rewritten by Johnson in 1983. The work is a product of an agreement between the United States Geological Survey and the Saudi Arabian Ministry of Petroleum and Mineral Rersources. The authors are grateful to D. P. F. Darbyshire and colleagues, N. J. Jackson, C. R. Ramsay, and M. J. Roobol for permission to use unpublished geochronologic data.

GEOLOGIC SETTING

Southwestern Saudi Arabia is underlain by tightly folded, regionally metamorphosed volcanic, volcaniclastic, and epiclastic rocks and many mafic to felsic plutons, all of late Proterozoic age. The region is part of the larger Arabian-Nubian Shield, which became a stabilized craton toward the end of the Precambrian and persisted as an essentially stable block until the early Miocene opening of the Red Sea. Proterozoic rocks are known as far as the Nile valley to the west and the Arabian Gulf to the east. In the western part of Saudi Arabia, they are exposed as the Arabian Shield; in the eastern part, they are concealed beneath the Phanerozoic sedimentary "cover rocks" that dip gently toward the Arabian Gulf.

The late Proterozoic rocks in the Jabal Ibrāhīm quadrangle are preserved as north-trending belts of layered formations cut by plutons and batholiths of chiefly dioritic to granitic composition. Two episodes of volcanism are represented by the layered formations: the oldest episode by the Baish and Bahah groups and the younger by the Qirshah and Khutnah formations. These units comprise volcaniclastic and subordinate flow rocks complexly interlayered with volcanically derived and epiclastic sedimentary rocks. Because both assemblages also contain plutons of diorite to tonalite and many hypabyssal intrusions, each constitutes an island-arc volcanic complex.

A third succession of layered Proterozoic rocks in the quadrangle, the Ablah group, also has a volcanic component, but it consists predominantly of epiclastic rocks. The group unconformably overlies the older (Baish-Bahah) volcanic arc.

Precambrian volcanism, sedimentation, and arc-related plutonism in the quarangle spanned the period from about 950 to 700 Ma. Younger intrusive rocks are syntectonic to posttectonic and consist of granodiorite to granite plutons. The granitic magmatism began during the orogeny that accreted the island-arc volcanic complexes to the African craton and contributed to the formation of a stabilized craton.

The youngest rocks within the quadrangle are Tertiary and Quaternary basalt flows and gabbro dikes. Both are associated with Red Sea rifting: the basalts are part of a large area of flow rocks and volcanic cones resulting from volcanic activity, whereas the gabbro dikes were intruded into tension fractures.

Overlying the bedrock are unconsolidated Quaternary deposits that include wadi alluvium, fanglomerate derived from the Red Sea escarpment, terrace gravels, coastal-plain silt, and eolian sand. These formed during the period of active erosion following the uplift of the region and the opening of the Red Sea, which caused the development of wadi systems draining to the east and west and the erosional retreat of the Red Sea escarpment.

PROTEROZOIC LAYERED ROCKS

In this compilation, Proterozoic layered rocks are assigned to the Baish and Bahah groups, the Qirshah and Khutnah

TABLE 1.—Correlation of map units used in this report with those used in the 1:100,000-scale source maps

[fm., formation; gp., group; pt., in part; —, not applicable]

1:250,000-scale	1:100,000-scale source maps					
20E Jabal Ibrāhīm	20/40 B wādī Salībah (Cater, 1977)	20/41 A Wādī Shuqub (Green and Gonzalez, 1980)	20/41 B[1]	20/40 D Jabal 'Afaf (Hadley and Fleck, 1980)	20/41 C Jabal Ibrahīm (Greenwood, 1975c)	20/41 D Al 'Qqīq (greenwood, 1975a)
Quaternary and Tertiary rocks						
Qa	—	Qa	Qs	Qal	Qal	Qal
Qes	—	—	—	Qes	—	—
Qs	—	—	—	Qs	—	—
Qt	—	—	—	Qg	Qg	—
QTb	—	Qb	Qtb	—	Qb	Qb
Tgb	—	—	—	Tgb	—	—
Proterozoic intrusive rocks						
rh	—	—	—	—	qp	rp
mgb	qmf (pt.)	—	—	gbm	gbm	gbm
gb	gb	—	—	gbc	—	gb
dg	—	dg	—	—	—	—
st	—	st	—	—	—	—
gr	—	gr	—	—	—	qmp (pt.)
gpm	gpm	—	—	—	—	—
gbh	qmf (pt.)	—	—	gcb	qmp	—
grh	—	—	gp (pt.)	—	—	qmc, qmf
grb	qmg (pt.)	grb (pt.)	—	qmb, grb	qms	—
gtn	—	—	—	—	—	qd_3
gdb	gdqm	—	gp (pt.)	gnb	—	qms, qmr, qmp (pt.)
gto	—	—	—	tnb	gn (pt.)	—
gd	gdb	—	—	gdpb	—	gd
gdb	cg, dqd (pt.)	grg	—	—	—	—
gn	qmg (pt.), gng	—	—	—	—	gn, qmp (pt.)
gg	qmb	grb (pt.)	—	gdb	gn (pt.)	—
td	—	—	—	dhn	—	di_1 (pt.), di_2
tn	—	—	—	—	—	qd_1 (pt.), qd_2
ddg	cd	—	—	—	—	—
di	dqd (pt.)	td (pt.)	gg	dih, dbm, dh	di	di_1 (pt.)
ti	—	—	—	—	—	—
qd	qdgd	td (pt.)	—	qdh, qlh, tqdb	qd, gn (pt.)	qd_1 (pt.)
pd	pd	—	—	—	—	—
px	—	px	—	—	—	—
ser	—	—	—	—	—	—
Proterozoic layered rocks						
aa Ablah gp. undivided	msq	—	—	ag	—	—
at Ablah gp. Thurat fm.	—	—	—	—	—	at
aj Do Jerub fm.	—	—	—	—	—	ajb
ar Do Rafa fm.	—	—	—	—	bhs	ar
kh Khutnah fm.	—	—	—	—	—	jdk
qh Qirshah fm.	—	—	gd	—	—	jdq
qhr Do	—	—	gr (pt.)	—	—	—
qhv Do	—	—	gr (pt.)	—	—	—
br Bahah gp. Ras fm.	—	m_3, m_4, m_5	—	—	bhr	bhg
bb Bahah and Baish gps. undivided	—	—	—	bba (pt.)	—	—
ba Do	jdq, qz	m_6	—	bpt	bj (pt.), bha (pt.), bja	bg (pt.)
bam Do	ags	—	—	am, bba (pt.) bhbs bhhs	bga, bha (pt.)	—
bj Baish gp. Jof fm.	—	m_1, m_2	sc	—	bj (pt.)	bg (pt.), bga

[1]No named 1:100,000-scale source map available; correlations are from Brown and others (1963).

formations, and the Ablah group. The earliest investigators mapped the layered rocks in the quadrangle as unnamed units of chlorite schist; sericite-chlorite schist; andesite and diabase; amphibolite schist; a complex of metadiorite, metagabbro, and amphibolite; and shale and conglomerate (Brown and others, 1963). Subsequently, Metz and others (1971) mapped unnamed units of phyllite, greenschist, and quartz-sericite schist in the Wādī Bīdah area in the center of the quadrngle. In the following year, Jackaman (1972) divided the layered rocks in the vicinity of Wādī Bīdah into the Sharg, Bidah, and Gharb groups, but during 1:100,000-scale mapping of the Jabal Ibrāhīm (20/41 C) quadrangle, Greenwood (1975c) reassigned all three groups to the Jof formation of the Baish group. Subsequent authors (Riofinex, 1979; Smith and others, 1983) reverted to Jackaman's earlier divisions of the rocks in the Bīdah area, but Greenwood's divisions are utilized in this compilation because they are the most consistent with those used in the geologic compilation of other quadrangles in the southern part of the Arabian Shield. In this report, the Baish group includes sequences of metavolcanic and subordinate metasedimentary rocks in the Wādī Bīdah area itself, where Greenwood first introduced the term, as well as previously unnamed formations mapped by Greene and Gonzalez (1980) in the Wādī Shuqub quadrangle to the north.

The Bahah group first named by Schmidt and others (1973) for outcrops near Al Bāḩah, consists of metasedimentary rocks that interfinger with or overlie the Baish group. The name was extended to similar sequences in adjacent quadrangles by Greenwood (1975a, d). It is also used, in this report, for some of the units mapped by Green and Gonzalez (1980) in the northern part of the quadrangle.

Several units of amphibolite, metavolcanic rocks, and metavolcaniclastic rocks that crop out in the western part of the quadrangle were originally assigned to the Jiddah group (Cater, 1977), but farther south and west similar rocks were mapped as units of the Baish and Bahah groups by Hadley and Fleck (1980). These rocks are compiled as units of the Baish and Bahah group undivided, as are amphibolite in the center of the quadrangle and some units of volcanic and sedimentary rocks on the southern border that, farther south, form the Duqah formation of the Baish group (Prinz, 1983).

A variety of names has been applied to the metavolcanic and metasedimentary rocks in the southeastern part of the quadrangle. Originally called the Aqiq Series by Metz and others (1971), similar rocks were mapped in the early 1970's as the Wadi Dumah and Wadi Shwas formations (Ozawa, 1977). Greenwood (1975a) subsequently renamed them as Qirshah andesite and the Khutnah formation and later Bokhari and Kramers (1981) called them the Surgah and Shwas formations. In the present compilation, Greenwood's nomenclature is modified to the Qirshah and Khutnah formations. Greenwood (1975a) correlated the formations with the Jiddah group, although Ozawa (1977) suggested that they have affinities with the younger Halaban group. In the Wādī Bīshah quadrangle (Simons, in press), adjacent to the east, these formations are assigned to the Jiddah group, but recent Rb-Sr (rubidium-strontium) data (Bokhari and Kramers, 1981; D. P. F. Darbyshire and others, written commun., 1983) suggest that the Qirshah and Khutnah formations are about 728-721 Ma old and are, therefore, younger than the conventional age of Jiddah group (Schmidt and others, 1973; Greenwood and others, 1976). However, the geochronologic data are difficult to interpret, and the results appear to conflict with an older age obtained from tonalite that intrudes the Qirshah and Khutnah formations (Marzouki and others, 1982) and with an older age obtained from the Ablah group (D. P. F. Darbyshire and others, written commun., 1983), which is generally considered to overlie the two formations. Because the data are ambigous and not completely reliable, the two formations are not assigned to any group.

The Ablah group consists mainly of a north-trending belt of epiclastic and volcanic rocks cropping out in the eastern part of the quadrangle (Brown and others, 1963; Igarashi, 1975; Greenwood, 1975a). A threefold classification for this group into the Rafa, Jerub, and Thurat formations is adopted in this compilation. Ablah group rocks are also shown on the compilation between the southern border and Wādī Rama, and as a sinuous belt of metasedimentary rocks farther west between Jabal al Aswadayn and Jabal Qalqal (Hadley and Fleck, 1980). The outcrop of the Ablah group near Wādī Rama is shown on the 1:100,000-scale source map (20/41 C) as part of the Baish group (Greenwood, 1975c), but in this report, it is reassigned to the Ablah group on the basis of the results of geologic compilation in the adjacent Al Qunfudhah quadrangle (Prinz, 1983).

Baish group

JOF FORMATION

The Jof formation of the Baish group (bj) crops out principally in the north-trending belt along Wādī Bīdah in the center of the quadrangle. The type area of the formation is in Wādī Jof in the south-central part of the quadrangle (Greenwood, 1975b). It consists of a complexly interfingering succession of volcanic, volcaniclastic and subordinate epiclastic rocks, together with abundant mafic and felsic sills and dikes. The formation has been metamorphosed regionally to the greenschist and locally to the amphibolite facies, folded into numerous open-to-tight north-trending anticlines and synclines, and cut by faults and shears. As a consequence, the stratigraphic succession of the formation is unknown. Jackaman (1972) proposed that the sequence becomes younger toward the west, whereas Riofinex (1979) concluded that the layered rocks become progressively younger toward the east. The base is not exposed, and only locally is the top of the succession observed.

Overall, the Jof formation consists mainly of mafic volcaniclastic rocks; mafic lavas are subordinate, and felsic volcanic and volcaniclastic rocks are rare but important as one of the host rocks for copper- and zinc sulfide mineralization in the area. The assemblage represents a bimodal suite of low-potassium tholeiite and low-soda dacite-rhyolite, which geochemically is similar to present-day island-arc volcanic complexes (Roobol and others, 1983).

The predominant mafic volcaniclastic rocks include tuffs, graded tuffites, and occasional coarse breccia units that crop out as thinly bedded greenschists or more massive greenstones of basaltic to andesitic composition. The rocks vary in grain size from fine to coarse and in places form beds 1-20 cm thick that are arranged in graded units as much as 20 m thick (Jackaman, 1972). Load and flame structures are common, and minor unconformities and pinch-outs are widespread. In contrast, other tuffs are massive, occurring in beds as much as 10 m thick, and can only be distinguished from lavas with difficulty. The rocks have a metamorphosed equigranular, blastoporphyritic texture consisting of subhedral hornblende and plagioclase megacrysts in a fine-grained matrix of feldspar, chlorite, epidote or clinozoisite, actinolite, and carbonate (Ramsay and others, 1981).

Subordinate mafic lavas occur in many parts of the formation, but are most common east of Wādī Bīdah. They range in composition from tholeiitic basalt to basaltic andesite. Most form massive flows, commonly 5 m but as much as 30 m thick (Jackaman, 1972), interbedded with coarse pyroclastic rocks. The flows are always vesicular and may have autobrecciated tops. In places, pillow lavas occur; a particularly prominent unit crops out in the central part of the quadrangle along the slopes east of Wādī Bīdah. Individual pillow flows are as much as 30 m thick and 1,000 m long. They consist of pillows, varying in diameter from 30 cm to 4 m, in a matrix of mafic tuff and minor jasper. In general, the lavas crop out as massive to schistose greenstones and greenschist. They are granoblastic, lepidoblastic, or blastoporphyritic in texture. Altered phenocrysts of clinopyroxene or hornblende and saussuritized plagioclase are present in a fine- to medium-grained matrix of altered plagioclase, epidote or clinozoisite, actinolite or chlorite, and quartz.

The coarse pyroclastic rocks interbedded with flows consist largely of hyaloclastic breccia. Blocks of amygdaloidal basalt and broken pillows as large as 3 m across are set in a volcaniclastic matrix of recrystallized vesicular glass and fragmental material of the same composition as the clasts (Greenwood, 1975c).

Rocks of felsic composition form a minor component of the Jof formation, but are notable hosts of copper and zinc mineralization in the Bīdah district. The rocks consist of varieties of chlorite-sericite-feldspar-quartz schist of dacitic or rhyodacitic composition. Primary textures are largely obliterated by the schistosity, and the rocks usually are difficult to distinguish from fine-grained quartzofeldspathic arenaceous or argillaceous rocks that also occur in the formation. The schists are inferred to represent predominantly lithic to crystal dacitic tuffs. They consist of inequigranular quartz, plagioclase and orthoclase feldspar, minor muscovite, epidote and (or) biotite, and chlorite enclosing megacrysts of plagioclase, quartz, or pyroxene, as well as lithic fragments. In places, relict angular breccia fragments as much as 30 cm long and 10-15 cm thick can be recognized. Fine compositional banding on a millimeter scale is present, as are rare graded beds in units as much as 1 m thick. Rocks made up of quartz, plagioclase, sericite, and epidote have been identified by Earhart and Mawad (1970) as quartz porphyry and are considered to be an ore control in the Bīdah district; however, their extreme variety in texture and composition led Greene and Gonzalez (1980) to conclude that they are metatuffs. Several other felsic-tuff horizons contain distinctive clear blue quartz megacrysts. Typically such units are strongly sheared and have been interpreted to be syntectonic felsic intrusions (Hopwood, 1979). Rhyolite flows are reported in a few places (Smith and others, 1983) as are banded vitric units 1 m thick that are marked by devitrified crusts.

Felsic hypabyssal intrusive rocks are probably present in the sequence, but they are difficult to identify and probably pass largely unrecognized. They include small rhyolite domes and sills (Moore, 1978).

The sedimentary rocks interbedded with the volcanic rocks of the Jof formation are mainly of volcaniclastic origin, but they include significant amounts of quartzofeldspathic rocks of inferred continental provenance (Ramsay and others, 1981). The sedimentary rocks are schistose, and most consist of assemblages of quartz, feldspar, sericite, chlorite, and carbonate; they represent ashfall tuffs grading into mudstones and carbonaceous pyritic shale. The quartzofeldspathic rocks, also schistose, comprise metamorphosed fine-grained srkosic arenite or siltstone. The sedimentary component of the Jof formation additionally includes interbeds of hematite-magnetite chert or jasper, derived from thin iron formation, and limestone and dolomite. These interbeds are common in the vicinity of Wādī Bīdah, usually at the interface between mafic and felsic volcanic rocks, and they host stratiform copper- and zinc-sulfide mineralization. North of about lat 20°30′ N., metasedimentary rocks are abundant in the formation (Greene and Gonzalez, 1980). Contiguous exposure of similar rock types, northward in the Turabah quadrangle, have been mapped as the Hawiyah formation (Ziab and Ramsay, 1983).

Bahah group

RAS FORMATION

The Ras formation of the Bahah group (br) crops out in a north-trending belt in the center of the quadrangle. The type area is Wādī Ra's in the Jabal Shadā (19/41 A) quadrangle shouth of Al Bāḩah (Greenwood, 1975d). The formation is closely associated with, and reported by Greenwood (1975c) to overlie, the Jof formation of the Baish group, although generally the two are considered to interfinger (Greenwood, 1975a; Prinz, 1983) or to be separated by sheared contacts (Ramsay and others, 1981). As with the Jof formation, the Ras formation is isoclinally folded and broken by numerous faults; therefore, the internal stratigraphy is unknown. Sedimentary structures are rarely preserved in the formation, but locally, grading and cut-and-fill structures can be recognized.

The formation consists chiefly of metamorphosed sandstone, siltstone, shale and mafic to felsic volcaniclastic rocks. These typically crop out as thinly bedded quartzofeldspathic schists, phyllites, blastopsammitic rocks, greenstones, and greenschists, and are intercalated with subordinate chert, marble, and conglomerate.

The metamorphosed sandstone includes quartzite, phyllitic quartzite, and graphitic or arkosic graywacke. Coarse- to medium-grained blastopsammitic textures are common, and the rocks contain subhedral plagioclase crystals and quartz and lithic, probably volcanic, fragments in a fine-grained matrix. The matrix commonly consists of chlorite, epidote or clinozoisite, carbonate, and biotite or actinolite, which correspond to greenschist-facies metamorphic assemblage. Finer grained rocks in the sequence are metamorphosed siltstone and shale. They are fine-grained blastopsammitic rocks that contains clasts of quartz, plagioclase, and assemblages of quartz and feldspar in a matrix of quartz, feldspar, muscovite, chlorite, and carbonate. Near the southern boundary of the quadrangle, conglomerate and coarse-grained arkosic graywacke are particularly abundant, evidence to Greenwood (1975c) that the Ras formation overlies the Jof formation. The conglomerate consists of boulders of amygdaloidal basalt and intraformational chips of silt and chert in a matrix of volcaniclastic graywacke or silt.

Other members of the formation include marble and graphitic and pyritic chert, which form massive to finely laminated beds and are intercalated with fine-grained graywacke and tuff. In places, the chert is recrystallized and consists of very fine grained, and slightly inequigranular, mosaic-textured quartz plus minor biotite, muscovite, graphite, carbonate, and feldspar.

Baish and Bahah groups undivided

BIOTITE SCHIST, HORNBLENDE SCHIST, AND AMPHIBOLITE

Many of the rocks assigned to the undivided Baish and Bahah groups crop out in the western part of the quadrangle as amphibolite-grade metamorphic rocks (bam). Like most successions in this composite Baish-Bahah group, the metamorphic rocks are interpreted to represent assemblages of volcaniclastic and volcanic rocks interbedded with variable amounts of epiclastic rocks. The unit is bounded primarily by faults or intrusions, and its correlation with other units of layered rocks in the quadrangle is unclear.

Biotite and hornblende schists of the unit are most common in the southwestern part of the quadrangle (Hadley and Fleck, 1980), where they crop out in a southwest-trending syncline. Hornblende schist in the core of the syncline is composed of anhedral to euhedral quartz, plagioclase, hornblende, biotite, epidote, and magnetite. Biotite schist is fine grained and, despite the high metamorphic grade, contains relict bedding in many outcrops. Quartz, plagioclase, biotite, and epidote are its main constituents. Locally, magnetite quartzite and thin-bedded quartz schist also occur (Bowden and Morfett, 1981).

Elsewhere in the western part of the quadrangle, amphibolite, amphibole schist, and hornblende gneiss of inferred mafic-volcanic origin are more abundant (Cater, 1977). The rocks are schistose to granoblastic in texture. They consist of assemblages of hornblende, plagioclase (An_{31-60}), and quartz; subordinate biotite, epidote, clinozoisite, and chlorite; and rare relict igneous plagioclase phenocrysts. Other rocks in the amphibolite-rich sections of the unit include quartzofeldspathic schists of andesitic, dacitic, or pelitic epiclastic origin composed of medium-grained quartz, feldspar, and some biotite, hornblende, and (or) chlorite, as well as magnetite-bearing quartzite, and marble.

BASALT AND DACITE

Undifferentiated assemblages of volcaniclastic and subordinate flow rocks and epiclastic rocks (ba) crop out in several discontinuous belts in the western part of the quadrangle. The unit is largely basaltic or dacitic in composition, and it is strongly deformed and generally metamorphosed to the greenschist facies. The rocks crop out as greenschsits, greenstones, phyllites, or schists containing various proportions of quartz, chlorite, sericite, and feldspar. In some areas of higher metamorphic grade, they resemble rocks in the biotite schist, hornblende schist, and amphibolite map unit (bam) and probably contain a greater proportion of sedimentary rocks than elsewhere; the schists contain biotite-garnet-quartz and biotite-muscovite-plagioclase-quartz assemblages.

Volcaniclastic rocks predominate as lithic, crystal, and ash-fall tuffs, occurring in beds 5 to 15 cm thick in many places, and as agglomerate (Hadley and Fleck, 1980). Clasts are generally flattened in the cleavage plane. In places, felsic tuffs are associated with pyritic schists or flow-banded, pyritic, cherty rhyolite (Bowden and Morfett, 1981). Flow rocks are amygdaloidal and are separated by layers of pyroclastic material. The subordinate epiclastic rocks include rare conglomerate layers, phyllite, fine-grained metaquartzite, black slate, and marble.

Many of the flow rocks are similar in appearance to those in the basalt and andesite unit (bb). Geochemical data reported by Reischmann and others (1984) indicate that the chemistry is strongly bimodal: basalt and dacite-rhyolite are the most common rock types; andesite is rare. They form an assemblage that has a tholeiitic trend and resembles lavas from present-day immature island arcs.

In the belt of rock intruded by the Ibrahim pluton structural sketch map of biotite-hornblende granite (gbh), and elsewhere locally, the unit is metamorphosed to the amphibolite facies. In these areas, amphibolite and greenstone are abundant and are interlayered with gneiss and subordinate metasedimentary rocks (Greene and Gonzalez, 1980). The amphibolite varies from greenish gray to black and has an indistinct to strongly developed lineation. The mineral assemblage includes either actinolite, plagioclase, and epidote, or hornblende, plagioclase, quartz, and epidote. Some gneiss layers consisting of quartz, plagioclase, and biotite may represent metadacite, but those with a high quartz content are probably metasedimentary in origin (Green and Gonzalez, 1980). Close to the pluton, metasedimentary rocks are noticeably abundant, occurring as quartzofeldspathic mica schists composed of blastopsammitic assemblages of quartz, feldspar, biotite or muscovite, garnet, graphite, and chlorite or carbonate, probably derived from fine-grained quartzofeldspathic arenite and siltstone (Ramsay and others, 1981).

BASALT AND ANDESITE

Unnamed units of mafic volcanic rocks (bb) crop out near the southwestern corner of the quadrangle and extend westward into the Al Līth quadrangle (Pallister, 1986). Basalt and andesite flows predominate; they are intebedded with mafic volcaniclastic rocks of similar composition. Despite the extensive development of greenschist- and, locally, amphibolite-facies metamorphic assemblages and strong shearing, primary textures and flow features of the rocks are discernible in many places (Hadley and Fleck, 1980). The flows range from 2 to 10 m thick and are dark to medium green, medium to fine grained, and commonly porphyritic and amygdaloidal. They are composed of magnetite, amphibole, chlorite, and, in places, relict plagioclase phenocrysts.

The subordinate volcaniclastic rocks include agglomerate and varieties of tuff, some of which are intensely sheared between the more competent flow units.

Qirshah formation

The Qirshah formation (qh, qhv, qhr) crops out in north-trending belts in the eastern part of the quadrangle. It is named after Wādī Qirshah in the Al 'Aqīq quadrangle (Greenwood, 1975a). The unit continues to the south into the Al Qunfudhah quadrangle as the Qirshah andesite assigned to the Jiddah group (Prinz, 1983), and it continues to the north and east into the Al Ufayriyah quadrangle (20/42 A) as unnamed units of meta-andesite and metarhyolite (Greene, 1982); in the Wādī Bīshah quadrangle map (Simons, in press) adjacent to the east, contiguous exposures are sampled as unnamed andesitic rocks of the Jiddah group.

The formation is essentially volcanic and contains a bimodal suite of low-potassium tholeiitic basalt and subordinate andesite, dacite, and rhyolite of calc-alkalic trend (Roobol and others, 1983), similar in composition to modern island-arc volcanic complexes. Although not shown on the map, the formation is cut by many dikes of metabasalt, meta-andesite, diorite, and aplite. The rocks are tightly folded and moderately to well cleaved; dips are steep, and strike-slip faults abound. Regional metamorphism of the greenschist facies affected all of the formation. Because of its structural complexity, the internal stratigraphy of the formation is unknown.

In most of the formation mafic and felsic pyroclastic rocks, minor flow rocks, and lesser sedimentary rocks interfinger (qh) although, north of the Rafa'ah pluton, units of andesite (qhv) and rhyolite (qhr) are separately mapped. The mafic rocks include basaltic breccia and tuff, scoriaceous pillow lava, andesitic flows, andesitic flow breccia, and andesitic tuff. Some breccia consists of heterogeneous clast of welded to nonwelded lithic and crystal tuff. Andesitic flows, commonly dark reddish gray to greenish gray, are composed of phenocrysts of clinopyroxene and plagioclase in a trachytic, usually amygdaloidal, groundmass (Greenwood, 1975a). These mafic rocks crop out as greenschists. Plagioclase phenocrysts range from An_{33} to An_{49} and are set in a metamorphic assemblage of albite, actinolite, chlorite, brown biotite, stilpnomelane, pyrophyllite, epidote, carbonate, quartz, and sphene.

The felsic rocks include, well-bedded, light-gray to green ash and lapilli tuffs, locally containing flattended pumice balls and relict glass shards; amygdaloidal dacitic flow rocks composed of quartz and plagioclase phenocrysts; and some massive to brecciated rhyolite. Many of the felsic volcanic rocks in the formation are silicified and (or) sericitized. They crop out as chlorite-sericite-quartz schists, which are very similar to some of the metasedimentary argillaceous interbeds in the formation. Other interbedded sedimentary rocks are marble units as much as 30 m thick, feldspathic and volcanic wacke, mudstone, red chert, and jasper (Greenwood, 1975a; Fujii, 1979).

Khutnah formation

The Khutnah formation (kh) is mainly in fault contact with the Qirshah formation, but the two are grouped together in all the source literature. Greenwood (1975a) and Bokhari and Kramers (1981) believed that the Khutnah overlies the Qirshah.

The formation is an assemblage of coarse- to fine-grained sedimentary rocks including volcaniclastic wacke, volcanic and intraformational conglomerate, arkose, siltstone, marble, and subordinate mafic and felsic tuffs and basaltic to andesitic flow rocks. In contrast with the Qirshah formation, the volcanic rocks in the Khutnah formation compose a suite of mainly calc-alkalic composition; tholeiitic basalts are only a minor component (Bokhari and Kramers, 1981). A conglomerate, disconformably overlying basalt, was reported by Greenwood (1975a) to occur at the base of the formation. It consists of volcanic pebbles and intraformational chip clasts in a matrix of locally graded tuffaceous sandstone to siltstone. The pebbles include granophyric quartz-plagioclase rock, trachytic andesite, irregular scoriaceous welded tuff, and devitrified glass. Elsewhere, brown marble occurs at the base. The volcaniclastic wacke often forms graded units 5 cm thick; the rock is coarse to fine grained, is calcareous, and has clasts of variolitic to spherulitic glass, trachytic andesite, and euhedral to angular plagioclase. Nongraded rock units include laminated, fine-grained, calcareous feldspathic quartzite or siltstone, and they contain thin beds of medium-grained, tuffaceous arkosic wacke. The tops of some beds bear oscillation ripple marks. Overall, the Khutnah formation is metamorphosed to the greenschist facies and crops out as albite-quartz-epidote-carbonate-actinolite-chlorite schists.

Ablah group

The Ablah group, named after the 'Ablah prospect near the southeastern corner of the quadrangle (Brown and Jackson, 1960), crops out in the eastern and western parts of the quadrangle. In the type area, three formations occur: the Rafa, Jerub, and Thurat, together composing a succession of epiclastic and volcanic rocks. In the west, units assigned to this group include sedimentary to high-grade metasedimentary rocks shown on the source maps as Ablah group rocks (Hadley and Fleck, 1980), the Sama formation of the Bahah group (Greenwood, 1975c), and unassigned medium- to high-grade metamorphic rocks (Cater, 1977).

The Ablah group is largely bounded by faults, but south of Jabal ar Rafā'ah, the Rafa formation rests unconformably on the Qirshah formation, and southwest of Al 'Aqīq, it rests unconformably on the Baish group (Greenwood, 1975a). Some of these rocks have been dated, but the results appear to contradict the geologic relationships. The Qirshah and Khutnah formations are reported to be 728 to 721 Ma old (Bokhari and Kramers, 1981; D. P. F. Darbyshire and others, written commun., 1983), whereas the Jerub formation, from the middle of the Ablah group, is reported as 740 Ma old (D. P. F. Darbyshire and others, written commun., 1983), which implies that the Ablah group is older than the Qirshah and Khutnah formations. As a further complication, the Qirshah formation is intruded by the Thurat pluton of younger diorite (td) and tonalite (tn), which is dated by Marzouki and others (1982) as 744 Ma old. More detailed mapping and further geochronologic studies are required to reconcile the ambiguities of these data.

RAFA FORMATION

The Rafa formation (ar) is the most widespread unit of the Ablah group. It was named for the earlier transliteration of the type area near Jabal Rafā'ah, northeast of Al 'Aqīq (Greenwood, 1975a). It is characterized by reddish-brown and purple to gray and gray-green, medium, to coarse-grained sedimentary rocks of plutonic to volcanic provenance. In the type area, the formation rests unconformably on isoclinally folded volcanic rocks of the Qirshah formation. Here, and southwest of Al 'Aqīq, conglomeratic, usually nonbedded, arkosic graywacke predominates. The pebbly arenaceous rock consists of poorly sorted, subangular to rounded clasts in a matrix of medium- to coarse-grained angular feldspathic sandstone to arkosic graywacke. Clasts included tonalite, trachytic and porphyritic andesite, jasper, andesitic tuff, and deformed greenstone. The conglomerates are interbedded with coarse-grained feldspathic sandstone, arkose, calcareous arkose, feldspathic siltstone, and minor marble. Graded bedding, crossbedding, and ripple marks occur in the finer grained beds. The formation is regionally metamorphosed to the greenschist facies, and mineral assemblages include albite, quartz, actinolite, epidote, carbonate, chlorite, sphene, and sericite. Vertical cleavage, related to upright anticlines and synclines, is well developed in the rocks.

Metasedimentary rocks correlated with the Rafa formation crop out on the southern border of the quarangle in the vicinity of Wadi Rama. These rocks were originally mapped by Greenwood (1975c) as the Sama formation and assigned to the Bahah Group; however, in conformity with lithologic evidence (Johnson, 1983) and the interpretation of contigous outcrops in the Al Qunfudhah quadrangle (Prinz, 1983), these rocks are assigned to the Ablah group in this report. Conglomeratic arkosic graywacke is the main metasedimentary rock type here. It is generally thick bedded to massive, although some cut-and-fill structures and crossbedding are preserved. The rocks are strongly deformed and, where both schistosity and bedding can be measured, they are parallel. The rocks are generally metamorphosed to the greenschist facies, but close to the southern margin of the quadrangle, amphibolite-facies biotite-garnet schist and gneiss are present.

JERUB FORMATION

The volcanic Jerub formation (aj), named after an earlier transliteration of Wādī al Jurab in the east-central part of the quadrangle (Greenwood, 1975a), is distinguished from the volcanic rocks of the Qirshah and Khutnah formations by the absence of dike rocks; the abundance of felsic units; the gray, green, or maroon coloration of the beds; a slight metamorphism; and an absence of penetrative deformation structures.

Andesitic, dacitic, and rhyolitic pyroclastic and flow rocks predominate; rhyodacitic flows, basalt agglomerate, and pillow lava are minor components, together with volcaniclastic sedimentary rocks and marble beds. The pyroclastic rocks, which form some 70 percent of the exposed section, include graded airfall, waterlaid, and ash-flow tuffs composed of vitric, lithic, and crystalline materials. Clasts of plagioclase, quartz, and potassium feldspar are common. Welded units contain schlieren, flattened pumice balls, and arcuate glass shards. The coarsest pyroclastic rocks are agglomerates, composed of angular to subangular rock fragments as much as 20 cm in diameter in a matrix of rock fragments, fine-grained ash, and aggregates of hematite, magnetite, and limonite (Zakir, 1972). Most flow rocks contain phenocrysts in a trachytic groundmass: clinopyroxene and plagioclase in andesite, quartz and plagioclase in dacite, potassium feldspar in rhyodacite, quartz and potassium feldspar in rhyolite, and clinopyroxene and plagioclase in basalt. Rhyolitic flows have micrographic, myrmekitic, and spherulitic textures, and some are hematitic. Marble, consisting of calcite or dolomite, is purple, thin to medium bedded, and fine grained. It is well bedded and intercalated with the volcanic rocks.

The Jerub formation is only slightly metamorphosed. Zeolite or lower greenschist assemblages, including quartz, ziosite, prehnite, or carbonate, are common. Upright anticlines and synclines deform the rocks, but pervasive cleavage is absent.

THURAT FORMATION

The Thurat formation (at), named after an earlier transliteration of Wādī Tharād in the southeast part of the quadrangle (Greenwood, 1975a), is confined to a complexly folded, down-faulted block that trends south from Wādī Thurād to Wādī Khalāh. It unconformably overlies the Jerub formation. The basal members consist of 100–300 m of coarse-grained to conglomeratic gray or red to brown arkosic volcanic wacke overlain by gray, locally stromatolitc, sandy marble which in turn is overlain by red sandstone and siltstone.

Many outcrops of the formation consist of red, brown, green, and gray medium- to coarse-grained and conglomeratic clastic rocks. Clasts in the coarse-grained arenaceous rocks include tonalite, andesite, marble, quartz porphyry tuff, quartz latite tuff, and intraformational chips. Many units are arkosic and are composed of 20-40 percent feldspar, dominantly plagioclase, and 25-45 percent quartz. Large-scale crossbedding and channel structures occur.

Greenschist metamorphism affected the formation; the metamorphic assemblages typically include albite, quartz, chlorite, epidote, carbonate, some pyrophyllite, and clinozoisite.

Interbedded in the upper part of the formation are basaltic and andesitic flows, welded to nonwelded rhyolitic tuffs, and rhyolitic flows. Locally, marble beds contain rhyolitic glass, other tephra, and clasts of quartzofeldspathic rock. The formation also includes many sills of basalt, rhyodacite, and red-weathering porphyritic rhyolite, locally containing abundant fluorite. These sills are folded with the clastic rocks; later dikes or rhyolite postdate folding and faulting.

Ablah group undivided

Strongly deformed, amphibolite-grade metasedimentary rocks crop out in the western part of the quadrangle in a sinuous belt of exposure, the pattern of which reflects a major north-trending anticline cored by gneiss (gg). The rocks were assigned by Hadley and Fleck (1980) in the Jabal 'Afaf quadrangle 20/40 D) to the Ablah group and, for that reason, are shown on the present compilation as Ablah group undivided (aa). However, they are dissimilar in lithology and metamorphic grade to the Ablah group rocks in the type area. In addition, they are similar, in both respects, to the Sadiyah formation of the Al Līth quadrangle to the west, which is interpreted by Pallister (1981) as being among the oldest layered rocks of the region, coeval with the Baish group. The correlation of these rocks, therefore, appears to be ambiguous and requires clarification.

The sequence includes amphibolite, quartzite, calcitic marble, black slate, calcite-quartz-sericite phyllite, graphite-staurolite-hornblende-garnet-biotite schist, and quartz-plagioclase-biotite-garnet gneiss (Hadley and Fleck, 1980; Cater, 1977). On the eastern limb of the anticline, kyanite-bearing rocks crop out as kyanite quartzite, kyanite-muscovite schist, and gneiss (Gaskill, 1970; Cater, 1977). Locally, metaconglomerate is reported (Bowden and Morfett, 1981).

The rocks are thoroughly sheared or recrystallized. Sedimentary structures are largely obliterated, except for rare preservation in marble, and the rocks have fine- to medium-grained granoblastic, lepidoblastic, and cataclastic textures.

PROTEROZOIC INTRUSIVE ROCKS

Proterozoic intrusive rocks underlie most of the western one-third of the quadrangle, as well as substantial areas elsewhere. Following the system of rock-type nomenclature recommended by Streckeisen (1976), the plutonic rocks range in compostion from serpentinite to syenite, although diorite, tonalite, granodiorite, and monzogranite predominate. The rocks have been grouped into seven categories, based on the inferred ages of the intrusions and on petrologic and petrogaphic similaarites among them: (1) ultramafic rocks, (2) a set of plutons of older diorite and tonalite, (3) a set of younger diorite and tonalite plutons, (4) a group of syntectonic granitic intrusions, (5) a large group of late- to posttectonic granitic intrusions, (6) a small set of intrusions of unassigned gabbro, norite, and diorite, and (7) a group of unassigned hypabyssal intrusive rocks.

Rocks of the first two categories include the oldest plutons in the quadrangle. They intrude the Baish and Bahah groups and range in age from 901 to 838 Ma. The plutons of younger diorite and tonalite are petrologically similar to the older diorite and tonalite, but intrude the Qirshah and Khutnah formations and the Ablah group; geochronologic measurements indicate that they were emplaced about 744 Ma ago, although this age appears to be anomalously old with respect to reported geochronologic dates for the country rocks. The syntectonic granitic rocks are characterized by a strongly developed foliation; members of the group are gneissic, and the plutons represent a major phase of syntectonic intrusion in the region. Other granitic plutons in the quadrangle tend to be massive and represent late-tectonic to posttectonic magmatism.

Additional Proterozoic intrusive rocks in the quadrangle include plutons of gabbro, norite, and undivided diorite and gabbro. These rocks are variably deformed and appear to be of several different ages. They are, therefore, compiled as an unassigned group of plutonic rocks. Hypabyssal intrusions are also common, although not all can be shown at the 1:250,000 scale of the map. They range from subvolcanic intrusions contemporaneous with Baish group volcanism to late-stage crosscutting mafic and felsic dikes.

Ultramafic rocks

Peridotite (pd) forms small exposures in the northwestern part of the quadrangle, close to the Red Sea escarpment; pyroxenite (px) crops out in the north-central part of the quadrangle east of Wādī Bīdah, northeast of Al Mulqaṭah; and serpentinite and talc schist (ser) occur along major faults in the southeastern part of the quadrangle. The precise age of the rocks is uncertain, but peridotite predates tonalite of the older diorite and tonalite in the Wādī Salibah quadrangle, and the ultramafic rocks are, therefore, believed to be among the oldest plutonic rocks in the region.

The peridotite (pd) comprises large to small xenoliths in foliated granodiorite and granite; two exposures are shown on the map southeast of Jabal 'Asharah. The rock is coarse grained, black to dark green, and variably altered (Cater, 1977). Augite-olivine peridotite predominates, but locally the rock grades into pyroxenite, containing augite and accessory olivine, or into layered gabbro. Close to contacts with the granitic rocks, the peridotite is partly altered to antigorite and magnetite or to hornblende and epidote.

A small body of dark-gray-green, medium-grained pyroxenite (px) intrudes the Jof formation of the Baish group close to Wādī Bīdah in the north-central part of the quadrangle (Greene and Gonzalez, 1980). The rock consists of some 80 percent clinopyroxene, 20 percent hornblende altered from clinopyroxene, and minor altered plagioclase and epidote.

Small lenses of serpentinite and talc schist (ser), as much as 45 m wide, crop out in the southeastern part of the quadrangle along faults cutting the Ras formation of the Bahah group and the Jof formation. A few lenses contain chromite (location 61 on the mineral occurrence map, fig. 2).

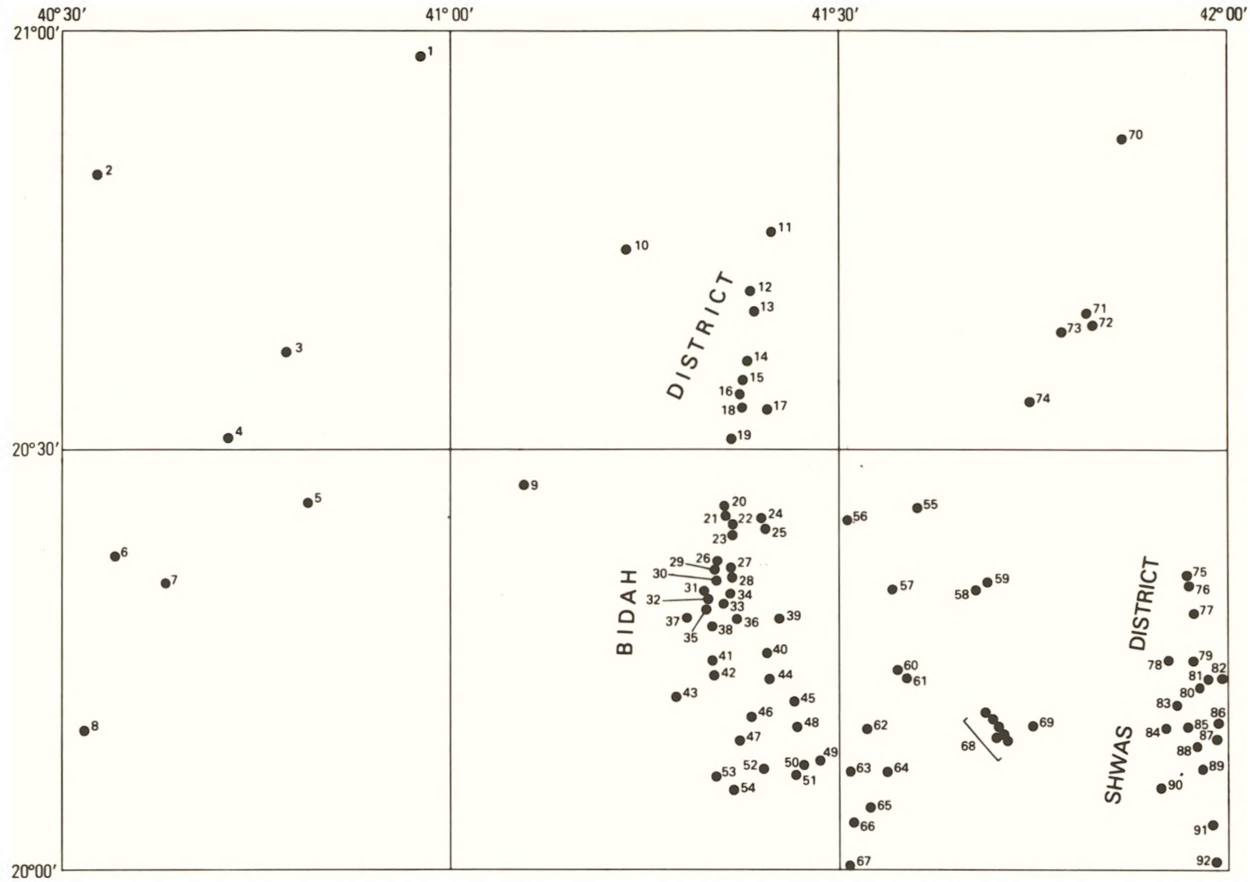

Figure 2.—Sketch map showing mineral occurrence localities in the Jabal Ibrāhīm quadrangle. Locality numbers refer to occurrences listed in table 3. Scale, 1:1,000,000.

Older diorite and tonalite

DIORITE AND TONALITE

Older diorite (di) and tonalite (ti) crop out in the central and western parts of the quadrangle. They are typically represented by the Bidah, Dhara, and Shaggan plutons, the locations of which are shown on the Structural Sketch Map. Overall, the rock include diorite and tonalite, and subordinate gabbro, quartz diorite, and granodiorite. Isotopic data suggest that two sets of plutons may be present: an older set, such as the Bidap pluton, about 900 Ma old, and a younger set, such as the Dhara and Shaqqah plutons, about 850 to 840 Ma old (table 2).

Mafic members of this category of rocks, through diorite and quartz diorite and, in the Wādī Salibah quadrangle in

TABLE 2.—Summary of geochronologic data for the Jabal Ibrāhīm quadrangle

[—, not applicable; NA, not available]

Locality number[1]	Formation or pluton (as cited in source)	Rock type (as cited in source)	Material analyzed	Isotopic age (Ma) K-Ar	Isotopic age (Ma) Rb-Sr	Initial $^{87}Sr/^{86}Sr$	Reference
			Proterozoic layered rocks				
1	Jof formation	Metavolcanic rocks	Whole rock	—	[2]943	NA	D. P. F. Darbyshire and others, written commun., (1983).
2*	Baish and Bahah groups undivided (Kulada suite)	do	do	—	847±34	0.7031	Kroner and others (1984).
3	Ras formation	do	do	—	[2]810	NA	D. P. F. Darbyshire and others, written commun., (1983).
4*	Qirshah formation (Surgah formation)	do	do [3]	—	[2]721±55	.705	Bokhari and Kramers (1981).
5	Thurat formation	Basalt	do	585±39	—	—	Brown and others (1978).
6	Do	do	do	576±39	—	—	Greenwood (1975a).
7	Ablah group	Paraschist	Muscovite	595±12	—	—	Brown and others (1978).

TABLE 2.—Summary of geochronologic data for the Jabal Ibrâhīm quadrangle—Continued

[—, not applicable; NA, not available]

Locality number[1]	Formation or pluton (as cited in source)	Rock type (as cited in source)	Material analyzed	Isotopic age (Ma) K-Ar	Isotopic age (Ma) Rb-Sr	Initial $^{87}Sr/^{86}Sr$	Reference
			Older diorite and tonalite				
8*	Bidah pluton	Tonalite	Whole rock	—	[2]901±37	.7025	Marzouki and others (1982).
9*	Do	do	do	—	[2]901±37	.7025	Do.
10*	Do	do	do	—	[2]901±37	.7025	Do.
11	Do	Granodiorite	Hornblende	932±46	—	—	Brown and others (1978).
	Do	do	do	912±18	—	—	Do.
	Do	do	do	821±16	—	—	Do.
12	Do	do	do	920±46	—	—	Greenwood (1975a).
	Do	do	do	903±18	—	—	Do.
13	Shaqqah pluton	Quartz diorite	Whole rock	—	853±72	.7030	Fleck and others (1980).
14	Do	do	do	—	853±72	.7030	Do.
15	Unnamed intrusion	Tonalite-diorite	Hornblende	827±16	—	—	Brown and others (1978).
16	Dhara pluton	Tonalite	Whole rock	—	838±93	.7026	Fleck and Hadley (1982).
17	Do	do	do	—	838±93	.7026	Do.
18	Do	do	do	—	838±93	.7026	Do.
19	Unnamed pluton	Quartz diorite	Biotite	615	785	—	Aldrich (1978).
20	Shaqqah pluton	Gneiss	Hornblende	717±18	—	—	Brown and others (1978).
			Younger diorite and tonalite				
21*	Tharad pluton	Tonalite, trondhjemite	Whole rock	—	744±22	.7028	Marzouki and others (1982).
22*	Do	do	do	—	744±22	.7028	Do.
23*	Do	do	do	—	744±22	.7028	Do.
24*	Do	do	do	—	744±22	.7028	Do.
**	Do	do	do	—	779±49	.7026	Do.
			Late- to post-tectonic granitic rocks				
25	Ibrahim pluton	Biotite-muscovite-granite	Biotite	610±7	—	—	Fleck and others (1976).[5]
	Do	do	Whole rock	—	[4]657	.7032	Fleck and others (1980).
26	Intrusion in Shuwas pluton	Quartz monzonite	do	—	636±21	.7035	Do.
	Do	do	Biotite	587±7	—	—	Fleck and others (1976).[5]
	Do	do	Hornblende	576±7	—	—	Do.
	Do	do	do	566±7	—	—	Fleck and others (1976).
27	Do	do	Whole rock	—	636±21	.7035	Fleck and others (1980).
	Do	do	Biotite	656±6	—	—	Fleck and others (1976).[5]
	Do	do	Hornblende	565±7	—	—	Do.
28	Do	Granodiorite	Whole rock	—	617±10	—	Brown and others (1978).
29	Do	Red granite	do	—	630±10	NA	Greenwood (1975a).
30	Rafah pluton	Peralkaline granite	Biotite	565	575	—	Aldrich (1978).
	Do	do	Feldspar	—	565	—	Do.
	Do	do	Biotite	555	—	—	Greenwood (1975a).
	Do	do	Feldspar	—	580	—	Do.
	Do	do	Hornblende	—	590	NA	Do.
31	Turabah pluton	Syenite-trondhjemite	Whole rock	—	550	NA	G. F. Brown, oral commun., cited in Greene and Gonzalez (1980).
32	Do	do	do	—	550	NA	Do.
			Hypabyssal intrusive rocks				
3*		Diorite	Whole rock	—	827±16	NA	D. P. F. Darbyshire and others, written commun., (1983).
33		Muscovite-biotite granite	Biotite	400	515	—	Aldrich (1978).
		do	Feldspar	—	635	—	Do.
34		Quartz monzonite	Whole rock	—	582±20	—	Brown and others (1978).
35		Porphyry sill	do	595±20	—	—	Greenwood (1975a).

[1]*, Approximate locations; ** locations unknown.
[2]Errorchron.
[3]Nd-Sm model age: 757±256.
[4]Model age.
[5]Result as recalculated by Gettings and Stieser (1981).

the northwest, to gabbro, are compiled as diorite (di). Typically these rocks are dark gray, medium grained, and hypidiomorphic. The diorite consists of 1525 percent hornblende altered to chlorite or actinolite, 70-80 percent zoned plagioclase occurring as saussuritized andesine, and less than 10 percent strained quartz and accessory epidote, sphene, and opaque minerals. Some diorite bodies contain 10-20 percent biotite instead of hornblende.

The tonalite map unit (ti) is mainly tonalitic in composition but includes diorite, quartz diorite, and granodiorite. It is conterminous with the Dhuqiyah complex in the Turabah quadrangle to the north (Ziab and Ramsay, in press). The tonalite is medium to coarse grained, is gray to white, and contains abundant mafic xenoliths or screens, particularly near contacts with the Baish groups. The principal constituents of the tonalite are 45-75 percent plagioclase, sometimes zoned; 0-5 percent potassium feldspar; 5-35 percent quartz; and biotite or, less commonly, hornblende. Biotite ranges from 1 to 20 percent; hornblende locally reaches 30 percent. Both mafic minerals are partly altered to actinolite and chlorite. Some plagioclase is zoned with An_{45} cores and oligoclase rims; much of the plagioclase is saussuritized albite. Potassium feldspar occurs as sparse antiperthitic lamellae in plagioclase and is most common in the southern part of the Dhara pluton. Near some of its contact, the tonalite is gneissic and develops a lepidoblastic and cataclastic texture; elsewhere, the rock is massive and has a hypidimorphic-granular texture. Gneissic structure is well developed in the Dhara pluton, and at least two periods of intrusion are indicated. The principal intrusive episode was contemporaneous with deformation of the Baish and Bahah groups and resulted in conformity between schistosity in the layered rocks and gneissic layering in the pluton (Greene and Gonzalez, 1980).

DIORITE AND GRANODIORITE COMPLEX

A complex (ddg) of diorite, tonalite, and lesser amounts of granodiorite, gabbro, and stoped blocks of Baish and Bahah group metmorphic rocks underlies the northwestern part of the quadrangle. It is conterminous with the Dhara complex in the Turabah quadrangle to the north (Ziab and Ramsay, 1983) and with the Khasrah complex in the Al Līth quadrangle to the west (Pallister, 1986). Contact relations within the complex indicate that the granodiorite was the last intrusive phase, as it cuts the diorite and tonalite. These earlier mafic rocks contain numerous xenoliths of gabbro and layered rocks. The stopped blocks of metamorphic rocks, the larger of which are shown in the compilation, range from slightly to almost wholly assimilated.

Younger diorite and tonalite

Younger diorite (td) and tonalite (tn) crop out in the Tharad and Shuwas plutons in the eastern part of the quadrangle and in one pluton in the west. Smaller bodies of similar rock type in the eastern part of the quadrangle are also included in this category, although their age relationships to the larger plutons are uncertain. Compositionally the diorite and tonalite are similar uncertain. Compositionally in the diorite and tonalite are similar to the older mafic rocks that intrude the Baish and Bahah groups, typified by the Bidah pluton (di) (Greenwood, 1975a), but the results of dating the Tharad pluton (table 2; Marzouki and others, 1982), together with the fact that the rocks of this unit intrude the Ablah group and the unassigned Qirshah and Khutnah formations, suggest that they belong to a younger phase of intrusion.

The Shuwas pluton is cut be metagabbro (unit mgb) and younger granodiorite and monzogranite (unit gdb), the larger units of which are shown on the compilation. The Thurad pluton is more complicated than shown on the source maps; it includes tonalite, gabbro, diorite, quartz diorite, granodiorite, and trondhjemite (Marzouki and others, 1982). However, in the absence of more detailed maps, the pluton is shown as mapped by Greenwood (1975a).

Both the younger diorite and tonalite rock units are fine to coarse grained and have hypidiomorphic and weakly porphyritic textures. The diorite (td) has as much as 35 percent hornblende and is dark gray; the tonalite (tn) contains biotite and as much as 20 percent hornblende and is medium gray. Plagioclase, forming 60 to 70 percent of the rock, is generally zoned and altered to aggregates of epidote and sericite. The mafic minerals are partly to completely altered to chlorite and actinolite.

Syentectonic granitic rocks

These granitic rocks are characterized by foliation or gneissic layering and are interpreted to be syntectonic intrusions. Other granitic rocks in the quadrangle are more massive in structure and homogeneous in composition, and they are compiled as units of late-tectonic to posttectonic granodiorite and granite.

GRANODIORITE AND GRANITE

A broad, discontinuous belt of moderately to strongly foliated to gneissic granodiorite and granite (gg) dominates the western part of the quadrngle. These rocks form estremely rugged terrain in mountain ranges rising from the coastal plain to the top of the Red Sea escarpment. Local relief in the Afif pluton reaches as much as 1,000 m. North of the escarpment, the unit underlies more gently undulating terrain and extends into the Turabah quadrangle as the Qiya complex (Ziab and Ramsay, 1983).

Granodiorite and monzogranite are the chief components of the unit. Local facies include tonalite, quartz monzonite, quartz monzodiorite, and syenogranite. Much of the unit is red, pink, or gray, medium to coarse grained, and equigranular or slightly porphyritic. The rock contains 40-60 percent slightly saussuritized oligoclase, 15-45 percent perthitic microcline, and 10-30 percent quartz. Biotite, the dominant mafic mineral, constitutes 5-10 percent of the rock; hornblende is the second most common mafic component. Both are partly replaced by chlorite and epidote.

Xenoliths abound in some exposures and consist of hornblendite, amphibolite, and hornblende gneiss derived from the Baish group, as well as gneissic monzogranite, gabbro, and peridotite. The larger xenoliths are shown on the map.

The rocks are strongly foliated and schistose and have a vertical to steep eastward dip. The structure resulted from cataclasis and recrystallization during syntectonic emplacement in domal plutons. Although the precise age of these rocks is unknown, they are reported by Hadley and Fleck (1980) to resemble the 780- to 763-Ma-old Baqarah orthogneiss dome (Copper and others, 1979), which intrudes Ablah-group rocks in the Al Qunfudhah (Prinz, 1983) and Abhā (Greenwood, 1986) quadrangles south of the map area. Intrusive contacts between different members of the unit suggest, however, that the granodiorite and granite were emplaced over a considerable period of time (Cater, 1977). The plutons believed to be younger are generally more massive and contain more inclusions than those considered to be older.

ORTHOGNEISS

Small bodies of strongly foliated granodiorite are compiled as orthogneiss (gn) in the southeastern and northwestern parts of the quadrangle. A large batholith of similar rock crops out farther west, in the Al Līth quadrangle (Pallister, 1986). Near At Tā'if, northwest of the map area, Naseef and Gass (1977) reported foliated granite of the same type to have a Rb-Sr age of 595 50 Ma.

These orthogneiss intrusions have conformable to discordant contacts with the enclosing rocks. The foliation in the gneiss, however, is parallel to the schistosity in the country rocks which indicates pretectonic to syntectonic intrusion of the orthogneiss. In the southeast the orthogneiss crops out in gently plunging anticlines. It is predominantly medium- to fine-grained granodiorite, consisting or aggregates of potassium feldspar, quartz, oligoclase, biotite, minor hornblende and actinolite, accessory zircon, epidote, and chlorite, and, locally, garnet. Platy quartz and feldspar and aligned mafic aggregates define a strong cataclastic schistosity that is crosscut by a steeply dipping secondary cleavage related to the broad folding that formed the anticlines.

DIORITE, GRANODIORITE, AND GRANITE COMPLEX

A heterogeneous complex of granodiorite and granite (gdg) containing subordinate diorite, tonalite, and minor gabbro crops out in several irregular bodies in the northwestern section of the quadrangle (Cater, 1977; Green and Gonzalez, 1980). Amphibolite and hornblende gneiss xenoliths, probably derived from contiguous metamorphosed Baish group rocks, are conspicuous in the complex. The rocks are strongly deformed and have gneissic textures.

Late- to posttectonic granitic rocks

Massive to moderately deformed granitic rocks crop out in numerous subcircular to irregular plutons in many parts of the quadrangle. Their intrusive relationships and structure indicate that they are late-tectonic to posttectonic in origin, although the ages of the plutons relative to one another are poorly known. The intrusive rocks are compiled and named in this report mainly on the basis of their gross lithologies, but in a few instances the map units are named after individual plutons.

GRANODIORITE

Granodiorite (gd) crops out in the Hitay pluton in the south central part of the map area, in several plutons that form a northeasterly trending belt in the northwestern part, and in two smaller plutons in the southeastern part. The unit usually consists of hornblende-biotite granodiorite, but includes subordinate granite and tonalite. The rock is light gray, is medium grained, and ranges in texture from strongly porphyritic to hypidiomorphic granular. Phenocrysts include plagioclase and microline. The groundmass contains 10-25 percent weakly kaolinized microcline and orthoclase and 45-60 percent weakly saussuritized oligoclase or andesine. The essential mafic minerals are biotite and lesser clinopyroxene-cored hornblende; they locally constitute as much as 25-30 percent of the rock. Accessory minerals include muscovite, chlorite, sphene, magnetite, calcite, and apatite. Plagioclase has delicate oscillatory zoning from cores of labradorite (An_{62}) to oligoclase. In general, the rock is homogeneous and undeformed, although moderate to intense cataclasis affects it in the southeastern part of the quadrangle. Dikes of granophyric granite and of porphyritic andesite containing plagioclase and clinopyroxene phenocrysts commonly cut the granodiorite plutons.

TONALITE AND GRANODIORITE

A small intrusion of tonalite and granodiorite (gto) containing subordinate quartz monzodiorite straddles the central western border of the quadrangle, crossing Wādī al Fajj and Wādī ar Raşafah. It is fault bounded and its geologic relationships are uncertain. Pallister (1986) assigns the contiguous outcrop in the Al Līth quadrangle suite. The intrusion forms a north-northeast-trending block elongate along a zone of strong faulting, close to which the rock is mylonitized and foliated. The tonalite and granodiorite body is light pink and strongly porphyritic; it contains microcline phenocrysts in a medium-grained, chloritized, strongly foliated, and cataclastic groundmass.

GRANODIORITE AND MONZOGRANITE

Hornblende-biotite granodiorite and monzogranite (gdb) crop out as an irregularly shaped northeast-trending pluton and in other smaller plutons in the northwestern part of the quadrangle and as the circular Harmah pluton in the southwestern part. Other irregular plutons of this rock type occur in the Shuwas pluton and along faults in the southeastern area of the quadrangle, as well as in the east-central part of the quadrangle. In the southeast, three phases of granodiorite and monzogranite are shown on the source map (Greenwood, 1975a) as successive rings, cone sheets, or irregular bodies intruding the Shuwas pluton. They are combined into one unit in this report because of compositional and geochronologic similarities. The Harmah pluton is also compositionally variable and contains subordinate quartz monzodiorite and tonalite.

The granodiorite and monzogranite are light pink to gay and medium to coarse grained. Locally they have a porphyritic, hypidiomorphic-granular textures and are composed of partly saussuritized oligoclase or sodic andesine, 8-25 percent quartz, microcline microperthite, and 1-5 percent hornblende and (or) red-brown chloritized biotite. The granodiorite and monzogranite are usually massive, but near the margins of some plutons, become foliated or strongly cataclastic.

TONALITE

Tonalite (gtn) crops our northeast of Al 'Aqīq, on the northwestern margin of the larger Thurad pluton. Although the rock is petrologically similar to the tonalite of the adjacent pluton, its massive nature and an absence of dikes distinguish it from other tonalites. This absence of dikes suggests also that the tonalite is younger than the nearby granodiorite (gdb).

The tonalite is medium to fine grained, consists of hornblende, quartz, and plagioclase, and forms a hypidiomorphic-granular texture. Brown-green, partly chloritized hornblende composes 15-20 percent of the rock, and quartz, 15-25 percent. The plagioclase is zoned, containing oligoclase (An_{22}) cores and albite rims, and is usually altered to sericite and clinozoisite.

BIOTITE MONZOGRANITE

Biotite monzogranite (grb) and, locally, syenogranite form subcircular to irregularly shaped plutons in the western two-thirds of the quadrangle. The plutons often contain large numbers of mafic xenoliths that range from a few centimeters to several hundred meters across, and, in places, the plutons are cut by many metabasalt, meta-andesite, and aplite dikes. For the most part, the monzogranite is massive, medium to coarse grained, and hypidimorphic granular. However, in parts of several plutons where the rock becomes strongly foliated, cataclastic textures occur.

The rock is light gray, pink, or orange. It is principally composed of quartz (30 percent), oligoclase (15-60 percent), and potassium feldspar (25-45 percent). Biotite forms 2-5 percent of the rock, although it locally reaches 15 percent; hornblende is an accessory mineral.

HORNBLENDE MONZOGRANITE

Hornblende monzogranite (grh) crops out at the Rafaah pluton named for Jabal Rafā'ah on the eastern boundary of the quadrangle. It is mainly a pink- to light-gray, coarse-grained micrographic rock containing as much as 5 percent blue-green chloritized hornblende plus plagioclase and potassium feldspar. The plagioclase is zoned, ranging from andesine (An_{32}) in the cores to albite rims, and the potassium feldspar was reported by Greene (1982) to form as much as 65 percent of the rock in the adjacent Al Ufayriyah quadrangle. The interior of the pluton is cut by light-gray, fine-grained, micrographic hornblende monzogranite that represents a younger phase of intrusion.

BIOTITE-HORNBLENDE GRANITE

Plutons underlying the prominent Jabal Ibrāhīm, the smaller Jabal Nays in the southern part of the quadrangle, and Jabal Hayn in the west are composed of biotite-hornblende granite (gbh). The plutons range from massive, particularly in their inner parts, to slightly foliated on their margins. In the Ibrahim pluton, the foliation is primary, but the Hayn pluton has been affected by deformation near a north-northeast-trending fault zone. The contacts of the pluton dip steeply inward or outward. Monzogranite predominates, although subordinate tonalite and quartz diorite occur in the Hayn pluton. This pluton, because of its strongly foliated nature, was mapped as one of the oldest plutonic rocks in the Wādī Salibah quadrangle (Cater, 1977), but it is interpreted to be a late intrusion in the Jabal 'Afaf quadrangle (Hadley and Fleck, 1980).

The rock ranges in color from light gray to light pink or orange and is medium to coarse grained. Although similar to the biotite monzogranite (grb), the unit is mapped separately, as it is porphyritic and contains both biotite and hornblende. Feldspars are the dominant mineral, there being much as 48 percent kaolinized microcline perthite and 26 percent saussuritized oligoclase. Quartz constitutes 20-25 percent of the rock, and combined biotite and hornblende make up 3-8 percent.

GRANOPHYRIC GRANITE

A northeast-trending pluton and a very small satellite body of granophyric granite (gpm) crop out in the northwestern part of the quadrangle. The small intrusion and several others not shown at the scale of this compilation are mostly dikes and irregular masses of granitic rock. The rock is resistant to erosion and forms rugged land forms. It is red to greenish gray, fine grained, and granophyric in textures. Quartz is the dominant mineral, occurring as micrographic intergrowths with potassium feldspar. Biotite constitutes less than 5 percent of the rock. The rock is irregularly altered, and in places, magnetite and muscovite completely replace the biotite.

GRANITE RING DIKES

Granite (gr) forms discontinuous ring dikes outlining circular structures, which were probably cause by cauldron subsidence (Green and Gonzalez, 1980), in the north-central and southeastern areas of the quadrangle. The rock is light pink to gray, medium grained, and porphyritic; it ranges in composition from hornblende-biotite monzogranite to granodiorite. The granite contains 25-30 percent quartz, as much as 50 percent potassium feldspar, and 20-35 percent plagioclase. In the area of 'Aqīq, the plagioclase in the granite has delicate oscillatory zoning from a core of oligoclase (An_{20}) to an albite rim. Microperthite crystals as large as 5 cm enclose quartz, plagioclase, and mafic minerals. Dark-green hornblende and red-brown biotite make up 6-10 percent of the rock; they are slightly chloritized.

Potassium-feldspar porphyry dikes too small to be shown at the map scale range in composition from monzogranite to granodiorite. Because they cut many of the older rocks in the quadrangle, they may be related to the granite ring-dike phase of intrusion.

SYENITE AND TRONDHJEMITE

A complex of syenite and trondhjemite (st) constitutues the Turabah pluton in the center of the circular structure defined by a granite ring dike (gr) in the north-central part of the quadrangle (Greene and Gonzalez, 1980). The syenite consists of potassium feldspar, about 1 percent each of plagioclase and quartz, and trace amounts of biotite, alkali (?) amphibole, epidote, zircon, and opaque minerals. The trondhjemite consists of 60 percent plagioclase, 40 percent quartz, and less than 1 percent accessory biotite, amphibole, zircon, and opaque minerals. Other intrusive phases may be present, but relatively little information about the complex is available. Nevertheless, the massive nature of the pluton and its presence in an inferred cauldron structure indicate that it was emplaced late in the geologic history of the quadrangle.

Gabbro, norite, and diorite

Gabbro, norite, and minor diorite form small plutons in several parts of the quadrangle. They include massive and unaltered, as well as deformed and metamorphosed, rocks, which together indicate that the plutons are of several ages. Therefore, these rocks are not assigned to any of the groups already described, but are shown on the compilation as separate units of metagabbro (mgb); massive gabbro, locally including norite (gb); and undivided diorite and gabbro (dg).

Metagabbro (mgb) crops out in fault-bounded blocks and in a sinuously deformed pluton on both sides of Wādī Manzāh in the western part of the quadrangle. It is composed of clinopyroxene, plagioclase, and 2-4 percent biotite. It also forms small oval plutons north of Al Bāḩah in the south-central part of the quadrangle. These plutons, near Wādī Bīdah, are thoroughly metamorphosed to greenschist- and amphibolite-facies mineral assemblages, although the coarse grain size and relict textures indicate that the metamorphosed bodies were originally gabbro. One pluton has an anorthositic marginal phase. Farther east, similar rock constitutes part of the composite Shuwas pluton, where the metagabbro is interlayered with tabular masses of diorite and minor enclaves of metasedimentary rocks in a fault-bounded synformal structure. It consists of biotite, zoned plagioclase, and diopside altered to hornblende. In shear zones, the rock has been altered to actinolite, chlorite, albite, and epidote.

Rocks of the gabbro and norite unit (gb) are fresh and massive. The largest occurrence is the Aswaydayn pluton in the southwest; smaller plutons occur in the southeast in the Al 'Aqīq quadrangle and several are present in the northwest in the Wādī Salibah quadrangle. The Aswadayn pluton is coarse grained and very dark gray gabbro. The rock has a holocrystalline hypidiomorphic-granular texture and is almost entirely undeformed and unaltered. It consists of 70-80 percent augite, 20-30 percent labradorite, and 5-10 percent combined magnetite, apatite, calcite, and sphene. To the east, two small gabbroid plutons occur, one of norite just northwest of the Shuwas pluton and the other of gabbro farther north near the Rafaah pluton. Greenwood (1975a) suggested that they form parts of the same pluton offset some 35 km by strike-slip faulting. The southern intrusion is fine- to coarse-grained, allotriomorphic to granoblastic olivine norite containing anorthosite layers. The plagioclase composition varies from An_{50} to An_{60}. The northern pluton consists of cummingtonite-diopside gabbro containing peridotite and anorthosite layers. The plagioclase in both plutons is generally unaltered, although the mafic minerals are commonly represented by secondary cummingtonite, anthophyllite, and tremolite; cataclasis is locally intense. Near the northwestern corner of the map area, abundant, black, mafic-rich, porphyritic gabbro and lesser, gray, medium-grained, feldspar-rich gabbro occur (Cater, 1977). The mafic gabbro most commonly consists of over 50 percent augite, 30 percent labradorite, and 20 percent olivine. Augite megacrysts, as much as 10 cm across, poikilitically enclose smaller grains of augite, labradorite, and olivine. The more felsic variety contains about 45 percent each of coarsely ophitic augite and labradorite and 10 percent olivine. Some plutons in this part of the quadrangle are sheared altered, but they are not shown separately from undeformed plutons.

Undivided diorite and gabbro (dg) occur along the northern border of the quadrangle and cross into the Turabah quadrangle to the north (Ziab and Ramsay, 1983), where they are assigned to Salim complex. The plutons are medium to coarse grained, massive, and undeformed, although from place to place they are variably altered (Greene and Gonzalez, 1980). The diorite contain 60-88 percent fresh and well-twinned plagioclase; 5-30 percent hornblende; partly to wholly altered, fibrous hornblende; chlorite; and epidote. Where the diorite is altered, 1-15 percent chlorite and 1-5 percent epidote are present, and where it is most altered, interstitial quartz is developed. The gabbro consists of 40–60 percent fresh plagioclase, 20–50 percent clinopyroxene, and, in some samples, as much as 20 percent olivine, slightly altered to iddingsite, clinopyroxene, and hornblende. This diorite-gabbro unit intrudes the Baish and Bahah groups, the older tonalite unit (ti), and the granodiorite to granite complex (gdg), but it is cut by the biotite monzogranite unit (grb).

Hypabyssal intrusive rocks

A variety of sills and dikes intrude the Proterozoic rocks in many parts of the quadrangle, although relatively few are shown in the geologic compilation because of the scale of the map.

The intrusive rocks represent several episodes of emplacement. The oldest are subvolcanic intrusions in the Jof and Qirshah formations and their associated diorite and tonalite plutons. These intrusions consists of basaltic, andesitic, dacitic, and aplitic rocks that were metamorphosed and deformed contemporaneously with the enclosing rocks, as well as include the schistose quartz porphyry (rh) shown separately in the Bīdah district. The quartz porphyry forms dikes ranging from a few centimeters to 500 m thick. These dikes are subparallel to the foliation in the Jof formation, although, in detail, their contacts are slightly discordant to the foliation. The same penetrative schistosity is developed in both the intrusive and the intruded rocks, and the schistosity in the quartz porphyry and the enclosing rocks is crenulated and isoclinally folded by a second deformation as well.

A set of younger sills and dikes of ophitic basalt, rhyodacite, and red, porphyritic rhyolite, locally containing abundant fluorite, occurs in the Thurat formation. The larger felsic sills (rh) are shown on the map. A similar set of dikes, and fluorite-rich quartz veins and pegmatities, cut granodiorite and monzogranite bodies (gdb) and older rocks in the Shuwas pluton. The dikes probably form a coeval group of intrusions related to emplacement of the granodiorite and monzogranite. The tonalite (gtn) in the southeastern part of the quadrangle is not cut by, and is, therefore, inferred to be younger than, this dike set.

The youngest intrusions in the quadrangle include unmetamorphosed and undeformed mafic and felsic dikes of rhyolite, granite, basalt, diabase, and andesite. They were intruded, typically, into west-northwest-trending fractures, some, of which are fault zones, as indicated by shearing and offsets along the dikes.

TERTIARY INTRUSIVE ROCKS

An anastomosing network of subparallel to bifurcating and intersecting Tertiary gabbro dikes (Tgb) cuts the Shield rocks near their juncture with the coastal plain in the southwestern corner of the quadrangle. Although dikes are mainly gabbro (Hadley and Fleck, 1980), they are composed of quartz monzonite in some places. They are 50–200 m wide, medium to dark gray, and fine to very coarse grained. The borders are chilled, are very fine grained, and form resistant ridges. The textures of the intrusions are diabasic, gabbroic, and ophitic. Coarse-grained poikilitic augite crystals constitute 40–60 percent of the rock, labradorite, 30–40 percent, and serpentinized olivine, 2-5 percent.

The unit forms part of the Tihamat Asir complex, which includes mafic dikes, gabbro, and granophyric plutons (Coleman and others, 1979). Of oceanic-tholeiitic parentage, the assemblage was intruded into the continental margin of the Arabian Shield during the onset of sea-floor spreading about 20 Ma ago (Schmidt and others, 1982). The dikes coincide with linear anomalies on the airborne magnetometer survey map of the quadrangle (Andreasen and Petty, 1974). A prominent anomaly of the same type, present over part of the coastal plain in the quadrangle, is inferred to reflect an unexposed dike.

TERTIARY AND QUATERNARY EXTRUSIVE ROCKS

The northeastern section of the quadrangle is covered by the Buqum basalt of the Nawasif group and cinder cones that form the lava field of Ḩarrat al Buqūm (QTb). The lava field is the southernmost of several fields that together form a nearly continuous tract of lava fields extending from the Jabal Ibrāhīm quadrangle north-northwest for 1,000 km, almost of Tabūk (fig. 1). The lavas were extruded during a second stage of sea-floor spreading in the axial trough of the Red Sea (Schmidt and others, 1972). Potassium-argon measurements on lava from the eastern part of Ḩarrat al Buqūm, east of the quadrangle, yield dates of 3.5±0.3 Ma, 1.72±1.16 Ma, and 1.1±0.3 Ma (Hotzl and others, 1978).

Flows of the Buqum basalt, between 1 and 15 m thick, form the bulk of the lava field. They are dark gray to black, unaltered, aphanitic to fine grained, alkali-olivine basalt containing 40–60 percent plagioclase, 15–40 percent clinopyroxene, 5-10 percent olivine, and 1–10 percent glass and altered glass.

Original flow surface are well exposed, and one or more flows are observed to be superimposed. The direction and extent of individual flows can be locally traced, and some are extensive. They were extruded onto a surface of low relief, which is at the present wadi level in the north, but it is at progressively higher level than the present wadi system toward the south. To the south, the lava flows crop out as plateau or terraces perched high on the sides of wadis.

Most flows are probably derived from fissures (Greenwood, 1975a), but many cones in the harrat were local vents for the basalt. The cones rise as much as 200 m above the lava field. Although a few are entirely composed of lava, most consist of well-stratified, steeply dipping cinder or cinder intercalated with lava (Greene, 1982).

QUATERNARY SURFICIAL DEPOSITS

Terrace and alluvial-fan deposits

Terrace and alluvial-fan deposits (Qt) occur at the foot of the Red Sea escarpment and along some of the larger wadis draining towards the coast. The deposits consist of unconsolidated, poorly sorted talus, formed by recent active erosion of the escarpment. They consist of pebbles and boulders, as much as 0.5 m in diameter, containing intercalated lenses and channel fill of pebbles and sand. The deposits are as much as 10 m thick and are often well stratified. They are older than, and consequently are being dissected by, the present wadi system.

Floor- and coastal-plain deposits

Much of the southwestern corner of the quadrangle is underlain by a sheet of sand, gravel, and silt (Qa) deposited on pediment and coastal plain of the Tihāmat. Gravel is preferentially concentrated near rock outcrops, but parts of the Tihāmat are covered by lag-gravel deposits. The sand is fine to medium grained and is intermixed with silt and clay. Adjacent to some wadis, the sand and silt form massive and well-stratified flood-plain deposits, as much as 3 m thick, particularly where wadis have been dammed for agricultural purposes. The present wadi system is dissecting the deposits.

Eolian deposits

Eolian sand (Qes) forms dune fields and linear sand ridges. The dune fields are markedly banked against the southwest flank of Jabal 'Adīf, where aerial transport of sand is impeded. The fields consist of fine to medium sand in continuous sand hills or of areas covered by closely spaced dunes separated by barren, delated ground. Dunes are as much as 5 m high. The linear sand ridges lie atop the dune fields or overlie the coastal plain. The ridges are 20-100 m wide and as much as 5.5 km long; they consists of fine- to medium-grained sand. They are molded by prevailing southwesterly winds for much of the year.

Alluvial deposits

Alluvial material (Qa) fills all the wadis in the quadrangle. It consists of poorly to well stratified sand, gravel, minor silt, and cobbles 1-3 m thick. Channeling and crossbedding are common. The unit includes undifferentiated terrace and eolian deposits.

GEOCHRONOLOGY

The reference souces provide an abundance of geochronologic data, of uneven reliability, pertaining to the Jabal Ibrāhīm quadrangle. Greenwood (1975a), Fleck and others (1976), Aldrich (1978), and Brown and others (1978) present an array of dates determined by the K-Ar (potassium-argon) method, whereas an even larger body of data was collected in connection with Rb-Sr studies (Greenwood, 1975a; Fleck and others, 1980; Bokhari and Kramers, 1981; Fleck and Hadley, 1982; Marzouki and others, 1982; Kröner and others, 1984; D. P. F. Darbyshire and others written commun. 1983). In addition, Bokhari and Kramers (1981) reported a Nd-Sm (neodymium-samarium) model age for some of the metavolcanic rocks. The reported localities are shown on the map, and the age determinations are listed in table 2. The information in the table is divided according to the map units used in this compilation, but the rock names in the description are those used by the original authors. The K-Ar dates shown for Fleck and others (1976) have been recalculated by Gettings and Stoeser (1981) using international standard decay constants. Other sources used the standard constants.

Proterozoic layered rocks

The oldest age reported for rocks of the quadrangle is about 943 Ma, shown as locality 1 of the present compilation (D. P. F. Darbyshire and others, written commun. 1983). The age, derived from metavolcanic rocks of the Jof formation (Baish group), is an unreliable Rb-Sr errorchron; it may be metamorphic rather than an extusive, age. However, the extent of error is constrained by the dating of a dioritic hypabyssal dike (locality 3) and of the Bidah pluton (localities 8, 9, 10), which intrude the Jof formation and thus provide a minimum age for it.

A suite of Baish- and Bahah-group metavolcanic rocks near Dār al Khuld, farther northwest in the quadrangle (locality 2) and referred to by the original authors as the "Kulada suite," yielded a four-point Rb-Sr isochron of 847±34 Ma (Kröner and others, 1984). This result is comparable with a 3-point Rb-Sr isochron age of 812±19 for similar layered rocks in the Al Līth quadrangle (Kröner and others, 1984).

The Rb-Sr age of 810 Ma reported for the Ras formation of the Bahah group (locality 3) (D. P. F. Darbyshire and others, written commun., 1983) is an errorchron and is probably a metamorphic age. Conventionally, the Bahah group is considered to be coeval with the Baish group; a reliable depositional age for these rocks would likely be between 900 and 950 Ma.

Eleven samples from locality 4 in the southeast corner of the quadrangle provided a Rb-Sr apparent age of 721±55 Ma for metavolcanic rock of the Qirshah formation, referred to by the authors (Bokhari and Kramers, 1981) as the "Surgah formation." Although this is an errorchron, not an isochron, the result is comparable with a Nd-Sm model age of 757±256 Ma obtained by Bokhari and Kramers (1981) from four samples at the same locality. It is also compatible with a Rb-Sr errorchron of 728±65 Ma, obtained from metavolcanic rocks of the Khutnah formation west of Jabal Balas in the Al Qunfudhah quadrangle, which is directly south of the Jabal Ibrāhīm quadrngle (D. P. F. Darbyshire and others, written commun. 1983). Altogether, these data indicate that the Qirshah and Khutnah formation probably belong to a volcanic assemblage approximately contemporaneous with the Halaban group of the southern Shield, rather, than to an assemblage of the Jiddah group, which is conventionally considered to be greater than 800 Ma old.

The Ablah group is not already dated in the quadrangle. Potassium-argon whole-rock ages of basalt, reported by

Greenwood (1975a) for locality 6 and by Brown and others (1978) for localities 5 and 7, are probably reset. A Rb-Sr isochron age of 740±139 Ma (D. P. F. Darbyshire and others, written commun., 1983), later determined for metavolcanic rocks of the Jerub formation in the Al Qunfudhah quadrangle, is, as of 1983, probably the most reliable age for part of the group.

Proterozoic intrusive rocks

The ages of the older dioritic and tonalitic rocks are based on two clusters of dates, both of generally poor reliability. The oldest pluton in the group appears to be the Bidah pluton, for which an errorchron of 901±37 Ma was obtained from nine samples at localities 8, 9, and 10 (Marzouki and others, 1982). This age is in fair agreement with previously determined K-Ar mineral ages at localities 11 and 12 (Greenwood, 1975a; Brown and others, 1978). Other plutons (table 2) range from 853 to 838 Ma in age. The Shaqqah pluton (localities 13 and 14), in the southwestern part of the quadrangle, bears a date of 853±72 Ma (Fleck and others, 1980). However, the eight samples measured, four from each locality, show considerable scatter on the Rb-Sr isochron diagram, so the result is unreliable. For the Dhara pluton (localities 16, 17, and 18), the Rb-Sr data yield a comparable apparent age of 838±93 Ma. Six points were plotted, but there is some scatter. As a consequence of the poor reliability of the geochronologic results, the significance of most of the ages determined for the older diorite and tonalite group of rocks is equivocal. Younger K-Ar and Rb-Sr dates for this group (localities 19 and 20) are metamorphic mineral ages and probably reflect the ages of metamorphism.

Rubidium-strontium measurements for the younger diorite and tonalite rocks in the Tharad pluton were obtained from samples at localities 21 through 24 and resulted in an eleven-point isochron of 744±22 Ma. The isochron indicates the age of intrusion of the pluton within an acceptable range of error (Marzouki and others, 1982). Determinations on dike rocks from the same pluton yielded an age of 779±49 Ma, but the data points are unacceptably scattered and are thus unreliable.

On the basis of one sample, the posttectonic granitic pluton at Jabal Ibrāhīm (locality 25) has a Rb-Sr model age of 657 Ma (Fleck and others, 1980); the results was calculated using and initial strontium ratio of 0.7032 averaged from those of other posttectonic granodiorite and granite plutons in the southern Shield. For posttectonic granitic rocks that cut the tonalite (tn) of the Shuwas pluton, a more reliable four-point isochron was obtained from samples at localities 26 and 27 within the quadrngle and from two other localities in the adjacent Biljurshi quadrangle (19/41B); it provides an Rb-Sr age of 636±21 Ma (Fleck and others, 1980). At localities 28 and 29 in the pluton, near the southern border of the quadrangle, Rb-Sr results of 617±10 Ma and 630±10 Ma (Brown and others, 1978; Greenwood, 1975a) are compatible with this age. They suggest that the granodiorite and monzogranitic rocks that cut various parts of the pluton were contemporary. The K-Ar results from localities 26 and 27 are reported to be discordant (Fleck and others, 1980).

The reliability of younger Rb-Sr ages reported for the Rafaah pluton (locality 30), the Turabah pluton (localities 31 and 32), and granitic hypabyssal intrusions at localities 33, 34, and 35 is unknown because the sources provide neither analytical details nor a discussion of the results.

STRUCTURE AND METAMORPHISM

The rocks of the Jabal Ibrāhīm quadrangle are multiply deformed and metamorphosed. At least two sets of folds affect many of the layered rocks, sets of faults displace both the layered and plutonic rocks, and greenschist- to amphibolite-grade metamorphic mineral assemblages are widespread. Most of the deformation and coeval metamorphism developed during a late Proterozoic orogenic event dominated by east-west compression and referred to as the Hijaz tectonic cycle (Greenwood and others, 1976), which resulted in a dominant north-trending fabric (fig. 2). Later faulting, the emplacement of a gabbro dike swarm, and the extrusion of alkali-olivine basalt were associated with tensional structures developed during the late Tertiary opening of the Red Sea and the concomitant attenuation of the Proterozoic crustal rocks on its margins

Conceptually, the Jabal Ibrāhīm quadrangle can be divided from west to east into three tectonic-metamorphic domains (see Structural Sketch Map). The western domain is dominated by batholiths of syntectonic (F_2) gneissic granodiorite and granite, large folds of a second folding episode (F_2), amphibolite grade mineral assemblages, and late Tertiary faults and dikes. The central domain is characterized by tight to isoclinal early folds and related penetrative schistosity, lesser F_2 folds, greenschist mineral assemblages, and major north-trending wrench faults and shears. The eastern domain is marked by a complex north-trending fault structure, penetrative deformation (F_1) of the Qirshah and Khutnah formations, and an abundance of small- to medium-scale folds affecting both the Qirshah and Khutnah formations and the Ablah group. The relative age of these structures in the three domains is not clearly stablished. They probably vary from domain to domain, and it is possible that the second folding episode (F_2) in the western domain correlates with the earliest (F_1) penetrative deformation in the Qirshah and Khutnah formations of the eastern domain, but further observations are required to clarify these issues.

In the western domain, the earliest F_1 structures are represented by foliation in the Baish and Bahah groups along the western margin of the quadrangle, where the rocks are metamorphosed to the greenschist facies. Subsequent F_2 deformation produced the dominant folds of the area and was associated with amphibolite-facies regional metamorphism and the emplacement of gneissic granodiorite to granite batholiths. High-grade metamorphic rocks are abundant in the eastern part of the domain, where amphibolite is common. In addition, schist and gneiss of the Ablah group have assemblages of hornblende, garnet, staurolite, and kyanite; and schists of the Baish and Bahah groups contain hornblende and biotite. The major F_2 folds generally plunge northward. They are upright or overturned to the east and have tight closures; in many places, their limbs are intensely sheared. The earlier metamorphic F_1 foliations in the Baish and Bahah groups were refolded during this phase of deformation, and a large, complex antiform developed in Ablah-group rocks in the center of the area. The F_2 structures are probably reflected by the elongate outcrop patterns of gneissic granitic batholiths and discontinuous units of amphibolite.

Northwest- and northeast-trending faults of various ages are common in the area. West-northwest-trending fractures are occupied by late Proterozoic mafic and felsic dikes, and Late Tertiary olivine gabbro dikes in the southwestern part of the quadrngle occur along some of the more recent faults in the area.

The boundary between the western and central tectonic-metamorphic domains lies just west of Jabal Ibrāhīm. In the south, it is marked by faults that juxtapose amphibolite-grade metamorphic rocks in the west against greenschist-facies metamorphic rocks in the east. Some of the faults are believed to be thrusts that dip gently west and have reverse-slip movement of as much as 14 km (Greenwood, 1975c). North of Jabal Ibrāhīm, the boundary between the domains is less distinct. It approximately follows the eastern contact of the gneissic granodiorite to granite batholiths (gg) and is marked by a gradual decrease in metamorphic grade toward the east.

Within the central domain, the rocks of the Baish and Bahah groups are in tight to isoclinal, north-trending folds. The folds and related lineations plunge gently to moderately north or south. Lineations include mineral streaking, cleavage and bedding intersections, elongation of volcanic and sedimentary clasts, rodding, and, on a large scale, elongation of sulfide lenses. Prograde greenschist-facies metamorphism is ubiquitous. Typical mineral assemblages include actinolite, albite, epidote, chlorite, and carbonate. A penetrative schistosity developed parallel with the axial planes of the folds, and the rocks crop out as greenstones, greenschists, and quartzofeldspathic schists containing granoblastic, lepidoblastic, and blastoporphyritic textures. On limbs of tight folds, the schistosity is commonly parallel to relict sedimentary layering. In region of intense deformation, fold limbs are sheared along bedding contacts, and in fold closures, the bedding is transposed. During a subsequent phase of deformation, the earlier folds and schistosity were folded about generally north-trending axes. In parts of the area, a second generation of cleavage developed, and syntectonic granodiorite orthogneiss (gn) was emplaced in the core of F_2 anticlines. Amphibolite-grade metamorphism occurred on the flanks of such gneissic domes.

The major north-trending faults and shear zones in the central domain have a complex history. They cut some of the late-tectonic granite plutons, but probably originated during the earliest phase of deformation as conformable slides or thrusts on the limbs of regional folds. Left-lateral wrench faulting and recurrent faulting and folding of early schistosity about shallow-dipping to steeply dipping axes occurred along the Wadi Bidah fault zone (Structural Sketch map). The zone extends for over 100 km, across the entire quadrangle. It consists of several subparallel faults and is characterized by extensive hydrothermal alteration and sections of sheared rock as much as 20 m wide.

The circular structures in the central tectonic-metamorphic domain near Wādī Turabah and at Al ʻAqīq probably originated by cauldron subsidence. The Turabah structure near the north end of the domain is believed to represent the foundering of a block of country rock above an emptied magma chamber. A circular fracture defined the block and was the locus of intrusion of a granite ring dike. Additional stoping and intrusion in the center of the block created the syenite-trondhjemite Turabah pluton (Greene and Gonzalez, 1980).

The eastern boundary of the central domain coincides with the Aqiq fault zone (Structural Sketch map), a major structural lineament in this part of the quadrangle. The two periods of oblique-slip, as well as large vertical movements, occurred along the fault (Greenwood, 1975a). The zone separates the Baish and Bahah groups on the west from the Qirshah and Khutnah formations on the east. It also separates areas in which Ablah-group rocks rest directly upon the Baish group in the west from areas where the Ablah group rests on the Qirshah formation in the east. The orientations of barite-fluorite and gold-quartz veins in the area are controlled by the fault and a related conjugate system of fractures.

In the eastern domain, there is evidence for two periods of deformation. The earlier period is represented by penetrative cleavage and schistosity in the Qirshah and Khutnah formations, commonly subparallel to the sedimentary layering, and prograde greenschist-facies metamorphism. The foliations are vertical to steeply dipping, and tight to isoclinal F_1 folds are inferred to be present, despite the general absence of observable fold closures.

The second phase of deformation in the eastern domain occurred after deposition of the Ablah group. It resulted in upright, north-trending folds and, locally, a related axial-plane cleavage in the Ablah group, a refolding of the earlier foliation in the underlying rocks, and a superimposition of an F_2 cleavage on the earlier fabric. The Ablah group itself is preserved mainly as a north-trending, faulted-bounded block of intricately folded rocks. The lower Rafaah formation is metamorphosed to the greenschist facies, whereas the upper two (Jerub and Thurat) formations are metamorphosed to the zeolite or lower greenschist facies and contain assemblages of albite, chlorite, zoisite, prehnite, and pyrophyllite; these latter two formations generally lack a penetrative cleavage.

ECONOMIC GEOLOGY

The Jabal Ibrāhīm quadrangle contains almost 100 known ancient workings and minerals occurrences that cover a range of commodities including copper, zinc, gold, silver, barium, fluorine, tin, chromium, nickel, manganese, kyanite, marble, and lightweight aggregates (pozzolan) (fig. 2, table 3). In two districts hosting copper and zinc mineralization, the Bīdah district in the center of the

TABLE 3.—Mineral occurrences in the Jabal Ibrāhim quadrangle

Locality number[1]	MODS number	Name of Occurrence[2]	Commodity	Status
1	0037	Salaga	Au	Ancient working.
2	3005	Wadi al Filh	Gossan, Cu	Occurrence.
3	2723	Jabal Shada	Kyanite	Do.
4	3004	Jabal Qalqal	Gossan, Cu	Do.
5	0039	Wadi ad Arj (Wadi al Arj)	Kyanite	Do.
6	0038	Wadi Minsah	Marble	Do.
7	1135	Wadi Minsah East	Cu, Pb	Do.
8	3008	Wadi Lyar	gossan, Zn	Do.
9	0045	Ri' as Ssifer	Cu, Ag, Zn	Ancient working,
10	0043	Bajila	Au	Occurrence.
11	0467	Mulgatah (Jabal Malas)	Cu, Zn, Ag, Au	Ancient working.
12	0468	Gehab (Izhab)	Cu, Zn, Au, Pb, Ag, Ba	Do.
13	2013	Wadi Leif	Zn, Cu, Au, Ag, Ba	Occurrence.
14	0464	Sha'ab at Tare (Sha'ab el Tare)	Cu, Au, Zn, Ag, Pb, gossan	Ancient working.
15	2827	Jabal Mohr	Cu, Zn, Ag, gossan	Occurrence.
16	0467	Mehaid	Cu, Au, Zn	Ancient working.
17	2704	Rabathah North (Rabathan North, Rabathan 5, 7, and 8)	Cu, Zn	Occurrence.
18	0466	Mulhal	Ag, Au, Cu, Pb, Zn, Ba	Ancient working.
18a	2702	Mulhal 2	Ag, Au, Cu, gossan	Occurrence.
19	2703	Bilajamaj (Bilajimah)	Zn, Cu, Ag, gossan	Do.
20	1310	Khayal al Masma'ah	Au, Ag, Cu, Zn, gossan	Ancient working.
21	1309	Umm al Janadel	Au, Cu, gossan	Do.
22	1308	Shiab al Wial (Shi'b al Wi'l)	Au	Do.
23	1307	Bal Maadan, RGWS	Au	Do.
24	2701	Rabathan area	Cu, Zn	Occurrence.
25	0463	Rabathan (Rabathan 1, 2, 3, 4, and 6)	Cu, Ag, Au, Zn	Ancient working.
26	0047	Asswada, Manhal (Manhal North)	Au, Ag, Cu	Do.
27	1312	Jabal Hariq	Cu(?)	Do.
28	0046	Abu al Maadan (Abu al Ma'adan, As sut, Asut)	Au, Ag, Cu	Do.
29	1313	Abu Suddra	Au(?)	Do.
30	1314	Argub	Au(?)	Do.
31	0048	Ma'adan, Mahawiyah area (Mayawiyah-ma'adan, Maadan)	Zn, Cu, Au, Ag, gossan	Do.
32	1315	Jabal al Ahmar	Au(?)	Do.
33	0049	Wadi Mandaha, Mindaha North (Wadi Mandaha)	Cu, Zn	Do.
34	1343	Jabal al Azzhar (Jabal al Azhar)	Au	Do.
35	1316	Al Banaan	Au(?)	Do.
36	1317	Umm al Mahal (Upper Manhal, Umm al Mahel)	Cu	Do.
37	1319	Bayt al Faggar	Cu(?)	Do.
38	2716	Wadi Bathan East	Fe	Occurrence.
39	1318	Sh'ab Anhal, Sh'ib Anhal	Au, Ag, As	Ancient working.
40	1334	Al Arwaq	Au, Ag, As	Do.
41	1335	Kharb al Rahyour	Cu, Ag	Do.
42	1336	Hush al Salman	Cu	Do.
43	1338	Jabal Nahlah	Cu	Do.
44	1337	Jabal Isan	Au, Ag, As, gossan	Do.
45	2700	Haffa Abith	Au, Ag	Do.
46	1339	Umm al Khabath	Cu, Zn, Ag, gossan	Do.
47	1340	Sh'ib Assidar	Cu	Do.
48	0030	Wadi Khadhra, Jabal al Azzhar (Wadi al Khadra)	Gossan, Cu, Ni	Do.
49	3180	Waiss	Au	Do.
50	0035	Hazim al Hadid, Jabal al Azhar (Jabal al Azhar-North)	Au	Do.
51	0034	Bani Sar, Al Siran, Jabal Mussad (Al Ssiram-North)	Au, Ag	Do.
52	1320	Arqub al Hazim	Cu, gossan	Do.
53	1341	Assifar (As Saifer, As Ssifer)	Cu, Au, gossan	Do.
54	1342	Jabal al Hamatin	Cu, Au	Do.
55	0026	Ar Rudha (Ar Raduh)	Au	Do.
56	0025	As Sadeeh	Au, Ag	Do.
57	1381	Wadi Kara	Au	Ancient working.
58	0024	Al Aqiq	Au, Ag	Do.
59	2849	Aqiq Ghamid (Ghaza, Aqiq Ghamid)	Au	Do.
60	1344	Wadi Aqiq manganese	Mn	Occurrence.

TABLE 3.—Mineral occurrences in the Jabal Ibrāhīm quadrangle—Continued

Locality number[1]	MODS number	Name of Occurrence[2]	Commodity	Status
61	1345	Wadi Aqiq serpentinite	Cr	Do.
62	0032	Umm Errhi	Au, Ag, Cu, Zn	Ancient working.
63	3181	Jabal Gahab	Au	Do.
64	0031	Jabal Murryyi (Gennaida, Al Khathamah, Jabal Muryii)	Cu, Ag	Occurrence.
65	2826	Wadi al Mazra	Au	Ancient working.
66	0028	Wadi Fig South	Cu, Au, Zn	Do.
67	0029	Wadi Fig	Cu, Au, Zn, gossan	Do.
68	1382,	Al Aqiq barite	Ba, F, Zn	Occurrence.
	3169-3178	Al Aqiq barites (several locations)	Ba, F, Zn	Do.
69	1099	Jabal Rumur	Cu	Do.
70	2768	Harrat al Buqum, ZAN 228	Lightweight aggregate (pozzolan)	Do.
71	2765	Harrat al Buqum	do	Do.
72	2767	Harrat al Buqum, ZAN 223	do	Do.
73	2766	Harrat al Buqum	do	Do.
74	1101	Jabal Rafa	Cu, Ag, Zn	Ancient working.
	0021-0023	Jabal Budiyah, zones C, BD, A	Cu, Ag, Zn	Do.
75	1104	Al Gherayah, Raniyah area	Au(?), Ag(?)	Ancient working.
76	1105	Al Mukalsrah, Raniyah area	Au(?), Ag(?)	Do.
77	1106	Abu Sydra, Raniyah area	Ag, Cu, Zn	Do.
78	1115	Sharay, Raniyah area	Cu(?)	Do.
79	0020	Wadi Raniyah	Au, Pb(?), Be(?)	Do.
80	1081	Hajeej mine	Cu	Do.
81	0643	Ahdairah	Cu, Zn, gossan	Do.
82	1079, 1080	Wadi Qurdah, Ghadmat Sharyan	Cu	Do.
83	1113	Wadi Abinnah, Raniyah area	Ag, Pb, Cu	Do.
84	0027	Ablah	F, Cu, Pb, Zn, Ag, Mo	Do.
85	1075	Assous, No. 1	Au, Ag	Do.
86	1074	Tenadeb	Cu, Zn	Do.
87	0645	Iktinah (Kithalnah, Qitina, Estaynah)	Cu, Zn, gossan	Do.
88	1076	Assous, No. 2	Cu, Ag	Do.
89	0642	Qirdan	Cu, Zn, gossan	Do.
90	3207	Ablah, ABH 196	Sn	Occurrence.
91	1073	Bengerdan (Wadi Raniyah area)	Cu	Ancient working.
92	1962	Ysrah	Gossan	Occurrence.

[1] Locality numbers are shown in the mineral occurrence map (fig. 3).
[2] Alternate names and spellings occurring in the literature are shown in parentheses.

quadrangle and the Shuwaş district in the extreme southeast, extensive geological exploration has taken place over nearly 50 years and has failed to identify exploitable resources. The potential of most other occurrences of metallic minerals is low, despite the large number of prospects. These prospects include copper in epiclastic rocks at Jabal Murryyi; auriferous quartz veins at the southern end of the Bīdah district and near Al ʻAqīq; traces of copper and nickel at Wādī Khaḍra'; fluorine, copper, and silver in an unusual pegmatite at ʻAblah; chormium in a small lens of serpentinite south of Al ʻAqīq; and tin reported from a geological anomaly in granites of the Shuwas pluton. A preliminary exploration program for fluorite and barite, south of Al ʻAqīq, has recently been completed; quarries for marble are sited along Wādī Bīdah; and lightweight aggregate has been located in the Tertiary basalt field of Ḩarrat al Buqūm.

Copper and zinc mineralization

BIDAH DISTRICT

The Bīdah district consists of a belt of copper and zinc occurrences trending north for over 70 km along the course of Wādī Bīdah. The district comprises almost half of the total known mineral occurrences in the quadrangle, most of which are marked by ancient workings for copper and gold. In this century, the area has been of interest for exploration since 1930's when Larken (1936) first reported on Jabal as Azzhar (locality 34, MODS 1343). Investigations of five occurrences within the district had been undertaken prior to World War II, which made them among the earliest prospect examined by modern exploration programs in the Arabian Shield. Investigations in the Bīdah district have continued until the present; a recent report by Smith and others (1983) summarizes this extensive history of exploration and discusses the geology and geochemistry of several of the occurrences. The district represents mineralization in one of the oldest volcanic complex of the Arabian Shield and is therefore, one of the earliest components of the metallogenic cycle of the region (Johnson and Vranas, 1984).

The mineral deposits are contained in volcaniclastic and volcanic rocks that constitute a bimodal suite of basalt and soda dacite-rhyolite correlated with the Baish group. Mineralization consist of two types: (1) apparently stratiform lenses of disseminated to massive sulfides, and (2) subordinate discordant lenses and veins of disseminated sulfides associated with quartz in shears, faults, or fractures.

The most significant occurrences (table 4) primarily lie in the northern third of the district, west of Wādī Bīdah. They are hosted by rocks assigned by Jackaman (1972), Riofinex (1979), and Smith and others (1983) to the Gharb group. East of the wadi smaller occurrences at the Rabaḏān ancient

TABLE 4.—Principal mineral occurrences in the Bidah district

Locality number	MODS number	Name	Grade and estimated size	Summary of geologic setting and features of mineralization
11	0467	Mulgatah[1]	140,000 metric tons to 100 m: 0.28 percent Cu, 0.87 percent Zn, 15 g/t Ag, 0.75 g/t Au	Ancient workings on gossan 1-3 m thick, intermittently developed along a strike of 165 m, in sheared and sericitized dacitic volcaniclastic rocks (chlorite-sericite-quartz schist) underlain by andesitic breccia and tuffs (chlorite schist). Mineralization includes disseminated to massive pyrite and minor sphalerite and chalcopyrite in shear zone and in quartz veins in dacitic rocks.
12	0468	Gehab[1]	1.4-1.9 million metric tons at 0.64-1.26 percent Cu, 1.45 percent Zn, 0.09 g/t Au, 5.3 g/t Ag	Ancient workings on gossan that extends intermittently 700 m along strike in dacitic volcaniclastic rocks (sericite-quartz schist) at the interface between a hornblende porphyry sill (amphibolite) and locally pillowed basalt lavas (chlorite schist) and that overlies dacitic volcanic rocks. Mineralization includes disseminated to massive pods and lenticles of pyrite, minor chalcopyrite and sphalerite with or without barite and minor free gold in a unit of quartz-chlorite-sericite schist, chert, hematitic chert (iron formation), and pyritic carbonaceous chert; mineralization is associated with sericitization.
13	2013	Wadi Leif[1]	under 0.5 million metric tons at 0.8-2.5 percent Zn, 0.07 percent Cu, 0.1 g/t Au, 6.6 g/t Ag.	Gossan 7 m thick and over 450 m in strike length occurring as an interfingering and gradational sequence of andesitic and basaltic pyroclastic rocks (actinolite-chlorite schist), lavas, and mafic dikes plus subordinate dacitic and rhyodacitic pyroclastic rocks and lavas (chlorite-feldspar-quartz schist containing blue-quartz eyes). Mineralization includes massive to disseminated, elongate lenses of pyrite, minor sphalerite, very minor chalcopyrite, and barite in a unit of iron formation (ferruginous quartz and carbonate rock) and ferruginous sericite-talc schist within a volcanic sequence that passes along strike into hematite-magnetite chert; mineralization is associated with talc and sericite alteration.
14	0464	Sha'ab at Tare[1]	2.4 million metric tons at 0.37 percent Cu, 0.5 percent Zn	Ancient workings on gossan extending discontinuously for 600 m along strike at interface between mafic to intermediate and volcaniclastic rocks (chlorite-sericite-quartz and chlorite schists) and overlying felsic volcanic rocks (sericite-quartz schist). Mineralization includes disseminated to massive lenses of pyrite, minor sphalerite, and chalcopyrite and barite associated with minor iron formation; mineralization is associated with shearing and sericitization.
18	0466	Mulhal[2]	Samples of vein, gossan, and shear zone: 0.5-112 g/t Ag (mean 16.55 g/t), 0.06-29.6 g/t Au (mean 4.01 g/t), more than 0.3 percent Cu, and more than 0.8 percent Pb	Ancient workings on small gossans in a zone 100 m wide by 400 m long in a sequence, having gradational contacts, of andesitic to dacitic pyroclastic rocks, quartz-crystal pumiceous lapilli tuff (quartz-sericite-chlorite schist), blue quartz-eye crystal tuff (quartz-sericite-chlorite schist), basaltic to andesitic to andesitic tuffs and flow rocks (greenstones, chlorite schist), and mafic dikes and sills. Mineralization includes pyrite, chalcopyrite, sphalerite, galena, and tetrahedrite present: (1) as stratiform layers associated with barite along interface between quartz-crystal pumiceous tuff and basalt; or (2) is disordant, green, chromium-rich mica-quartz-barite veins in shears, faults, and fractures; mineralization is associated with a shear zone and extensive hydrothermal alteration.

TABLE 4.—Principal mineral occurrences in the Bidah district—Continued

Locality number	MODS number	Name	Grade and estimated size	Summary of geologic setting and features of mineralization
25	0463	Rabathan[3]	Two ore bodies: 1.5 million metric tons at 2.58 percent Cu, 0.03 percent Zn, 0.16 g/t Au, 2.85 g/t Ag, and 0.6 million metric tons at 2.2 percent Cu, 1.51 percent Zn, 4 g/t Au, 5 g/t Ag	Ancient workings on gossans discontinuously developed along a strike of 1.5 km in a sequence of fine-grained tuffs and mudstones (calcareous quartz schist), carbonaceous shale (carbonaceous schist), dolomite, and manganese-rich iron formation (hematite-pyrolusite chert). The sequence is underlain by basaltic and andesitic flow rocks, tuffs, and breccias, and it is overlain by tuffaceous graywacke, dacitic lapilli tuff (pyroxene-chlorite-sericite schist), pyroclastic breccia, and flow rocks (pyroxene-chlorite-quartz-sericite schist). Mineralization includes disseminated to massive pyrite, chalcopyrite, and minor sphalerite at the interface between dolomite and carbonaceous-tuffaceous schist or within calcareous quartz schist; some sulfide lenses pass into cherty iron-manganese formation; mineralization is associated with sericitic and chloritic alteration.

[1]Primary reference: Riofinex (1979).
[2]Promary reference: Smith and others (1983).
[3]Primary references: Riofinex (1979); Smith and others (1983).

working (locality 25, MODS 0463) and in areas to the north are hosted by rocks assigned by these same authors to the Bidah group. Although in this compilation these rocks are all assigned to the Baish group, the lithologies do appear to vary from east to west across the wadi, which would reflect a difference in volcanic and sedimentary environments.

Volcanic and volcaniclastic rocks of felsic to mafic composition predominantly occupy the western part of the district. The rock types abruptly interfinger but gradational contacts are common. They include flow and pyroclastic rocks that are generally coarser grained than those to the east. Thin units of marble, argillaceous rocks, iron formation, and chert occur at some interface between felsic and mafic volcaniclastic sequences; they are the preferred sites of stratiform mineralization.

East of Wādī Bīdah, along the strike of the Rabaḍān occurrences, sedimentary rocks are more abundant in the succession. Metasedimentary rocks include calcareous and carbonaceous schists, chlorite schist, chlorite-sericite schist, hematitic chert and iron formation, and dolomite; subordinate volcanic units in the sequence are andesitic to dacitic lavas and pyroclastic rocks and massive to pillowed mafic lavas and breccias. These volcaniclastic rocks tend to be finer grained than those west of the wadi. The stratiform mineralization here is concentrated at the interface between dolomite or calcareous rock and carbonaceous or tuffaceous schists.

Overall, the stratiform mineralization in the Bīdah district manifests a high degree of uniformity. The sulfide assemblage occurrs as chiefly disseminated to massive pyrite and subordinate chalcopyrite and sphalerite in layers and lenses. Galena, although rare, does occur, as at Mulhal (locality 18, MODS 0466) (Smith and others, 1983) and at Abū al Ma'ādin in the Mahwīyah area (locality 31, MODS 0048) (Al Koulak, 1981). Many occurrences contain free gold and silver. Barite is present at four places west of the wadi: Qihāb (locality 12, MODS 0468), Wādī Leif (locality 13, MODS 2013), Shi'b aṭ Ṭā'ir (locality 14, MODS 0464), and Mulahhi. Iron formation, consisting of hematitic chert or banded ferruginous quartzite, occurs at several stratigraphic positions and is associated with mineralization at Qihāb, Wādī Leif, and Shi'b aṭ Ṭā'if. At Bilajamah (locality 19, MODS 2703), Rabaḍān, and Aṣ Ṣafrās (locality 53, MODS 1341), iron formation is also common, but includes manganese as pyrolusite (Smith and others, 1983).

Although the mineralization is conformable with respect to the enclosing rocks and is believed to be stratiform, the host rocks are metamorphosed and deformed; schistosity and shear planes occur parallel to the lithologic boundaries, transposed bedding is present, and some sulfide lenses are elongated parallel to fold axes and to lineations formed by intersections of cleavage and bedding. Therefore, the relationship of lenses to the original bedding is uncertain.

Shear zones in the district are accompanied by tight, steeply plunging, small-scale folds, boundinage, and localized strong schistosity. The adjacent rocks are characterized by intense hydrothermal alteration. These zones display a transition in type of mineralization from stratiform to discordant. The discordant mineral deposits, representing a second common type in the district, consist of disseminated sulfides in a quartz-barite gangue; they fill fractures, shears, and faults. Such deposits are common at Mulahhi and Khayāl al Masnāh (locality 20, MODS 1310) ancient workings (Smith and others, 1983), in prominent shear zones marked by green chromium mica (fuchsite). At Umm al Khabath (locality 46, MODS 1339), the remobilized mineralization is present in a quartz-pyrite stockwork (Worl, 1977). These discordant occurrences have been a significant exploration target both in ancient and recent times because, locally, they contain a relatively high gold and silver content. This content is as much as 29.6 g/t of gold and 112 g/t of silver, but generally only a few grams per metric ton of both metals are present.

The mineral deposits of the Bīdah district are analogous to base- and precious-metal deposits in volcanic terranes elsewhere in the world. The close association with chemogenic units and rocks indicative of pauses in active volcanism, the simple mineral assemblage, and the rhyolite doming occurring some localities (Moore, 1978) all suggest that the stratiform sulfides developed through fumarolic activity. The site of some mineralization, as at Rabadān, was distal with respect to volcanic vents, whereas at Qihāb, was Shi'b aṭ Ṣā'ir, Mulahi, and others, it was proximal. Significant amounts of the original deposits were subsequently mobilized and relocated in discordant structures formed by deformation contemporaneous with the development of the Bidah (Baish) group and (or) during later orogenic events.

SHUWĀṢ DISTRICT

Along the southern east edge of the Jabal Ibrāhīm quadrangle and south into the northeastern part of the Al Qunfudhah quadrangle, a series of small deposits of low-grade copper and zinc mineralization constitutes the Shuwāṣ district. The district trends north for some 60 km, parallel to the regional strike, and is underlain by a bimodal sequence of sheared and altered volcanic and volcaniclastic rocks of tholeiitic and calc-alkalic composition of the Qirshah and Khutnah formations. Contemporary research in the area began in the 1950's, and exploration to date gives every indication that the deposits are small, are low grade, and have little economic potential. Jadmah, the largest deposit, lies just south of the quadrangle boundary. It is estimated to contain a possible reserve of 1.2 million metric ton, with grades of 0.9 to 4.6 percent copper and 1.0 to 3.6 percent zinc (Fujii and Kato, 1979b).

The occurrences in the Shuwāṣ district within the Jabal Ibrāhīm quadrangle are considerably smaller than those of the Jadmah deposits. The largest, Kutaynah (locality 87, MODS 0645), has estimated reserves of about 500,000 metric tons of 1-2 percent copper. No concentrations of zinc, gold, or silver have been found (Igarashi, 1977). Mineralization in the supergene zone at Kutaynah is expressed as concentrations of secondary copper minerals, chiefly malachite, chrysocolla, and subordinate cuprite, disseminated in sheared and brecciated metarhyolite (Igarashi, 1977). The metarhyolite is represented by sericite-chlorite-quartz schist; adjacent to the steeply dipping mineralized shear zones, the rock is chloritized and becomes chlorite-quartz schist. Pyrite, or limonite pseudomorphs, is widespread in the chloritized schist. In drill core, the mineralization is present as a network of malachite veinlets in brecciated metarhyolite, and below the supergene zone, aggregates and streaks of chalcopyrite are disseminated with fine-grained pyrite and rare veinlets of sphalerite (Igarashi and Goto, 1977).

Farther south, stratiform mineralization is indicated by thin ironstone beds in schistose rhyolite at Ysrah prospect (locality 92, MODS 1262) (Fujii and Kato, 1979a) and by bedded, disseminated, and massive sulfide lenses at the Jadmah prospect 2 km farther south.

Most occurrences in the Shuwāṣ district evidence a greater degree of structural control than do those of the Bīdah district; the mineralization occurs in shears and fractures and appears to be largely epigenetic. However, the co-occurrence of mineralization with felsic volcanic rocks, the conformable nature of mineralization, and the banding, grading, and folding of sulfide layers in some lenses suggest that the original mineralization was volcanogenic. The coarse-grained textures of the volcaniclastic rocks and the preponderance of volcanic and volcaniclastic rocks in the sequence indicate that the site of mineralization was more proximal than in the Bīdah district. The occurrences are part of an island-arc volcanic complex that developed approximately contemporaneously with the Halaban group and formed part of a second phase of volcanogenic base-metal mineralization in the southern part of the Arabian Shield (Johnson and Vranas, 1984).

JABAL MURRYYI COPPER PROSPECT

Copper in epiclastic rocks is well known in the Ablah group of the Yiba district, just over 100 km south of the Jabal Ibrāhīm quadrangle (Riofinex, 1977). The Jabal Murryyi prospect (locality 64, MODS 0031) and several nearby occurrences are examples of the same type of mineralization within the Jabal Ibrāhīm quadrangle (Worl and Flanigan, 1977).

The prospect area is underlain by metamorphosed, medium- to coarse-grained clastic rocks of the Rafa formation that rest unconformably on volcanic and volcaniclastic rocks of the Baish and Bahah groups. Several bodies of coarse- to medium-grained granodiorite and dikes and sills of potassium-feldspar rhyolite intrude both sequences. The regional structure is dominated by northeast to northwest-trending shear zone and parallel schistosity that obscure most primary features.

The mineralization of this prospect does not yield gossans, but the copper-stained rocks were explored by ancient workings. Disseminated malachite and chrysocolla and finely dispersed chalcocite are present in sheared, folded, and faulted beds of felsic and mafic wacke that lie at the gradational contact between conglomerate and arkosic graywacke. Malachite and chrysocolla occur within lithic fragments of quartz monzonite, both as ragged grains within the relict sedimentary layering of the graywacke and as veinlets along fractures and cleavage. Chalcocite occurs as scattered irregular grains and as part of the fine-grained dusty material distributed through much of the rock. Neither chalcopyrite nor pyrite appears to be present.

The Jabal Murryyi prospect is one of several copper occurrences in metamorphosed clastic rocks of the Rafa formation in the area. On average, the prospect contains 1.5 percent copper and 22 g/t of silver over a mineralized area 250 m in length and 4 m in width.

Significantly, the copper mineralization is present in fine-grained clastic rocks above a conglomerate that constitutes the basal part of a transgressive shallow-water sedimentary sequence. It is believed by Worl and Flanigan (1977) to represent mineralization of the type found, for example, in the Katangan system of the copper belt of Zaire and Zambia.

Gold and silver mineralization

Some remobilized mineralization in the Bīdah district carries concentrations of gold and base metals in quartz-barite gangue. Such mineralization is transitional to occurrences of auriferous quartz veins. These veins, at the southern end of the Bīdah district, were primarily explored for gold. Ancient gold mines were developed in the area on quartz stringers and stockworks within lenses of ferruginous chert or diorite and granodiorite intrusions (Worl and Smith, 1982). The mines include Banī Sār (locality 51, MODS 0034), the largest; Umm ar Raḩā (locality 62, MODS 0032); Shi'b an Naḩl (locality 39, MODS 1318); Al Arwāq (locality 40, MODS 1334); Jabal 'Aysān (locality 44, MODS 1337); Haffa Abith (locality 45, MODS 2700); Jabal al Qahbah (locality 63, MODS 3181); and Wādī al Mazra'ah (locality 65, MODS 2826). Many of these occurrences, particularly those related to ferruginous chert lenses, appear to lie within a single metasedimentary and volcanic unit. This unit correlates with the sequence hosting the Rabaḑān copper-zinc sulfide occurrences (Worl and Smith, 1982), which underscores the importance of ferruginous chemogenic formations as a guide to exploration in the district. In samples of the quartz veins at these occurrences, the gold content varies from 0.1 to an exceptional 53.5 g/t, but it averages between 1.0 and 5.4 g/t. The silver content is consistently low, ranging between nil and 4.0 g/t and averaging between 0.9 and 1.6 g/t.

Worl (1982) described a second group of ancient gold mines developed on quartz veins in the Al 'Aqīq area: Ar Rawḑah (locality 55, MODS 0026), As Sadīn (locality 56, MODS 0025), Wādī Karā (locality 57, MODS 1381), and Al 'Aqīq (locality 59, MODS 2849). Many of the veins are associated with crosscutting aplitic dikes in diorite and tonalite of the older diorite-tonalite suite and with porpylitic, argillic, and carbonate alteration. The veins lie close to, and are believed to be controlled by movements along, the Aqiq fault zone (Structural Sketch map). Sulfides are rare, but include pyrite and arsenopyrite, which produces an arsenic anomaly in several sets of veins. Unlike the northern Bīdah area, no fuchsite is reported here. The gold values of the veins are erratic, as they range from 0.3 high of 18.2 g/t; the averages of sets of samples from different ancient mine dumps and stopes range from 2.4 to 5.9 g/t. This range is similar to that of the quartz veins in the Bīdah district. The silver content is also low, ranging from 0.5 to 2.0 g/t for individual samples. The greatest potential for gold is estimated to be at the Al 'Aqīq Ghazzah cluster of workings, where some 400,000 metric tons containing 17-24 g/t of gold may be present to a depth of 150 m (Worl, 1982).

Copper and nickel mineralization

A copper and nickel anomaly exists at Wādī Khaḑrā' (locality 48, MODS 0030) near the southern end of the Bīdah district, but its geologic setting is in marked contrast with the other copper deposits of the district. At this occurrence, ancient workings, gossans, and geochemical and geophysical anomalies are located in metavolcanic rocks of the Baish group, but they are confined to the contact-metamorphic aureole of a gabbro intrusion (Worl and Wynn, 1982). Indications of mineralization extend some 1,600 m north to south within 150 m of the contact of the gabbro. Gossans are of two types: stringers and disseminations of iron oxides, as well as individual massive lenses and irregularly shaped pods. The gossans are thought to reflect primary stringers, disseminations, and thin massive lenses of pyrrohotite or pyrite that contain pentlandite and chalcopyrite. Copper and nickel values in gossan samples reach a maximum of 1.4 and 1.1 percent, respectively.

Fluorine, silver, and molybdenum mineralization

The 'Ablah ancient working (locality 84, MODS 0027) is a small, but unusual, mineral occurrence that contains an estimated 20,000 metric tons of acid-grade fluorite to a depth of 50 m (Kemp, 1972), as well as silver, copper, zinc, and molybdenum, in pegmatite. The mine site, composed of quartz-potassium feldspar pegmatite, is a prominent, white, cone-shaped hill near the northern margin of the composite Shuwas pluton. A vein of fluorite, probably exploited as a flux for ancient smelting sites elsewhere in the region, crops out near the crest of the hill over a width of 20 m. Most fluorite ore occurs as a mixture of fluorite and quartz crystals, but a few, massive, high-grade aggregates of fluorite crystal are present. The fluorite and quartz-fluorite rocks contain a moderate amount of malachite and some limonite, but at the surface, neither the sulfide minerals nor their alteration products are a major part of the rock.

Mineralization is probably irregular at the 'Ablah ancient workings. The grade of the ore varies at the surface from 30 to 60 percent CaF (Igarashi, 1975), but at depth in the drill core, the grade is less than 3 percent, and other minerals become important. Narrow sections of the pegmatite contain as much as 124 g/t of silver and nearly 1 percent of copper in sympathetic association; in separate zones, molybdenite veinlets are found, antipathetically related to the silver and copper (Allcott, 1970). Other minerals in the pegmatite, reported from the drill core, include sphalerite, pyrite, galena, and tourmaline.

Barium and fluorine mineralization

Structurally controlled hydrothermal barite and fluorite veins crop out in the area south-southeast of Al 'Aqīq (locality 68, MODS 1382, 3169-3178) (Cartier, 1983). The cluster of veins, along almost 5 km of strike, is hosted by a block of Bahah-group rocks bounded by the Aqiq fault zone. The largest vein is in the north; it is estimated to contain some 40,000 metric tons of barite and 7,000 metric tons of fluorite. Massive ore in this vein assays as much 70 percent barium and 13 percent fluorine as well as 0.3 percent zinc contained in sphalerite. The veins are oriented N. 20° W. They occupy tension gashes that are controlled by set of subvertical to steeply east-dipping faults trending N. 20°-60° W. within the Aqiq fault zone or, to a lesser extent, that are controlled by the regional schistosity. Barium and zinc anomalies are developed in the wallrocks for as much as 100 m on either side of the veins. Although the massive ore is high grade, the tonnage present is small, with the result that the potential of the region is only small.

The barite-fluorite veins, the mineralized pegmatite as 'Ablah ancient workings, and a tin geochemical anomaly reported some 8 km south of 'Ablah ancient working (Cartier, 1983) (locality 90, MODS 3207) are characteristic of a hydrothermal phase of mineralization associated with a late-tectonic granite enriched in fugitive elements. Further evidence for such a hydrothermal phase of mineralization includes fluorite-bearing quartz veins in the Shuwas pluton and fluorite-bearing sills of porphyritic rhyolite in the Thurat formation of the Ablah group (Greenwood, 1975a). These various types of mineralization are believed to be related to the late-tectonic granodiorite and monzogranite unit (gdb) that is present in the southeastern part of the quadrangle.

Nonmetallic occurrences

MARBLE

Marble deposits have been investigated at Wādī Manzah (locality 6, MODS 0038) in rocks of the Bahah and Baish groups undivided in the southwestern part of the quadrangle (Laurent, 1969). White and gray banded, nearly pure calcite marble crops out there in units 40-70 m thick. These occurrences are estimated to contain more than 2 million m^3 of easily quarried, high-calcium marble that includes considerable quantities of marble suitable for architectural use (Gaskill, 1970).

Marble is also exploited, on a moderate scale, at occurrences southwest of the junction of Wādī Bīdah and Wādī Turabah (not referenced in the MODS files) (Dehlawi, 1971). The quarry, located on the west bank of Wādī Bīdah, exploits a marble bed a few meters thick. Although this marble occurrence is small, it is reported to be of good quality and attractive for dimension stone, as it is creamy to white and contains brown and green banding (Greene and Gonzalez, 1980).

KYANITE

Kyanite is present in quartzite and muscovite schist at Jabal Shadā (locality 3, MODS 2723), and at Wādī al 'Irq (locality 5, MODS 0039) in the western part of the quadrangle (Gaskill, 1970). Kyanite-bearing rocks occur there in lenses as much as 500 m long and 7-20 m thick. The greatest concentrations, between 8.5 and 15.9 percent kyanite, are in quartzite. Typically, crystals of kyanite lie along the foliation planes in the quartzite bodies as single blades, bladed masses, or flattened radial aggregates. In other places, clusters of thick, prismatic crystals occur. Individual cyrstals are as much as 13 cm long and 1 cm or more wide.

LIGHTWEIGHT AGGREGATE

In the northeastern part of the Jabal Ibrāhīm quadrangle, several recent cones within the Ḩarrat al Būqum lava field contain deposits of siliceous tuff interbedded with layers of basaltic and andesitic agglomerate that consists of scoriaceous cinder, breccia fragments, and bombs. In places, the felsic pyroclastic material has the character of pozzolan, particularly at locality 70 (Ḩarrat al Buqūm, ZAN 228, MODS 2768) (Laurent and Al Nakhebi, 1979). Other occurrences are at localities 71 (MODS 2765), 72 (MODS 2767), and 73 (MODS 2766). The bedded tuff is potentially a valuable lightweight aggregate for cement, although its exploitation depends on the development of a road network in the area.

GEOLOGIC HISTORY

The oldest rocks in the quadrangle are those of the Baish and Bahah groups. They represent a volcanic episode older than 900 Ma and constitute a bimodal suite of sodic low-potassium tholeiitic basalt and low-soda dacite-rhyolite. Compositionally, the rocks closely resemble the lava of present-day immature island arcs (Roobol and others, 1983). The well-bedded nature of the tuffaceous rock, the pillow structures in some lavas, and the occurrence of black, pyritic shales, cherts, limestone, and dolomite are indications of submarine deposition. Volcaniclastic rocks predominate, and much of the succession appears to have been deposited in a distal volcanic environment, although subordinate massive and pillow lavas and coarse-grained pyroclastic rocks in the sequence indicate that extrusive centers were present locally. In general, the Baish and Bahah group are considered to have originated in a depositional basin associated with an oceanic island arc. However, the presence of fine-grained quartzofeldspathic rocks of an inferred continental provenance, which occur in parts of the succession (Ramsay and others, 1981), suggests that a certain amount of sediment was carried into the basin from the African craton. A similar provenance is suggested by Pallister (1986) for the Sadiyah formation in the adjoining 1:250,000-scale Al Līth quadrangle.

The Baish and Bahah groups were intruded about 900 Ma ago by the Bidah pluton (Structural Sketch map), a chemically immature body of mafic rock that has a very low initial Sr/ Sr ratio (0.70246) and a calc-alkalic fractionation trend; this pluton was derived from a parent magma of an inferred mantle origin. The geologic and geochemical features of the Bidah pluton indicate that it is broadly coeval with the volcanic rocks of the Baish and Bahah groups; together, these volcanic and plutonic rocks constitute an intraoceanic island-arc volcanic complex. The complex is the oldest one-documented in the Arabian Shield; it is inferred to have developed offshore from the African craton. By implication, the volcanogenic polymetallic mineral deposits in the complex are the oldest components in the metallogeny of the region (Johnson and Vranas, 1984).

Volcaniclastic and subordinate volcanic rocks compiled as Baish and Bahah groups undivided on the western margin of the quadrangle also form a bimodal suite of basaltic and dacitic-rhyolitic lavas. Their major- and trace-element contents are comparable to those of present-day ocean-floor, island-arc rocks (Reischman and others, 1984).

Petrographically they resemble the rocks farther east, but they appear to be younger. A Rb-Sr date of 847±34 Ma for the Baish-Bahah group rocks ("Kulada suite" of Kröner and others, in press) on the edge of the Red Sea escarpment indicates that they formed some 50 million years after the emplacement of the Bidah pluton. The date agrees with ages of 830-821 Ma obtained from similar volcanic assemblages farther west (Kröner and others, 1984). The date is also similar to unreliable ages of 853 Ma for the Shaqqah pluton and 838 Ma for the Dhara pluton, bodies of diorite and tonalite that are inferred to be genetically related to the volcanic rocks they intrude. Elsewhere in the western part of the Arabian Shield, other plutons of diorite and tonalite of similar age occur, which together indicate persistent mafic plutonism in the region. These include the Wadi Khadrah pluton, 895 Ma (Fleck and others, 1980); the Biljurshi pluton, 890 and 848 Ma (Fleck and others, 1980); the Qanunah pluton, 846 Ma (Fleck and others, 1980); and the eastern part of the An Nimas pluton, 837 and 816 Ma (Cooper and others, 1979; Fleck and others, 1980). The geologic character of these plutons is similar to that of the Bidah, Shaqqah, and Dhara plutons, and they are probably also broadly coeval with the volcanic rocks they intrude.

These observations suggest that the western part of the Shield is composed of several island-arc complexes that, if judged by the available radiometric data, formed about 950-800 Ma ago. Pallister (1986) and Reischmann and others (in press) came to similar conclusions about the volcanic sequences of the Al Līth region, west of the Jabal Ibrāhīm quadrangle.

Younger volcanic and volcaniclastic rocks in the quadrangle are represented by the Qirshah and Khutnah formations. Chemically they are somewhat more mature than the lavas of the Baish group, being of bimodal low-potassium tholeiitic and calc-alkalic composition, but their major- trace-element contents are comparable to those of present-day island arcs (Roobol and others, 1983). The geochemistry of the lavas indicates that the parent magma was of mantle origin, although the initial $^{87}Sr/^{86}Sr$ ratio (0.705) of Qirshah formation rocks is anomalously high for such an origin; however, the high initial ratio may have been caused by contamination with radiogenic strontium from seawater (Bokhari and Kramers, 1981). The rocks include pillow lavas, well-bedded tuffs, and marble; they contain an abundance of sedimentary structures, which indicate that they are deposited in largely marine environment. The abundance of lavas and coarse breccias in the succession suggests that they accumulated in a proximal volcanic basin. These rocks interfinger with immature, coarse-grained, volcanically derived sedimentary rocks and contain copper and zinc sulfide minerals formed during a second phase of volcanogenic mineralization in the quadrangle. The Tharad pluton intrudes these layered formations. The mafic phase of the pluton, having a low initial $^{87}Sr/^{86}Sr$ ration (0.70281), was derived from a magma of mantle origin (Marzouki and others, 1982). An island-arc volcanic complex believed to have been formed by the layered and intrusive rocks some 750-720 Ma ago represents continued growth of the Arabian Shield through intraoceanic volcanic processes.

East-west compression, deformation, and prograde greenschist regional metamorphism followed deposition of the Qirshah and Khutnah formations. Tight to isoclinal folds, penetrative schistosity, and shear zones developed in all the rocks. Differential uplift occured, for example, across the Aqiq fault zone, and the rocks were eroded. Marine transgression across the resulting surface initiated deposition of the Ablah group. In the eastern part of the quadrangle, the Ablah group consists of epiclastic, and andesitic to rhyolitic and subordinate basaltic volcanic rocks. The sedimentary rocks are coarse grained and immature; conglomerate and arkosic graywacke are common. The sedimentary units are often poorly sorted or show large-scale crossbedding and channeling. They are red, gray, or green, and some stromatolitic sandy marble is present. The provenance of the Ablah group in the eastern part of the quadrangle consisted of older volcanic and mafic plutonic rocks, and the sediment was deposited in a continental to shallow-marine environment (Greenwood, 1975a). The lower Rafa formation is considered to have been deposited by turbidity currents in structurally controlled troughs, and the upper Thurat formation, by a large delta draining from the north into a shallow sea. The volcanic rocks of the middle Jerub formation are believed to be caldera or caldera-margin deposits.

To the west, the Ablah group crops out as high-grade metasedimentary rocks that were originally finer grained and more mature than those in the east. The succession includes quartzites, pelitic schist rich in aluminosilicate minerals, black slate, and pure calcitic marble. The nature of the rocks indicates that a marine depositional environment existed in this part of the quadrangle and that a distant and (or) deeply weathered provenance suplied little coarse terrigenous material.

After deposition of the Ablah group, east-west compression and deformation resumed, and a second generation of open to tight folds and related penetrative foliations developed. The rocks were metamorphosed weakly in the eastern belt of Ablah-group rocks but intensively and to high grade in the west, concomitant with the intrusion of abundant syntectonic granitic gneiss batholiths. Accretion of the two island-arc volcanic complexes of the region to each other and to the African craton probably occurred during this phase of orogeny.

Subsequently there occurred several episodes of late-tectonic to posttectonic granite intrusion, late-stage hydrothermal mineralization, retrogressive metamorphism along major faults such as the Wadi Bidah fault zone, and emplacement of mafic and felsic dikes.

The most recent geologic events in the quadrangle include late Tertiary rifting in the extreme southwest, intrusion of gabbro dikes into related fractures in the crustal rocks, extrusion of Pliocene to Pleistocene lavas in the northeast, erosion of the Red Sea escarpment, and development of the major wadi systems.

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