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Reconnaissance geology of the Wadi Habawnah quadrangle, sheet 17/44 A, Kingdom of Saudi Arabia

by

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RECONNAISSANCE GEOLOGY OF THE

WADI HABAWNAH QUADRANGLE, SHEET 17/44 A,

KINGDOM OF SAUDI ARABIA

by

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ABSTRACT

The Wadi Habawnah quadrangle, in the southeastern part of the Asir province, is underlain mostly by Precambrian plutonic and polymetamorphosed plutonic and layered rocks. Mapped units of the Halaban group are: meta-andesite and metabasalt flow rock; mixed metavolcanic flow rock, dacitic volcaniclastic rock and metasedimentary rock; and tuffaceous first-cycle wackes with pelitic, carbonate, and graphitic beds. Leucogneiss, probably paragneiss, and biotite quartz schist occur in discontinuous belts. Septa of the flow rock also occur within an early plutonic complex of metadiorite and metagabbro.

A succession of increasingly felsic and alkalic intrusive events followed this early activity. Rocks of a tonalite-granite suite reflect a major syntectonic magmatic event that resulted in the A'ashiba gneiss complex. This event included development of tonalite, granodiorite, and biotite monzogranite by alteration of pre-existing mafic rocks or as intrusive bodies. Granitic magmatism of a young intrusive suite included the emplacement of late syntectonic or post-tectonic biotite-amphibole granite, late tectonic or post-tectonic calc-alkaline biotite monzogranite as diapiric intrusions, and relatively passive emplacement of biotite gabbro and diorite in patterns that followed the pre-existing structural framework. Clinopyroxene quartz syenite and clinopyroxene alkali-feldspar granite were emplaced in small stocks. A main phase of granitic plutonism included passive emplacement of large bodies of coarse-grained perthite alkali feldspar granite with alkali facies, which preceded or was coeval with the intrusion of coarse-grained biotite syenogranite.

Precambrian tectonic events included east-west compression that followed volcanic activity and clastic deposition, and possible subsequent north-south wrench faulting. Later tectonism, contemporaneous with or after a late phase of granitic intrusion, may have included east-west compression

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with resultant northeast and northwest shears, some with lateral movement.

The Precambrian complex was deeply eroded to a nearly planar surface. Coarse sand and minor gravelly sediments from a southern or southwestern source area were cemented by iron oxides and hydroxides and carbonate to form the Wajid Sandstone of Cambrian and Ordovician age. Some basement faults were reactivated as extensional faults following lithification of the Wajid. Tertiary and Quaternary events include probable extensional faulting and volcanism, major uplift with accompanying active erosion, and deposition of alluvial, colluvial, and eolian deposits. Holocene time has been marked by aggradation of major stream valleys and development of arid conditions.

Numerous small gossan, earthy ferruginous rocks, and exposures of massive and disseminated sulfide deposits are mostly associated with metavolcanic flow rocks and felsic dikes. Results of chemical analyses show relatively few anomalous trace-element values. Fluorine and lithium anomalies occur in the Najran, Ghezm, and Thar plutons, and tin and molybdenum anomalies in the Ghezm pluton.

INTRODUCTION

The Wadi Habawnah quadrangle, sheet 17/44 A, in the southeastern part of the Arabian Shield (fig. 1), covers an area of about 2,860 km^2 and lies between lat 17°30' and 18°00' N. and long 44°00' and 44°30' E. The quadrangle is at the western edge of the Rub al Khali desert, and drainage flows eastward into this huge basin. Two main wadis flow through the quadrangle, Wadi Habawnah in the central part and Wadi Najran in the south. Main south-flowing tributaries of Wadi Habawnah are Wadi Thar and Wadi Khutan. Wadi Arjan is a major north-flowing tributary of Wadi Habawnah that drains a large area in the eastern and central parts of the quadrangle. General gradients of Wadi Habawnah and Wadi Najran in this quadrangle are roughly 3.1 and 3.5 m per km, respectively.

Topography in the quadrangle includes about 25 percent low-slope gravel- and sand-covered plains and wide main wadi valleys that range from about 1,270 m altitude in the northern part of the quadrangle to less than 1,120 m along Wadi Habawnah at the eastern quadrangle boundary. An upland plateau, formed on the Wajid Sandstone of early Paleozoic age, covers about 15 percent of the central and western parts of the quadrangle. The plateau surface is made up of barren low rolling hills punctuated by isolated hills and steep-sided outliers that have maximum altitudes of slightly more

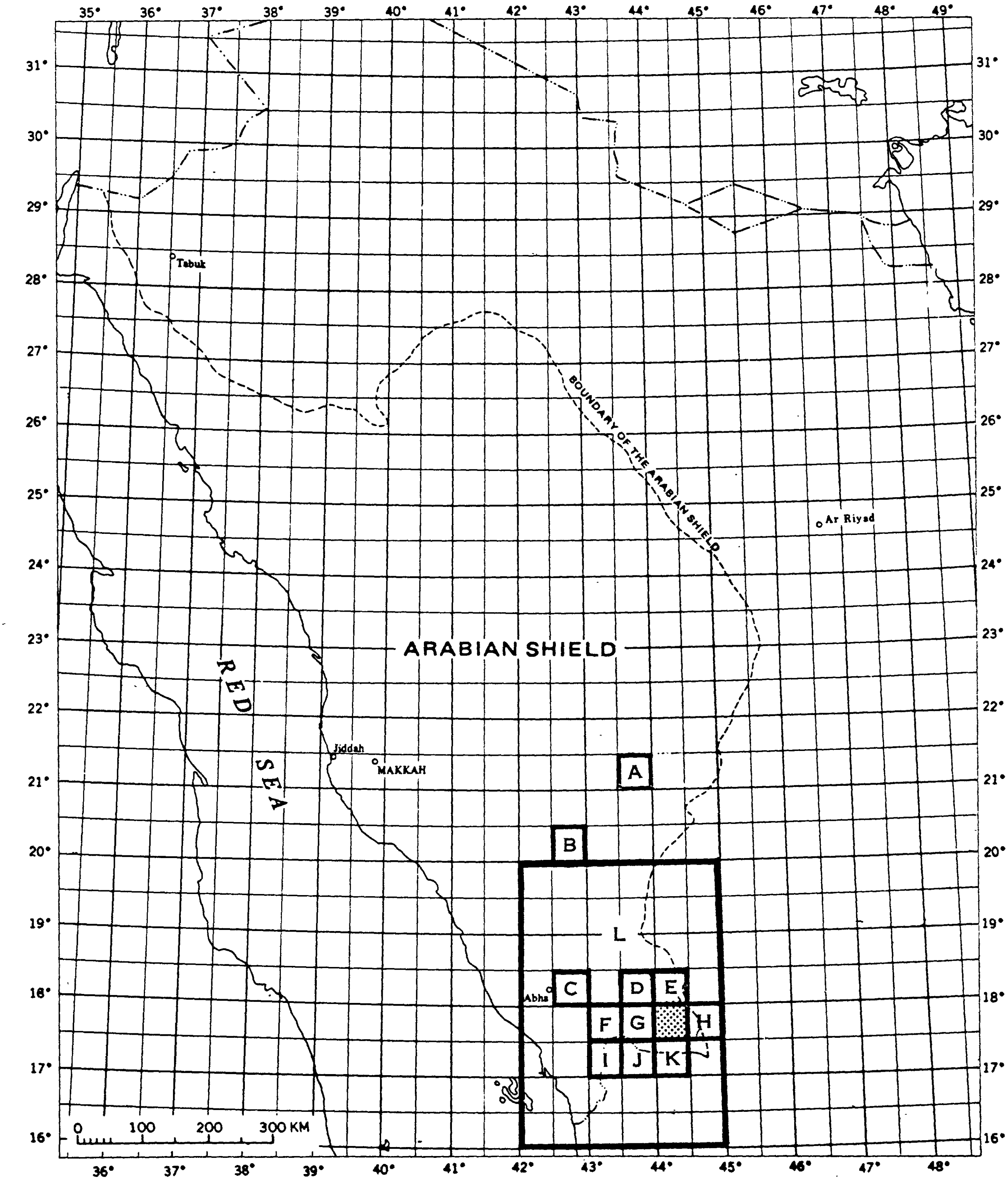


Figure 1.--Index map of western Saudi Arabia showing location of the Wadi Habawnah quadrangle (shaded) and other quadrangles referred to in this report: A, Bi'r Juqjuq (Hadley, 1976); B, Al Junaynah (Schmidt, 1980); C, Khamis Mushayt (Coleman, 1973); D, Wadi Malahah (Greenwood, 1980b); E, Wadi Wassat (Greenwood, 1980a); F, Wadi 'Atf (Anderson, 1979); G, Mayza' (Anderson, 1979); H, Jabal Shaqran (Sable, in press); I, Jabal Fayfa (Fairer, in press); J, Wadi Amadin al Husn (Conway, in press); K, Najran (Sable, in press); L, Asir (Brown and Jackson, 1959).

than 1,900 m. The remaining 60 percent of the quadrangle is generally highly dissected, rugged upland mountainous country having deeply incised wadis, some of which flow through gorges; except for the paucity of vegetation, it is a moderately scenic area. Much of the area is continuous weathered outcrop with scattered inselbergs in lowland areas.

The main settlement is Najran, a small city made up of several variously named populated areas adjoining Wadi Najran, but only the northeastern part of the city is in this quadrangle. Other settlements are Khadarah (Habawnah), a village at the western boundary of the quadrangle along Wadi Habawnah, and smaller villages at Bir Husaniyah and Bir Khadra in the northeastern and southeastern parts of the quadrangle, respectively. Small groups of buildings and (or) tents are at a few wells such as Bir Askhar, Bir Salwa', and Wadi Thar.

Narrow areas along Wadi Najran and Wadi Habawnah are intensively farmed for grains, vegetables, and fruit such as dates. The sparse countryside vegetation is heavily grazed by goats, sheep, and camels that support nomadic Bedouin families.

The Najran area was an important locality along ancient north-south trade routes at least as long as 2,600 years ago; some ancient ruins still stand along Wadi Najran. Petroglyphs and graffiti, some of which appear to be very old, are present on many rock walls, and very crude Paleolithic(?) stone implements are relatively common.

The main paved highway from Khamis Mushayt to Najran passes through the southern part of the quadrangle, and another continues northeastward to Ar Riyad past the Najran airport. Other roads, such as those going northward to Bishah and ones from the main highway to Khadarah (Habawnah), are unpaved but are occasionally graded.

The geology of the Wadi Habawnah and adjacent quadrangles was mapped at 1:500,000-scale by Brown and Jackson (1959). The present report is the result of geologic field studies conducted intermittently from December 1978 through May 1979; parts of quadrangles to the south (Najran, 17/44 C) and east (Jabal Shaqran, 17/44 B) were also mapped during this period. 1:50,000-scale aerial photographs flown in January 1951 were used to plot field information and to prepare 1:50,000-scale geodetically controlled photomosaics, which also were used during field work. The geologic map was prepared on a 1:100,000-scale controlled photomosaic base using the above photographs. More than 500 thin sections were examined, and 134 modal analyses were calculated from stained slabs and standard-size thin sections.

The purposes of the study were to map the geology of the quadrangle and to search for evidence of mineral deposits. No ore deposits or ancient mines had been reported in this area prior to the present study. During the course of the investigation scattered occurrences of gossan, disseminated and massive sulfide deposits, and earthy ferruginous rocks were found in several areas.

The work on which this report is based was performed in accordance with a work agreement between the U.S. Geological Survey (USGS) and Saudi Arabian Ministry of Petroleum and Mineral Resources.

Chemical analyses (spectrographic, atomic absorption, colorimetric, and specific-ion electrode) were performed by the USGS/DGMR laboratory, Jiddah. X-ray diffraction work and some microscopic petrographic identifications, including examinations of polished massive sulfide mounts, were done by personnel of the USGS petrographic and mineralogical laboratories, Jiddah. X-ray fluorescence qualitative elemental determinations on polished massive sulfide mounts were done by E. A. du Bray (USGS), and normative calculations and plots using the GNAP program were done by G. I. Selner (USGS). Details of analyses presented in this report are available through the U.S. Geological Survey computer center in Jiddah under RASS II, Rock Analysis Storage System for Chemical Data (Wilch, 1978), program numbers 3860 and 8850.

I wish to thank the following people for their direct assistance in the field and office: Ghanim Jeri Al Harbi, prospector; Ghufun Misfir Al Yami, guide; Ali Mohammed Hassen, cook; Ahmad Hamdan Al Bazli and S. T. Rooney, geologic assistants; Francois Elsass, M. R. Brock, and D. B. Stoeser, geologists.

PRECAMBRIAN LAYERED ROCKS

Metavolcanic and metasedimentary rocks form less than 20 percent of surface-rock exposures in the quadrangle (pl. 1). Metavolcanic flow rocks are predominant in three separate belts, and interlayered metasedimentary and volcanic rocks occur along the western boundary of the quadrangle. In addition, gneissic schistose and slaty rocks of mafic to felsic composition are mapped in several belts and areas in the southern part of the quadrangle. Although considerably recrystallized and sheared, these rocks are interpreted to be at least in part of sedimentary and volcanic origin.

The layered rocks are referred to the Halaban group as used by Greenwood in the Bir Idimah (sheet 18G) quadrangle (in press). The metavolcanic flow rocks in all three belts are similar in lithology and composition, are considered correlative, and are mapped as meta-andesite (ma). Near the western boundary of the quadrangle, a unit of metavolcanic and metasedimentary slaty and schistose rock is mapped as meta-andesite and schist (mas). A third unit consisting of predominantly light-hued pelitic to psammitic tuffaceous metasedimentary rock interlayered with beds of metamorphosed felsic tuff of largely dacitic composition, minor carbonate rock, and graphitic schist is mapped as biotite schist (bs).

The stratigraphic succession for the quadrangle as a whole is uncertain because bedding attitudes are steep and indications of bedding tops are few. In general, a steep westerly dip is dominant in the belts adjoining the western boundary of the quadrangle; there, rare graded bedding and small-scale crossbedding in a few tuffaceous wacke beds indicate tops to the west. These relationships suggest that the meta-andesite, meta-andesite and schist, and biotite schist units are progressively younger units in a stratigraphic succession. Such an interpretation, that older mafic rocks are overlain by progressively more felsic rocks, also has been indicated by authors of adjoining quadrangles, although a different interpretation has been proposed by the Riofinex Geological Mission (1978).

Meta-andesite

Metamorphosed andesitic and basaltic flow rock (ma) crop out as three north-trending belts north and south of the Ghezm pluton along and near the western border of the quadrangle, along Wadi Ithaiba in the south-central part of the quadrangle, and crossing Wadi Khutan in the northeastern part. Volcanic flow rocks also occur in smaller discontinuous septa within intrusive units. Where the flow rocks occur as discrete bodies, they are mapped as meta-andesite; where they do not, they are included in an undivided unit of meta-diorite-metagabbro volcanic flow rock (dgv). The septa range from several tens to several hundreds of meters wide and are abundant along Wadi Gurra, Wadi Thar, and the lower part of Wadi Arjan. Their distribution and trend suggest that the Wadi Khutan and Wadi Ithaiba belts were continuous before intrusion of plutonic rocks; similarly, the belts in the westernmost part of the quadrangle were probably continuous prior to emplacement of the Ghezm pluton. With the exception of these western belts, the other septa of flow rocks are probably "rootless" septa in the plutonic complex.

Greenish-weathering massive to schistose amphibolite and amphibolite schist are exposed along the western boundary of the quadrangle west of the metasedimentary rock unit (bs) are also mapped as the meta-andesite unit. Lepidoblastic textures are dominant; essential minerals are poikiloblastic very light green amphibole, reddish-brown biotite, andesine(?), and locally abundant epidote.

In the western and southern belts of outcrop, volcanic flow rock is resistant, massive to weakly cleaved, and crops out as high cliffs along minor drainages and as ribs projecting from surfaces of steep slopes. In the northeastern belt along Wadi Khutan, topography is more subdued because the rock is less resistant as a result of shearing and pervasive chloritic alteration.

The meta-andesite is dark gray (color index 40-80) and weathers gray and grayish green. It is dense, aphanitic to finely crystalline, in part porphyritic, in part amygdaloidal, with chlorite, sericite, and iron oxide as vesicle fillings. Pillow structures are present in two places near the western border of the quadrangle, and spheroidal weathering suggestive of pillows is common. Flow breccia (clasts as large as 30 cm) are also in the western belt of exposure. Thickness of individual flows is uncertain because of schistosity and cleavage subparallel to bedding but is estimated to range from about 2 to more than 20 m.

Phenocrysts in porphyritic rocks are anhedral to subhedral, as much as 2 cm wide, and consist of mafic minerals within relict euhedral pyroxene crystals, and plagioclase. The rocks typically contain 20 to 40 percent phenocrysts. The groundmass of the flow rock is commonly a fine-grained to cryptocrystalline aggregate with pilotaxitic, diabasic, or trachytic texture that in places exhibits flow structure around phenocrysts and clasts. Groundmass minerals are subhedral plagioclase, brownish biotite and hornblende, and less than 5 percent quartz. Rare microcline or untwinned potassium feldspar occurs either as fracture fillings or anhedral grains. Accessory minerals are mostly magnetite and sphene. Secondary minerals include calcite, actinolite, pyrophyllite, or talc, and locally abundant epidote and zoisite.

Replacement of augite phenocrysts is similar to that reported in adjoining quadrangles (Anderson 1979; Greenwood, 1980a,b). Phenocrysts of augite are rimmed or replaced by brown to green hornblende, by light-green to colorless amphibole, by brown to olive-green biotite, and by magnetite. Single crystals of replacement hornblende are commonly poikiloblastic. Chlorite and sericite are common alteration minerals. Sphene occurring as rims on magnetite indicates probable exsolution from original ilmenite.

Plagioclase phenocrysts are anhedral to subhedral, commonly zoned (An_{40-70}), and are partially to nearly totally replaced by sericite, muscovite, epidote, and carbonate. In some samples plagioclase is rimmed and replaced by albite, and near granitic intrusive rocks is rimmed and partially replaced by potassium feldspar.

Minor devitrified tuff and breccia and epiclastic siltstone and shale are intercalated with the basaltic and andesitic flow rocks. Angular to subrounded clasts of andesitic rock, as much as 5 cm in diameter and similar to those described above, are enclosed in a groundmass of spherulitic devitrified glass. Shards are also common in some samples. Subround crystals of quartz, potassium feldspar, and plagioclase characterize other vitrophyric rocks.

Mafic rock interpreted to be metabasalt occurs in all three belts but is most common in the northeastern belt adjacent to Wadi Khutan. The metabasalt includes chloritic schist and amphibolite characterized by light greenish, bluish, and yellowish amphiboles. Mineral assemblages include chlorite-plagioclase-sericite-quartz, biotite-plagioclase-quartz, hornblende-biotite-sericite-plagioclase-epidote, and epidote-hornblende-chlorite-plagioclase.

Metasomatic effects on andesite and basalt include partial to total replacement of plagioclase by potassium feldspar containing quartz intergrowths and veins of epidote, chlorite, carbonate, and pyrite. These effects are common near granitic intrusive rocks and do not appear to be the result of pervasive alteration.

Pyrite is locally common in the volcanic flow rock and occurs as very fine grained disseminations, as partial replacements of cores of plagioclase phenocrysts, mafic minerals, and magnetite, and as replacement patches. The meta-andesite is the most common host rock unit in the quadrangle for massive sulfide deposits, which consist mostly of pyrite and pyrrhotite and which are expressed as earthy gossan.

The relationship of the belts of volcanic flow rock to adjacent rocks is poorly understood. The meta-andesite is clearly intruded and locally altered by granitic rocks of different compositions and different inferred ages. Outcrops near the Ghezm pluton are invaded by apophyses, dikes and lenses of granite and quartz syenite. Granitic rocks in many parts of the quadrangle contain xenoliths of rock similar to the volcanic flow rock. The flow rock also appears to be altered to fels by intrusive granite of the Najran, Ya'arah, and A'Sud plutons (see rhyolite-dacite fels). The relationship of the meta-andesite to plutonic dioritic and gabbroic rocks is vague, and definitive contacts are rarely seen in the field. These plutonic rocks, however, locally do contain xenoliths and large septa of andesitic and basaltic rock similar to those in the mapped belts. The contact between the interlayered metavolcanic and metasedimentary rock (mas) and the meta-andesite along the western boundary of the quadrangle appears to be gradational, the result of an apparent gradual westward increase in clastic rocks.

Rocks of the meta-andesite unit are compositionally similar to those mapped as the Wassat Formation of the Jiddah Group in the Wadi Wassat quadrangle (Greenwood, 1980a) and to the metavolcanic rock unit of the Jiddah Group mapped in the Mayza quadrangle (Anderson, 1979). They are considered to be the oldest layered rocks in the Wadi Habawnah quadrangle. The mineral assemblages indicate regional amphibolite-facies metamorphism. These rocks are reported to be polymetamorphosed in adjacent quadrangles (Anderson, 1979; Greenwood, 1980a) on the basis of relict textures of hornblende and biotite preserved during later recrystallization and cross-cutting multiple foliation. Suggestion of these mineralogical and textural overprints were also seen in several thin sections of these rocks from the Wadi Habawnah quadrangle.

Meta-andesite and schist

Undivided metavolcanic and metasedimentary rock (mas) is estimated to consist of roughly 50 percent metabasalt and meta-andesite, 30 percent slate and wacke, 10 percent or less graphitic slate and schist, 10 percent or less dacitic crystal and lithic tuffs, and very minor dark carbonate rock. Probable sills of aphanitic mafic to felsic rock also occur in this unit.

Flow rocks in this unit are similar to the flow rocks and flow breccias in the meta-andesite unit; some include vitric flow rocks with andesine phenocrysts and sand-sized lithic clasts probably of andesite or basalt. Light-gray and greenish-gray aphanitic cherty-appearing rock interpreted to be metadacite contains probable devitrified glass shards but lacks lithic fragments. Slightly coarser yellowish-orange-weathering dacitic crystal and lithic tuffs contain flattened lapilli, shards, and phenoclasts of quartz and highly sericitized plagioclase. Silt- to granule-size tuffaceous wacke exhibits rare graded bedding and fine crossbedding. Some wacke contains appreciable amounts of ferruginous(?) dark carbonate matrix. Slate and phyllite are mostly medium gray but some are variegated reddish and greenish. They are quartzofeldspathic, sericitic, and chloritic and have slaty to pencil cleavage.

Graphitic in part tuffaceous slate, schist, and metamorphosed mudstone weather to distinctive surfaces having whitish to grayish coatings. In them, graphite occurs as irregular laminae along schistosity, as lenticular concentrations, and as concentrations along zone boundaries within some plagioclase crystals. Pyrite is commonly associated with graphite. Some interlayered poorly foliated microcrystalline rocks with lepidoblastic texture contain fine crystals of muscovite and plagioclase associated with graphite, or with bands and lenses either of calcite-muscovite-graphite or of calcite alternating with bands and patches of ferruginous carbonate. The selective replacement of plagioclase indicates that the graphite, probably of sedimentary origin according to Greenwood (1980a), may have been remobilized during metamorphism, judging by the selective replacement of plagioclase. Extensive replacement of plagioclase by calcite in some metamorphosed crystal tuffs also indicates introduction or remobilization of calcite.

The carbonate rock is medium-dark- to dark-gray, generally equigranular to slightly foliated (dolostone?) marble that commonly contains graphite and sericite in grain interstices. It occurs in boudins less than a few meters thick, and weathers with distinctive yellowish-brown to orange hues. In places the rock contains irregular, dismembered fragments of black chert, but no bedded chert was observed.

The psammitic clastic rocks are poorly sorted and contain considerable interstitial clay-derived material; thus, they are immature and were deposited without much reworking. Deposition was probably in relatively deep water or during generally passive weather or tidal conditions. No coarse-grained epiclastic rocks were seen, but the outcrop belts were not traversed in their entirety, and such rocks, reported in adjoining quadrangles (Anderson, 1979; Greenwood, 1980a; Conway, in press), may be present.

Biotite schist

Biotite schist (bs) includes schist, slate, and metamorphosed mudstone (about 40 percent of the unit), metatuff and tuffaceous metawacke (30 percent), graphitic slate and schist (less than 20 percent), carbonate rock (less than 10 percent), and flow rock and sills (less than 10 percent). Rocks of this unit are similar to those described for the meta-andesite and schist unit but generally have lighter hues and higher quartz content.

Both the biotite schist and meta-andesite and schist are metamorphosed mostly to greenschist facies. Mineral assemblages include albite-quartz-biotite-calcite, albite-biotite-muscovite-quartz, chlorite-albite-muscovite-biotite, plagioclase-biotite-muscovite-carbonate-quartz, and plagioclase-carbonate-sericite. The assemblage hornblende-biotite-plagioclase-carbonate-epidote occurs in a few samples and indicates perhaps low-grade hornblende-hornfels-(amphibolite)-facies metamorphism.

Moderate to weak schistose foliation and cleavage characterize the unit, but rocks along shear zones are highly foliated or mylonitized. Foliated rocks have mostly lepidoblastic texture, although nematoblastic hornblende occurs in some of the rock altered to amphibolite. Cross-cutting foliation is indicated in thin sections of some rocks and in a few field localities, where cleavage due to micaceous minerals intersects what was interpreted as a pre-existing metamorphic layering. Metamorphic effects include replacement of biotite by muscovite, replacement of many minerals by carbonate, and formation of pyrite and epidote.

One X-ray fluorescence analysis of a sample of biotite schist (RASS number 137201) is shown in table 1.

Biotite-quartz schist

Biotite-quartz schist (bqs) makes up a north-northeast-trending belt near the southern boundary of the quadrangle at Shieb Ajama, a short, narrow north-northwest-trending belt in the headwaters of Wadi Arjan, a north-northeast-trending belt east of Wadi Ithaiba, and an east-northeast-trending belt north of Wadi Eargairth. The rocks include tonalite gneiss, quartz diorite gneiss, and amphibolite gneiss, which appear to be interlayered with leucocratic biotite-muscovite schist and gneiss, biotite-hornblende schist, biotite-amphibole schist, and calcite-zoisite-chlorite schist. The rocks are layered on a gross scale, are locally sheared, and contain zones of augen gneiss. This layering may be the result of shearing, recrystallization, and metamorphic differentiation of intrusive and volcanic rocks, although compositional differences, such as high quartz content, suggest that they are largely sedimentary protoliths. They seem to represent synforms or septa mainly in diorite and tonalite or between sills of diorite.

Leucogneiss

Leucogneiss (lg), interpreted to contain paragneiss and associated schist and amphibolite, crops out along the southern border in the southeastern part of the quadrangle, where, very leucocratic (color index less than 10), in part almandine-quartzofeldspathic gneiss, amphibolite, and biotite-quartz schist are associated with granitic rocks. This assemblage resembles that of a leucogneiss unit in the Najran quadrangle to the south (Sable, in press) that strikes north toward these exposures, and the rocks are provisionally correlated.

PRECAMBRIAN INTRUSIVE AND MIXED ROCKS

Plutonic and metaplutonic rocks constitute most of the surface bedrock in the Wadi Habawnah quadrangle, and include bodies of calc-alkalic and alkalic granite, metadiorite and associated metagabbro, syenite, and gabbro. Tonalite, quartz diorite, and granodiorite, which are present in bodies having diffuse contact relationships in migmatite terrane, are for the most part gneissic and may have been metasomatically altered to a significant extent from an original simple dioritic composition.

The plutonic rocks are classified and described on the basis of petrographic modal composition according to the scheme of Streckeisen (1973, 1976) and into intrusive suites using structural and petrographic criteria. Textural terminology is largely from Williams and others (1954). Named plutons are shown on figure 2; unnamed bodies of granitic rocks also occur in the center of the quadrangle south of Jabal Walih. The southernmost exposure of a large elongate monzogranite pluton exposed in the Wadi Wassat quadrangle (Greenwood, 1980a) occurs in the extreme northwestern corner of the Wadi Habawnah quadrangle. Elsewhere in the quadrangle the main phaneritic rock types form a "framework" of fine- to medium-grained metadiorite and metagabbro, quartz diorite, tonalite, and granodiorite, which have been altered in places to migmatites by granitic magmatism. Only the thicker or persistent dikes, sills, and lenses are shown on the geologic map.

Mapped units range from discrete homogeneous plutons to heterogeneous units in which all rock types are not shown. An example of the latter is the extensive metadiorite terrane south of Wadi Habawnah where metadiorite, granite, and gabbro in bodies of various sizes are in complex intermingled relationships. In most areas where diorite, granite, or gabbro are shown as individual units, they are the predominant lithic type although other lithologies are commonly present. The heterogeneous units therefore are symbolized according to their main rock component or are referred to as undivided units in which the main components are defined.

Precambrian plutonic and hypabyssal rocks in the Wadi Habawnah quadrangle compose three suites: the diorite-gabbro suite emplaced or remobilized about 640 Ma ago; a tonalite-granite suite consisting of gneissoid rocks, also about 640 Ma old; and a young intrusive suite, consisting of monzogranite, syenogranite, alkali-feldspar granite, syenite, and gabbro that occur in discordant bodies, probably less than 640 Ma old. Rocks of the diorite-gabbro and young intrusive suites appear to reflect original crystallization compositions, but many rocks of the tonalite-granite suite such as tonalite, quartz diorite, and granodiorite may have resulted from alteration of pre-existing diorite-gabbro suite rocks by melt injection and potassium metasomatism during the earliest phase of granite emplacement.

Diorite and gabbro suite

Metadiorite and metagabbro

Melanocratic to dark leucocratic hornblende-biotite metadiorite, metagabbro, and amphibolite (dg) containing septa of andesite and greenstone constitute the predominant country rock in large areas of the quadrangle. This unit crops out south of Wadi Habawnah west of Wadi Na'aman, is included in the Zilm plutonic complex, and extends north of Wadi Habawnah as septa in granitic and migmatitic rocks into the Wadi Wassat quadrangle. It also occurs in smaller areas in the southern and southeastern parts of the quadrangle, and is believed to be the main lithic unit underlying broad areas of Wajid Sandstone in the central and west-central parts. Melanocratic, fine-grained gabbro appears to dominate the unit in its northwestern exposures, whereas diorite seems to be more common in the west-central part of the quadrangle. The unit also contains quartz diorite and tonalite, and locally includes minor leucogabbro, anorthosite, leucodiorite, and albite-quartz pegmatites.

The metadiorite and metagabbro is moderately to poorly resistant to weathering and erosion, and locally metamorphosed to amphibolite and biotite schist. Light-hued exposure belts in some areas such as at Jabal Zilm are interpreted to be the result of alteration and bleaching during intrusion of later granite. Primary fabric was generally not recognized in these rocks, but they locally possess crude compositional layering. Petrographically the rocks are fine-to medium-grained equigranular with ophitic, diabasic, or recrystallized allotriomorphic texture, and are weakly foliated to schistose. They contain poikiloblastic greenish to brownish hornblende and brownish to green biotite or phlogopite that enclose relict cores of altered clinopyroxene, probably augite. Biotite glomerocrysts as wide as 3 cm are common in some localities. Subhedral plagioclase in diorite is sodic to calcic andesine (An_{35-48}), commonly with oscillatory and normal zoning, and in metagabbro is calcic labradorite (An_{60-70}), commonly with undulose extinction. Labradorite anorthosite containing scarce blue-green amphibole occurs at a few localities. Magnetite-ilmenite (locally as much as 10 percent), sphene, apatite, rutile, and zircon are locally abundant accessory minerals. Light-greenish-blue to yellow amphibole rims and replaces hornblende. Plagioclase is commonly saussuritized, and locally is rimmed by albite or microcline. Chlorite, sericite, epidote, and calcite in some places mask original texture and mineralogy. Evidence of saussuritization and chloritization, showing relatively few secondary foliate textures, suggests either normal retrograde cooling or an episode of static metamorphism following consolidation.

Mixed layered, intrusive, and migmatitic rocks

Two units of mixed rocks are mapped in the quadrangle: (1) isolated septa of andesite and basalt metavolcanic flow rock associated with metadiorite and metagabbro (dgv); and (2) rocks of granitic to metadioritic-metagabbroic composition in migmatite terrane that are structurally too complex and too poorly understood to be shown at map scale (dgg). Gneissose rocks in the A'ashiba gneiss complex, which are also in part migmatitic, are somewhat similar to rocks of unit dgg, but are mapped on the basis of their dominant lithologies as biotite tonalite gneiss (tbg) and undivided granodiorite gneiss and monzogranite (gdmg).

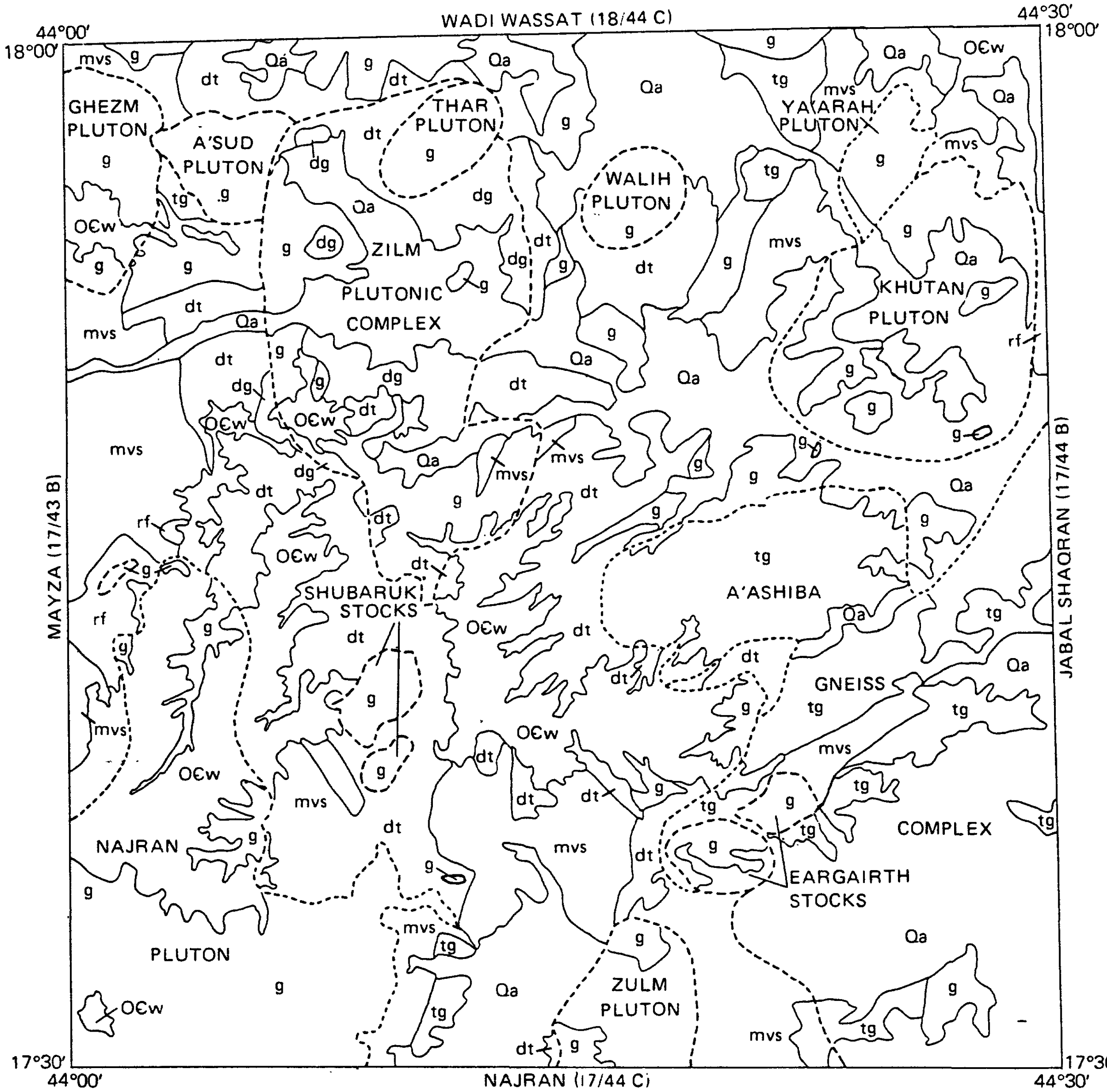
Tonalite-granite suite

Three main units compose the tonalite-granite suite: biotite tonalite gneiss with subordinate granodiorite gneiss (tbg), granodiorite gneiss with subordinate monzogranite (gdmg), and monzogranite (mgb and mgbc). These units are exposed in and adjoining the A'ashiba gneiss complex and in smaller areas near the northern quadrangle boundary near Wadi Khutan and adjoining the Ghezm pluton. In these areas the gneissic rocks appear to be gradational with one another. In the A'ashiba gneiss complex they contain septa of the biotite-quartz schist unit and are intruded by generally foliated monzogranite of the tonalite-granite suite and by discordant stocks of pyroxene syenite of the young intrusive suite. Granitic rocks of the tonalite-granite suite include an area of granite (mgbc) at the southern edge of a pluton in the northwestern part of the quadrangle, and granite (g, mgb) in smaller elongate and dike-like bodies mostly around Jabal Walih and along Wadi Arjan. These dike-like bodies and the septa form the leucocratic part of the mixed dgg unit and delineate arcuate patterns that in part may be expressions of the upper parts of circular diapiric plutons of the young intrusive suite.

A'ashiba gneiss complex

The A'ashiba gneiss complex, named after Wadi A'ashiba, is exposed east of Wadi Arjan between Wadi Habawnah and Wadi Najran (fig. 2) and extends southward and southeastward into the Najran and Jabal Shaqran quadrangles. This area of more than 600 km^2 is made up of foliate granitoid rocks of intermediate, felsic, and mafic compositions that appear to be monotonously similar when viewed from the air. They comprise tonalite, quartz diorite, granodiorite, and lesser monzodiorite, monzogranite, and diorite (fig. 3a).

Two main units are mapped in the complex: biotite tonalite gneiss (tbg), and undivided granodiorite gneiss and monzogranite (gdmg). Their contacts are gradational and very



EXPLANATION

Qa	Quaternary deposits	dg	Gabbro and diorite
OЄw	Wajid Sandstone	tg	Tonalite and granodiorite gneiss (dgg, tbg, mgb)
rf	Rhyolite-dacite fels	dt	Diorite and tonalite (includes mixed and altered rocks; dgg, dg, dgv)
g	Granite and syenite (agpa, grba, sp, mgbc, mgb, agm	mvs	Metavolcanic and metasedimentary rocks (ma, bqs)

Figure 2.--Generalized geologic map of the Wadi Habawnah quadrangle showing named plutons and plutonic complexes. Qa, Quaternary deposits; OЄw, Wajid Sandstone; rf, rhyolite-dacite fels; g, granite and syenite; dg, diorite and gabbro; tg, tonalite and granodiorite gneiss; dt, diorite and tonalite, includes mixed and altered rocks; mvs, metavolcanic and metasedimentary rocks.

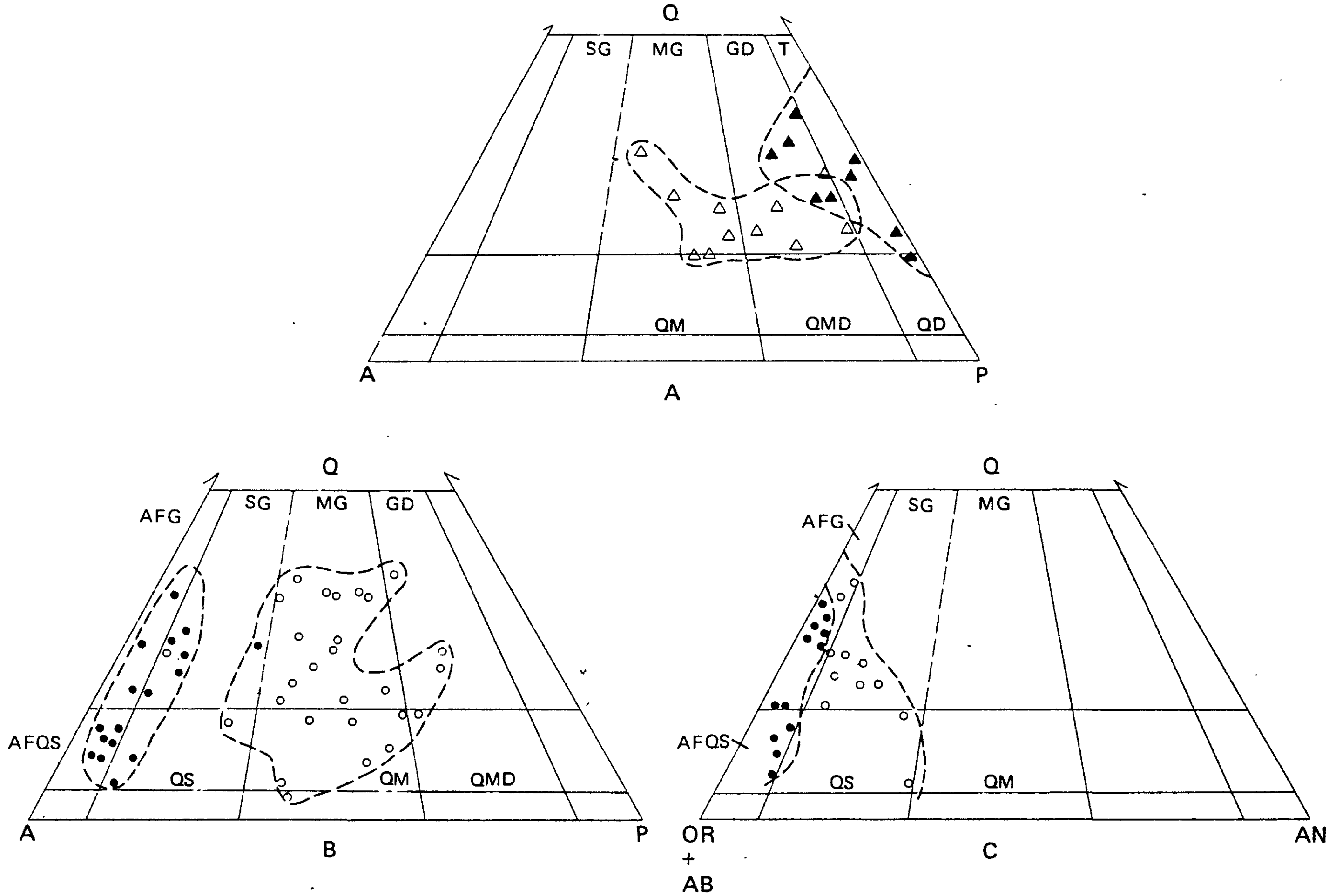


Figure 3.--Ternary diagrams showing compositional distribution of tonalitic and granitic rocks from the Wadi Habawnah and Najran quadrangles. Modes determined from stained slabs and standard-size thin sections, norms calculated from rapid rock analysis values. Q, quartz; A, alkali feldspar; P, plagioclase; AN, anorthite, OR+AB, orthoclase + albite. Fields labelled as follows: AFG, alkali-feldspar granite; SG, syenogranite; MG, monzogranite; GD, granodiorite; T, tonalite; AFQS, alkali-feldspar quartz syenite; QS, quartz syenite; QM, quartz monzonite; QMD, quartz monzodiorite; QD, quartz diorite. (A) Modal compositions of tonalitic rocks from the southeastern part of Wadi Habawnah and eastern part of Najran quadrangles (△) and representative compositions of rocks interpreted to be more felsic equivalents (▲) from the A'ashiba gneiss complex. (B) Modal compositions of samples from Ghezm, Najran, and Ya'arah plutons (•) and from Walih pluton and plutons in the headwaters of Wadi A'ashiba and along Wadi Gharb (o). (C) Normative compositions of samples from Ghezm and Najran plutons, including samples from Najran quadrangle (•) and from Khutan and Walih plutons and pluton in the headwaters of Wadi A'ashiba (o).

approximate. In places the units encompass septa of metadiorite, metagabbro, schistose rocks, and greenstone. These septa, and lineaments and textural differences observed on aerial photographs, serve to define the northeast trend of the complex. They also indicate westwardly convex-curved contact patterns, and show the nearly circular pattern of granitic dikes and lenses in granodiorite and dioritic country rock in and adjoining the complex.

Biotite tonalite gneiss (tbg), with local quartz diorite and granodiorite variants, is a distinctive rock characteristic of the southern end of the A'ashiba gneiss complex. It is typically light to medium gray (color index 12-40), fine to medium grained, equigranular, mildly to strongly foliated, and has ophitic-diabasic texture. Brown biotite in aggregates of small crystals is the most abundant mafic mineral; colorless clinopyroxene (probably augite), green to brown hornblende, and magnetite form crystal aggregates and crude mineral layering. Anhedral to subhedral sodic andesine (An_{30-40}) contains sericitized cores, but much plagioclase is fresh and appears recrystallized. Microcline occurs as rare porphyroblasts and rims on plagioclase. Accessory minerals are sphene, apatite, zircon, red spinel, and magnetite. Plagioclase is highly saussuritized at some localities.

Granodiorite gneiss (gdmg) is fine to medium grained, mesocratic (color index 15-25), allotriomorphic, and contains pink microcline porphyroblasts concentrated in roughly northeast-trending zones. Zoned sodic andesine (An_{30-38}) and oligoclase (about An_{17-20}) having albite and microcline rims, are commonly strained, but a diabasic-ophitic texture is characteristic of these rocks and seems to be a relict texture of earlier tonalite and quartz diorite. Mafic and felsic minerals form crude layering subparallel to foliation. Brown biotite and hornblende are dominant, although augite or augite-aegirine are present as single crystals or in the cores of biotite and amphibole. Some amphibole may be in part sodic or iron-rich (ferrohastingsite(?)) and occurs as patches and partial rims on hornblende. Quartz is moderately to highly strained. Accessory minerals are locally abundant and include magnetite, red spinel, sphene, zircon, and apatite. Epidote and calcite are locally common.

In the southern part of the A'ashiba gneiss complex, tonalite gneiss and quartz diorite gneiss are dominant. Northward, quartz content increases slightly, and biotite tonalite gneiss having crude mineral layering becomes the dominant rock type. Farther north, microcline porphyroblasts as much as 2 cm in diameter are concentrated along apparent east-northeast trends. These increase northward and locally make up as much as 20 percent of the rock. Rock groundmass becomes more leucocratic, and quartz content increases slightly. Lenses of granite, lit-par-lit fashion, are common along gneissic layering. Stringers and dikes of granite also increase. The resulting country rock in places is clearly migmatitic.

The modal compositions (fig. 3a) of samples collected from south to north across the A'ashiba gneiss complex emphasize the transition from tonalite to granodiorite. In these samples, the greatest increase is in potassium feldspar. A change in mafic minerals from predominantly biotite to biotite-hornblende with other amphiboles apparently accompanies the general northward compositional change to more felsic rocks.

Groundmass textures in tonalite and granodiorite in the A'ashiba gneiss complex closely resemble those in the metadiorite-metagabbro unit, but additional quartz and porphyroblastic microcline are present. Instead of representing a discrete intrusive body or bodies, the tonalitic and granodioritic rocks may have originally been rocks of the metadiorite and metagabbro unit that have been invaded, migmatized, and altered by potassium metasomatism during emplacement of syntectonic granite of the tonalite-granite suite.

Similar assemblages of gradational gneissic rocks mapped as biotite tonalite gneiss crop out north of the Walih pluton and east of the Ghezm pluton. These rocks are broadly similar to the rocks in the A'ashiba gneiss complex and may be coeval.

Granite

Granite of the tonalite-granite suite is dominantly biotite or biotite-hornblende calc-alkaline granite that commonly occurs in irregular, elongate outcrop patterns or lense-like concordant stringers. It is commonly foliate and locally exhibits textures and mineralogy that indicate recrystallization under deformational stress, including possible development of granulite. These granite bodies occur in and adjoin migmatite terrane in the A'ashiba gneiss complex, southeast of the Walih pluton, southeast of the Ghezm pluton, and between Wadi Gharb and Wadi Arjan.

The granite, mostly monzogranite with syenogranite facies, is pink to reddish-orange, fine to medium grained (mgb), and coarse grained (mgbc), with seriate, commonly granuloblastic texture. Mafic minerals constitute 10 to 30 percent of the rock, commonly occur as glomerocrysts, and include brown or rarely green biotite associated in part with lesser amounts of brown to greenish hornblende, minor clinopyroxene, and locally magnetite, or magnetite associated with red spinel. Groundmass microcline is mostly weakly perthitic;

microcline porphyroblasts or phenocrysts are moderately perthitic. Plagioclase is mostly weakly zoned oligoclase (An_{20-30}) with lesser, variable amounts of albite. Quartz is moderately to highly strained, and commonly mosaicked and sutured. Muscovite occurs as a minor late primary or secondary mineral associated with biotite in some samples. Accessory minerals include zircon, allanite, spinel, sphene, rutile, fluorite, and apatite. Zircon is slightly metamict. Alteration and vein minerals are mostly quartz, epidote, chlorite, sericite, and iron oxides and hydroxides. In many samples, plagioclase is replaced by microcline, and biotite has been completely converted to green chlorite. Hornblende is commonly poikiloblastic, and quartz-eye and perthite blasts are common. Minor magnetite leuco-monzogranite is also present in the biotite-monzogranite unit east of the Ghezm pluton. These features indicate recrystallization of granite under deformational stress, possible addition of potassium feldspar, and retrograde metamorphism or hydrothermal alteration. The migmatitic nature of the rocks, their sutured granuloblastic textures, and possibly the association of magnetite and spinel may indicate that the granite was subjected to middle crustal or deeper conditions either during or after emplacement.

Dike-like and irregular small bodies of undivided granite (g) mapped from south of the Thar and Walih plutons to the Najran pluton are probably mostly monzogranite related to the tonalite-granite suite, but probably also include granite varieties of the young intrusive suite.

The mapping distinction between the biotite monzogranite of the tonalite-granite suite (mgb, mgbc) and the biotite-amphibole granite (grba), which is provisionally ascribed to the young intrusive suite, is uncertain in many areas, such as along the boundaries of the A'ashiba gneiss complex and the Khutan pluton, the southern boundary of the A'Sud pluton, and in the Zilm plutonic complex south of Wadi Habawnah. Rocks of these units are megascopically indistinguishable at many localities, and each unit as mapped contains granite facies which satisfy the criteria used to classify the other. These granite units may be comagmatic. However, the different dominant lithologies, principally the differences in mafic mineral compositions, and apparent differences in gross textural features support the interpretation that they represent different episodes of granite emplacement.

Young intrusive suite

Granitic rocks crop out over 35 percent of the Wadi Habawnah quadrangle, and the granitic rocks of the young intrusive suite comprise the greatest volume. They include biotite-amphibole granite, alkali-feldspar granite, syenite, alkali-feldspar syenite, and monzonite. Alkali granite facies are characteristic of rocks in some plutons. Rocks related to the emplacement of the young intrusive suite, and therefore included in it, are biotite-olivine gabbro and diorite, pyroxene-olivine syenite, rhyolite-dacite fels, and granitic rocks complexly interlayered with older country rocks mapped as mixed-rock units.

Granitic rocks of the Najran, A'Sud, and Ya'arah plutons, the Ghezm pluton, the Thar and Walih plutons, the Shubaruk and Eargairth stocks, and the southern margin of the pluton northeast of the Thar pluton are all discordant bodies (fig. 2) and are included without reservation in the young intrusive suite. Granitic rocks which are provisionally included in the young intrusive suite are those of the Khutan pluton, the Zulm pluton, and rocks along the northern boundary of the quadrangle north of the Walih pluton. These rocks vary in composition and in the degree of foliation and cataclasis. They range from biotite-hornblende and biotite granite to biotite-amphibole granite containing probable ferrohastingsite as the distinctive amphibole (D. B. Stoeser, written commun., 1982). Their fabric ranges from massive to moderately foliate, and they occur in discordant to apparently concordant bodies.

Whether plutonic rocks of the young intrusive suite represent more than one major magmatic event is not known. Some of the plutons clearly cross-cut other granite bodies also ascribed to the young intrusive suite. The relative times of emplacement of granitic units of the young intrusive suite are believed to be, in chronological order: biotite-amphibole granite (grba), fine-grained biotite monzogranite (mgbf) of the Thar and Walih plutons, coarse-grained syenogranite (sgc) of the Ghezm pluton that was perhaps emplaced nearly concurrently with the perthite granites with alkali facies (agpa) of the Najran, Ya'arah, and A'Sud plutons. Stocks of pyroxene syenite (sp) and magnetite pyroxene alkali-feldspar granite (agm) are interpreted to be related to perthite granite (agpa), as are small bodies of pyroxene-olivine syenite (spo), rhyolite-dacite fels (rf), and the syenogranite aplite dike (sap) south of the Walih pluton.

A general discussion of the composition, texture, and structure of these granitic rocks is summarized below:

1. Both subsolvus (two feldspar) and hypersolvus (one feldspar) granites occur in sharply to poorly defined plutons, dikes, and pod- or lens-shaped bodies. Subsolvus granites are subaluminous to metaluminous, commonly monzogranitic, but also syenogranitic in composition. In these, potassium feldspar is characteristically nonperthitic to weakly perthitic microcline (0 to 25 percent albite). Mafic

minerals are commonly biotite and hornblende, but include other amphiboles such as probable ferrohastingsite (D. B. Stoeser, written commun., 1982).

Hypersolvus granites may include some peralkaline granite facies although the chemistry is not strictly peralkaline (Shand, 1947). These include perthite granite, syenite, and alkali-feldspar and pyroxene syenites. These granites are characterized by highly perthitic microcline to mesoperthite and antiperthite. Mafic minerals include biotite, hornblende, probable ferrohastingsite, and other amphiboles. Clinopyroxenes are common in many of these granitic rocks. Arfvedsonite and riebeckite occur in alkali-granite facies.

2. Modal compositions of granites from the Wadi Habawnah quadrangle (fig. 3b) show that these rocks form distinct compositional groups, one mostly in the monzogranite field, and the other near the alkali-feldspar granite-syenite field boundary. Normative mineralogy (fig. 3c) shows a similar pattern although the separation into two groups is less distinct, and the overall calculated compositions are more alkaline than the modal ones.

3. Clinopyroxene minerals are present in many of the granitic rocks in the Wadi Habawnah quadrangle, probably more common than previously reported from the Arabian Shield (D. B. Stoeser, written commun., 1982). They consist of colorless to pale-tan pyroxene identified petrographically as augite, and in one sample as diopside by X-ray diffraction analysis; nonpleochroic medium-green pyroxene identified as aegirine-augite; non-pleochroic very pale green and olive-drab-green pyroxene, possibly ferroaugite; and unidentified slightly pleochroic light-green to light-yellow-green pyroxene. Optic angles are generally moderate, about 30° to 45°. The pyroxenes occur mainly in alkali-feldspar granite and syenite, but also in syenogranite. Their habit is single crystal grains or cores of grains made up mostly of amphiboles. As such, they appear to be primary minerals, partly replaced by amphiboles during a late stage of crystallization or from later hydrous reactions.

4. Granite plutons in this quadrangle can be roughly defined as syntectonic or posttectonic based on the degree and kind of deformation and alteration displayed by the crystal fabric and mineralogy. Monzogranite seems to be syntectonic in many areas, and is foliated and gneissose in areas such as along Wadi Arjan and along the northern boundary of the quadrangle where it intrudes the metadiorite-metagabbro unit. Elsewhere, such as in the small pluton at the headwaters of Wadi A'ashiba in the east-central part of the quadrangle, the granite appears relatively unaltered and is weakly foliated. Most felsic dikes and lenses seem to be of monzogranite composition, and their trends and proximity to foliated granite indicate that they are comagmatic with the foliated rocks.

Most syenogranites and alkalic granites appear to have been emplaced in posttectonic stress environments. The alkalic granites in the Najran and Ya'arah plutons apparently were both intruded and cooled in a largely passive tectonic stress environment, but those in the A'Sud pluton are characterized by foliation and cataclastic textures. Rocks in the Ghezm pluton show relatively few strain effects. Granites of the Thar and Walih plutons are also considered to be posttectonic; their flow foliation is interpreted to result from diapiric intrusion rather than from an imposed external stress field.

5. Plan shape of granitic plutons ranges from irregular amoeboid (granite of the Zilm plutonic complex; Najran pluton) to ovoid and circular (Thar, Walih, Khutan and Ghezm plutons). The circular and ovoid Thar and Walih plutons suggest diapiric emplacement such as those reported in many areas of the Arabian Shield (Greenwood and others, 1980, p. 21-22). Concentric dikes of granite in the metadiorite-metagabbro unit and other rocks in the headwaters of Wadi Na'aman, east of Wadi Ithaiba, and in the Zilm plutonic complex outline circular to ovoid structures. These are interpreted to be ring dikes derived from subjacent plutons similar to those now exposed at Wadi Thar and Jabal Walih. Most of these granites are biotite and biotite-amphibole monzogranites, and are considered to be cogenetic with the granite of these plutons. Their occurrence may have structural implications as well. The plug and ring plutons appear to have pierced higher levels of the crust along a northwestern trend north of Wadi Habawnah. This might be the result of a fault or hinge line along Wadi Thar and Wadi Habawnah, north side up, having subsequent deeper erosion on that side, or might simply represent intrusion at different crustal levels.

Most granites in the quadrangle probably were emplaced at intermediate crustal depths or were subjected to middle crustal environment perhaps by loading of stacked thrust plates with resulting anatexis. Criteria for rocks of middle crustal origin given by Hamilton (1981; oral commun., 1982) include the presence of: migmatites and amphibolite-facies rocks; minerals of generally water-rich aluminous magmas; and at least locally two-mica granites having late muscovite and mesoperthitic (nearly peralkaline) granites. These features are characteristic of many granitic rocks in the Wadi Habawnah quadrangle. The abundance of pegmatites cited by Hamilton as characteristic of middle crustal conditions, however, does not seem applicable; pegmatites are rare in the quadrangle, and those that are present are simple quartz-feldspar varieties.

Criteria for rocks of lower crustal origin (Hamilton, 1981) include the abundance of anhydrous minerals and magmatic volume greater than that of the pre-existing rocks. Relatively abundant clinopyroxenes in the quartz-deficient perthitic alkali-feldspar granites and syenites of the area may suggest lower-crust derivation for these rocks. Features ascribed to granulites in syntectonic granite and associations of locally common magnetite and spinel may also be suggestive of these environments. Extensive replacement of the anhydrous mafic minerals by amphiboles and biotite may indicate that the plutons reached middle crustal depths before they solidified.

Sub-upper crustal environments are also suggested by the absence of felsic rock counterparts of the granitic rocks, although rocks of the rhyolite-dacite fels unit may represent shallow equivalents of the alkalic granitic rocks. The numerous dikes in parts of the quadrangle also indicate fracturing of brittle country rock at relatively shallow crustal depths.

Biotite-amphibole granite

Biotite-amphibole granite (grba) comprises the southern part of the Zilm plutonic complex, the Khutan pluton east of Jabal Ya'arah, and the northernmost part of the Zulm pluton along the southern boundary of the quadrangle, which is mostly exposed in the adjoining Najran quadrangle (Sable, in press). This granite also comprises the southernmost edge of a circular ring pluton mostly exposed in the Wadi Wassat quadrangle to the north (Greenwood, 1980a) where it was termed biotite-riebeckite-arfvedsonite quartz monzonite (equivalent to monzogranite of terminology in this report).

Biotite amphibole granite is pink to reddish-orange, mostly seriate, fine to coarse grained, weakly to moderately foliate, and in places possibly recrystallized from an earlier coarser granite. Granite ranges from monzogranite to syenogranite in composition, with some cataclastic-textured quartz monzonite and rare alkali-feldspar granite that may represent younger granite intrusive into the biotite-amphibole granite unit.

Mafic minerals constitute 3 to 15 percent of the granite. Biotite is generally dark brown or olive green to yellowish and appears to be generally a later mineral than essential amphiboles. Amphiboles include probable ferrohastingsite, hornblende, and amphiboles exhibiting a wide variety of pleochroic hues ranging from dark green to blue green, yellow, and colorless. Quartz occurs as a mosaic, as interstitial grains and clots, and as porphyroblasts. Potassium feldspar occurs as slightly perthitic groundmass microcline and microcline having patch and vein perthite that generally occurs as clots of crystals and single large porphyroblast-like crystals. Plagioclase is sodic to median oligoclase and albite in part in equilibrium with microcline. Rare clinopyroxene occurs as ragged crystals partly replaced by amphibole. Accessory minerals are locally abundant and include large grains of magnetite and zircon, sphene, apatite, and allanite and minor fluorite. Minor chlorite replaces biotite in some samples, and minor sodic(?) amphiboles occur as patch and rim replacements of ferrohastingsite and hornblende.

Fine-grained biotite monzogranite

Fine-grained biotite monzogranite (mgbf) occurs in the north-central part of the quadrangle in the Thar and Walih plutons, two circular to ovoid bodies interpreted to be diapiric intrusions. The Thar pluton lies within the Zilm plutonic complex and contains an interior ring of essentially unaltered biotite gabbro and diorite (gdb) that is younger than the granite. The Walih pluton contains a central area of undivided granitic and dioritic(?) rock (dgg) interpreted to be mostly country rock.

Fine- to medium-grained, leucocratic to mesocratic biotite monzogranite is grayish pink, pale red, and moderate reddish orange, has moderate to strong foliation, and in part gneissoid mineral layering that conforms to the shape of the pluton margins. The foliation and layering are considered to be primary. Textures are mainly allotriomorphic granular, with seriate to bimodal grain size, suggesting hypabyssal or near-surface crystallization. Mafic minerals are brown to brownish-gray biotite and minor hornblende that constitute 1 to 15 percent of the rock. Perthitic microcline occurs as porphyroblasts or phenocrysts, and also partly replaces plagioclase; groundmass microcline is nonperthitic to weakly perthitic. Plagioclase is median oligoclase and appears to be generally out of equilibrium with potassium feldspar. Magnetite (as much as 2 percent) is commonly associated with or replaces mafic minerals, particularly in the Thar pluton. Granophyre and myrmekite are locally present. Late muscovite is present in a few samples. Accessory minerals are zircon, magnetite, apatite, and fluorite. Alteration includes darkening of biotite to almost opaque mica and replacement of biotite by chlorite and opaque minerals.

Biotite gabbro and diorite

Fresh, massive, melanocratic biotite gabbro and diorite (gdb) is associated with metagabbro-metadiorite and granite mostly in the Zilm plutonic complex in the northwestern part of the quadrangle and in some areas in the southeastern part. The unit locally includes rocks of the older metadiorite and metagabbro unit and in places the younger rocks are mapped with that unit. Gabbro is gray to dark gray but weathers dark brown as a massive to bouldery, extremely tough rock. It is generally fine to medium grained and locally coarse grained. No mineral alignment or layering was seen in the gabbro. The coarse-grained rock is essentially unaltered. Gabbro in the Thar pluton transects foliation of the granite there. The gabbro and diorite are interpreted to be post-tectonic bodies injected into the more highly metamorphosed rock matrix of the earlier hornblende-biotite metadiorite and metagabbro and locally into granite; where seen, contacts with adjoining granite were sheared and no inclusions in either rock type were observed.

The gabbro is allotriomorphic equigranular, contains 40 to 60 percent mafic minerals, reddish-brown titaniferous biotite, olivine, and augite, less common secondary greenish pyroxene, and reddish-brown poikiloblastic kaersutite. Biotite is locally poikiloblastic. Feldspar is subhedral labradorite (An_{55-70}). The order of crystallization of mafic minerals appears to be olivine, augite, kaersutite, and biotite. Glomerocrystic clusters of biotite and kaersutite 1 to 6 cm wide are common in some localities. Accessory minerals are calcite (automorphic?), apatite, magnetite-ilmenite, and minor quartz. Green clinopyroxene and amphibole rims on augite, and hypersthene rims on olivine and augite are common.

Nearly unaltered hornblende gabbro and diorite and biotite-hornblende gabbro having diabasic texture occur in and south of the Thar pluton and are also included in this unit. These medium- to coarse-grained rocks are associated with biotite-olivine gabbro south of the Thar pluton. Plagioclase is calcic andesine to labradorite (An_{45-65}), and hornblende occurs as relict pyroxene crystal "ghosts" having cores of colorless pyroxene (augite?) in some samples. Magnetite is locally abundant and one sample contains 5 percent quartz. These rocks appear to be continuous with those of biotite-hornblende diorite unit of the Wadi Wassat quadrangle (Greenwood, 1980a) which has been dated at 640 Ma. Age of the biotite gabbro and diorite unit relative to perthite granite and its presumed correlativers described below is uncertain.

Sodic amphibole perthite granite

Sodic amphibole perthite granite (agpa) is distinctive and comprises three plutons in the quadrangle: the extensive Najran pluton or batholith that crops out over more than 350 km^2 in the southwestern part; the Ya'arah pluton that crops out over about 25 km^2 in the northeastern part; and the A'Sud pluton that crops out over about 24 km^2 in the northwestern part of the quadrangle (fig. 2). The Najran and

Ya'arah plutons are discordant bodies having textures and mineralogy that reflect little deformation or alteration except for probable late- or post-emplacement cataclastic effects. Rocks of the A'Sud pluton are more highly deformed. Granite in the Najran and Ya'arah plutons weathers into large joint blocks and gigantic wind-scoured rounded boulders.

The unit is mostly perthite granite with alkali granite facies. Minor constituents are syenogranite, perthite-amphibole syenite, quartz syenite, and monzogranite. Magnetite-riebeckite porphyritic leucomicrogranite occurs as a minor facies in the A'Sud pluton.

The granite is mostly brownish gray to olive gray, and ranges to reddish brown. It is leucocratic to submesocratic, medium to coarse grained, massive, and mostly structurally isotropic to weakly foliate. Cataclastic textures include augen gneiss and mylonite along zones of shear. Essential mafic minerals include several amphiboles associated with reddish-brown to brown late biotite which commonly occurs as small interstitial grains. Amphiboles include probable ferrohastingsite (pleochroic dark apple green - dark olive green - light olive green, length slow, with small 2V), arfvedsonite (pleochroic blue to blue green - apple green - olive brown), green to brown hornblende, light-green to yellowish hornblende(?), and riebeckite (smokey blue to light blue green) in large single crystals and late small acicular crystals, and minor unidentified greenish to yellow amphiboles. Minor aegirine-augite appears to have been an early mineral replaced by amphiboles. Microcline, largely patch and vein mesoperthite having rims and patch replacements of late albite, constitutes nearly all of the potassium feldspar. Antiperthite is also present. Minor plagioclase in discrete grains is albite (An_{5-10}) with sericitized cores. Quartz grains are weakly stressed. Accessory minerals are locally abundant and commonly occur in large grains. They include allanite and sphene that form irregular clots with mafic minerals, zircon, magnetite, magnetite-ilmenite, ilmenite, apatite, fluorite, and unidentified minerals that include a pleochroic yellow mineral and a pleochroic yellow-brown to red-brown mineral with negative sign and large optic angle. Rutile occurs as exsolved crystals in aegirine-augite. Chlorite locally replaces biotite, and epidote occurs in plagioclase.

In the Najran pluton the content of sodic amphibole relative to that of biotite and ferrohastingsite may increase westward. Scattered samples indicate westward changes of mafic mineral assemblages from monomineralic biotite to biotite-hornblende to ferrohastingsite with only minor biotite and, finally, to arfvedsonite and riebeckite. In addition, country rock and rhyolite-dacite fels along the western boundary of the Najran pluton are higher in sodic amphiboles than country rock to the north or east.

The perthite granite may include some peralkaline facies as indicated for rocks of the Najran pluton by Stoeser and Elliott (in press), but chemical compositions of the few samples analyzed (table 1) are not strictly peralkaline according to the scheme of Shand (1947).

Pyroxene syenite and magnetite alkali-feldspar granite

Areas of alkaline rock in the Eargairth and Shubaruk stocks (fig. 2), pyroxene syenite (sp) and magnetite alkali-feldspar granite (agm), are poorly defined because few sharp color or textural differences exist between them and the country rock, because they contain vague septa of country rock, and because the granitic rocks also occur as small bodies in country rock near the stocks. In outcrop they are characterized by yellowish-brown-weathering colors resulting from pervasive intergranular iron hydroxides. Minor amounts of diorite and mixed rock in these areas may be septa or xenoliths. Gabbro, olivine gabbro, and granite, which may be younger than the granitic and syenitic rocks, also are locally present. On aerial photographs, these areas are characterized by finely dissected drainage patterns.

The rocks are dominantly syenite and alkali-feldspar granite, and include magnetite alaskites in the Eargairth stocks. They are leucocratic to mesocratic, gray to brownish gray, fine grained, weakly foliated and locally cataclastic, and generally seriate to porphyritic in texture. The rocks contain microcline mesoperthite and orthoclase, minor amounts of quartz with weak undulatory extinction, very minor sodic andesine(?), and about 0 to 10 percent mafic minerals including augite(?), aegirine-augite(?), greenish to brownish hornblende, and minor biotite. Blue-green to green amphibole rims are common on pyroxene and hornblende. Clinopyroxene is commonly altered and replaced, and occurs as relict cores in aggregates of amphiboles, biotite, magnetite, and sphene in some samples. Accessory minerals are apatite, zircon, magnetite, and sphene. Iron hydroxide staining is common, and mafic minerals, particularly biotite, commonly show bleaching, chloritization, and replacement by magnetite, which also occurs in skeletal replacement textures after clinopyroxene.

Contacts with country rock were not seen in the field, but are assumed to dip steeply, similar to the foliation in the surrounding rocks. The plutons are discordant and post-date adjoining diorite and tonalite and the biotite quartz schist unit. They are interpreted to be related to intrusion of perthite granite.

Table 1.--Chemical compositions and agpaitic ratios of representative Precambrian rocks from Wadi Habawnah and Najran (NJ) quadrangles
[Analysis using X-ray fluorescence rapid rock method by USGS/DGMR laboratories, Jiddah. All values are in weight percent. Leaders (--), not available]

RASS sample number	General location	Latitude (N.) and longitude (E.)	Rock Type	SiO_2	Al_2O_3	Fe_2O_3
137587	Wadi Gurra	17°45'01" 44°14'47"	MVF	44.98	8.78	8.90
137659	Wadi Khutan area	17°59'25" 44°23'40"	MVF	45.60	17.01	8.24
137331	Wadi Khutan area	17°53'14" 44°21'20"	MVF	50.50	13.40	3.98
145260	Wadi Ithaiba area	17°38'31" 44°11'44"	MD	52.80	14.21	4.61
137502	Zilm pluton	17°47'55" 44°00'03"	GA	44.80	18.04	7.79
145272	South of Jabal Zilm	17°43'10" 44°09'59"	DR	54.38	18.09	3.00
137612	A'ashiba complex	17°44'05" 44°21'40"	TO	63.12	16.93	2.79
137975	East of Ghezm pluton	17°53'52" 44°05'15"	GD	66.70	15.86	1.47
137686	Jabal Ya'arah	17°53'04" 44°28'26"	QM	67.54	15.81	1.25
137214	East of Ghezm pluton	17°58'33" 44°01'28"	MG	74.40	12.15	2.13
137273	Thar pluton	17°54'38" 44°17'24"	MG	72.60	13.90	0.56
137592	Thar pluton	17°56'04" 44°16'40"	MG	72.45	14.52	.61
137344	Thar pluton	17°54'08" 44°17'47"	MG	76.60	13.00	.22
137596	Head of Wadi Na'aman	17°44'31" 44°17'32"	MG	70.40	14.31	1.04
137484	Head of Wadi A'ashiba	17°40'27" 44°19'34"	MG	76.20	13.80	.79
137189	Wadi Gharb	17°42'30" 44°05'10"	MG	76.40	12.55	.62
137698	Isolated; north of W. Najran	17°32'49" 44°21'17"	MG	67.20	15.10	1.22
137886	Zulm pluton NJ	17°26'05" 44°14'15"	MG	67.70	15.68	2.45
137930	Zulm pluton NJ	17°25'47" 44°18'18"	MG	76.20	11.23	.61
137927	Wadi Farah pluton NJ	17°25'04" 44°15'43"	MG	74.20	15.66	1.18
137935	Wadi Silah pluton NJ	17°25'42" 44°19'32"	MG	72.30	13.76	1.04
137153	Najran pluton	17°34'04" 44°02'09"	SG or AFG	64.30	16.10	1.39
137353	Najran pluton	17°31'33" 44°08'52"	SG or AFG	68.00	14.40	.82
145197	Najran pluton	17°52'13" 44°00'50"	SG or AFG	76.20	12.44	.42
145132	Najran pluton NJ	17°22'42" 44°06'43"	SG or AFG	67.50	13.20	2.16
145144	Najran pluton border NJ	17°26'37" 44°01'13"	SG or AFG	75.40	10.60	2.85
137376	Near Shubaruk stock	17°37'28" 44°06'55"	SG	77.10	12.10	.27
137474	Shubaruk stock	17°36'45" 44°19'37"	AFG	76.40	12.45	.49
137201	3 km east of west boundary	17°47'43" 44°01'31"	BS	65.70	8.60	2.72

Table 1.--Chemical compositions and agpaitic ratios of representative Precambrian rocks from Wadi Habawnah and Najran (NJ) quadrangles--Continued

FeO	MgO	CaO	Na_2O	K_2O	H_2O	TiO_2	P_2O_5	MnO	Total Oxides	Agpaitic Ratio[1]
(Total Fe)	12.42	20.42	2.00	0.41	--	0.37	0.50	0.18	98.81	0.44
5.73	7.09	10.80	2.27	1.26	1.17	.58	.15	.18	101.08	.30
6.24	6.05	10.40	1.75	3.32	0.94	1.05	.36	.36	98.35	.38
7.07	3.20	6.30	3.72	1.44	1.82	2.19	4.80	4.15	98.31	.54
1.03	8.44	14.60	1.74	.73	1.76	1.05	.31	.14	100.43	.20
5.43	2.82	5.50	4.56	1.34	1.26	1.71	.40	.13	99.64	.49
1.03	1.74	5.46	4.33	1.98	1.56	.32	.14	.08	99.46	.55
2.09	1.77	3.30	3.83	3.46	1.01	.53	.15	.06	100.23	.60
2.15	4.68	2.00	4.18	4.74	.64	.40	.11	.07	103.57	.76
1.15	0.09	0.92	3.20	5.00	1.01	.12	.03	.01	100.21	.88
0.97	.23	1.58	4.20	4.12	1.25	.16	.06	.06	99.69	.82
1.12	.40	1.65	4.00	4.09	.57	.07	.04	.06	99.59	.76
.36	.07	1.10	4.04	3.95	.98	.03	.02	.01	100.38	.84
2.11	.79	1.94	4.01	4.33	.46	.45	.13	.05	100.02	.79
1.32	.01	1.51	0.21	4.02	1.37	.25	.06	.03	99.52	.34
1.14	.09	.77	3.18	4.72	.75	.01	.01	.05	100.29	.82
1.83	1.35	2.82	3.53	4.37	1.51	.53	.17	.05	99.68	.70
.35	.52	1.35	4.21	5.00	3.90	.32	.05	.04	99.58	.86
1.83	.06	1.19	2.65	4.75	1.00	.14	.06	.04	99.76	.85
.93	.04	.88	3.75	4.64	.85	.07	.08	.03	102.29	.72
1.75	.15	1.00	3.28	5.52	1.21	.22	.12	.04	100.39	.83
3.56	.25	1.54	4.59	5.90	1.33	.47	.06	.09	99.58	.87
3.96	.14	1.43	4.58	5.17	1.08	.43	.07	.07	100.15	.91
.50	.03	.67	3.49	5.48	1.11	.05	.01	.01	100.31	.94
4.00	.34	1.72	4.36	4.97	1.11	.56	.13	.09	100.14	.95
.40	.27	.45	3.81	3.74	1.26	.18	.11	.01	100.01	.97
.48	.10	1.11	3.21	4.59	.81	.04	.02	.01	99.84	.85
.24	.07	.38	4.00	4.59	1.31	.03	.01	.01	99.98	.95
.04	.30	10.47	3.35	.75	1.34	.30	.37	.41	99.69	
								(CO_2 5.34)		

[1]Agpaitic ratio, molecular Na_2O+K_2O/Al_2O_3, used to classify igneous rocks on basis of degree of aluminum oxide saturation (Shand, 1947). MVF, metavolcanic flow rock; MD, mafic dike; GA, gabbro; DR, diorite; TO, tonalite; GD, granodiorite; QM, quartz monzonite; MG, monzogranite, SG, syenogranite; AFG, alkali-feldspar granite; BS, biotite schist

Pyroxene olivine syenite

Pyroxene olivine syenite (spo) is present in two localities in the Wadi Habawnah quadrangle: along Wadi Shilya (lat 17°36'51" N., long 44°09'53" E.), and west of Wadi Eargairth (lat 17°36'28" N., long 44°20'30" E.). The rock is olive gray to olive black, fine to medium grained, allotriomorphic equigranular to seriate, structureless, and unaltered. It is composed of 15 to 35 percent mafic minerals including olive-green clinopyroxene (ferroaugite(?)), apple-green clinopyroxene (aegirine-augite(?)), and fayalite with associated magnetite; 50 to 65 percent perthitic microcline and orthoclase(?) rimmed by albite; 5 to 15 percent calcic oligoclase (An_{25-30}); and minor quartz as single grains or in granophyre. Brilliant blue-green amphibole (arfvedsonite or riebeckite?) rims on mafic minerals are present in all samples. Accessory minerals are locally abundant apatite, zircon, magnetite, and an unidentified yellow mineral.

The pyroxene-olivine syenite occurs as small, probably tabular bodies associated with the perthite granite of the Najran pluton and pyroxene syenite of the Eargairth stocks. The mapped limits are very approximate; the syenite bodies may be sills or segregations related to the larger alkaline masses. The rock resembles the pyroxene syenite in the Shubaruk and Eargairth stocks except that it is melanocratic and contains olivine.

The pyroxene olivine syenite is similar in composition to shonkinite but contains fewer mafic minerals. Shonkinites have been reported in the southwestern part of the Arabian Shield in the Khamis Mushayt (Coleman, 1973) and Jabal Fayfa (Fairer, in press) quadrangles.

Rhyolite-dacite fels

Dark-hued, reddish- to dark-gray, flinty rhyolite-dacite fels (rf) having conchoidal fracture crops out over a few square kilometers in two main areas, along the west-central boundary and along the eastern boundary of the quadrangle. It also occurs in small areas in the southwestern corner of the quadrangle, in the A'ashiba gneiss complex, and in the A'Sud pluton. Most of the fels is located in or near alkalic granites and contains septa of greenstone or andesite flow rocks. In one area along the western boundary, the unit seems to intrude diorite and gabbro. Similar fels in the adjoining Mayza (Anderson, 1979) and Wadi Wassat (Greenwood, 1980a) quadrangles was termed a granophyre and granofels, respectively.

The fels is porphyritic to equigranular, structureless, and rhyolitic to dacitic in composition. It has a microcrystalline groundmass that is mostly allotriomorphic-granular but ranges to spherulitic devitrified glass. Phenocrysts or phenoclasts as much as 1 cm in diameter consist of subround quartz, antiperthitic plagioclase, and microcline. Biotite as single crystals or aggregates is the chief mafic mineral, but some samples along the western boundary of the quadrangle commonly contain riebeckite and arfvedsonite. Plagioclase phenocrysts range from medium oligoclase to albite and rare andesine; some show oscillatory zoning or sericitic cores. Feldspar is generally subhedral. One sample exhibited classic granophyric texture. Accessory minerals include apatite, zircon, rutile, carbonate, and opaque minerals.

At the western boundary of the quadrangle, the cross-cutting pattern of the fels suggests it is an intrusive or "alteration-halo" body in the meta-andesite unit related to the intrusion of the adjoining perthite granite. Elsewhere the fels adjoins mafic flow rocks, and the layered banded patterns extending from the flow rocks into fels, the apparent relict diabasic flow textures and the biotite and sodic amphibole mineralogy suggest that volcanic flow rocks have undergone partial alteration and recrystallization related to intrusion of the adjoining coarser-grained Najran and Ya'arah plutons.

Coarse-grained biotite syenogranite

Coarse-grained biotite syenogranite (sgc) occurs in the Ghezm pluton in the northwestern corner of the quadrangle. The pluton is a discordant elongate north-trending body that lies between the north-trending belts of volcanic and sedimentary rocks along the western boundary of the quadrangle and the granitic to dioritic migmatitic terrane to the east. It lies along the southern extension of the Ashara fault zone of Greenwood (1980a) and may transect part of the zone. The southern part of the pluton is massive, rugged mountains whereas the northern part is rounded hills of low relief characterized by highly fractured granite and marked by low linear ridges resulting from differential weathering of quartz-epidote veins and mafic dikes. Contacts with country rock are sharp and dip outward at moderate angles. Country rock inclusions are locally abundant near pluton margins; they are angular, sharply defined, and include tonalite, biotite augen gneiss, quartz diorite, diorite, and amphibolite. The only contact effect observed is hornfels less than a few meters thick.

The granite is fairly uniform, coarse to medium grained and structureless, pale to moderate red, and porphyritic to holocrystalline. Mild cataclastic and weakly foliated textures are locally present.

Mafic minerals include 4 to 11 percent brown to reddish-brown biotite and greenish hornblende, 35 to 60 percent moderately perthitic microcline having albite rims, 11 to 20 percent sodic oligoclase, and locally common minor late primary or secondary muscovite, and fluorite. Unidentified amphiboles partially replace hornblende. Accessory minerals are magnetite, allanite, fluorite, zircon, apatite, and sphene. Alteration and vein minerals are quartz and chlorite, sericite partially replacing plagioclase, and epidote occurring both in veins with quartz and partially replacing plagioclase and mafic minerals. The granite contains locally anomalous amounts of tin, molybdenum, and fluorine.

Age of this unit relative to that of the sodic amphibole perthite granite (agpa) is uncertain. The perthite granite of the A'Sud pluton appears to penetrate the syenogranite of the Ghezm pluton, but the A'Sud pluton granite is foliate and deformed relative to that of the Ghezm pluton. The syenogranite of the Ghezm pluton is here provisionally considered to post-date the perthite granite although it has been depicted to be monogranite older than the perthite granite (Sable, in press).

Zilm plutonic complex

The Zilm plutonic complex, a large, north-trending ovoid structure about 20 km long, lies between the Ghezm and Walih plutons (fig. 2) in the northwestern part of the quadrangle. Four distinctly different rock units are mapped in the complex and, in interpreted chronological order, are metadiorite and metagabbro (dg), syntectonic(?) biotite-amphibole granite (grba, g, in part), fine-grained biotite monzogranite (mgbf), and biotite gabbro and diorite (gdb).

In a regional structural context, the Zilm complex is outlined by present drainage patterns. The size and shape of this megastructure and the association of granitic and mafic rock types in it suggest that it may represent a fault-bounded collapsed caldera in which the latest phase of magmatism was passive emplacement of the young gabbro (gdb).

Dikes and sills

Many concordant and discordant tabular bodies of felsic to mafic composition intrude all mapped Precambrian units. All tabular bodies are referred to in this report as dikes for purposes of brevity, and only the most prominent dikes or those for which attitudes were measured are shown on the geologic map. Dikes range from a few centimeters to more than 300 m wide but most are 10 to 30 m wide. Along Wadi Arjan, they constitute about 30 percent of the outcrop. Most dikes are felsic, few are mafic, and those of intermediate composition (dacite to andesite) are rare.

Felsic dikes range in composition from rhyolite to dacite, are reddish gray to medium-dark gray, have a flinty appearance and conchoidal fracture, and are commonly porphyritic. Quartzofeldspathic groundmass is cryptocrystalline to fine grained and in some samples consists of devitrified spherulitic glass. Groundmass contains quartz, albite, oligoclase, microcline, and biotite. Phenocrysts of potassium feldspar, plagioclase, and quartz are as much as 1 cm long. Potassium feldspar includes perthite and microcline and in some samples partially replaces plagioclase. Plagioclase is albite-oligoclase. A few dikes in the northwestern and westernmost parts of the quadrangle contain arfvedsonite or riebeckite associated with biotite. Quartz occurs in single grains and in granophyric intergrowths. Most aphanitic felsic dikes lie along straight linear trends, but in some areas, such as in the metadiorite and metagabbro unit west of Wadi Arjan, they are folded, sheared, and dismembered.

Some felsic dikes, which have intruded migmatitic terrane along Wadi Arjan and Wadi Shilya, are coarser grained than the aphanitic dikes discussed above although their mineralogy is similar. They are commonly gneissic, complexly folded, and locally have been cataclasized and recemented by epidote and quartz. These are locally cut by felsophyric dikes and mafic dikes.

Mafic dikes are basalt, andesite, and greenstone; they are equigranular to porphyritic with diabasic and locally trachytic textures. Laths of andesine (An_{40-50}) are as much as 2 cm long. Most clinopyroxene has been replaced by hornblende, biotite, magnetite, and chlorite. Groundmass in most samples is highly altered to chlorite and sericite with epidote; fresher samples contain light-green acicular amphibole, biotite, and plagioclase. Spherical and flattened amygdules are filled with calcite, epidote, chlorite, and iron oxides.

Three small elongate bodies of flinty, porphyritic rhyolite or dacite (rd) occur within the metasedimentary rock unit near the western boundary of the quadrangle. They weather with a distinctive iron stain and contain phenocrysts of untwinned potassium feldspar, quartz, and plagioclase in a biotite-bearing quartzofeldspathic groundmass. They are interpreted to be of shallow intrusive origin, but may be boudins of rhyodacitic volcanic rock.

Aplite dikes (ap) of monzogranite composition are relatively common and are prominant in the Najran pluton. A large syenogranite aplite dike (sap) south of the Walih pluton locally contains biotite and sodic amphibole and is believed to be genetically related to the perthite granite (agpa) of the Ya'arah pluton.

Pegmatites (not mapped) are relatively rare, occur as short lenses, and consist of perthite-quartz, perthite-quartz-biotite, and albite-quartz. Sparse tourmaline (dravite and schorl) is present at four localities near the northern boundary of the Najran pluton and in the Ya'arah pluton.

Two or more episodes of dike emplacement are indicated by cross-cutting relationships, but an integrated explanation of their age relationships has not been developed. The youngest, diabasic mafic dikes (—x—x—x—) cut all Precambrian units in the quadrangle including linear felsic dikes. These may be of Tertiary age but are shown as Precambrian on the correlation. Precambrian felsic dikes (—•—•—•—) are divided into two catagories: linear felsic dikes that intrude relatively young unaltered biotite gabbro and diorite (gdb); coarser grained folded felsic dikes that appear to be offshoots of small stocks or to be on the fringes of syntectonic granite plutons of the tonalite-granite suite. The folded dikes dikes are cut by younger linear felsic and mafic dikes, many of which are subparallel and may be coeval. Mafic dikes and sill-like bodies that intrude volcanic flow rocks of the meta-andesite unit may represent a still older intrusive dike event. At one locality, the fact that a microgabbro dike cuts a stratabound massive sulfide gossan in greenstone and schist suggests that the sulfide mineralization was coeval with the volcanic flow rock in which it occurs.

In a few areas dike swarms consisting mostly of felsic rock give the impression of layered rock in outcrop. In the Wadi Arjan area, dikes appear to have intruded linear fractures formed during intrusion of the Shubaruk stocks or appear to have been produced by later stresses that were influenced by the presence of the structurally competent crystallized stocks. These dikes are quartz-rich compared to the syenitic rocks of the stock and are considered to be younger than the stock.

Milky-white, grayish, and light-greenish (chloritic) quartz veins and lenses, ranging from a few centimeters to several meters thick, are common in and near granite plutons. Some are slightly iron stained. An irregularly-shaped concentration of quartz (qz), as much as 100 m across, and numerous quartz veins (—/////—) were mapped in granite of the Ghezm pluton; smaller concentrations of quartz also occur at various other localities but they are not shown on plate 1. Examination and analysis of a few quartz samples showed no anomalous concentrations of minerals.

Irregular areas of fine-grained quartz-epidote-magnetite rock (ep) are present in the Najran pluton and at other localities. Epidote is present as fine disseminations in quartz. Thin veins of quartz-epidote and quartz-potassium feldspar-epidote, mapped as quartz veins, are common in the Ghezm pluton and stand out as resistant linear ribs that resemble dikes. Epidote occurs in varying quantities in all Precambrian crystalline rocks in the quadrangle; together with quartz, it probably represents the latest stage of Precambrian deuteric alteration in the area.

GEOCHRONOLOGY AND AGE RELATIONSHIPS

There is little direct age information for the rocks of the Wadi Habawnah quadrangle, but several geochronologic studies conducted in areas to the north and west provide a basis for inferring the absolute ages of major rock units and lithogenic events. None of the units in the Wadi Habawnah quadrangle is believed to be more than 800 Ma old and there is no evidence of layered or plutonic rocks that predate the layered rocks mapped here.

Age-dating of volcanic rocks of the Halaban group (as used by Greenwood and others (1982)) has been done only on samples collected 350 km north in the Bi'r Juqjuq and Al Junaynah quadrangles; these samples produced primary whole-rock rubidium/strontium (Rb/Sr) isochron ages of 746±16 Ma and 785±96 Ma, respectively (Fleck and others, 1980). Although it is not known whether these absolute dates apply to the layered rocks mapped as Halaban group in the Wadi Habawnah quadrangle, they are at least consistent with the fact that no crosscutting plutonic rocks in the southeastern Shield are older.

Rocks ranging from tonalite to diorite in the southern extension of the Tarib batholith (Stoeser and others, in press) have been studied by Rb/Sr and uranium-lead (U-Pb) (zircon) methods in quadrangles northwest of the Wadi Habawnah quadrangle. The Suwaydah biotite-hornblende tonalite gneiss in the Wadi Malahah quadrangle is 725±30 Ma old on the basis of a Rb/Sr whole-rock isochron (Stoeser and others, in press) and 729±3 Ma old on the basis of U-Pb measurements of zircon (Greenwood and others, 1982). A similar quartz diorite, although without gneissic fabric, from the Wadi 'Atf quadrangle produced a similar U-Pb zircon date of 732±3 Ma (Greenwood and others, 1982). No rocks in the Wadi Habawnah quadrangle are known to correlate with those of the Tarib batholith, although parts of the metadiorite-metagabbro unit may.

Gneissic and foliated rocks of the tonalite-granite suite west of the Wadi Habawnah quadrangle appear to have been emplaced about 690 Ma to 640 Ma ago. Granodiorite and tonalite gneiss in the Malahah dome 40 km northwest of the Wadi Habawnah quadrangle produced a Rb/Sr whole-rock isochron age of 684±43 Ma (Fleck and others, 1980). Gneissic biotite monzogranite and trondhjemite gneiss, which intrude the Suwaydah tonalite gneiss in the Wadi Malahah quadrangle 30 km northwest of the Wadi Habawnah quadrangle, produced U-Pb zircon ages of 660±7 Ma (Cooper and others, 1979) and 657±3 Ma (Stoeser and others, 1983). Hornblende-biotite granodiorite gneiss from the A'ashiba gneiss complex collected near the Najran airport in the Wadi Habawnah quadrangle (RASS 128905, lat 17°37' N., long 44°29' E.) produced a U-Pb zircon age of 641±10 Ma (Stoeser and others, 1983). A similar age of 641±2 Ma was obtained from zircons in foliated quartz diorite in the Simlal area 10 km north of the quadrangle (Stoeser and others, 1983). This unit appears to be co-extensive with the metadiorite-metagabbro unit of this quadrangle.

No absolute ages are available for the granite and syenite units of the young intrusive suite nor is there much evidence from adjoining areas to infer their ages of emplacement. However, these plutons cut across the tectonic fabric common to the layered rocks and gneisses of the tonalite-granite suite. Therefore, they must be younger than about 640 Ma.

Field relationships of some units in the quadrangle give evidence for relative ages of Precambrian rocks:

1. The general westerly dip of the metavolcanic and metasedimentary rocks near the western boundary of the quadrangle and a few observations of bedding tops indicate a generally ascending stratigraphic sequence westward and a gradational boundary between the underlying metavolcanic unit and the overlying metasedimentary unit.

2. Microgabbro dikes in metavolcanic rocks of the Halaban group contain xenoliths of diorite and quartz diorite, and the metadiorite-metagabbro unit contains xenoliths of andesitic and basaltic rock. Boundaries between these volcanic and plutonic rocks are vague and diffuse, and the plutonic rocks of the metadiorite-metagabbro unit are interpreted to be essentially comagmatic or only slightly younger than the volcanic rocks.

3. Clasts in Halaban group metasedimentary rocks include quartz, plagioclase, and fragments of volcanic ejecta and intermediate composition crystalline rocks. No granitic clasts were observed.

4. Granitic rocks, such as those in the Ghezm and Najran plutons, contain xenoliths of dioritic and andesitic rock. Other granitic rocks contain blocks of diorite, gabbro, schist, amphibolite, and greenstone.

5. Plug- or ring-type circular plutons north of Wadi Habawnah are discordant with and younger than rocks of the diorite and gabbro suite and the tonalite-granite suite.

6. Amounts of potassium feldspar and to some extent quartz in tonalitic rocks in the southern and southeastern parts of the quadrangle increase in a more or less regular fashion northwestward as the result of the addition of potassium and silica. Consequently, quartz diorite gneiss and tonalite gneiss change compositionally to granodiorite and monzogranite.

7. Stress during crystallization or recrystallization is indicated by fragmented and recemented mafic minerals, cumulate textures, bent crystals and twinning in plagioclase, strained quartz and feldspar, and foliation resulting in structural anisotropism. Rocks of the Ghezm, Najran, and Ya'arah plutons and the biotite gabbro and diorite unit are nearly structureless; foliation is absent or poorly developed except near faults or shear zones.

8. The fact that the Thar and Walih diapiric plutons are locally concordant with intruded rocks but discordant with regional trends suggests that the country rocks were ductile during emplacement of the plutons. The ovoid Thar pluton cuts obliquely across a belt of north-trending country rock. The fact that mineral layering and foliation in this pluton follow its elliptical plan view suggests forceful intrusion of monzogranite magma. The circular Walih pluton is partly encircled by a narrow belt of amphibolite and chloritic schist of the metadiorite-metagabbro unit. Peripheral to this are outcrops of mixed granitic and dioritic rock (dgg) that give the impression of a concentric alternating ring-dike and country rock complex. The granitic rocks in the complex are thought to be older than, but may be co-magmatic with, those in the Walih pluton.

9. The Thar and Walih plutons cut granitic and dioritic rocks that contain amphiboles believed to be chiefly ferrohastingsite. Thus, the biotite monzogranite of these plutons probably postdates the ferrohastingsite-bearing granite.

10. The biotite gabbro and diorite unit (gdb) cuts rocks as young as the fine grained biotite monzogranite (mgbf) in the Thar pluton. Its relationships with perthite granite (agpa) and correlative units is not known. Its inferred age, older than perthite granite is speculative.

11. The long syenogranite aplite dike (sap), containing sodic amphiboles, cuts rocks south of Jabal Walih and is thought to have originated in the Ya'arah pluton because its texture becomes coarser toward that pluton. The dike occupies a northeast-trending fracture that is subparallel to relatively late faults and shear zones. This indirect evidence

suggests that the alkalic granites of the Ya'arah, Najran, and A'sud plutons postdate the fine-grained biotite monzogranite of the Walih pluton.

POTASSIUM METASOMATISM

Field and petrographic evidence from several plutonic rock units suggests alteration of rocks of mafic(?), intermediate, and felsic compositions by potassium metasomatism resulting in rocks that are increasingly felsic. The primary plutonic rocks are notably the dioritic and tonalitic gneissic rocks (tbg) of the A'ashiba gneiss complex, syntectonic granitic rocks (particularly granites of units mgb and mgbc, and possibly grba) such as those in the Zilm plutonic complex and the Khutan pluton, and in part syenitic rocks of the Shubaruk and Eargairth stocks.

Megascopic evidence for potassium metasomatism includes randomly to well-oriented crystals of potassium feldspar as much as 2 cm in diameter in the fine-grained, generally equigranular groundmass of tonalitic rock; seriate and bimodal grain-size textures produced by various-sized grains of potassium feldspar in granodiorite and granite; and clots and stringers of coarse-grained potassium feldspar and quartz grains in the more felsic rocks.

Tonalitic and granodioritic rocks commonly exhibit seriate textures of unaltered microcline perthite poikiloblasts, late interstitial microcline, and rims of potassium feldspar on saussuritized primary plagioclase, the plagioclase being intergrown with chloritized hornblende and biotite. The potassium feldspars clearly seem to have been introduced by replacement after crystallization and alteration of the more mafic rocks. Granite and syenite also exhibit seriate and bimodal porphyroblastic textures consisting of potassium feldspar and quartz. In some samples two generations of plagioclase occur: the first, in part altered, has reacted with and been partly replaced by unaltered microcline and the second, unaltered, is in apparent equilibrium with the microcline.

Some biotite monzogranite exhibits metamorphic fabric and more extreme textural and mineralogical indications of potassium metasomatism. Textures are generally foliate and highly seriate. Large, ragged to euhedral crystals of plagioclase and fine-grained quartzofeldspathic groundmass form a mosaic. Quartz-eye and perthite blasts are common. Groundmass quartz is commonly sutured. In some samples, biotite is altered to chlorite or occurs with blue-green and greenish amphibole. Poikiloblastic amphiboles transect earlier foliation. The biotite monzogranites of the tonalite-granite suite appear to have been granulites resulting from recrystallization of earlier granitic rocks under deforming stress.

PALEOZOIC ROCKS

Wajid Sandstone

The Wajid Sandstone (O€w) of Cambrian and Ordovician age (Brown and Jackson, 1959; Brown, 1970; Hadley and Schmidt, 1975; Powers and others, 1966) overlies Precambrian rocks with pronounced angular unconformity. The Wajid depositional surface in the Wadi Habawnah quadrangle is of very low relief and dips east-northeast at very low angles. A few channel-cut deposits less than 20 m thick were seen. Maximum thicknesses range from 135 m to 270 m, but no complete section of the Wajid is present because the top is the Holocene erosion surface. A thickness of 350 m is reported in the Wadi Wassat quadrangle to the north (Greenwood, 1980a), and 380 m between Precambrian and Jurassic(?) rocks in the Wadi 'Atf quadrangle to the northwest (Anderson, 1979).

The Wajid overlies Precambrian rocks in about 20 percent of the quadrangle. Two areas of about 100 km^2 each occur west and east of Wadi Arjan, and many smaller erosional remnants are mapped in other parts of the quadrangle. The western edge of a broad Wajid outcrop belt crosses the northeastern corner of the quadrangle.

Greenwood (1980a) gives a brief but penetrating discussion of interpretations of Wajid environments of deposition, and Alabouvette and Villemur (1973) report on trace fossils in this unit. Hadley and Schmidt (1975) interpret bouldery conglomerate beds in the Wajid and its equivalents in other areas to be of fluvial origin. Anderson (1979, p. 19) suggests that it represents intertidal sedimentation in a shallow epicontinental sea and cites other authors, who indicate that source areas were mostly southwest or southeast of the depositional sites.

The Wajid Sandstone in the Wadi Habawnah quadrangle is a moderately well sorted, coarse-grained quartz sandstone. It ranges from light to medium gray to reddish gray, is commonly crossbedded, and has carbonate and iron oxide-hydroxide cement and minor quartz overgrowths. Round to sub round grains of quartz, quartzite, chert, and scarce fresh-appearing microcline are characteristic; a few rock fragments of rhyolite(?) are present. Well-rounded granules and pebbles of varicolored quartz and chert occur near the base and at intervals throughout the unit. Planar and trough crossbedding having associated clay galls and scattered pebbles is common. Crossbedding dips dominantly northeast and to a lesser extent northwest (plate 1). The dip of planar crossbedding ranges mostly from 23° to 26° and locally is as much as 30°. Symmetrical low-amplitude ripple marks, seen in a few localities, strike northwest. Trace fossils (tracks, trails, and vertical tubes) are rare.

Iron oxides and hydroxides are common in the basal part of the Wajid in well-cemented and resistant beds from 1 to about 5 m above the base. They include botryoidal and stalactitic structures and planar-bedded to irregularly shaped concentrations of limonite, goethite, and hematite. Hematite is common as cement of sandstone and pebble conglomerate. Most of these iron oxides are interpreted to have been deposited in the vadose zone following lithification of the Wajid. Hematite cement may be depositional or diagenetic, however, originating as iron-rich clay from red-soil sources.

Basal contacts of the Wajid are sharp, and the formation rests either on a case-hardened surface on the Precambrian rocks or on rocks that are altered to a depth of 1 to 7 m. In this saprolitic zone, feldspars are altered to clay and mafic minerals to hydrous iron oxides. Good exposures of this alteration occur along the Khamis Mushayt-Najran highway near the western edge of the quadrangle. This type of alteration has been interpreted to be due to deep chemical weathering prior to Wajid deposition (Overstreet and Rossman, 1970) or alteration in the vadose zone following deposition and lithification of the Wajid (Greenwood, 1980a).

Grayish-red to maroon siltstone and shale occur within the lower approximately 10 m of the Wajid in a limited area at about lat 17°35' N. and long 44°10' W. The zone is estimated to be about 5 to 15 m thick, and is interpreted to represent deposition in a small protected bay or lagoon. Trace fossils (tracks and trails) are present in the fine-grained sediments. Adjoining this zone, south of the Khamis Mushayt-Najran highway and 10 km east of the western boundary of the quadrangle, the lowermost beds of the Wajid include about 1.2 m of whitish to iron-oxide-stained clay. One measured section above the base of the Wajid includes in ascending order: 20 cm limonite or goethite, homogeneous to banded, hard, massive; 16 cm siltstone containing hematitic cement; 30 cm clay, stained with iron oxides; 90 cm clay, very light gray, homogeneous; unmeasured sandstone, coarse grained, containing hematite cement.

Scattered altimeter observations indicate that the base of the Wajid slopes east-northeast at an average inclination of about 10 to 11 m/km across the Wadi Habawnah quadrangle. Irregularities in this slope include a minor north-south monocline, its western side down warped an estimated 25 m, in the southwestern part of the quadrangle and minor faults, many of which are not mapped. More gentle structures of larger scale may exist, particularly in the southwestern part of the quadrangle. The Wajid also occurs tilted and steeply dipping in a graben at lat 17°32'49" N., long 44°05'36" E.

Sandstone dike-like features were seen at two localities. In the northwestern corner of the quadrangle, one is expressed as a resistant ridge several meters wide composed of well-indurated Wajid Sandstone cemented by carbonate and quartz. Borders are obscure and the "dike" probably reflects cementation along a linear fracture. At the other locality, along the Khamis Mushayt-Najran highway at the western border of the quadrangle, three nearly vertical "dikes" of sandstone about 0.5 m thick occur within altered granite immediately below the contact and probably represent open fracture fillings.

CENOZOIC DEPOSITS

Most of the mapped surficial units, all of Quaternary age, were delineated from a few ground observations and by extrapolation from 1:50,000-scale aerial photographs. Alluvial and colluvial deposits include present wadi alluvium (mapped only for the larger wadis and a few upland tributaries), older alluvial terrace gravel deposits, loess-like silt deposits overlying the terrace gravel, gravel plain deposits that in part are topographically higher than the terrace gravel, and undivided alluvial fan and pediment gravel deposits and alluvium of small drainages. Eolian deposits consist of low, straight, southeast-trending linear dunes overlying gravel terrace or gravel plain deposits and areas of low irregularly shaped dunes that are transverse to the linear dunes and also overlie gravel terrace, gravel plain, and pediment surfaces. Patches of sand fill depressions in the upland area of the Wajid Sandstone. Tufa (not mapped) occurs in a few places, such as near the confluence of Wadi Shilya and Wadi Ithaiba where a waterfall has produced a very spectacular deposit, and in upland areas where small tufa deposits apparently result from intermittent or extinct springs.

Terrace gravel deposits (Qgt), 1 to 4 or 5 m above the present flood plains, are poorly sorted, locally derived gravel and sand. Gravel plain deposits (Qgp) resemble the terrace deposits and in some places are probably widespread extensions of them; in other places, however, they occur at least 1 or 2 m above the terrace gravel.

Terrace gravel deposits are abruptly overlain by patchy to extensive silt and silty marl deposits (Qst) 6 to 8 m thick along the major wadis. They weather to vertical faces similar to loess. One typical section on the northern side of Wadi Habawnah comprises in ascending order: present sand and gravel surface; 2 m of sand to cobble terrace gravel; 4 m of light-tan (nearly pale-yellow-brown 10YR 6/2) homogeneous silty marl; 0.3 m medium-grained sand containing approximately 10 percent scattered pebbles; 4 m silt and marly silt, similar in color to but somewhat darker than the basal marl bed, that locally contains very fine sand admixture. Farther downstream on Wadi Habawnah, one unit, interpreted to be either the uppermost unit of the previous section or a higher unit, is exposed above present wadi alluvium, and here it is an evenly laminated calcareous silt about 3.5 m thick, having fine crossbeds in the upper 1.5 m.

Small headwater tributaries of the larger wadis show evidence of previous impoundment. At lat 17°55'26" N., long 44°04'31" E., a cut bank exposes the following section in ascending order: basal lens of colluvium overlain by 0.6 m very light gray marl, the upper few centimeters of which is carbonaceous; 1.5 m of gray calcareous silt, the upper part of which grades into carbon-rich loamy silt; 0.7 to 1.5 m of reddish oxidized silt having granules and pebbles of diorite; and a gravelly surface layer containing mixed crude Paleolithic(?) and modern implements. The entire area in which this succession occurs is perhaps only a few thousand meters square and may represent an extinct pond or small lake. Although no fossils were found at this locality, tufa containing small gastropods was found in an adjoining small drainage 2 km east (H. McClure, oral commun., 1979).

Alluvial fan and pediment gravel deposits, alluvium of tributaries to the main wadis, and colluvium are mapped as one unit (Qfp).

Wadi alluvium (Qa) ranges from sand to boulder size; that in Wadi Habawnah and Wadi Najran has a high proportion of sand to gravel that visibly increases from the western to the eastern quadrangle boundary where the wadis enter the Rub al Khali.

Eolian deposits in upland areas (Qsu), are patches of light buff very fine to medium-grained sand that fills depressions in Wajid Sandstone topography. These are mostly locally derived and mixed with colluvium and pebble- and cobble-sized clasts of desert regolith, and Paleolithic(?) and Neolithic tools and chippings. Simple linear dunes and sheet sand (Qdl) comprise only two small areas in the eastern part of the quadrangle, and their source is probably alluvial sand from Wadi Habawnah.

In the southwestern part of the quadrangle the larger area of transverse dunes (Qdt) contains curved to sinuous shaped, low discontinuous dunes (sand ripples) that locally form dune complexes. They cannot be properly ascribed to either barchane or parabolic dunes, although they somewhat resemble the latter. They overlie desert regolith or thin sheet sand; individual dunes are less than a few meters high and less than 0.5 km long. They have encroached from the east-northeast onto the adjoining area mapped as a gravel plain, but at present many seem to be stabilized and have sparse vegetation on their flanks. Only small changes in dune shape, length, and position were detected by comparing 1951 and 1959 aerial photographs.

Evidence of early man is common throughout the quadrangle and consists mostly of very crudely flaked pebble- and cobble-size tools, nearly all of which were made from quartzitic Wajid Sandstone. Exposed surfaces of the tools exhibit a high degree of desert polish. Ancient circular arrangements of separated granite boulders (campsites?), which have sunk as much as 10 cm into underlying weathered granite bedrock, were seen at a few localities. Petroglyphs depicting animals, mostly ibex and camels, hunting scenes, and pictographs and inscriptions in South Arabian Musnad occur on the sides of cliffs and ledges along some wadis and in upland areas composed of Wajid Sandstone. Crude circular tumuli and piles of boulders constructed of Wajid Sandstone are also common in upland areas, and ruins of large, well-built fortifications are on some hilltops along Wadi Najran. Ruins of an ancient village, Khari Ghadima, on the southern side of Wadi Najran in the vicinity of Jabal Alaan, have been replaced by modern farms and residences.

STRUCTURAL GEOLOGY

Structural setting and tectonic history

The Wadi Habawnah quadrangle lies at the eastern edge of a 50-km-wide belt of north-striking, steeply dipping Precambrian metavolcanic and metasedimentary rocks that have been intruded by plutonic rocks that range in composition from granite to gabbro. East of this belt, within the Wadi Habawnah quadrangle, granitic, dioritic, and tonalitic rocks are dominant, and structural trends are largely northeast to north. The dominant northeast trend is best expressed in the A'ashiba gneiss complex in the southeastern part of the quadrangle. No clear boundary is evident between the north- and northeast-striking structural domains because they are separated by later magmatic intrusions. However, north of the Wadi Habawnah quadrangle, the boundary is reported to be a major structural discontinuity, the Ashara fault zone (Greenwood, 1980a; Greenwood and others, 1982), interpreted to represent a zone of thrust faulting followed by major left-lateral transcurrent fault movement.

In the Wadi Habawnah and Najran (Sable, in press) quadrangles, the area east of the Ashara fault zone is interpreted to represent part of a major province of syntectonic and posttectonic granitic plutonism. The metadiorite and metagabbro unit is believed to represent the oldest plutonic unit, part of an extensive old terrain of mafic rocks. This plutonic mass may have had a dominant north-south strike component prior to disruption and alteration by granite intrusion.

Tonalite and granodiorite of the A'ashiba gneiss complex are considered to be younger than the metadiorite-metagabbro unit and seem to be part of a large, mostly tonalitic mass that extends southward into the Najran quadrangle.

Granite plutons are positive structural features comprised of the following phases: 1) early, syntectonic(?) biotite-monzogranite; 2) syntectonic or later deformed biotite-amphibole granite; 3) posttectonic, diapirically intruded biotite monzogranite; 4) passively intruded alkali-feldspar granite and syenite that had higher contents of reacting constituents than earlier intrusive rocks and that accompanied formation of rhyolite-dacite fels; and 5) passively emplaced biotite syenogranite of the Ghezm pluton, which preceded, was coeval with, or succeeded granites of phase 4.

Developmental history of the Arabian Shield has been discussed by Greenwood and others (1976), Schmidt and others (1979), Fleck and others (1980), Greenwood and others (1980), and Schmidt and Brown (in press). The following discussion briefly explains the hypotheses and discusses their applicability to rocks of the Wadi Habawnah quadrangle.

The southern part of the Arabian Shield has been interpreted to consist predominantly of an older (1000-800 Ma) ensimatic volcanic-arc complex and a younger (800-700 Ma) continental-marginal (Andean-type) volcanic-arc complex. These arc complexes now lie between the more ancient continental masses of Africa to the west and Iran to the east. The accretion of the older ensimatic arc to the African craton and the subsequent collision of the continental-marginal arc with the Iranian craton produced a strong north-trending structural grain in rocks of the southern Arabian Shield. These structures appear to cut across major depositional facies of the arcs and may have been controlled by the orientation and shape of adjacent continental margins at the time of collision. The arcs appear to have been aligned northwest-southeast and formed above a west-dipping subduction plate (Schmidt and others, 1979; Greenwood and others, 1982).

Greenwood and others (1982) also divided the southern Arabian Shield into a series of generally north-trending belts that are delineated by major structural breaks. These belts comprise mostly contiguous exposures of layered rocks that may be generally contemporaneous. However, the apparent magnitude of dislocation along the belt boundaries makes straightforward stratigraphic correlation from belt to belt tenuous. Therefore, the relative ages of layered rock units between belts can only be inferred.

Layered rocks in the westernmost part of the quadrangle are southward continuations of the dominant north-south trends in the Asir province and are inferred to have formed in the younger continental-marginal arc complex. The layered rocks and the older plutonic rocks have been polymetamorphosed to greenschist and amphibolite facies during late Proterozoic time. They lie along the Ashara fault zone, a zone of major structural dislocation (Greenwood, 1980a). East of this zone, late Precambrian rocks include a high proportion of granitic rocks and a much higher proportion of alkalic granites than that reported farther west.

History of cratonization of the eastern and southern Arabian Shield according to Schmidt and others (1979) and Schmidt and Brown (in press) begins with an early phase of volcanism, plutonism, and resultant development of a shallow primitive crust composed chiefly of gabbro, diorite, and tonalite. These are interpreted to be generally comagmatic equivalents of the volcanic and volcaniclastic rocks and to be intrusive into them. The ages for these plutonic events in the eastern Arabian Shield are about 785 to 740 Ma for a first phase of shallow-seated plutonism and about 725 Ma for a second phase of intermediate-depth plutonism. Plate collisions of the shallow- and intermediate-depth rocks of the crustal block and the continental block to the east resulted in two orogenic episodes and cratonic development of the shallow and intermediate crustal block. Syntectonic plutonism, about 625 Ma and about 600 Ma, was characterized by the formation of domal or antiformal structures by intermediate-depth tonalitic and granodioritic rocks closely followed by the intrusion of granodiorite and monzogranite forming migmatite. Posttectonic plutonism, about 600 Ma, was characterized by intrusion of calc-alkalic and alkalic granites. Earlier pink monzogranite formed amoeboid-shaped plutons emplaced in slightly ductile country rock, and later red syenogranites were diapirically emplaced as circular or ovoid-shaped plutons in brittle crust at shallow depth, accompanied by intrusion of fractionated gabbro. The late gabbroic rocks are suggestive of emplacement beneath explosive caldera volcanoes, in part following conduits of earlier diapiric granite bodies.

Except for the specific age connotations, the foregoing models, derived from information in areas north and northwest of the Wadi Habawnah quadrangle, seem to be applicable to the plutonic rocks of this quadrangle. The fact that the oldest plutonic rock, the metadiorite-metagabbro unit (dg), has vague intrusive boundaries with meta-andesite (ma) indicates that these two units may be comagmatic. Together, they may represent the primitive or primary crust of Schmidt and others (1979) and Schmidt and Brown (in press). The A'ashiba gneiss complex is comprised essentially of the same rock varieties and fabric described by Schmidt and others (1979) to represent the syntectonic plutonism stage in the Al Quarah gneiss dome 275 km north of the Wadi Habawnah quadrangle. The older monzogranite (mgb) may equate with their syntectonic granite and may represent the earliest phase of granite intrusion. Fabric in many of these bodies indicates that most are syntectonic, but some appear to be structureless. Plutonic rocks of the young intrusive suite, the calc-alkalic granite in the Thar and Walih plutons, the alkalic granite of the Najran pluton, and the calc-alkalic syenogranite and monzogranite of the Ghezm pluton, seem to represent posttectonic plutonism. The diapiric Thar and Walih plutons appear to have been emplaced in a ductile, intermediate crustal environment, at least at the level now exposed by erosion, rather than in a brittle crust at shallow depth. The late gabbroic rocks (gdb) associated with posttectonic plutonism are associated with and appear to be younger than all granites of the Żilm plutonic complex.

The few ages known or inferred to be applicable for rocks in the Wadi Habawnah quadrangle suggest that the oldest crustal rocks are not as old as those in more northern and western areas of the Arabian Shield. Ages of around 640 Ma for rocks of the A'ashiba gneiss complex and at least part of the metagabbro and metadiorite unit may suggest a younger development for the primitive crust in the Wadi Habawnah quadrangle than that proposed elsewhere by Schmidt and others (1979). However, the textural fabric of some units, such as those in the A'ashiba gneiss complex, suggests extensive recrystallization. Recrystallization of all mineral components, including zircon at about 640 Ma, may have overprinted an earlier emplacement and crystallization of dioritic and tonalitic plutonic rocks.

Uplift and planation in latest Precambrian time were followed by uplift to the south and epeirogenic or basinal downsinking of the region. Deposition of epiclastic sediments from southern source areas formed the Paleozoic Wajid Sandstone, which was probably overlain by younger, now eroded, sedimentary rocks. Although there is no record of geologic events during most of Paleozoic and all of Mesozoic time in the quadrangle, strata of possible Jurassic age overlie the Wajid 80 km west of the Wadi Habawnah quadrangle (Anderson, 1979). High-angle faulting of probable Tertiary age ensued, probably related to formation of the Sadah graben (Grolier and Overstreet, 1978) to the south in Yemen. Evidence of Tertiary and (or) Quaternary mafic volcanism and hypabyssal intrusion in adjoining areas to the west (Anderson, 1979; Conway, in press) was contemporary with and was followed by further uplift and erosion.

Faults and shear zones

Northeast- and north-trending faults and shear zones appear to be the dominant structural dislocations in the quadrangle; west- to northwest-trending faults are interpreted to be subsidiary to the northeast-trending ones (fig. 4). Faults shown on figure 4 include known and inferred faults and shear zones and their projected extensions under Phanerozoic units. Linear features, particularly the northeast-trending ones, are recognizable on Landsat imagery, which covers the entire quadrangle, and on aeromagnetic maps, which cover only about the northwestern one-third. Some of these linear features coincide with mapped faults and shear zones which have been accentuated by erosion.

North-trending major faults occur in the westernmost part of the quadrangle and are considered to be related to the Ashara fault zone, an early feature of thrust-faulting and subsequent left-lateral movement (Greenwood 1980a; Greenwood and others, 1982). The north-trending fault cutting granite of the Najran pluton in the southwestern part of the quadrangle includes a small graben of Wajid Sandstone. This fault may be either a reactivated fault related to the Ashara fault zone, or may be related to Tertiary tectonism because it is subparallel to structural trends of the Sadah graben in Yemen (Grolier and Overstreet, 1978). Major northeast-trending lineaments are interpreted to represent mainly strike-slip shear faults resulting from east-west compression. These are present along part of Wadi Najran, in several belts between Wadi Najran and Wadi Habawnah, and as two major shears north of Wadi Habawnah. The lineaments are best expressed in and near large granitic bodies such as the Najran pluton. There, several east-southeast-trending faults, some with left-lateral displacement, appear to splay westward from the conjectured Wadi Najran left-lateral shear zone. North of Wadi Habawnah, two east-northeast lineaments are reflected by aeromagnetic data, but sense of movement on these is not known. An important point is that the main east-northeast to northeast structural trends of the Wadi Habawnah quadrangle are different from the north- and northwest-trending structural belts to the north and west of this area (Brown, 1972). Tectonic stresses and resulting northeast-trends of structural features in the eastern part of the Wadi Habawnah quadrangle may have been influenced by Precambrian tectonism and magmatism reflected in structures to the south and southeast in Yemen. There, trends on Landsat imagery and on a small-scale geologic map (Grolier and Overstreet, 1978) suggest structural fabric and style like those discussed in this report but unlike those in the southwestern part of the Arabian Shield of Saudi Arabia.

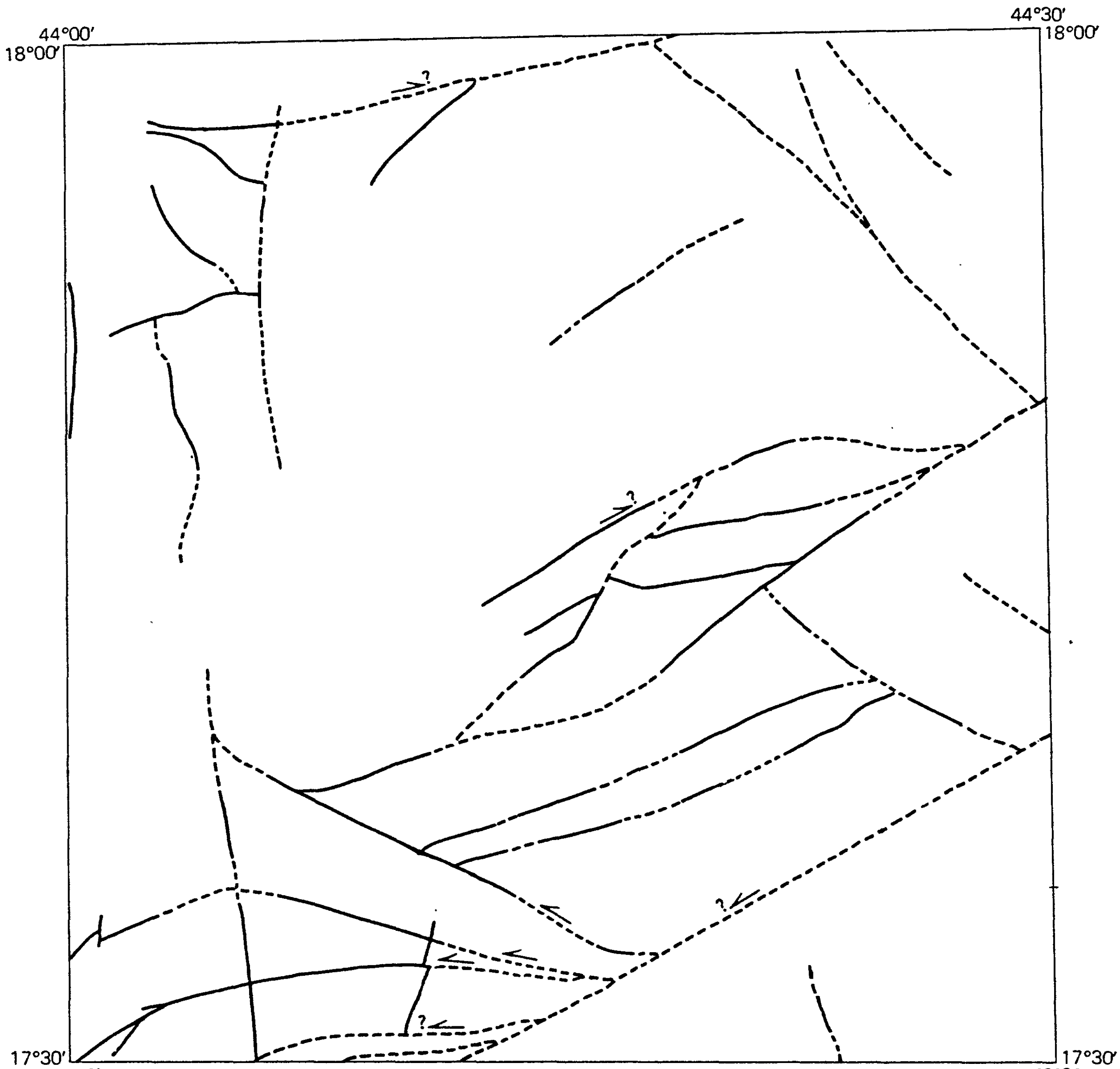


Figure 4.--Structural sketch map of the Wadi Habawnah quadrangle showing known and inferred faults and shear zones. Dashed lines represent major faults and(or) shear zones concealed by post-faulting deposits. Direction of displacement shown by arrows; queries indicate inferred direction of displacement.

The known left-lateral movement on northwest-trending faults in the southwestern part of the quadrangle and inferred left-lateral movement on northeast-trending faults suggest that they represent zones of shear in an east-west compressional stress field.

Foliation, joints, and dikes

Field observations of foliation attitudes included readings on cleavage and gneissic, schistose, and cataclastic foliation, and on mineral or fabric layering. A total of 347 readings, not differentiated as to kind, are represented in equal-area projections (fig. 5) that show contours of poles to foliation and represent pole readings in each of the four quarters of the quadrangle. These arbitrary divisions have been made because distribution of specific structural domains is not clear from examination of the geologic map. The quarters are labeled clockwise from the northwest quarter (I) by Roman numerals I-IV. Contours of pole projections in quarters I and II are strongly influenced by many readings in the Thar and Walih plutons. In quarters III and IV, readings are distributed more equally.

Because of the variety of Precambrian events that have taken place, the foliations consistently show a strong northeasterly component with steep dips except in quarter III, which shows a dominant north trend. Less common conjugate-appearing foliation is northwest-trending in quarter II and east-trending in III. A possible counterclockwise shift in major trends is indicated by successive comparison of quarters IV to III to II to I, in that order. This may indicate age differences of foliation trends or, if they are contemporary, a fan-shaped shear or compressional pattern with its locus south of the area. A post-compressional tensional pattern during magmatic events might be occupied by dikes, and so comparison of the above foliation trends to those of the dikes was attempted. In figure 6, projections A and B represent poles of felsic and mafic dike attitudes for the entire quadrangle, respectively. Their pattern roughly indicates a near girdling of the northern half-circumference of the projection with a steeply south-dipping, dominantly east-trending dike pattern and lesser north-northwest and north-northeast trends. They conform reasonably well to joint trends (fig. 6c) and in part to north-striking cleavage trends (fig. 6d), but do not correlate well with any of the foliation trends except possibly figure 5, III, in which the subordinate easterly trends appear to be similar.

Simple models to explain the features shown in figures 5 and 6 must make certain assumptions in light of the poorly known Precambrian history of the area: 1) that the dominant northeast and north foliation trends are the result of

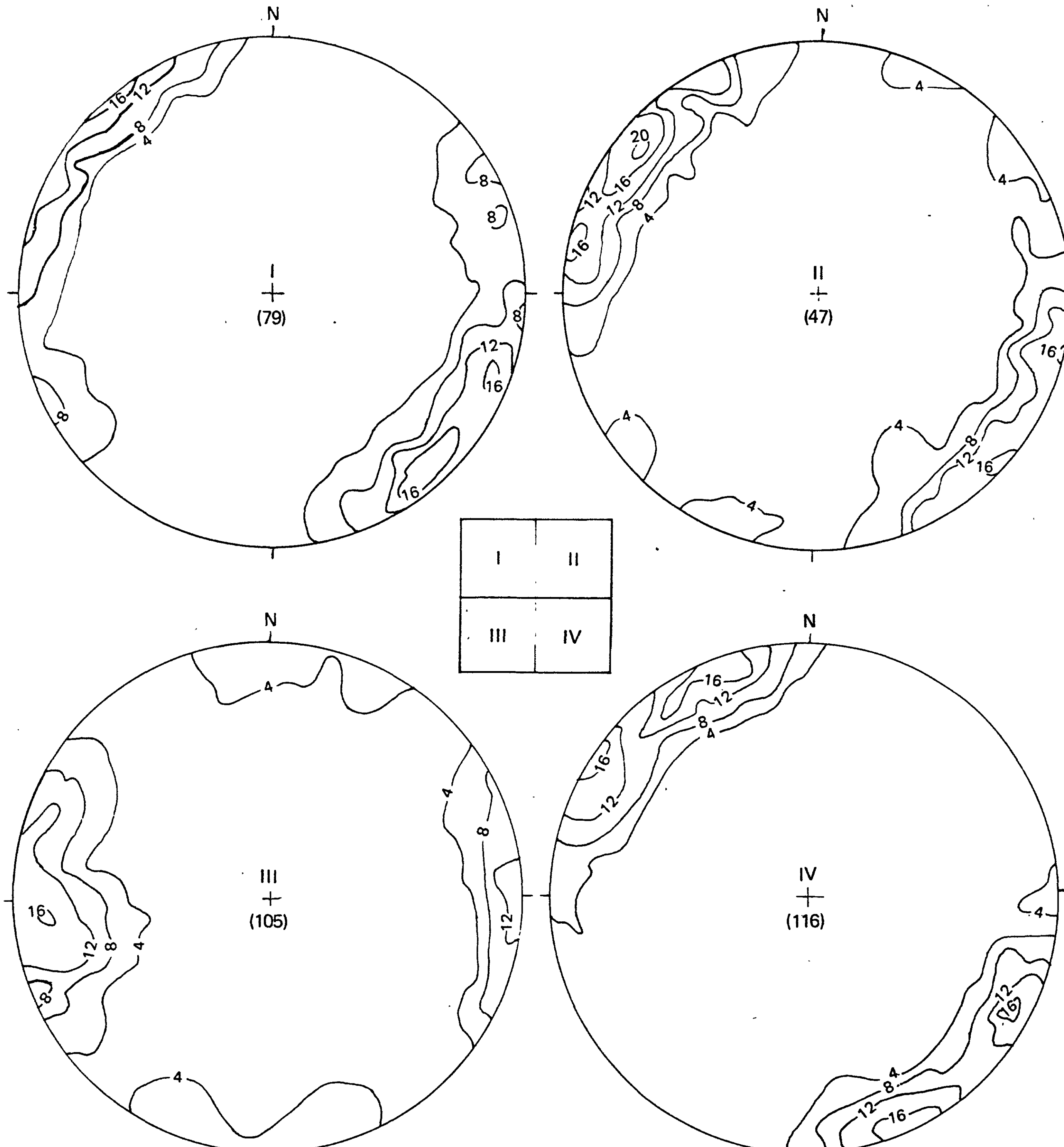


Figure 5--Lower hemisphere equal-area projections showing poles to foliation in each quarter area of Wadi Habawnah quadrangle. Roman numerals I to IV keyed to index map in center of figure. Number of poles shown in parentheses. Contours indicate percent per 1 percent of area.

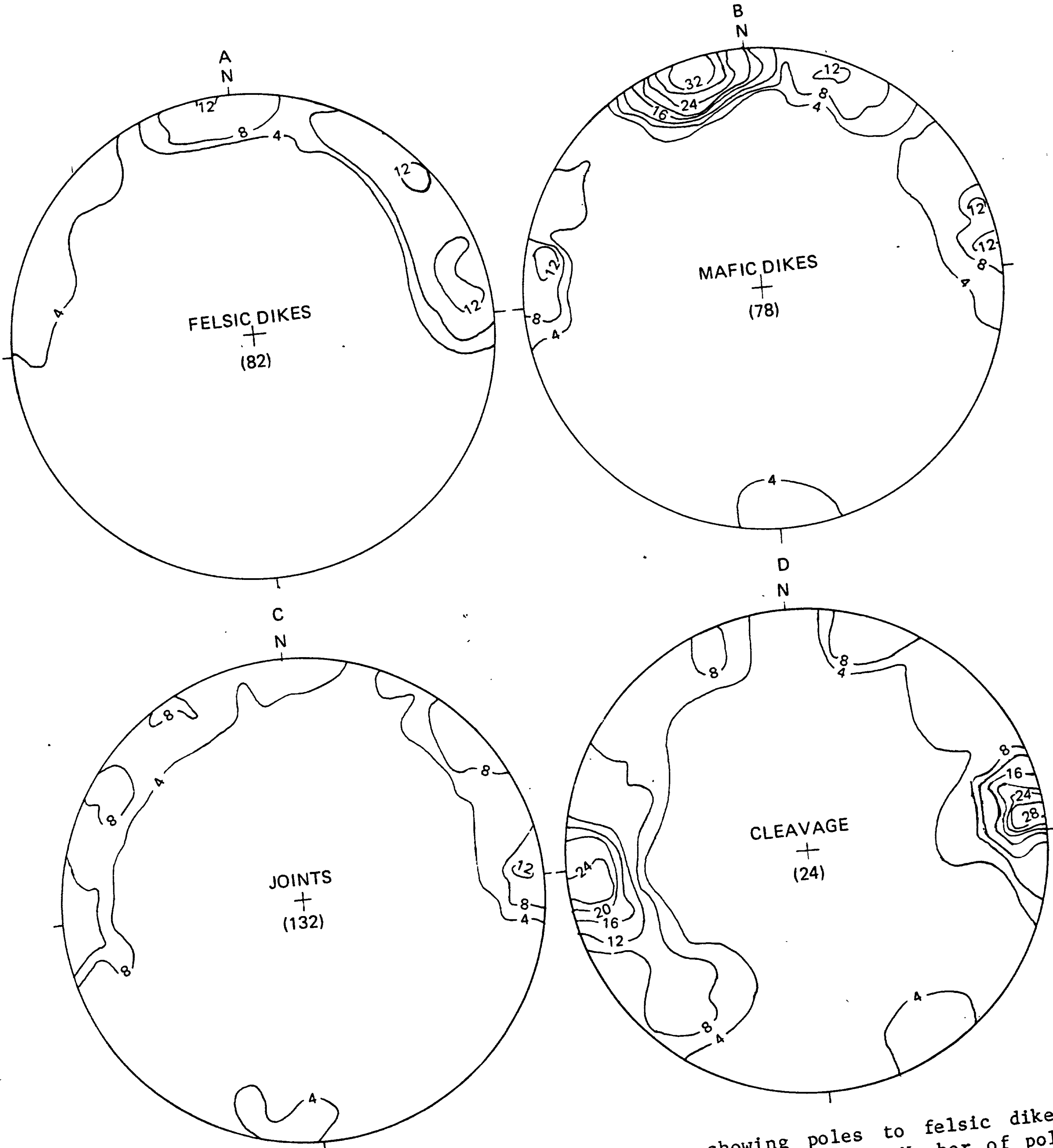


Figure 6.--Lower hemisphere equal-area projections showing poles to felsic dikes, mafic dikes, joints, and cleavage in Wadi Habawnah quadrangle. Number of poles shown in parentheses. Contours indicate percent per 1 percent of area.

unidirectional stress field or fields; 2) that stresses were either early or late in the history of the rocks exposed in the quadrangle; and 3) that foliation reflects either a shear or compressional stress field.

If a simple compressional stress field resulted from east-west or north-south crustal shortening, and the foliation is ascribed to an early stress event, then the dominant northeast foliation directions seem to indicate that they formed in a shear stress field. Conversely, northwest-southeast crustal shortening could also result in the patterns shown in quarters I, II, and III of figure 5, but they would result from direct compressional stress. The Thar and Walih plutons, considered to be about middle age in the younger magmatic history of the area, show strong northeast-striking primary foliation patterns (pl. 1), and the Thar pluton is also elongate northeast. This suggests that the dominant northeast foliation pattern is relatively young, that most of the foliation was formed in an east-west compressional stress field, and that granite and country rock were ductile during emplacement. The exception to this pattern (fig. 5, III) in part represents an older north-trending structural grain represented by cleavage in metasedimentary and metavolcanic flow rock and north-trending schistose and gneissose foliation in the metadiorite-metagabbro unit that preceded granite magmatism. In such a model, dike and joint trends may reflect both pre-granitic events (northerly trends) and intra- to post-granitic events (easterly trends).

GEOCHEMISTRY, MINERALIZATION, AND ECONOMIC PRODUCTS

Plutonic rocks

A total of 23 samples from the Wadi Habawnah quadrangle were analyzed for major elements (table 1). Values for minor (trace) elements from 114 samples of granitic rock, diorite and gabbro, and intermediate to mafic volcanic flow rock are shown in table 2, including minimum, maximum, and mean values (for unqualified values only, those values that are above the limit of detection for any of the methods used). Most values are not unusual. Somewhat higher values of tin, fluorine, and to a lesser extent lithium occur in a few samples; most of these are in or near relatively young granitic plutons.

Seven samples of granitoid rocks from the Thar pluton, the Najran pluton, the granite exposed in Wadi Gharb, and the older granitic rocks on the periphery of the Ghezm and Najran plutons show 10 to 15 parts per million (ppm) tin. They are widely spaced and represent rocks of several different compositions. Their fluorine and lithium contents are as much as 1760 and 63 ppm, respectively.

The Ghezm pluton, in part a biotite-muscovite granite, appears to be mineralogically similar to the Jabal al Gaharra tin-bearing granite (Elliott, in press; Greenwood, 1980a), which lies 8 km north. In 1977, J. E. Elliott of the U.S. Geological Survey, collected 6 rock samples and 61 stream sediment samples from 13 localities in and around the Ghezm pluton. Raw stream samples were sieved into two sizes (-10+30 and -30+80 mesh). Pan concentrates were also taken and separated into magnetic and non-magnetic fractions for each of the above sieve sizes. Samples were analyzed by standard spectrographic method. Most of the samples contained only ordinary concentrations of trace elements, but tin was found in a number of samples.

Tin content (not detected below 10 ppm), which ranged from 10 to 15 ppm in rock samples, has generally higher values in pan concentrates; 4 samples contained 15 ppm; one, 100 ppm. Highest concentrations of 50 ppm or more were only in the non-magnetic fraction of both sieve mesh sizes, whereas contents of 30 ppm were largely in the magnetic fraction. This suggests that cassiterite is probably the tin-bearing mineral. The values are less than those for the granite at Jabal al Gaharra, but they provide further evidence that the two plutons are probably genetically related.

Rock samples collected by Elliott include RASS 124077 which contains 300 ppm tungsten and 30 ppm molybdenum. Rock sample RASS 124078 contains 20 ppm molybdenum; and rock samples RASS 124071 and 124080 contain 2280 and 2040 ppm fluorine, respectively, but only 23.8 and 8.8 ppm lithium, respectively.

Stream sediment samples collected by Elliott, RASS 124534 to 124594, indicated generally low molybdenum content (not detected below 5 ppm), and one pan-concentrate magnetic fraction (sample 124587) contained 15 ppm. Several samples showed 10 to 15 ppm beryllium, and 2 samples showed 300 and 500 ppm copper. The range of tungsten content was from not detected to 50 ppm, and zinc content in several samples ranged from 500 to 1000 ppm.

A higher value of 1000 ppm tin from the Ghezm pluton is reported by du Bray and others (1982, plate 2) as well as maximum values of 91 ppm yttrium, 35 ppm niobium, 2760 ppm fluorine, 300 ppm tungsten, and 15 ppm beryllium. Metalliferous anomalies in the Ghezm pluton were considered by them to be less significant than those in other plutons to the north and northwest. Anomalous amounts of lanthanum, zirconium, fluorine, and niobium in a few samples from the alkalic granite of the Najran pluton (150 ppm, 1000 ppm, 2820 ppm, and 24 ppm, respectively) are also reported by du Bray and others (1982, plates 2 and 3). Compared to other areas of

Table 2.--Results of analyses of selected trace elements in Precambrian crystalline rocks from Wadi Habawnah quadrangle, showing low, high, and mean values [Analyses by USGS/DGMR laboratories, Jiddah. Values for Fe, Mg, Ca, and Ti in percent, all other values in parts per million. Leaders (--), not analyzed; N, not detected; L, detected but very low value not recorded. Mean values shown for unqualified values only]

Method of analysis and element	Granite plutons (all) (22 samples)			Alkalic granite plutons (7 samples)			Miscellaneous granitic rocks, northern areas (15 samples)		
	Value								
	Low	High	Mean	Low	High	Mean	Low	High	Mean
Spectrographic									
Fe	0.7	5	2.1	0.1	5	2.8	0.5	7.0	2.4
Mg	.05	0.7	0.3	.03	0.3	0.1	.1	1.0	.4
Ca	.1	1.5	.85	.1	1.5	.8	.5	2.0	1.1
Ti	.03	.5	.2	.1	.5	.3	.05	0.5	.2
Mn	150	1000	513	200	700	578	150	1000	433
B	N	30	--	N	30	--	L	--	--
Ba	70	1500	538	70	1500	612	70	1500	709
Be	15	15	10	.5	30	10	1.5	5.0	2.4
Bc	N	--	--	N	--	--	N	--	--
Cd	N	--	--	N	--	--	N	--	--
Co	N	7	--	N	7	--	5	15	12.5
Cv	150	300	190	150	300	178	150	200	183
Cu	5	50	19.5	10	50	23.5	.5	70	25
La	N	100	--	20	100	47	20	100	51
Mo	N	10	--	N	10	--	N	--	--
Nb	N	30	--	20	50	28.5	20	30	25
Ni	5	10	7	5	10	6	5	15	8.4
Pb	10	30	27	10	20	23	10	30	25
Sb	N	--	--	N	--	--	N	--	--
Sc	N	--	--	N	--	--	5	15	9.2
Sn	10	15	12	10	15	10.1	N	--	--
Sr	100	500	168	100	200	114	100	500	290
V	10	30	17	10	30	15	10	100	27
W	N	--	--	N	--	--	N	--	--
Y	15	100	34	15	100	50	10	70	32
Zn	N	--	--	N	--	--	N	--	--
Zr	50	1000	295	50	100	531	70	1000	397
Atomic absorption									
Cd	N	--	--	N	--	--	0	5	--
Co	0	15	--	0	15	4.3	0	10	--
Ni	0	10	--	0	10	4.3	0	10	--
Li	0	62.5	--	0	62.5	12.4	0	0	--
Au	.05	.1	.097	.05	.1	.08	.05	.10	.113
Ag	.5	.5	.5	L	--	--	.50	.90	.64
Colorimetric									
Mo	N	--	--	0	--	--	0	5	--
W	N	--	--	0	--	--	0	20	--
Cr	0	200	--	0	200	147	0	130	--
Selective-ion									
F	0	1760	--	0	1760	693	0	1140	410

Table 2.--Results of analyses of selected trace elements in Precambrian crystalline rocks from Wadi Habawnah quadrangle, showing low, high, and mean values--Continued

Miscellaneous granitic rocks, central areas (14 samples)			Miscellaneous granitic rocks, southern areas (9 samples)			Diorite and gabbro (27 samples)			Intermediate to mafic volcanic flow rocks (20 samples)		
Value											
Low	High	Mean	Low	High	Mean	Low	High	Mean	Low	High	Mean
1	15	4.8	1	7	2.9	7	15	5.7	1.0	15	5.8
0.15	5	1.5	0.07	3	6.5	0.07	10	3.1	0.7	3	3.0
.3	10	2.5	.07	3	1.4	.7	10	3.9	1.0	10	3.4
.1	1.0	0.4	.15	0.5	0.25	.07	1.0	0.5	.05	1	0.45
150	5000	723	300	1500	644	300	3000	1035	20	1500	1206
10	15	13	10	30	12.2	N	50	--	10	30	14
70	1500	651	300	3000	1266	20	2000	617	70	1500	557
1	10	3.6	1	3	1.8	1.0	5	1.8	1.0	5	2.5
N	--	--	N	--	--	N	--	--	N	--	--
N	--	--	N	--	--	N	--	--	N	--	--
5	70	36	N	20	--	5	70	32	5	50	35
70	1500	281	70	200	146	50	1500	238	70	500	210
5	300	68	5	100	23.8	5	150	44	5	150	62
20	100	51	20	70	30	N	300	--	N	70	--
N	15	--	N	--	--	N	30	--	5	7	5.4
20	30	24	N	--	--	N	30	--	N	--	--
5	700	128	5	50	13	5	200	42	5	100	40.1
10	30	18	10	30	16.7	N	30	--	10	30	17.8
N	--	--	N	--	--	N	--	--	N	--	--
5	50	22	N	15	--	N	50	--	5	50	26
N	--	--	N	--	--	N	--	--	N	--	--
100	1000	483	100	700	267	100	1500	675	100	1000	464
10	300	72	10	150	37	10	300	139	10	300	167
N	--	--	N	70	--	N	--	--	N	--	--
10	100	37	N	--	--	10	70	21	10	70	27
N	--	--	N	--	--	N	--	--	N	--	--
10	1000	312	20	1000	357	10	1000	165	10	1500	176
N	--	--	0	5	--	0	5	--	0	5	--
0	15	125	0	10	--	0	35	--	0	20	--
0	50	30	0	10	--	0	110	--	0	15	--
0	62.5	24	0	22	--	0	29	--	0	33	--
.05	.14	.900	.05	.1	.070	.05	.10	.07	.05	.44	.134
.3	8.4	.244	.5	.9	.580	.5	1.5	1.02	.5	1.5	.97
N	--	--	N	--	--	N	--	--	N	--	--
N	--	--	N	--	--	0	20	--	N	--	--
0	210	--	0	160	--	0	120	--	0	150	--
0	340	--	0	500	--	0	1120	--	0	1040	--

economic potential, neither geochemical nor radiometric results indicate general economic potential in the Najran pluton, although localized concentrations of minerals of economic value may be present.

Sulfide-bearing rocks

Sulfide-bearing rocks (s on plate 1) include: massive sulfide deposits, mostly associated with andesitic to basaltic volcanic flow rock, but in two localities with granitic rock; earthy gossans known in part to represent weathered massive sulfide deposits; and disseminated sulfides in felsic to mafic rock. Quartz veins and concentrations are not abundant; the few samples tested showed no unusual concentrations of metals.

Massive sulfide deposits, and earthy gossans known or suspected to overlie them, occur chiefly in three areas. From west to east, they are: 1) a linear north- to northwest-trending belt of massive sulfide deposits and gossan south of Wadi Habawnah near the central-western border of the quadrangle; 2) many small to moderate-sized (as much as 50 m wide and 200 m long) earthy gossans west of Wadi Arjan; and 3) earthy gossan and massive sulfide deposits along Wadi Gurra. Scattered gossans were also present along the southern side of Wadi Habawnah. Width and length of some gossans are exaggerated on the geologic map. No ancient mines or prospects were seen in the quadrangle.

A total of 54 samples of massive and disseminated sulfides and earthy gossans were analyzed by spectrographic and atomic absorption methods. Maximum, minimum, and arithmetic mean (for unqualified values only) values are given for 28 metals in table 3. Two samples contained particularly high concentrations of some elements: a sample collected along Wadi Shubaruk (RASS 73899) contained 10,000 ppm zinc; and a sample (RASS 137587) from the northern side of Wadi Gurra contained 1500 ppm chromium.

Subsequent to the reconnaissance geologic mapping of the Wadi Habawnah quadrangle, M. D. Fenton of the U.S. Geological Survey conducted further sampling of sulfide-bearing rocks, gossan, and stream sediments in the quadrangle (Fenton, 1982). He concluded that there may be potentially favorable areas for mineralization in rocks of the Najran pluton and the Wadi Silah pluton in the adjoining Najran quadrangle for niobium, rare-earth elements, zirconium, thorium, and fluorine. Anomalous copper values were also reported by him in the A'ashiba gneiss complex and in tonalite-granodiorite terrane northeast of Wadi Khutan. According to Fenton, the volcanic sequence has a low potential for economic stratiform base metal deposits (Fenton, 1982, p. 33). A detailed stream-sediment sampling program was also conducted by the Riofinex

Table 3.--Results of analyses of selected trace elements in 54 samples of Precambrian sulfide-bearing rock and earthy gossan from Wadi Habawnah quadrangle showing low, high, and mean values [Analyses by USGS/DGMR laboratories, Jiddah. Values for Fe, Mg, Ca, and Ti in percent, all other values in parts per million. Leaders (--), not analyzed; N, not detected; L, detected but very low value not recorded. Mean values shown for unqualified values only]

Method of analysis and element	Values		
	Low	High	Mean
Spectrographic			
Fe	0.7	20.0	11.1
Mg	.02L	7.0	--
Ca	.03	10.0	2.6
Ti	.15	1.0	0.3
Mn	2.0	5000	733.0
Ag	.5N,L	10.0	--
As	200.0N	--	--
Au	10.0N	--	--
B	10.0N,L	300.0	--
Ba	20.0N	2000.0	--
Be	1.0N	30.0	.8
Bi	10.0N	--	--
Cd	20.0N	--	--
Co	5.0N	150.0	--
Cr	20.0	1500.0	321.0
Cu	5.0	3000.0	207.0
La	20.0N	150.0	--
Mo	5.0N,L	15.0	--
Nb	20.0N,L	20.0	--
Ni	5.0N,L	700.0	--
Pb	10.0N,L	30.0	--
Sb	100.0N,L	700.0	--
Sc	5.0N,L	70.0	--
Sn	10.0N,L	--	--
Sr	100.0N,L	1000.0	--
V	10.0L	300.0	--
W	50.0N	--	--
Y	10.0N,L	50.0N	--
Zn	200.0N	1000.0	--
Zr	10.0N	1000.0	--
Atomic absorption			
Zn	5.0N	4000.0	--
Au	.05L	0.14	--
Ag	.5L	3.0	--
U	.0-20N	--	--

Geological Mission (1978) mostly west of and along the western boundary of the Wadi Habawnah quadrangle (Parker, 1982).

X-ray diffraction analyses of 17 rock samples containing massive to disseminated sulfide indicate that pyrite and pyrrhotite are the only sulfide mineral components associated with quartz, quartz-plagioclase-chlorite-mica, or quartz-hornblende-plagioclase and rare magnetite and fluorite.

Alteration associated with sulfide-bearing or other rocks with possible mineral potential in the Wadi Habawnah quadrangle is expressed as silicification and development of carbonate rock or vivid-green chloritic schist. Carbonate rocks with massive sulfide gossan in metavolcanic flow rocks are exposed in a tributary of Wadi Arjan at about lat 17°42'09" N., long 44°09'29" E. X-ray diffraction analysis of one sample (RASS 145018) from this locality shows the presence of calcite, muscovite, chlorite, hornblende, hematite, and traces of magnetite and chromite. The chloritic schist occurs along several tributaries of Wadi Arjan, mostly in metadiorite-metagabbro country rock but also associated with granitic rocks. Many such exposures were seen but not recorded because their association with mineralization was not realized. Further work in the area should include study of these chloritic rocks.

Rock materials

Granite

One quarry for ornamental stone along the Khamis Mushayt-Najran highway west of Bir Askhar, operated by the Bureau de Recherches Geologiques et Minieres, was active in 1978-1979. The quarried rock, the Bir Askhar brown granite (MODS 2852) (Deputy Ministry for Mineral Resources, Kingdom of Saudi Arabia, 1401H; Hazza and Baghdadi, 1982), is a brownish-gray variant of the alkalic granite of the Najran pluton and is used as facing stone.

A potential source of ornamental stone not previously reported is the dark-hued pyroxene olivine syenite (spo). Both of the known locations, along Wadi Shilya and west of the Najran airport, are easily accessible. The syenite bodies, however, appear to be of limited size, and their extent may have been exaggerated on the geologic map (plate 1).

Clay

About 1.2 m of whitish to iron-oxide stained clay crops out in an area of about 1 km^2 south of the Khamis Mushayt-Najran highway about 10 km east of the western boundary of the quadrangle. The clay has not been tested for ceramic properties, and much has been scraped away during highway construction. If of ceramic quality, a considerable amount could still be obtained by careful shallow strip mining.

RADIOACTIVITY

During fieldwork 111 measurements of total radiation decay counts were taken at bedrock outcrops. The readings ranged from 15 to 280 counts per second (cps). The lowest readings were obtained from metavolcanic flow rock and metagabbro; highest readings were from alkalic granites (parts of the Najran pluton and adjoining granite, and granite in the Ghezm pluton). The range of values for readings of granitic rocks in specific plutons and metavolcanic flow rocks are shown on table 4. The scintillometer used was not calibrated; therefore, the counts-per-second values shown in table 4 are relative and not necessarily reproducible.

DATA STORAGE

Petrographic descriptions, sample locations, thin sections, and results of chemical analyses are stored in data file USGS-DF-03-7 in the Jiddah office of the U.S. Geological Survey Saudi Arabian Mission.

No updated information was added to the Mineral Occurrence Documentation System (MODS) data bank, and no new files were established.

Table 4.--Scintillometer measurements of total-count radioactivity for bedrock in Wadi Habawnah quadrangle
[Geometrics scintillometer Model 101A, 43.1 cm^3 NaI crystal; range and approximate mean in counts per second]

Unit	Number of readings	Range	Approximate mean
Ghezm pluton	8	70-220	165
Thar pluton	5	80-130	80
Walih pluton	4	70-160	120
Ya'arah pluton (coarse facies)	4	85-150	115
Khutan pluton	13	90-170	115
Najran pluton	35	80-230	125
Granite north of Najran pluton in Wadi Gidda'h	5	220-280	225
Quartz syenite from Eargairth stock	8	40-140	75
Metavolcanic flow rocks along western border and Wadi Thar	9	35-80	50
Metavolcanic flow rocks Wadi Ithaiba belt	20	15-70	45

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