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Reconnaissance geology of the Qufar Quadrangle, sheet 27/41 D, Kingdom of Saudi Arabia

by

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ABSTRACT

The Qufar quadrangle, south of the city of Ha'il in the northern Arabian Shield is underlain by late Proterozoic granitic and dioritic rocks and two volcano-sedimentary sequences. Phanerozoic rocks include a few outcrops of the Cambrian and Ordovician Saq Sandstone and small remnants of Miocene basalt flows and plugs.

The oldest rocks in the quadrangle comprise the Nuf formation, a layered sequence of submarine, tholeiitic metabasalt and meta-andesite, and interbedded metagraywacke and marble. The Nuf formation may correlate with rocks mapped as Halaban or Hulayfah group (approximately 780-720 Ma old) to the south of the quadrangle. Cogenetic subvolcanic rocks include gabbro and diorite. Voluminous plutonic rocks of approximately monzogranite composition intruded and dismembered the Nuf formation, gabbro, and diorite, which were simultaneously metamorphosed and internally deformed. Metamorphism of the Nuf formation was variable, but generally upper greenstone-facies assemblages were produced.

Following a period of extensive erosion, the Hadn formation, dacitic to rhyolitic ignimbrite and flow breccia, and interbedded subgraywacke, arkose, and minor conglomerate was deposited. The Hadn formation may be a continental equivalent of the Murdama group, which is mapped to the south of the quadrangle and is approximately 650 to 610 Ma old.

Numerous plutons, predominantly monzogranite, but ranging from gabbro to alkali-feldspar granite, post-date the Hadn formation. Of these, the Malayhah granite is particularly noteworthy because it has a broad zone of cataclasis along the western and southern border. Country rock within several kilometers of the western contact is also highly sheared, predominantly along northerly trends. Locally, a melange of several rock types was produced. Contact metamorphism to garnet-amphibolite hornfels facies occurred at this time, and may be responsible for the formation of small sub-economic magnetite lenses interlayered with some of the marbles of the Nuf formation. In the northern part of the quadrangle, southeast dipping imbricate thrust faults probably closely

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post-date the emplacement of the Mulayhah granite. These thrusts were followed in time by predominantly northeast-trending high-angle faults.

The last major plutonic event in the area is the intrusion of the alkalic granite complexes at Jabal Aja and Jabal Salma about 580 Ma ago. Of particular note is a peralkalic border facies of the Jabal Aja complex that is associated with pegmatites enriched in thorium, niobium, and rare-earth elements.

INTRODUCTION

Geographic setting

The Qufar quadrangle (fig. 1) occupies a 2750 km^2 region between the two rugged and highly dissected granitic massifs of Jabal Aja and Jabal Salma in the northeastern corner of the Arabian Shield. Much of the area has been eroded to flat pediment surfaces, and large areas are covered by wadi sand and sheet-washed sand and silt deposits. Elevations range from 900 m in the northeastern corner of the quadrangle to about 1500 m at the highest peaks of Jabal Aja.

The city of Ha'il, the major administrative center for the region, is expanding rapidly into the northwest corner of the quadrangle. The region supports many farming communities along the various wadis, such as the rich farming strip along Wadi ad Dayra. Qufar, in the center of this agricultural belt, is the largest town in the quadrangle. The level of human activity is made possible by a sparse but sufficient rainfall, approximately 10.2 cm/yr (J. Whitney, written commun., 1982), and an ample ground water supply.

Previous investigations

The first geological investigations in the area were reported by Brown and Jackson (1960), and several years later Brown and others (1963) produced a reconnaissance geological map at a scale of 1:500,000 of the northeastern Hijaz region. Delfour (1980-81) has presented a broad picture of the Precambrian evolution of the northern part of the Shield, although most of his interpretations are based on observations made at least 100 km south of the Qufar quadrangle. He notes that many of the mafic terranes ("ophiolite belts") of the Urd group delineate large older regions of continental crust composed of granitic to dioritic plutonic rocks. These plutonic terranes he refers to as "older basement" to which he assigns an age greater than 880 m.y., an age suspected to be far in excess of any found in the Ha'il-Qufar region.

Chevremont (1982) has prepared a preliminary report and sketch map of the Jabal Nuf region, in the northeastern part

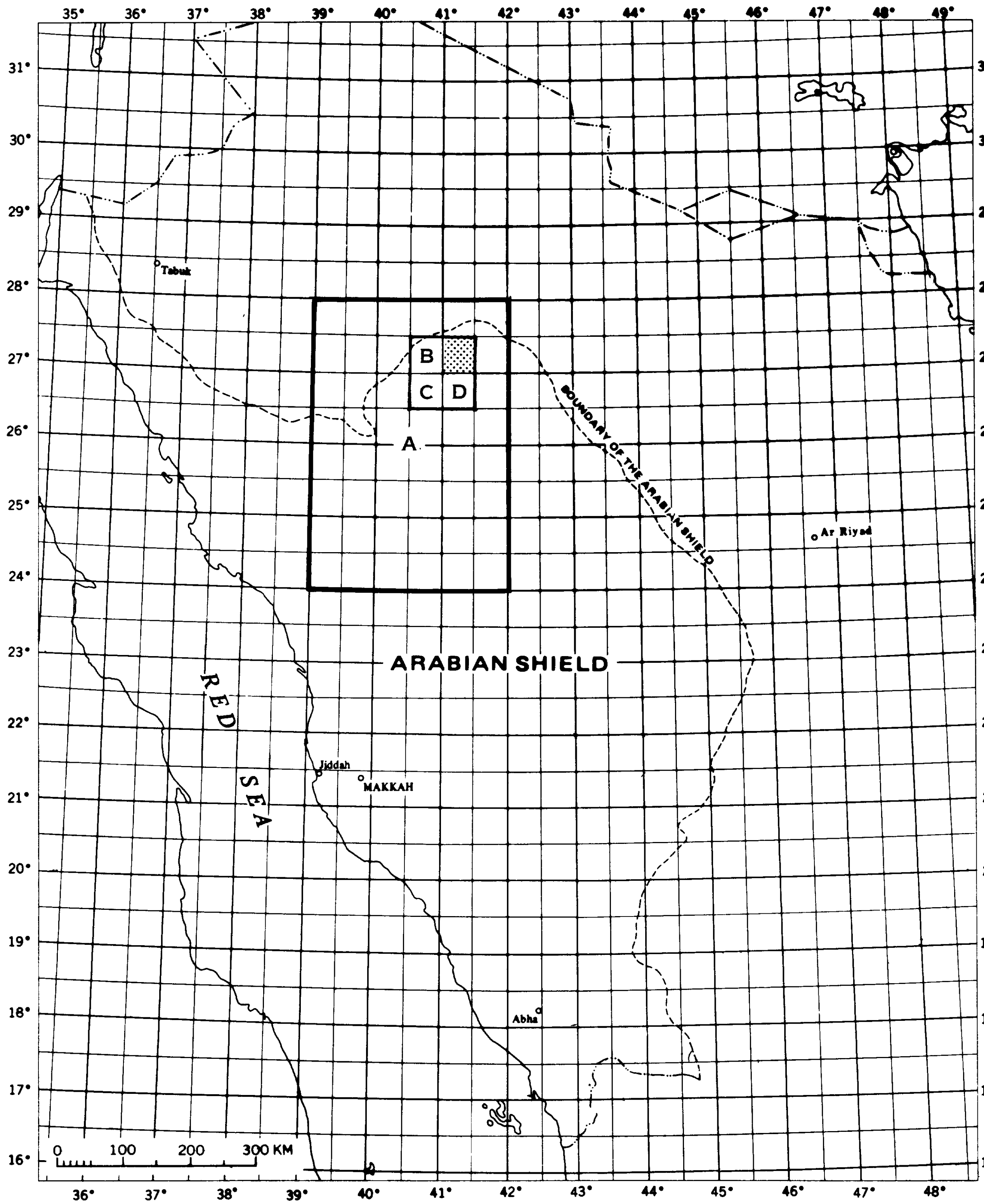

Figure 1.--Index map of western Saudi Arabia showing the location of the Qufar quadrangle (shaded) and other quadrangles referred to in this report: A, Northeastern Hijaz (Brown and others, 1963); B, Al Qasr (Stoeser, unpublished data); C, Ghazzalah (Quick, 1983); D, Al 'Awshaziyah (Leo, unpublished data).

of the quadrangle, in which he defines and describes rocks of the "Ha'il mafic-ultramafic complex". Chevremont (1982) names the mafic metavolcanic rocks and interbedded metasedimentary rocks of his "complex" the Nuf formation, a nomenclature adopted in this report. Chevremont speculates that the Nuf formation is correlative with the Hulayfah group, a term synonymous with the Halaban group (for example, Baubron and others, 1976).

Previous isotopic dating in the Ha'il area has so far been confined to rocks of the Jabal Aja and Jabal Salma granite complexes, which represent the last major period of plutonism in the northern Shield. Brown and others (in Aldrich and others, 1978, part 2) report Rb/Sr whole rock ages of 580 $\pm$ 18 Ma and 492 $\pm$ 15 Ma for two unspecified localities in the Jabal Aja complex, while Stacey and others (1980) report a zircon-Pb age of 570 Ma. Aldrich (in Aldrich and others, 1978; part 1) reports a Rb/Sr biotite age for Jabal Salma for 575 Ma and a K-Ar biotite age of 590 Ma (uncertainty unspecified for both dates).

Greenwood (1973) points out that the area around Ha'il occupies the axis of a broad north-south trending arch ("the Ha'il arch") that initially developed in pre-Permian time. Subsequent deformation along the same axis occurred in Late Cretaceous and Tertiary time, and outpourings of Tertiary alkali-olivine basalts, also oriented along north-south trends, reflect this period of tensional stress.

Present investigations

Field work for this report was done between October and December, 1981, with both helicopter and surface vehicle for support. This report is in accordance with a working agreement with the U.S. Geological Survey and the Ministry of Petroleum and Mineral Resources of the Saudi Arabian government. Special thanks is extended to D. B. Stoeser, J. S. Pallister, J. C. Cole, and J. E. Quick for their observations and comments both in the field and in the office, and to A. H. Al Bazli for his help in determining modes of stained rock slabs. Geology of the quadrangle is shown on plate 1; geography, culture, and sample localities are indicated on plate 2.

GENERAL LITHOSTRATIGRAPHY AND STRUCTURE

The Qufar quadrangle is characterized by a predominantly granitic batholithic assemblage, in which occur many roof pendants composed of mafic and ultramafic rocks of the Samra intrusive suite (named after Jabal Samra, a mountain just north of the quadrangle boundary that is underlain by metagabbro), and upon which have been deposited rhyolitic to andesitic volcanic rocks and interbedded, mostly clastic sedimentary rock of the Hadn formation (name proposed by D. B. Stoeser, written commun., 1981). Numerous stocks and batholiths, ranging in composition from alkali feldspar granite to gabbro, postdate the Hadn formation.

The highly folded, locally sheared, and metamorphosed rocks of the Samra intrusive suite consist of the layered rocks of the Nuf formation (Chevremont, 1982) and amphibolitized gabbro and highly sheared and serpentinized ultramafic rock. The metavolcanic and metasedimentary rock of the Nuf formation includes meta-andesite and metabasalt, locally pillowed, and subordinate metagraywacke and marble. Metamorphism predominantly of greenschist grade has affected all rocks of the Samra intrusive suite, probably during or immediately prior to the emplacement of the intrusive rocks of the pre-Hadn suite.

The voluminous granitic rocks of the pre-Hadn suite, which intrudes the Samra intrusive suite, are predominantly monzogranite, but range in composition from syenogranite to quartz diorite. They are equigranular to gneissic, and commonly recrystallized.

Rhyolitic ignimbrite, rhyolitic to dacitic flows, subordinate sandstone, and rare conglomerate of the Hadn formation overlie the older plutonic rocks.

Post-Hadn plutonic rocks, ranging in composition from monzogranite to alkali-feldspar granite, includes the voluminous Malayhah granite. A major period of predominantly north-south shearing and recrystallization may be related to the emplacement of the Malayhah granite. Imbricate southeast-dipping thrusts in the northern part of the quadrangle are associated with late stages of this period of shearing. It is to this period of deformaton that the informal terms "syntectonic" and "post-tectonic" refer.

Major plutonism culminated with the emplacement, about 580 Ma ago (Stacey and others, 1980; Aldrich and others, 1978), of the large alkalic to peralkalic granites at Jabal Aja and Jabal Salma.

Platform sedimentation in the area began in Cambrian time with the emplacement of the Saq Sandstone (Powers and others, 1966), which has been almost completely eroded from the quadrangle area. The last major faulting event in the area with probable normal displacement occurred along northeast-trending, high-angle faults some time after deposition of the basal Saq Sandstone.

Regional warping and uplift of the area began in Permian time, and continued intermittantly up to the present. The initial opening of the Red Sea in Miocene time (Hall, 1980, Kellogg and Reynolds, in press) was accompanied by a general uplift of the Red Sea margin and gentle tilting of the whole peninsula toward the northeast.

Basalt of late Tertiary age occurs extensively to the east of the Qufar quadrangle, although only one olivine basalt plug and two small remnants of a Miocene olivine basalt flow occur in the quadrangle area.

Extensive Quaternary deposits, predominantly wadi sands and sheet-washed gravel plains adjacent to mountain fronts, cover large areas of the quadrangle. A few small playa deposits occur in small closed basins. No dune fields, such as in the An Nafud, approximately 30 km north of the Qufar quadrangle, exist in the quadrangle.

PRECAMBRIAN SEDIMENTARY, VOLCANIC, AND METAMORPHIC ROCKS

Metamorphosed clastic rocks are classified according to the system of Pettijohn (1957); metamorphosed volcanic rocks are classified according to the system of Streckeisen (1979).

Nuf formation

Chevremont (1982) proposed the term Nuf formation for a suite of mafic metavolcanic rocks that crop out near Jabal Nuf. However, Jabal Nuf was mislocated by Chevremont, and is not underlain by rocks of the Nuf formation. Chevremont (1982) suggested that the Nuf formation forms part of an ophiolite suite, a contention that is supported by its tholeiitic composition (Kellogg, unpublished data). The thickness of the Nuf formation, the oldest unit in the quadrangle, is unknown; no basal contact has been found.

Meta-andesite and metabasalt member

Dark-green to black, very fine grained, porphyritic meta-andesite and basalt (nab) contain between 20 and 50 percent phenocrysts of lath-shaped plagioclase in a dark, cloudy matrix. The metabasalt and subordinate meta-andesite are dark green to black with a dull luster, and contain as much as 10 to 40 percent phenocrysts of orthopyroxene as much as 1 cm across, 20 to 50 percent saussuritized calcic plagioclase in a very cloudy fine-grained matrix of chlorite, epidote, hematite, actinolite (after pyroxene?), $\pm$ calcite, $\pm$ apatite. Locally, amphibolitized orthopyroxene or quartz phenocrysts occur. A foliation is commonly well-developed, and the rocks are generally metamorphosed to greenschist facies, although amphibolite paragneiss has also been placed within this unit. In a roadcut on the north side of Jabal Fitiq (locality 180839), a few vesicular basalt pillows in a sheared matrix occur. Numerous small irregularly-shaped stocks of hornblende gabbro (gbh), probably subvolcanic equivalents of the basalts, intrude this unit, and the mapped areas of meta-andesite and metabasalt may include such rocks.

Only one outcrop of laminated basaltic metagraywacke has been identified, interlayered with metabasalt. It occurs just north of the Ha'il-Buraydah highway in the northeast part of the quadrangle (locality 180466). Laminae in the metagraywacke are about 0.5 cm apart. The metasediment is composed of a fine-grained mosaic of calcic plagioclase, acicular actinolite, minor quartz and epidote, with clusters of larger sieve-textured, hornblende porphyroblasts up to 2 mm long. A trace of magnetite is concentrated in planes along laminae.

Locally foliated metabasalt and meta-andesite occur in the southeastern part of the quarangle near the town of Sab'an, and are intruded by numerous stocks, commonly also foliated, of hornblende gabbro and diorite. In outcrop, the meta-andesite and metabasalt of the Nuf formation typically weather to a distinctive, highly fractured gray and black mottled terrain, usually of low relief, with common visible quartz and epidote segregations.

Marble

A few small pods and tabular bodies of marble (m) are interlayered with the metabasalt and meta-andesite member. Marble also occurs as blocks within the serpentinite diapir (spn) north of Jibal Fitiq. One vein of yellow marble, probably a metasomatized serpentinite, occurs associated with an amphibolitized olivine gabbro at Jabal al Jenida. The marble is generally fine to medium grained, white to gray, and is commonly streaked white and gray. Pods of magnetite up to several cm thick are observed in association with some bodies of marble (Chevremont, 1982). A greenish-white, foliated tremolite-bearing marble (mtm) occurs 3 km southeast of Jabal Khafidh.

Andesite and dacite member

An andesite and dacite unit (nad) is the top member of the Nuf formation in the vicinity of Jabal Nuf. The rocks are predominantly black to dark green, porphyritic, with an aphanitic matrix. The dacites generally have a vitreous luster and conchoidal fracture, while the andesites, containing less or no interstitial quartz, are duller in luster. Cognate angular volcanic clasts to 10 cm are common with volcanic agglomerates. The rock is generally vesicular and epidote and quartz fill the vesicles. Secondary actinolitic amphibole commonly occurs as small needles.

A dark-gray to pinkish-gray, banded gneiss metamorphosed to the amphibolite grade on a hill about 8 km south of Jabal Nuf is included in this unit. The rock is a fine- to very fine grained, predominantly quartz-plagioclase-biotite-±hornblende gneiss, approximately dacitic in composition.

Relict quartz phenocrysts, now quartz mosaics, are observed. Accessory minerals are magnetite, epidote, apatite, ± zircon, ± garnet, ± calcite.

Mafic paragneiss

A light-gray to black, fine- to medium-grained, weakly to strongly foliated hornblende-plagioclase-±quartz paragneiss (nu), locally contains secondary biotite parallel to foliation. Where quartz is absent or sparse, the rock is an amphibolite. Accessary and trace minerals are epidote, chlorite, sphene, sericite, apatite, clinozoisite, and garnet. A hornblende-biotite-garnet gneiss along the east and west contacts of the Malayhah granite on Jabal al Malayhah contains euhedral porphyroblasts to 5 mm of blue-green hornblende representing late contact-metamorphic effects. A small outcrop of calc-silicate gneiss containing a typical skarn assemblage of approximately 40 percent diopside, 30 percent quartz, 20 percent epidote, 10 percent grossularite, and 1 percent apatite is found north of Jibal Fitiq (locality 180494), and is included in this unit. Undifferentiated rocks of the Nuf formation comprise most of the protolith for this unit, although foliated quartz diorite (qd) and gabbro (gbh) may occur locally within this unit.

Hadn formation

These rocks are inferred to correlate with a section of rhyolitic to intermediate flows, welded tuff, conglomerate and sandstone that crop out on and near Jabal Hadn, about 30 km west of the southwest corner of the quadrangle (D. B. Stoeser, written commun., 1981). Chevremont (1982) has adopted the term Hadn formation in his discussion of volcanic rocks of the Ha'il area, and the name is retained for this report. In a more regional context, the Hadn formation is part of a silicic volcanic and volcaniclastic sequence referred to as the Shammar group (e.g., Hadley and Schmidt, 1980).

The thickness of the Hadn formation is unknown because of discontinuous outcrop and extensive erosion of the upper part of the section. The Hadn formation rests on the 'Ishsh monzogranite, and is intruded by the Malayhah granite.

Conglomerate member

A thin, discontinuous conglomerate (hc), generally less than 10 m thick, is at the base of the silicic volcanic member in the northern part of the quadrangle, unconformably overlying the andesite and dacite member of the Nuf formation. This rock contains about 50 percent subangular to rounded clasts, as much as 5 cm in diameter, of silicic volcanic rock, and sparse subrounded, pink, granitic clasts, as much as 15 cm in diameter, in a gray, medium-grained, lithic-graywacke matrix.

Silicic volcanic member

The silicic volcanic member (hfl) is in two different principal areas: one in the southeastern corner, on and near Jabal as Shirah, and another in the northeastern part of the quadrangle, near Jabal Fitiq. This unit represents a sequence of thick (about 10 to 50 m each) gray to black, silicic, porphyry flows and ignimbrites. The matrix has devitrified from an original glass into a very fine grained mozaic of quartz and feldspar, with accessory magnetite, ± biotite, ± hornblende, ± zircon. These rocks are slightly metamorphosed, and may contain epidote, sericite, chlorite, green hornblende, calcite, and rarely fluorite and garnet. Phenocrysts as much as 4 mm in diameter of quartz and pink to white oligoclase are common, as are volcanic-lithic fragments. This unit weathers to a dull brownish-red rock that is usually highly fractured into angular blocks. About 4 km south of Jabal ash Shirah, in the al 'Awshaziyah quadrangle (G. W. Leo, unpub. data), the silicic volcanic member is observed resting disconformably on the 'Ishsh monzogranite (mge).

Sandstone and volcanic member

A sandstone and volcanic unit (hvs) that is prominant in several large hills to the southwest of Jabal al Malayhah consists of a sequence of interbedded gray siltstone and poorly-sorted subgraywacke, and gray rhyodacite or rhyolite quartz and feldspar porphyry flows. The volcanic rocks are mapped as the unit "hv" where they are more than about 500 m thick. Several smaller outcrops of this member crop out near the southeast corner of the quadrangle. The sequence is highly folded, and the beds are locally overturned.

Mixed metaplutonic and metavolcanic terrain

Two tectonically derived units are composed of several of the other units in the quadrangle and are characteristically sheared into a melange of rock types, and recrystallized. The cataclasis probably occurred at the same time as the shearing associated with the emplacement of the Malayhah granite.

Rhyodacite and mafic-rock melange

A melange (rmm) is composed of rhyodacite and mafic-rock lens-shaped blocks of orange-tan rhyodacitic to dacitic volcanic rock of the silicic volcanic member (hfl) of the Hadn formation, as much as several tens of meters long, suspended in a matrix of sheared and highly altered basalt, andesite, and gabbro derived from the Nuf formation and Samra intrusive suite. Partially sheared dikes of approximately andesitic composition are included in this unit. The shearing probably occurred during the pervasive deformation of the Malayhah granite.

Granite and mafic-rock melange

A granite and mafic-rock melange (gmm) is in the northeastern part of the quadrangle near Jabal Nuf, and on the western side of Jabal al Malayhah. The extensive melange terrane is composed of sheared lens-shaped blocks of fine-grained granite (sheared phase of the Malayhah granite), silicic volcanic rock (probably from the Hadn formation), very fine grained silicic hypabyssal rock, and a few blocks of vesicular basalt (part of the Nuf formation), floating in a matrix of olive-gray to dark-greenish-gray, highly sheared diorite, gabbro, and mafic volcanic rock of the Nuf formation.

PRECAMBRIAN INTRUSIVE ROCKS

Plutonic rocks are classified according to the recommendation of the International Union of Geological Sciences (Streckeisen, 1976).

Samra intrusive suite

Serpentinized harzburgite and wehrlite

At Jabal al Jenida, a shear-bounded block of serpentinized harzburgite and wehrlite (sph), about 50 m across, contains a dull-black, medium-grained, hypidiomorphic-granular rock that weathers to a reddish-brown color. Good mesh-structure is locally preserved. An estimate of primary harzburgite modal mineralogy is olivine (55 percent), orthopyroxene (30 percent), clinopyroxene (5 percent), spinel (5 percent), plagioclase (5 percent). Serpentine + calcite + hematite now occupy about 70 percent of the rock. More often, wehrlite contains abundant fine-grained serpentinized olivine as inclusions in large serpentinized clinopyroxene phenocrysts. About 5 percent opaques (spinel?) also occur. The gabbro in which this unit occurs is locally also serpentinized. Just south of the serpentinite, a 50-m-long north-trending zone of yellow marble (+++++) in gabbro may have formed by replacement of serpentinite by carbonate.

Sabihah serpentinite

In the northeastern corner of the quadrangle, just east of Jabal Sabihah, an approximately 6 km^2 area is underlain by a highly sheared black to dark greenish-black serpentinite (spn) that is locally replaced by carbonate. The serpentine mineral is probably lizardite that contains up to 5 percent disseminated spinel (chromite?). Calcite and secondary quartz are common. Small pods and disseminations of chromite have been reported (Chevremont, 1982). The contact with the surrounding volcanic rock and gabbro is mostly indistinct, with sheared stringers of serpentinite extending out into the country rock. Numerous blocks of amphibolitized gabbro, mafic volcanic rock and marble in the serpentinite suggest that the serpentinite body may have intruded diapirically. As a mantle source is suggested for this rock, it is considered to be the oldest in the quadrangle.

Gabbro

A fine- to coarse-grained, equigranular, hypidiomorphic, dark-greenish-gray to black gabbro (gbh) that generally contains substantial hornblende displays a considerable range in modal mineralogy. About one-quarter of the 24 thin sections observed contain clinopyroxene (up to 25 percent), which is usually partially amphibolitized. Plagioclase constitutes up to 70 percent of some of the more leucocratic varieties, and as little as 35 percent in the more mafic gabbros. Plagioclase composition ranges from An_{50} to An_{90}, averaging about An_{65}. Cumulus layering is observed on the eastern side of Jabal al Jenida and on the eastern side of Jabal Marorat. In the southeastern corner of the quadrangle and in association with the andesite and basalt member of the Nuf formation, the gabbro is leucocratic with color index commonly less than 50. The gabbro at Jabal al Jenida is in part a troctolite, containing up to about 10 percent olivine, and 5 percent orthopyroxene, both of which are partially serpentinized. Locally, the gabbro is sheared and recrystallized into a well-foliated amphibolite. A strongly foliated leucogabbro crops out on the ridge just east of the Ha'il airport. In outcrop, the gabbro is highly fractured and weathers to a greenish-gray soil. Rounded, black, well-indurated corestones are common.

Gabbro intrudes the rocks of the Nuf formation, and is intruded by rocks of the pre-Hadn suite. Large inclusions of gabbro, some over 1 km across, are common in the 'Ishsh monzogranite, the Ha'il granite, and the Malayhah granite.

Diorite orthogneiss

An orthogneiss (dgn) of quartz diorite-diorite-gabbro composition is light-gray to black, fine-to medium-grained, and weakly to strongly foliated. It consists of hornblende-plagioclase+quartz+biotite and it generally contains secondary chlorite, sericite, and epidote, and traces of titanomagnetite, sphene, apatite, and clinozoisite. Locally, it is a banded gneiss in which variations in the proportions of hornblende to plagioclase and quartz define highly folded and deformed bands and lensoid segregations and indicate ductile shearing during mineral segregation. This is particularly well-developed in the ridge just east of the Ha'il airport. The diorite orthogneiss, intruded by rocks of the Ha'il granite, weathers to a terrain of moderate to low relief with light-gray to greenish-gray regolith.

Pre-Hadn suite

Rocks predating the Hadn formation range in composition from quartz diorite to syenogranite. Collectively, they define a large intrusive complex of batholith size which underlies most of the southern part of the quadrangle and perhaps much of the central and northern parts as well. Numerous roof pendants and isolated blocks of the Ha'il complex occur throughout the batholith.

Quartz diorite

Heterogeneous quartz diorite (qd) underlies large regions in the southeast corner of the quadrangle, as well as an area to the west of Jabal al Uhaymir in the north-central part of the quadrangle. The range in modal mineralogy is shown in figure 2. The rock is a light- to very dark gray, medium- to coarse-grained, predominantly hornblende-biotite quartz diorite that grades from hornblende diorite to biotite-hornblende tonalite. The quartz diorite predates the 'Ishsh monzogranite, but contact relationships with the gabbro unit of the Samra intrusive suite have not been observed.

The composition of the plagioclase observed in 11 thin sections varies from about An_{20} to An_{42}. Highly strained quartz comprises up to 24 percent of the observed tonalites. Potassium feldspar may constitute up to 5 percent of some rocks. Accessory minerals include opaques, apatite, sphene, ± garnet, ± clinopyroxene, ± zircon. Alteration has produced assemblages of chlorite, epidote, actinolite, sericite, ± calcite, ± hematite. The rock is locally foliated and usually slightly mortar-textured. In outcrop, this unit weathers into small, rounded, olive-gray to black blocks and slabs.

Biotite-hornblende granodiorite orthogneiss

A biotite-hornblende granodiorite gneiss (gdb), predominantly gray to slightly pinkish-gray, medium-grained, weakly to strongly foliated, and often compositionally banded and/or migmatitic, ranges in composition from quartz diorite to biotite monzogranite. The plagioclase is oligoclase to andesine and the potassium feldspar is usually microcline. Both hornblende and biotite can occur in amounts up to 8 percent each, though biotite generally predominates over hornblende. The biotite is commonly in clots, typically about 1 cm long, elongated in the plane of foliation. Biotite also occurs in fine-grained, generally partially chloritized mozaics to 2 mm and as secondary large flakes in the plane of foliation. Accessories are magnetite, zircon, sphene, allanite, apatite, and garnet. Locally this unit contains coarse-grained felsic segregations, approaching a pegmatitic texture. Several periods of deformation are denoted by openly to isoclinally folded foliation planes. Boudins and fragment trains are locally observed. This unit weathers to a region of low relief.

Contact relationships are poorly exposed, but the outcrop pattern and the extreme deformation of the granodiorite orthogneiss suggest that this unit is older than the 'Ishsh monzogranite.

'Ishsh monzogranite

The 'Ishsh monzogranite (mge) is predominantly a medium-grained, gray to pinkish-gray, allotriomorphic-equigranular, biotite-hornblende monzogranite, though it grades locally into a granodiorite near contacts with quartz diorite (qd). The range of compositions observed in thin section is indicated on figure 2. The plagioclase composition is An_{10} to An_{20}, with a predominant composition about An_{12} (sodic oligoclase). The potassium feldspar is perthitic, and the quartz displays highly undulatory extinction. The rock contains up to 7 percent pleochroic brown to yellow biotite, and up to 6 percent green to light bluish-green hornblende (ferrohastingsite?). Accessory minerals include opaques, sphene, zircon, apatite, ±allanite, ±muscovite. Low grade metamorphic effects have produced assemblages of chlorite, epidote, and sericite. Contacts with the older quartz diorite are locally brecciated. The rock weathers to a characteristic light orange-tan, and occurs as low blocky outcrops on a nearly flat erosional surface. The monzogranite is cut by dikes of varying composition, including a dense set of basaltic to diabasic dikes, trending about N. 20° E., which clearly predate the Hadn formation.

A common feature of the 'Ishsh monzogranite is included blocks of fine-grained, commonly granophyric, pink aplite granite, of monzogranitic to monzodioritic composition, as much as several tens of meters long. These blocks probably represent stoped pieces of the magma chamber's roof zone (cauldera floor).

In many areas, stoped blocks or small roof pendants of older quartz diorite, diorite or gabbro (part of qd or gbh) are incorporated into the 'Ishsh monzogranite. From the air this association appears as a mottled reddish-tan (granite) and dark gray to black (diorite or gabbro).

Aplite dikes

A northeast-trending swarm of aplite dikes (ap), each up to several meters thick, is mapped just east of Jabal Sarrah and is tentatively related to the 'Ishsh monzogranite. Dike-on-dike features are common, and quartz diorite defines the

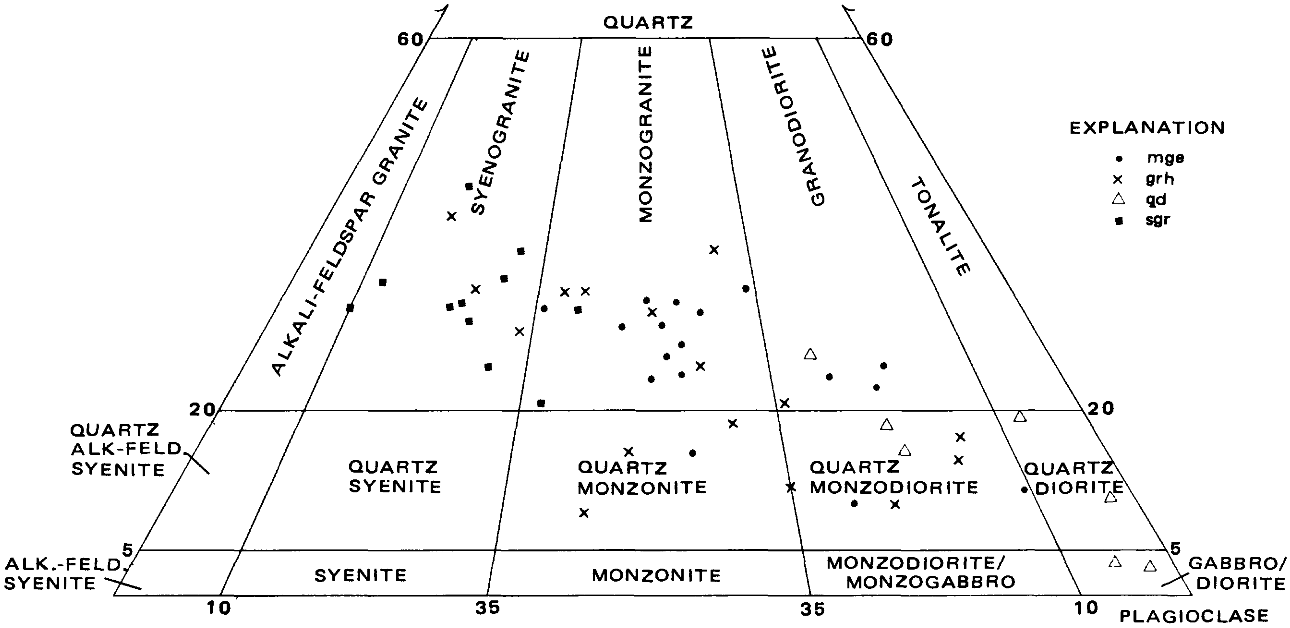

Figure 2.--Modal compositions of intrusive rocks of the pre-Hadn suite from the Qufar quadrangle: 'Ishsh monzogranite (mge,•); Ha'il granite (grh, x); quartz diorite (qd,△); and syenogranite (sgr,■). The plutonic rock classification is according to the recommendations of the International Union of Geological Sciences (IUGS) (Streckeisen, 1976).

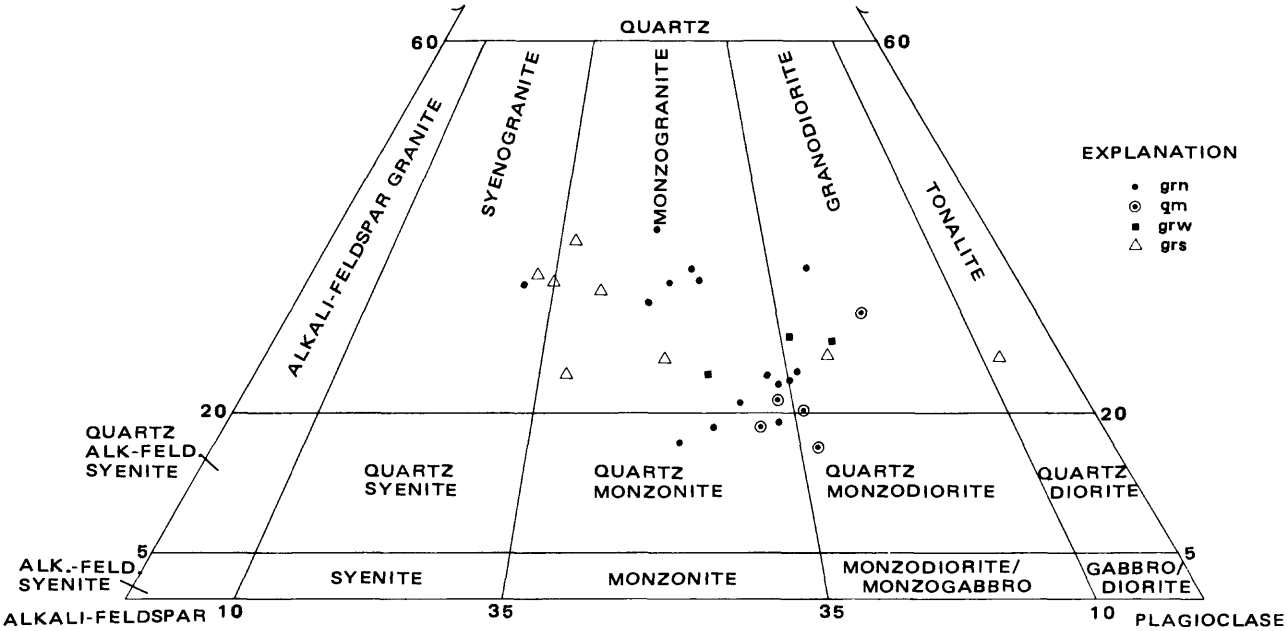

Figure 3.--Modal compositions of intrusive rocks from the Malayhah granite complex and the massive granite suite from the Qufar quadrangle: Malayhah monzogranite (grm,•); biotite quartz monzonite (qm,⊙); biotite monzogranite (mgb,■); Shatib monzogranite (grs, △).

country rock between some of the dikes.

Ha'il granite

An extensive pediment, which extends south and east of the town of Ha'il, is underlain by heterogeneous and poorly exposed granitic rocks collectively referred to as the Ha'il granite (grh). This unit ranges in composition from granodiorite to syenogranite, but is predominantly monzogranite (fig. 2). The rocks of this unit are generally gray to pinkish-gray, medium-grained, allotriomorphic equigranular, with mafic minerals in fine-grained multigranular clots, reflecting recrystalization. The unit is intruded by numerous dikes of various composition, and quartz veins, although the northeast-trending diabase dikes characteristic of the early 'Ishsh monzogranite (mge) were not observed. Much of the rock is cataclastically foliated, and lenses of older, foliated dioritic rock, oriented parallel to foliation, are common.

Much of the Ha'il granite contains ferrohastingsite(?), a yellow-green to blue-green highly pleochroic hornblende with low (0-20°) 2V. This mineral is not diagnostic, however, as it also occurs in many of the monzogranites of Jabal Mulayhah as well as in the 'Ishsh monzogranite (mge). Garnet was observed in 4 out of 33 thin sections, fluorite in one thin section, tourmaline (elbaite) in one thin section, and clinopyroxene in one example of quartz monzonite.

The relative age of the Ha'il granite and the 'Ishsh monzogranite (mge) is unknown, although they are suspected to be at least in part comtemporaneous. The principal distinction between the two is that the 'Ishsh monzogranite is intruded by the numerous northeast-trending diabase dikes that are known to predate the Hadn formation.

Pegmatite

Pegmatite (p) pods and dikes are in both the 'Ishsh monzogranite and the Ha'il granite. They are small (less than 2 m wide and 50 m long), commonly zoned (very coarse grained pink potassium feldspar and quartz along the margin, to coarse-grained with quartz-rich centers), and commonly podiform. Mafic minerals are virtually absent, though they occasionally contain conspicuous red garnets (almandine?).

Syenogranite

Syenogranite (sgr) is generally pinkish-gray to brick-red, medium grained, allotriomorphic-equigranular and leucocratic (color index less than 5). The potassium feldspar is coarsely perthitic; the plagioclase is albite or sodic oligoclase (An_{5-12}). Irregular-shaped syenogranite units in the

Ha'il granite have indistinct contacts, and are probably a potassium-rich facies. The rock typically weathers to reddish-brown blocks.

Biotite syenite dikes

Biotite syenite dikes are dark brick-red, fine grained equigranular, and nonporphyritic, and consist of mosaics of highly altered feldspar surrounded by interstitial, very fine grained hematite and 1 to 2 percent hematitized and chloritized biotite. The rock contains up to 5 percent sparry calcite and 1 percent quartz as void fillings. Traces of epidote and, at one locality, cancrinite was observed. Outcrops are isolated, but prominant 8-m-wide vertical dikes that cut quartz diorite in the vicinity of Jabal Gora Sanduk.

Leucogranophyre dikes

Leucogranophyre dikes (rp) are pinkish-gray, very fine grained, almost nonporphyritic, and silicic. Up to 2 percent muscovite and abundant hematite speckles occur in a granophyric groundmass. The dikes are rarely more than 1 m thick, are gently to steeply dipping, locally abundant, and commonly sheared into boudin-like blocks. They occur in the northeast corner of the quadrangle north of Jibal Fitiq and intrude only rocks of the Nuf formation and the Ha'il complex.

Diabase dikes

A swarm of north- to north-northeast-trending diabase dikes is mapped in the southern quarter of the quadrangle. These dikes are locally very numerous, and are as much as 10 m thick. They are generally subophitic and contain approximately 70 percent laths of plagioclase (about An_{50}) to 1 mm in length, about 20 percent augite to 2 mm in length, about 5 percent smectite after euhedral orthopyroxene, and about 2 to 3 percent opaques (probably hematite after magnetite). The plagioclase is highly sausseritized, and the pyroxenes are extensively altered to actinolite. Other alteration minerals, epidote, chlorite, and calcite, indicate greenschist-facies metamorphism. These dikes define a strikingly lineated terrain from the air.

Granodiorite megabreccia

Granodiorite megabreccia (gdv) outcropping in the vicinity of Jabal Hadbah is composed of angular blocks as much as several tens of meters across of rhyolitic volcanic rocks and granophyric rocks in a generally granodioritic matrix that ranges from granodiorite to monzogranite. The blocks are locally as much as about 70 percent of the outcrop. The volcanic rocks, tentatively correlated with the Hadn formation, are dark-gray to pink, locally porphyritic and eutaxitic, and consist of a very fine grained mosaic of quartz and feldspar (largely potassium feldspar) that enclose phenocrysts of potassium feldspar and rarely hornblende. The granophyric rocks are pink to maroon, fine grained, with up to 6 percent hornblende plus biotite in small clots. Micrographic potassium feldspar is 50 to 70 percent of these rocks. The granitoid matrix rocks are light-gray to pale yellow-tan, fine to medium grained, hypidiomorphic-inequigranular, granodiorite to monzogranite (4 thin sections studied). The potassium feldspar in the more felsic rocks is perthitic. One observed rock contained 5 percent phenocrysts of antiperthitic feldspar as much as 5 mm in diameter. Varietal minerals are biotite (2 to 5 percent), ± green hornblende (0 to 2 percent). Trace minerals include allanite, zircon, opaques, apatite, sphene, and secondary epidote and chlorite.

It is suggested that the granodiorite and the contained blocks are all part of a comagmatic suite and represent the root zone of a cauldera. In this model, granodiorite magma has stoped blocks of the overlying hypabyssal and volcanic rocks.

Malayhah granite complex

Malayhah monzogranite member

The relatively undeformed facies, the Malayhah monzogranite (grm), of this batholith-size intrusive complex is a light-grayish-pink to gray, medium grained, allotriomorphic-equigranular biotite-hornblende monzogranite (fig. 3). The plagioclase is sodic oligoclase (An_{10-12}), and the potassium feldspar is commonly finely perthitic, although homogeneous microcline is also common. The rock typically contains 2-5 percent biotite and 0-2 percent ferrohastingsitic hornblende; both phases are usually in clots associated with magnetite, sphene, and zircon. Additional trace minerals are apatite and ± allanite. Grain boundaries between feldspars, and between feldspar and quartz, are embayed, and mortar texture is common. The rock crops out in characteristic orange-brown domes and craggy hills, and is often highly fractured. Some areas contain numerous stoped blocks, as much as several tens of meters across, of hornblende gabbro.

Granophyre member

A granophyre member (gpm) crops out most prominently on the prominant eastern mountain of Jibal Fitiq, and also as isolated intrusions along the eastern margin of Jabal al Malayhah. The contact between this unit and the medium-grained Malayhah granite is gradational. The granophyre is brick red, medium grained, equigranular, granophyric, and approximately monzogranitic in composition. The color index is only two, the mafics are distinctive small clots of fine-grained magnetite, biotite, sphene, and epidote that collectively resemble magnetite grains in hand specimen; and there is a trace of primary muscovite, allanite, apatite, fluorite, and garnet. The rock weathers to a fractured deep reddish-brown. A common feature of this rock is prominent parallel joints that gives the outcrop a distinct layered appearance. On Jibal Fitiq, for example, the jointing dips prominently to the east.

Cataclastic granite member

The cataclastic granite (grmc) is a sheared and foliated rock that occurs most prominently along the west and south-west sides of Jabal al Malayhah. Flaser gneiss and fine-grained mylonite extend discontinuously for several km across the foliation on the west side of Jabal al Malayhah. Fracture cleavage and closely spaced joints parallel to the shear-foliation are observed in many places, giving the reddish-brown rock an overall layered appearance. Where the border facies is less foliated, the rock is commonly granophyric. In addition to the minerals found in the less foliated Malayhah monzogranite member (grm), the cataclastic granite member locally contains fluorite, garnet, muscovite, chlorite, epidote, and calcite.

Massive granite suite

Circular to approximately oval monogranite stocks and dikes of various compositions are older than the Jabal Aja and Jabal Salma granites (which are about 580 Ma old) and younger than the rocks of the Malayhah granite complex. Though flow foliation may be well developed, the rocks are relatively undeformed.

Biotite-quartz monzonite

Two plutons of biotite-quartz monzonite (gm), containing subordinate monzogranite and quartz diorite (fig. 3), crop out along the west border of the quadrangle. The rock is pale grayish-tan, medium to course grained, with an allotriomorphic- to hypidiomorphic-inequigranular texture. Pinkish-brown potassium feldspar and white plagioclase are easily differentiated in hand specimen. Plagioclase is about An_{12-14}, potassium feldspar is microcline, locally finely perthitic, quartz varies in content from 15 to 29 percent, the biotite content is as much as several percent, and green hornblende is from zero to one percent. Accessories and trace minerals are opaques, sphene, zircon, apatite, $\pm$ allanite, $\pm$ rare garnet (as small inclusions in biotite). Plagioclase is commonly sausseritized and contains minute crystals of sericite and epidote. This unit weathers to a very light-tan grussy plain with a few small inselbergs.

The biotite quartz monzonite is correlated with the Jufayfah granite of Quick (1983) and Stoeser (unpub. data) that intrudes the Hadn formation.

Shatib monzogranite

An 8 km wide ring of prominent light-orange-tan granite domes, including Jabal Shatib and Jabal Arkan, is underlain by the Shatib monzogranite (grs). The rock is a light-pinkish-gray, medium- to coarse-grained, allotriomorphic-inequigranular monzogranite (fig. 3). It contains 10 to 25 percent albite or oligoclase (An_{5-15}), 35 to 43 percent microcline or finely perthitic potassium feldspar, 25 to 43 percent quartz, 2 to 6 percent blue-green hornblende (ferrohastingsite?), less than 5 percent yellow to brown biotite, less than 1 percent sphene, less than 1 percent magnetite, and a trace of apatite, zircon, and allanite. The hornblende to biotite ratio increases toward the border, from about 2:1 in the flat eroded core-area to an almost biotite-free rock at the craggy margin. Observed alteration minerals are calcite, hematite, and chlorite. The hematite is observed most prominantly growing between the flakes of biotite; the alteration of biotite may be the mechanism controlling disaggregation of the rock. The rim area of the pluton displays a pronounced flow foliation, generally parallel to the border. The contact of this pluton with the surrounding country rock is not necessarily vertical; at the west end of Jabal Arkan the contact with quartz diorite country rock is observed dipping about 40° towards the interior of the monzogranite pluton.

Biotite monzogranite

Two stocks of biotite monzogranite (mgb) are in the south-central part of the quadrangle and in the north-eastern corner. The rock is pale pinkish-gray, medium to coarse grained, and hypidiomorphic-equigranular (fig. 3). Plagioclase is calcic albite to sodic oligoclase (An_{6-11}), the potassium feldspar is coarsely perthitic in the coarser grained varieties, and the quartz shows slight undulatory extinction. Biotite content varies from 2 to 9 percent. The accessories and trace minerals are iron ore (less than 1 percent), primary muscovite (less than 1 percent), apatite and zircon. The rock weathers to a white, grussy gravel plain; the white color is due to accumulations of lag quartz and feldspar.

Biotite syenogranite and quartz syenite

Several small stocks of biotite syenogranite and hornblende-augite quartz syenite (sy) are near the west border of the quadrangle and about 5 km south of Jabal al Malayhah. The biotite syenogranite is brick-red, medium grained, allotriomorphic-equigranular and contains about 20 percent sericitized plagioclase (An_{10}), 45 percent coarsely perthitic, cloudy potassium feldspar, 36 percent slightly undulatory quartz, 2 percent biotite altered to hematite and chlorite. Epidote occurs along cracks. The stock, which straddles the western border of the quadrangle, is a brick-red, medium-grained, hypidiomorphic-equigranular quartz syenite containing about 4 percent hornblende, 2 percent augite, and 1 percent biotite. All of these rocks weather in outcrop to rounded reddish-brown to maroon crags and slabs.

Red andesite porphyry dikes

Very fine grained, dark-brick-red andesite porphyry dikes (ro) that contain as much as 5 percent phenocrysts of subhedral and saussuritized plagioclase as much as 3 mm in diameter, and rare phenocrysts of quartz and a highly altered mafic mineral. The matrix is a felted intergrowth of plagioclase, magnetite, and altered biotite. Deuteric alteration has produced abundant hematite, epidote, sericite, and calcite. The dikes occur in an east-trending 100 m thick zone in the northeastern part of the quadrangle. They are clearly younger than the leucogranophyre dikes (rp).

Undifferentiated felsic dikes

Felsic dikes of unknown composition were undifferentiated during mapping.

Monzogranite dikes

Pinkish-gray, medium-grained, equigranular, commonly propylitically altered dikes of approximately monzogranite (gr) composition have been mapped.

Undifferentiated dikes

Dikes of unknown composition that appear conspicuously on air photographs are shown on Plate 1.

Quartz plugs and veins

Plugs, as much as 30 m in diameter, and veins of massive white quartz (q) cut all Precambrian units in the quadrangle except possibly the biotite monzogranite (grw) and the rocks of the Jabal Aja and Jabal Salma complexes. These veins and plugs locally form quartz-country rock breccias and are unmineralized at all observed occurrences. Quartz was probably emplaced during several plutonic events, particularly following the emplacement of the 'Ishsh monzogranite and Ha'il granite, although it is indicated on the correlation chart for its last major episode of formation.

Melanogranite porphyry dikes

Two dike swarms of melanogranite porphyry trend west-north-west in the west-central and northern parts of the quadrangle. Isolated dikes of the same rock also are in a large part of the quadrangle. They intrude both the biotite-quartz monzonite and the biotite monzogranite, although they are offset by the late stages of thrust faulting in the northern part of the quadrangle. The rock is predominantly a medium- to dark-gray, fine-grained, allotriomorphic-inequigranular monzogranite to syenogranite porphyry that contains as much as 10 percent each of quartz and potassium feldspar phenocrysts, and as much as 15 percent hornblende phenocrysts. Biotite may be present in the groundmass to about 8 percent. Accessory and trace minerals include opaques, apatite, and rare fluorite. The mafics in some dikes are altered to chlorite and epidote. Locally, granophyric textures are observed.

Mafic intrusive rocks

Pyroxene-olivine melagabbro

Several small pyroxene-olivine melagabbro (gbp) stocks in the northern part of the quadrangle are probably relatively young, as several of the stocks intrude rocks interpreted to be part of the Malayhah granite. Most of these rocks appear fresh in hand specimen. They are black, medium to coarse grained, and hypidiomorphic, with as much as 60 percent bytownite (An_{76-80}), 25 to 30 percent augite, 5 to 15 percent poikilitic brown hornblende, 15 percent olivine (rarely serpentinized), and 1 to 2 percent opaque minerals. Cumulus layering is locally developed. The unit weathers to a well-fractured, black rock with common, rounded, well-indurated core-stones.

Gabbro dikes

Several large (as much as 50 m across) vertical, east-northeast-trending gabbro (gb) dikes cut the rocks of the Malayhah granite complex on Jabal al Malayhah. A few similar dikes cut the Ha'il granite. The rock is a highly altered and deeply eroded very dark green to black, coarse-grained, allotriomorphic-equigranular hornblende gabbro. About 60 percent of the rock is highly sausseritized calcic plagioclase (An_{65}), about 40 percent is actinolite in ragged clusters, about 1 percent is magnetite, and there is trace of zircon, apatite, and chlorite (after biotite?). The granitic country rock for several meters from the contact is hematized and forms two impressive, erosionally resistant, parallel walls as much as several tens of meters high.

Late diabase dikes

Isolated dikes of diabase (n) cut rocks of the Malayhah complex. In hand specimen, the diabase appears slightly chloritized, and the dikes generally trend about easterly.

Red syenogranite and rhyolite porphyry dikes

Red syenogranite and rhyolite porphyry dikes (rh) are brick-red to maroon, very fine to medium grained, allotriomorphic-inequigranular, commonly granophyric syenogranite or rhyolite porphyry. Phenocrysts are euhedral "beta-quartz," (as much as 20 percent) and euhedral potassium feldspar (orthoclase?; as much as 10 percent) that contains very fine grained sericite and hematite. Local potassium-feldspar granite contains as much as 1 percent sodic amphibole (riebeckite?) and as much as 2 percent allanite. Trace minerals include opaques, zircon, apatite, and ± clinopyroxene. Alteration minerals are sericite and hematite (in potassium feldspar), chlorite, epidote, and calcite (after the mafic minerals). Coarser grained varieties are in the large irregular dikes, as much as 1 km wide, that are in an arcuate-shaped area in the southwestern part of the quadrangle. Because the dip of these dikes is highly variable, from steep to gentle, the outcrop patterns are complex.

Alkali granite suite

The alkali granite suite comprises elliptical batholiths and large stocks in the northeastern part of the Arabian Shield (e.g., Stuckless and others, in press) that have been dated at about 580 Ma (Brown and others, in Aldrich and others, 1978, part 2; Stacey and others, 1980; Aldrich, in Aldrich and others, 1978, part 1). These rocks represent the last major plutonic event of the northeastern Shield, and crop out in characteristic high mountain massifs.

Aja complex

Peralkaline granite member (aje).--This unit forms a 1 to 3 km wide belt along the eastern margin of the Aja complex, and is a light-brown to gray, medium- to coarse-grained, allotrimorphic-equigranular, coarsely perthitic aegerine-arfvedsonite-alkali-feldspar granite (fig. 4). Sodic plagioclase, quartz, and mafic minerals are as much as 7, 37, and 8 percent of the rock, respectively. Minor and accessory minerals are riebeckite, opaque minerals, chlinochlore(?), zircon, ± blood-red aenigmatite, ± bright yellow allanite, ± rutile (as very fine grained needles in quartz), and ± fluorite. This unit underlies a spectacular, jagged mountain front to the east of Ha'il and Qufar that rises abruptly to about 500 m above the almost flat alluvial fan and pediment adjacent to Wadi ad Dayra. From the air, the light-brown peralkaline granite is easily differentiable from the brick-red, leucocratic syenogranite member (ajc), and the contact between the two is sharp. On the ground, however, an intrusive contact between the two rock units has not been found, so the relative ages are unknown.

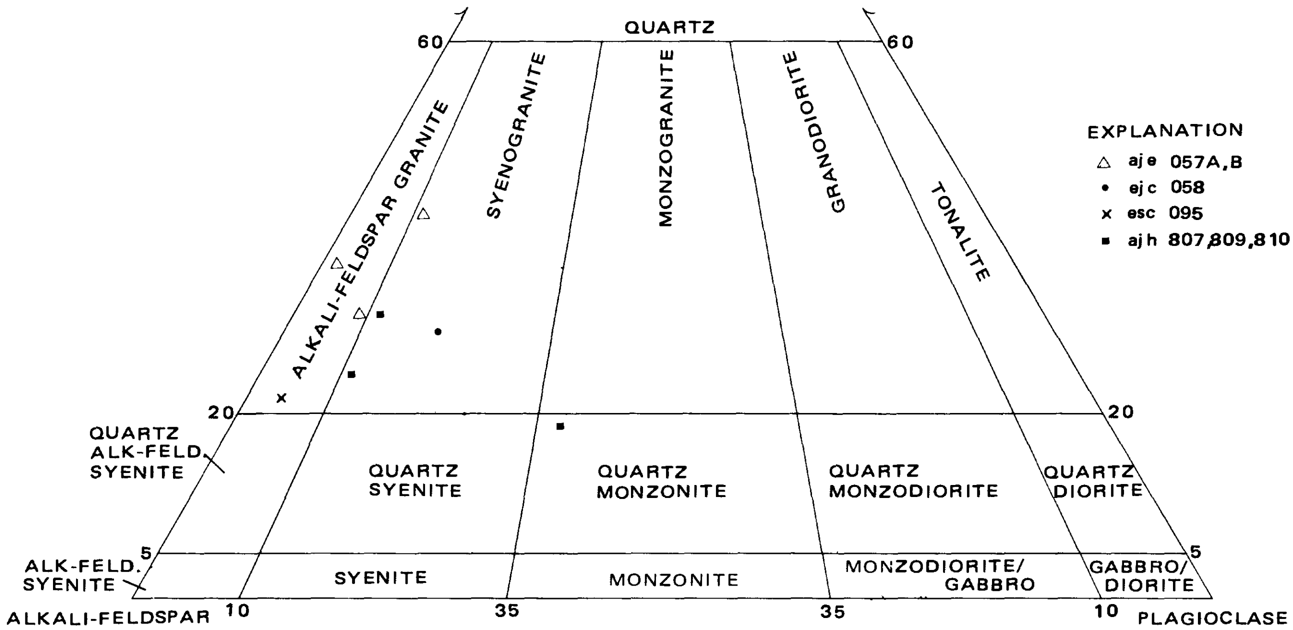

Figure 4.--Modal compositions of granitic rocks from the Aja and Salma complexes, Qufar quadrangle: peralkaline granite of the Aja complex (aje, △); leucocratic syenogranite of the Aja complex (ajc, •); hornblende syenogranite of the Aja complex (ajh, ■); and the hornblende alkali-feldspar granite of the Salma complex (asc, x).

Leucocratic syenogranite member (ajc).--This unit is a light brick-red, medium-to coarse-grained, allotriomorphic-equigranular, leucocratic syenogranite containing typically 65 percent coarsely perthitic, cloudy-brown potassium feldspar, typically 25 percent slightly undulatory quartz, about 10 percent cloudy fractured plagioclase, less than 1 percent small clots of secondary epidote after some unknown mafic mineral, and about 1 percent slightly purple fluorite. The core syenogranite weathers to large reddish domes with widely spaced multi-directional joints.

Hornblende syenogranite member (ajh).--This rock is brownish-pink, coarse-grained, hypidiomorphic-equigranular hornblende syenogranite. The potassium feldspar is perthitic, and the hornblende (up to 3 percent) is green and poikilitic, containing fine-grained crystals of magnetite, potassium feldspar, zircon, and allanite. Minor and accessory minerals include about 1 percent magnetite (associated with hornblende), and traces of zircon, allanite, apatite, and secondary epidote. The unit weathers to large domes and slabs, similar to the leucocratic core granite, but with a slightly browner cast.

Granophyre member (ajp).--Subhorizontal to steeply dipping sheet-like masses of granophyre, as much as about 300 m thick, cut all other units of the Aja complex. The rock is brick-red to grayish-pink, medium to coarse grained, equigranular to inequigranular and granophyric. The granophyre that cuts the peralkaline granite member (aje) is brick-red and leucocratic, with about 30 percent early euhedral non-graphic microcline phenocrysts to 3 mm in a granophyric matrix; a trace of biotite is largely altered to hematite and chlorite. The granophyre that cuts the leucocratic syenogranite and hornblende syenogranite members contains as much as 2 percent hornblende which is partially altered to mosaics of biotite. Minor and secondary minerals in the granophyre include magnetite, fluorite, sphene, and epidote. Locally it contains trace amounts of a deep blue amphibole (riebeckite?) in association with secondary biotite. This unit generally forms ridges because it is more resistant than the surrounding granite.

Pegmatite (p)--The pegmatite of the Aja complex occurs in numerous (as much as 10 percent of rock volume) gently dipping dikes (as much as 30 cm thick) in the country rock adjacent to the peralkaline granite of the Aja complex. These dikes are composed of a light-pink intergrowth of very coarse grained potassium feldspar and quartz, and commonly grade to aplitic core. Occasional grains of fluorite are observed. Detailed petrography of these dikes was not performed.

Studied in more detail are isolated steeply dipping brecciated and mineralized zircon-rich pegmatites that cut the rocks of the peralkaline granite member of the Aja complex, as at locality 180746. These pegmatites are highly radioactive and contain niobium, thorium, and rare-earth elements (Matzko and Naqvi, 1978), and are discussed more thoroughly in the section on economic geology.

Salma complex

Hornblende alkali-feldspar granite member (asc).--This unit is a pink, medium-grained hypidiomorphic-equigranular alkali-feldspar granite containing coarsely perthitic potassium feldspar, about 3 percent green hornblende, minor (less than 3 percent) plagioclase, and trace amounts of allanite, zircon, relict biotite (altered to hematite plus chlorite), and apatite (fig. 4). The rock crops out in large orange-brown domes and spires in the extreme southeastern corner of the quadrangle.

Granophyre member (asp).--The rock is a fine- to medium-grained, bright-pink, equigranular, leucocratic, granophyric syenogranite that contains a trace of chlorite and epidote after biotite. Early euhedral microcline is enclosed in a fine-grained graphic matrix, similar to the granophyre that cuts the eastern rim granite of Jabal Aja. The rock is hydrothermally altered, highly fractured, and cut by numerous brick-red aplite dikes that resemble many observed phases of the large rhyolite dikes (rh) found in the southwest part of the quadrangle.

PHANEROZOIC ROCKS

Saq Sandstone

Only the lowermost several tens of meters of the Ordovician and Cambrian Saq Sandstone (OЄs) (Brown and others, 1963) unit are in the extreme northeastern corner of the quadrangle. The basal 10 m of rock is a pinkish-brown shaley siltstone, overlain by a chocolate-brown, well-sorted orthoquartzite, containing well-rounded quartz grains, 1 to 2 percent interstitial hematite, and traces of ragged shreds of muscovite and clear, subangular fragments of tourmaline. A few well-rounded, white quartz pebbles less than 2 cm in diameter also occur scattered in the lowermost 2 to 3 m of the orthoquartzite.

Miocene olivine basalt

Two small circular remnants of basalt (tb) flows cap hills of altered Ha'il granite (grh) just east of Jabal al Malah. One plug of olivine basalt also occurs just south of Jabal al 'Ugaylah. The flows are black, vitrophyric, olivine-calcic plagioclase (An_{65}) basalt, containing about 10 to 15 percent slightly zoned euhedral olivine phenocrysts (as much as 5 mm in diameter) in a fine-grained felted matrix of about equal parts plagioclase, olivine, and about 3 percent magnetite. The flow rock also contains numerous (about 5 percent) xenoliths (as much as several cm in diameter) of medium-grained, equigranular, dark-green harzburgite. The basalt outcrops with highly fractured, curving columnar joints, spaced as much as 15 cm apart.

A whole-rock K-Ar age of 23.4 ± 0.2 Ma[1/] been obtained from the southernmost outcrop at Jabal al Malah (The Australian Mineral Development Laboratories, written commun., 1981).

The basalt plug (Tba) south of Jabal al 'Ugaylah is black, hyalopilitic, porphyritic, and xenocrystic, and contains about 15 percent euhedral to fragmental olivine phenocrysts to 2 mm, as well as a few rounded, highly resorbed quartz xenocrysts surrounded by reaction rims containing fine-grained clinopyroxene and plagioclase. The quartz grains probably came from the underlying granitic basement. The glassy matrix contains numerous, very fine grained microlites of calcic plagioclase, olivine, and magnetite. The rock contains numerous small (less than 1 cm in diameter) xenocrysts of harzburgite(?). Curved columnar joints are prominent in outcrop.

Quaternary surficial deposits

Alluvial deposits

Alluvial deposits (Qal) consist of yellowish-tan to dark-brown wadi sand, light-brown silty terrace deposits, light-gray, tan, and brown sheet sand, gravel plains that form thin veneers on pediment surfaces, and reddish-brown to tan alluvial fan deposits composed of clasts up to cobble size. Subordinate eolian deposits, small isolated dunes and areas of wind-deposited sheet sand, are included in this unit. Large, gently sloping fan deposits are found along the southeast side of Jabal Aja and the southwest side of Jabal al Malayhah. Quaternary alluvial deposits (Qal) are indicated only in major wadi channels and where it occurs in areas greater than about one km^2.

Lake deposits

Lake deposits (Qp) are light-tan, poorly consolidated, moderately stratified water-lain silt deposits deposited in small enclosed basins. They locally contain white encrustations of undetermined composition. The largest of these

1/ Measured analytic values are: percent K = 0.887, $^{40}Ar^* = 0.36248 \times 10^{-10}$ moles/gm, $^{40}Ar^*/^{40}Ar$ total = 0.756. Constants used are: ^{40}K = 0.01167 atom percent, $\lambda_\beta = 4.962 \times 10^{-10}\ yr^{-1}$, $\lambda_\varepsilon = 0.5811 \times 10^{-10}\ yr^{-1}$.

deposits occurs in a small playa just southwest of Jabal al Malayhah.

STRUCTURE

Gneissic rocks within the pre-Hadn basement display a complex geometry that reflects at least two major tectonic events. The first recognized event occurred during or shortly after the intrusion of the 'Ishsh monzogranite and probably the Ha'il granite, and was accompanied by the local development of gneissic foliation and metamorphism to as high as amphibolite grade. This earlier deformation can be seen extensively in the rocks of the Samra intrusive suite, which commonly occur as roof pendants in the older granitic rocks. The granodiorite orthogneiss also formed during this orogenic phase, and may be a remnant of a remobilized granodiorite pluton.

During this early period of deformation, compositionally zoned fabric of diffuse mafic and felsic segregations and folded foliation planes were locally well developed. Locally, migmatites are developed, such as along the west side of Wadi 'Ugaylah, west of Jabal Arkan. Another good example of the early period of deformation is the foliated hornblende gabbro (gbh) in the ridge just east of the Ha'il airport. This rock probably represents a roof pendant in the Ha'il granite. Here, the gabbro is foliated along northerly trends that are generally parallel to those in the surrounding gneissic granite (foliated Ha'il granite). The tightly folded foliation, with approximately horizontal fold axes, within the foliated gabbro was caused by horizontal easterly compression.

Folding within the layered rocks of the Nuf formation is even more complex. The cleavage (axial plane?) directions are locally chaotic, although south of Jibal Fitiq, the foliation in the mafic paragneiss (nu), derived largely from the rocks of the Nuf formation, defines a broad, steeply plunging fold. Recognition of stratigraphic horizons is difficult due both to the degree of shearing and to the inherent massive nature of the rock.

Localized remobilization and metamorphism of many of the earlier rocks in the quadrangle occurred during the second recognized period of deformation, probably during the emplacement of the Malayhah granite complex. Gneisses formed during this period of deformation are commonly cataclastic, with well-developed augen, flaser, and granoblastic mortar textures.

The cataclasis within the Malayhah granite complex is extremely pervasive along its west and southwest margins, and is well developed in both the granophyric border facies and in the coarser grained monzogranite member. Cataclasis grades to the west, over several kilometers, from the undeformed core into augen gneiss, flaser gneiss, and locally into pseudotachylite gneiss. The gneiss in this region is locally highly lineated, with axes that plunge steeply to the south, and with planes of foliation that dip steeply west. The lineations are defined both by mineral axes and by lensoid trains of sheared and recrystallized minerals, and represent the probable last direction of transport of the Malayhah granite body as it rose steeply to the north and cataclastically deformed its margins. The shearing extends for at least several km into the surrounding country rock, which includes rocks of the Samra intrusive complex, the older granites, and the Hadn formation. Melange zones, composed of lensoid blocks of several diverse rock types in a sheared matrix, are probably also related to this period of deformation. In the north-central part of the quadrangle, zones of intensely sheared and foliated granitic rock trending about N.20°E. are possibly also related to the emplacement of the Malayhah granite complex.

Forceful emplacement of the Malayhah granite complex is only one explanation for this period of deformation. An alternative explanation is that broad regional shearing along a major fault zone produced the observed cataclastic features; that is, the Malayhah monzogranite represents a "mega-augen" along this zone of deformation. This model seems unlikely, however, for several reasons. First, the zone of deformation is very irregular in extent, and does not trend continuously along a single zone of shearing for more than several km in any direction from the margin of the Malayhah granite. In addition, the shearing is most intensely developed near the margins of the Malayhah granite.

Bateman and others (1983) discuss a cataclastically deformed and lineated leucotonalite pluton in the Sierra Nevada mountains of California, whose structural setting is strikingly similar to that of the Malayhah granite complex. They attribute the deformation in and adjacent to the pluton to the forceful emplacement of a high viscosity magma in which the liquid phase constituted about 30 percent or less of the melt. Like the cataclastic granite member of the Malayhah granite complex, the leucotonalite discussed by Bateman and others (1983) is granoblastic to granoblastic mortar textured, with streaked mineral lineations both within the pluton and in the surrounding country rock.

Zones of imbricate thrusts that strike generally northeasterly and dip to the southeast, are in the north-central part of the quadrangle, within the Ha'il granite. The thrust planes are locally parallel to the cataclastic foliation in the surrounding rocks, though locally cut across it, suggesting that thrust faulting was a brittle, late-stage, possibly more shallow-seated event that post-dates the shearing associated with the emplacement of the Malayhah granite complex. In these zones the Ha'il granite is extensively brecciated, altered (hematized), and disaggregated along and immediately adjacent to the thrust planes, and recrystallization during and after thrusting has not greatly affected these rocks. Moreover, the northwest-trending melanogranite dikes, which intrude several of the posttectonic plutons, are offset by thrusting along the intensely sheared zone near the north boundary of the quadrangle.

Except where it is foliated and deformed adjacent to the Malayhah granite complex near Jabal al Malayhah, the Hadn formation is only locally folded and mostly homoclinally tilted. Folds, where they occur, are open, with gently plunging fold axes, and the beds are rarely overturned. Steep axial plane cleavage is only locally developed. Open folds within the rocks of the Hadn formation are much more extensively developed just south of the quadrangle, in the Al 'Awshaziyah quadrangle. The period of folding and tilting in the Hadn formation is uncertain, although probably closely post-dates the emplacement of the Malayhah granite complex.

Probably the youngest set of high angle faults trends approximately N.60°E. to N.70°E. Because these faults are associated with local brecciation and vuggy silicification, the faulting probably was relatively shallow. The movement on this last set of faults is apparent right-lateral-slip, an observation supported by mapping in the Ghazzalah quadrangle to the southwest (Quick, 1983). Up to several km of apparent strike-slip movement has occurred, and probably postdates the emplacement of the large, red rhyolite dikes in the southwestern part of the quadrangle. In the north, last movement clearly postdates the northeast-trending thrust faults, as well as the deposition of the Cambrian to Ordovician Saq Sandstone. A small wedge of Saq Sandstone is preserved along one of these northeast faults just south of the Hail-Buraydah highway, about 14 km from the nearest flat-lying exposures of Saq Sandstone.

In addition to faults with relatively large displacements, numerous, short, randomly-oriented, high angle faults of small displacement outline polygonal fault blocks. These faults that resulted from small adjustments, probably during and immediately after pluton emplacement, are differentially eroded and well-delineated by wadi channels. Only the larger of these faults are shown on the map.

METAMORPHISM

The mafic and carbonate rocks of the Nuf formation have been mostly metamorphosed to greenschist facies, and locally to as high as garnet-amphibolite facies. A typical metamorphic assemblage in the metavolcanic rocks of the Nuf formation is saussuritized and partially albitized plagioclase, chlorite, epidote, hematite, actinolite, biotite (chloritized), and ± secondary quartz. Plagioclase phenocrysts are approximately labradorite in composition. Impure dolomitic rocks in the northeast corner of the quadrangle (locality 180494) contain an assemblage typical of skarn deposits: diopside, quartz, epidote, and grossularite. Green tremolitic marble, containing about 30 percent tremolite, plus calcite, is just south of Jabal Khafidh (locality 180322).

Sheared and contact metamorphosed (to almadine-amphibolite-hornfels facies) andesitic rocks mapped as part of the Nuf formation adjacent to the Malayhah granite complex in the central part of the quadrangle contain almandine in addition to amphibole, labradorite, biotite, magnetite, and a trace of quartz and epidote. Sheared andesites on the northeast margin of the Malayhah granite complex contain euhedral porphyroblasts of blue-green hornblende as much as 2 mm long.

Metamorphic effects in the intermediate to felsic rocks of the Hadn formation are not as apparent in hand specimen as in the older mafic rocks. Regionally, the rocks of the Hadn formation have been weakly metamorphosed to greenschist facies as indicated by assemblages of albite-chlorite-epidote±biotite in the rhyodacitic volcanics, and chlorite-epidote±actinolite-sericite in subgraywackes. Along the west margin of the Malayhah granite complex on Jabal al Malayhah, in rhyodacite porphyries, the plagioclase is oligoclase in association with traces of almandine, indicating the effects of probable amphibolite facies contact metamorphism.

Most of the granitic rocks suspected to predate the Hadn formation (predominantly the 'Ishsh monzogranite and the Ha'il granite) have undergone varying degrees of recrystallization, as indicated by a locally developed, though thorough recrystallization of the original mafic minerals (probably mostly hornblende) to fine-grained clots of magnetite, sphene, epidote, biotite, and occasional blue-green hornblende. These mineral assemblages may have resulted from recrystallization (accompanied by deuteric alteration?) during the emplacement of the Malayhah granite.

ECONOMIC GEOLOGY

Niobium, thorium, and rare-earth-bearing veins

Along the eastern margin of the peralkaline granite (aje) of the Aja complex occur numerous pink and black brecciated, pegmatitic veins as much as 4 m across and several hundred meters along strike. Some of these veins have been reported by Matzko and Naqvi (1978), who found that they contained as much as about 0.5 percent niobium and as much as about 0.1

percent each of cerium, lanthanum, yttrium, and thorium. Additional rare earths were not analyzed. These rocks are composed of coarsely perthitic potassium feldspar, black-stained (hematitic?) quartz; brick-red, doubly-terminated zircon (as much as 10 percent of a cut slab); a trace of sodic amphibole (riebeckite?); and as much as about 5 percent black to reddish-brown opaque minerals that are mostly hematite, but include thorium and rare-earth bearing minerals. Scintillation measurements (gamma radiation) on these veins are as much as 30 times normal background radiation. Samples from a vein (location 180746; application made for MODS number) at the contact of the peralkaline granite with the Ha'il granite country rock, and from a similar vein (locality 180747; application made for MODS number) approximately 10 km north of the quadrangle, (lat 27°37'45" N., long 41°40'15" E.), were analyzed by semiquantitative spectrographic analysis (table 1). The results from a fresh sample of peralkaline granite (locality 180682) are included for comparison. Additional chemical data were obtained from X-ray fluorescence (XRF) analysis, which indicated a significant (but unspecified amount) of thorium and cerium. No uranium was detected by XRF analysis. X-ray diffraction analysis indicated the presence of the uranium-bearing minerals abernathyite ($KUO_2AsO_4 \cdot 3H_2O$) and maswyite ($PbUO_3 \cdot H_2O$), as well as bastanaesite [$(Ca,La)(CO_3)F$], thorite ($ThSiO_4$), synchysite [$(Ca,Ce)(CO_3)_2F$], the amphibole ferropargasite, the chlorite mineral richterite, quartz, hematite, ilmenorutile and fluorite (I.M. Naqvi, oral commun., 1982).

Chromite- and nickel-bearing serpentinites

Small massive pods and dessimated bodies of chromite occur in the serpentinite body east of Jabal Sabihah (MODS 2175 and 3028) and have been discussed by Chevremont (1982). These occurrences are small, composed of lenticular bodies of massive chromite probably not exceeding 1 m^3. No bodies of massive chromite were found during the present investigation, however. Chevremont (1982) considers this chromite occurrence to be subeconomic. Two representative samples of the serpentinite were analyzed by semiquantitative spectroscopic analysis, and are shown in table 1. A dolomitized fault zone, at location 180604, about 5 km southwest of Jabal Shatib, is also indicated on table 1. This rock probably represents a thin sliver of dolomitized serpentinite (listwänite), now surrounded by a sheared granitic gneiss. The serpentinite and the dolomite all show high values for nickel (1,500 to 2,000 ppm) and cobalt (70 ppm), as well as chromium (2,000 to 3,000 ppm). These values are, however, not unexpected from an ultramafic rock. Analyses for mercury were not made, but they might be in any future studies.

Table 1.--Semiquantitative spectrographic analysis of selected elements for samples collected from the Qufar quadrangle (27/41 D)

[Ali Bone analyst, DGMR laboratory, Jiddah. Results for iron, magnesium, calcium and titanium in percent; all other elements in parts per million. ND = not detected; L = detected but below limits of measurement.]

Sample number	180682	180746	180747	180425	180459	180604
Rock type	(fresh granite)	(radioactive veins)		(serpentinite)		(dolomite)
	Jabal Aja eastern rim granite					
Iron	3	2	5	7	5	1.5
Magnesium	L	L	0.02	>10	>10	>10
Calcium	0.2	0.1	0.7	L	0.5	10
Titanium	0.07	0.02	0.3	L	L	ND
Manganese	700	200	2,000	1,000	300	500
Boron	L	10	L	15	15	L
Barium	ND	20	70	ND	ND	20
Beryllium	7	15	20	ND	ND	L
Bismuth	ND	ND	15	ND	Nd	ND
Cobalt	ND	ND	ND	70	70	50
Chromium	150	150	100	2,000	3,000	700
Copper	7	7	50	15	5	5
Lanthanum	150	>1,000	>1,000	L	L	L
Molybdenum	ND	10	ND	ND	ND	ND
Niobium	30	150	1,500	L	L	L
Nickel	5	L	ND	2,000	1,500	500
Lead	20	300	50	ND	ND	10
Scandium	L	ND	50	5	5	ND
Tin	L	50	ND	L	ND	ND
Strontium	ND	ND	L	ND	ND	300
Vanadium	10	L	L	20	15	10
Tungsten	ND	ND	ND	ND	ND	ND
Yttrium	100	>2,000	2,000	ND	ND	ND
Zinc	200	200	ND	ND	ND	ND
Zirconium	>1,000	>1,000	>1,000	ND	ND	ND

Massive magnetite

Small lenses of massive magnetite, up to several tens of cm thick and up to about 5 m long, occur interlayered with marble near the eastern border of the quadrangle, at locality 180360 (MODS 2176). The magnetite probably resulted from metasomatic reactions produced during intrusion of the Malayhah granite complex, although mineral assemblages typical of a skarn deposit are not associated with the magnetite. Chevremont (1982) suggests that the granite of Jibal Fitiq (incorrectly named Jabal Nuf by Chevremont), which he calls a "magnetite granite", and which is tentatively included in this report with the Malayhah granite complex, may be the source for the magnetite deposits. Petrographic analysis of this granite, however, indicates that the sparse grains (up to 2 percent) of "magnetite" are actually mosaics of very fine grained magnetite, biotite, sphene, and epidote resulting from the metasomatic breakdown of previously existing mafic minerals.

Chevremont (1982) found that the carbonates associated with the magnetite deposits are virtually barren of tungsten; less than 20 ppm tungsten was reported.

Aggregate

Aggregate is currently being quarried at numerous localities along the mapped thrust fault zones in the northern part of the quadrangle. The low angle fault zones have produced a shattered rock that is easily ripped. The resulting gravel clasts are highly angular, a desirable quality for construction grade aggregate. Future quarrying along the mapped zones of thrust faulting is recommended.

Marble

The observed outcrops of marble are probably either too highly fractured, too sparse, or not sufficiently aesthetic to be considered for construction stone. The lack of tonnage and an unacceptably high MgO content (C. Spencer, oral commun., 1982) also make the marbles unsuitable for use as cement.

DATA STORAGE

Updated information was added to the Mineral Occurrence Documentation System data bank. A base-data file has not been established for this project.

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