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Reconnaissance geology of the Al Mukhul quadrangle, sheet 26/42 B, Kingdom of Saudi Arabia

by

E. A. bu Bray 1/

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1/ U.S. Geological Survey
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RECONNAISSANCE GEOLOGY OF THE AL MAKHUL QUADRANGLE, SHEET 26/42 B, KINGDOM OF SAUDI ARABIA

by

Edward A. du Bray 1/

ABSTRACT

The Al Makhul quadrangle (26/42 B) lies in the northern part of the Arabian Shield between lat 26°30' and 27°00' N. and long 42°30' and 43°00' E. Amphibolite, the oldest metamorphic rock exposed in the quadrangle, crops out in a restricted area in the south-central part of the quadrangle. Younger, weakly metamorphosed rhyolite, basalt, and graywacke sandstone on the west edge of the quadrangle are correlated with lithologically similar rocks exposed to the southwest that comprise the Hibshi formation. The Turmus formation, located in the north-central part of the quadrangle, is composed of weakly metamorphosed andesite flow rocks, andesitic agglomerate, and related volcanic graywacke and is similar in metamorphic grade, age relations with intrusive rocks, and structural character to the rocks on the west edge of the quadrangle; it is thought to be approximately coeval with them.

Seven plutonic units, ranging in composition from gabbro and diorite to alkali-feldspar granite, intrude the weakly metamorphosed rocks. Some of these plutons are offset along a northwest-trending fault of the Najd fault system but their emplacement postdates all other major tectonic episodes in the area. The weakly metamorphosed rocks were deposited on an erosional surface underlain by a pluton composed of quartz diorite.

Quaternary alkali basalt crops out in the northwest part of the quadrangle. These rocks are at the southeast edge of Harrat al Hutaymah, a basalt field composed of flow rocks, tuff rings, and cinder cones.

Mineral potential in the quadrangle is low. At a very small prospect pit in the north-central part of the quadrangle, massive, milky quartz veins cutting weakly metamorphosed volcanogenic sedimentary rocks are stained blue and green by copper minerals. A previously reported mine site in the southern part of the quadrangle was not relocated.

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

INTRODUCTION

The Al Makhul quadrangle covers an area of about 2,770 km^2 and is located between lat 26°30' and 27°00' N. and long 42°30' and 43°00' E. (fig. 1) on the eastern edge of the Arabian Shield in the Najd province, Kingdom of Saudi Arabia. Three principal drainage systems including Wadi al Ghaymar, Wadi al Makhul, and Wadi at Turmus traverse the area. All three drainages are dendritic and drain to the northeast. The southern half of the quadrangle, where elevations range between 900 and 950 m above sea level, is a region of subdued pediment topography. Relief in the northern half of the quadrangle, where rounded hills range from 1,000 to 1,500 m above sea level, is only slightly greater.

The principal settlement in the quadrangle is the village of Al Makhul located in the southwestern part of the quadrangle. Smaller villages and enclaves, including Ath Thuaylibi, are located throughout the area. No paved roads cross the quadrangle; the villages are connected by an irregular network of dirt tracks.

The geology of the Al Makhul quadrangle was first mapped as part of the 1:500,000-scale geologic map of the Wadi ar Rimah quadrangle (Bramkamp and others, 1963). Mytton (1970) subsequently studied the mineral deposit potential of the area and identified an ancient mine site, Gerthemi, near the southern boundary of the quadrangle.

The present report is the result of helicopter-supported geologic mapping conducted during parts of December, 1982 and May, 1983 from the U.S. Geological Survey Samiraḥ field camp, lat 26°30' N., long 42°03' E. The author wishes to thank P. L. Williams and J. S. Pallister, who mapped adjacent quadrangles, for helpful discussions and F.S. Simons who reviewed the report. The author would also like to thank Ahmed Hamdan al Bazli who performed all modal analyses of granitic rocks. The work for this report was done in accordance with the work agreement between the U.S. Geological Survey and the Saudi Arabian Ministry of Petroleum and Mineral Resources.

PRECAMBRIAN METAMORPHIC ROCKS

Metavolcanic rocks, including metarhyolite, metabasalt, and the meta-andesitic rocks of the Turmus formation constitute the bulk of the metamorphic rocks in the Al Makhul quadrangle; graywacke sandstone and amphibolite form the remainder. Except for the amphibolite, which was metamorphosed in amphibolite facies conditions, these rocks all were metamorphosed in low-grade conditions.

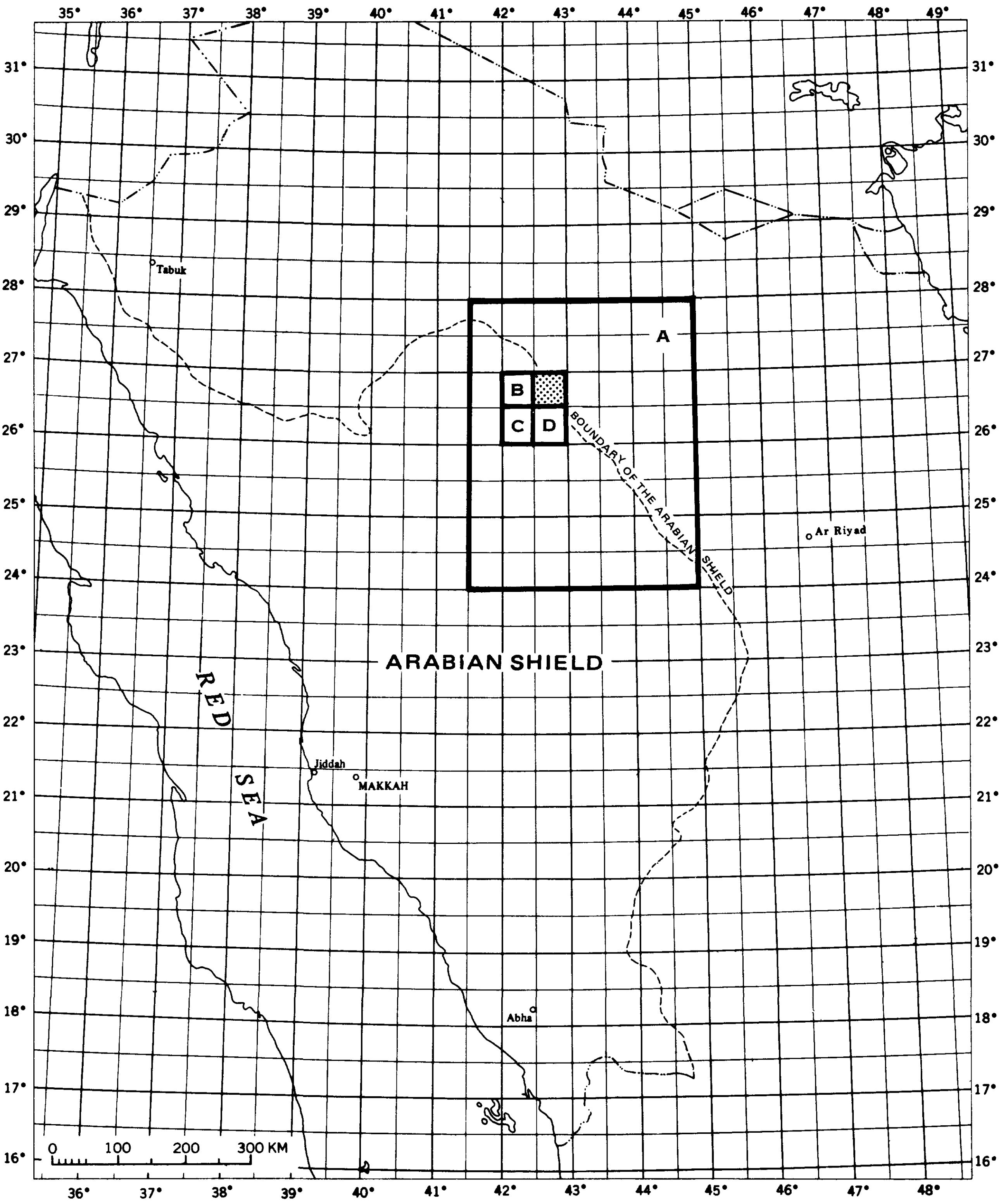

Figure 1.--Index map of western Saudi Arabia showing the location of the Al Makhul quadrangle (shaded) and quadrangles referred to in the text: A, Wadi ar Rimah (Bramkamp and others, 1963); B, Harrat al Hutaymah (Pallister, 1983 unpub data; C, Samirah (Williams, 1983); D, Jabal as Silsilah (du Bray, in press).

The metarhyolite, graywacke, and metabasalt exposed at Jabal Aba al Liqah are considered to be correlative with lithologically similar rocks included in the southwest-trending Hibshi formation that is exposed for 80 km along strike starting 12 km southwest of the Al Makhul quadrangle. The graywacke exposed south of Jabal Aba al Liqah is stratigraphically above the metarhyolite and metabasalt (Pallister, 1983) and is considered to be correlative with green graywacke sandstone included in the Hibshi formation by Williams (1983) in the Samirah quadrangle (fig. 1). The Turmus formation, named for exposures composed of weakly metamorphosed andesitic flow rocks and agglomerate, and tuffaceous volcanic sandstone located 15 km west of Wadi at Turmus in the Al Makhul quadrangle, cannot, however, be correlated with other nearby stratigraphic units. Rocks of the Turmus formation and those exposed at Jabal Aba al Liqah are similar in lithology, structural character, and metamorphic grade and are considered coeval. Amphibolite mapped in the south-central part of the Al Makhul quadrangle may be correlative with amphibolite mapped in the Samirah quadrangle (Williams, 1983). It is the result of metamorphism at moderate- to high-grade conditions that are atypical of metamorphic rocks exposed elsewhere in the quadrangle. The position of the amphibolite, surrounded by a single body of intrusive rock, suggests that it is a large xenolith.

Intrusive relations indicate that emplacement of all but one pluton postdates deposition of the metasedimentary and metavolcanic rocks. The weakly metamorphosed rocks exposed at and immediately south of Jabal Aba al Liqah rest unconformably on a pluton composed of quartz diorite and are, therefore, younger than the quartz diorite. Because the Turmus formation is considered to be coeval with the rocks exposed at Jabal aba al Liqah, it too is considered to be younger than the quartz diorite. Age relations between the amphibolite and the quartz diorite are indeterminate; the amphibolite, however, clearly has been intruded by younger plutons.

Classification of the metavolcanic rocks was facilitated by major element chemical analyses (see section on geochemistry and petrogenesis); it is difficult to assign fine-grained rocks such as these to the proper compositional group on the basis of petrography alone.

Amphibolite

Amphibolite (am) crops out in low, rolling hills that cover about 13 km^2 in the south-central part of the quadrangle. It is dark-greenish-gray, is weakly foliated but otherwise structureless, and is cut by dikes that emanate from the surrounding plutons. The amphibolite is very fine grained and hypidiomorphic inequigranular and its composition is variable. Some samples are composed of intergrown quartz and feldspar with interstitial red-brown biotite. A more common mineral assemblage is pale-green hornblende and clinozoisite set in an anhedral matrix composed of equigranular quartz and feldspar. Opaque oxides compose about 3 percent of the amphibolite and are the only accessory minerals. Secondary, interstitial calcite was identified in several samples.

Metarhyolite

The term metarhyolite has been used to categorize a thick section of texturally diverse, weakly metamorphosed felsic extrusive rocks (mr) exposed at Jabal Aba al Liqah that rest unconformably on an erosional surface of quartz diorite; the composition of these metavolcanic rocks may range between dacite and rhyolite. These rocks form prominent dark-colored ridges and hills as much as 100 m high. Most of the rocks are weakly to moderately welded pyroclastic deposits, although porphyritic lava flows and densely welded tuffs are also represented. Rapid lithologic variation along strike and vertically within the section precludes differentiation of pyroclastic rocks from flow rocks on the geologic map. Parting along surfaces parallel to compaction planes is well developed in the pyroclastic rocks; the lavas are massive and structureless. The base of the metarhyolite is marked by a basal conglomerate that is as much as 30 m thick. Several lenses of associated volcanic sandstone (gwe) have also been mapped within this unit.

The pyroclastic rocks are light-greenish-black on fresh surfaces. Textural variability is the hallmark of these rocks; pyroclastic textures, including flattened pumice blocks and angular lithic fragments are ubiquitous. Felsic pumice blocks range from about 2.5 mm to 5 cm in length and are set in a very fine grained matrix of quartz and feldspar. No primary mafic silicates were identified in these rocks although very fine grained anhedral aggregates of both chlorite and epidote compose part of the matrix. Phenocrysts and (or) xenocrysts of albite, potassium feldspar, and quartz were identified in most samples. The feldspar in many samples is sericitized and the quartz shows undulatory extinction.

The lava flows and densely welded tuffs are grayish red and are composed of a very fine grained felsitic matrix that contains phenocrysts of gridiron- and Carlsbad-twinned potassium feldspar and rounded quartz. Some samples contain phenocrysts of albite-twinned plagioclase. Feldspar is sericitized in many samples. No primary mafic silicates were identified but a trace of epidote and chlorite was observed in the anhedral groundmass. Opaque oxides and secondary calcite are the accessory minerals.

The interbedded graywacke (gwe) is a massive, medium-gray, poorly-sorted, medium-grained clastic rock composed of subangular to subrounded grains of quartz and albite and subrounded felsic volcanic lithic fragments (45, 30, and 25 percent, respectively). The ratio of clasts to matrix is variable, although most of the graywacke is grain-supported. The matrix is a turbid intergrowth of quartz, feldspar, opaque oxides, and chlorite. Trace amounts of anhedral epidote in granular clusters were also observed.

The basal conglomerate is a poorly-sorted deposit composed of rounded pebble- to cobble-size clasts of quartz diorite, tonalite, and granodiorite set in a well-indurated matrix composed of quartz diorite grus. The erosional unconformity between the quartz diorite and the overlying metarhyolite indicates that the metarhyolite is younger than the quartz diorite and the clasts found in the conglomerate probably were derived from the underlying quartz diorite. The conglomerate varies in thickness from several meters to about 30 m but it is absent in several places along the western base of Jabal Aba al Liqah; the full thickness of metarhyolite is not exposed at these places. The metarhyolite is correlated with similar rocks included in the Hibshi formation by Williams (1983).

Metabasalt

Massive, dark-gray, weakly metamorphosed porphyritic basalt (mb) crops out over about 25 km^2 at Jabal Aba al Liqah. The metabasalt is internally structureless, probably consists of thick flows, and forms resistant hills and ridges as much as 50 m high.

Moderately to strongly zoned, euhedral, albite-twinned plagioclase phenocrysts are set in an intergranular matrix composed of very fine grained chlorite, plagioclase microlites, and opaque oxides. Some phenocrystic laths of plagioclase are as much as 4 mm long, although most are between 0.5 and 1 mm long; the laths exhibit trachytic layering in some samples. Chlorite has pseudomorphously replaced most primary mafic minerals, but in some rocks subhedral laths of hornblende are only partly replaced by chlorite. Anhedral grains of epidote and clinozoisite as much as 0.1 mm in diameter compose between 1 and 10 percent of the metabasalt. Very fine grained subhedral to euhedral crystals of opaque oxides compose as much as 15 percent of the metabasalt, and calcite-filled vesicles as much as 1 mm in diameter form as much as 5 percent of the rock. Secondary quartz was observed in some samples. Apatite was the only trace mineral identified.

Metabasalt rests depositionally on, and is therefore younger than, the metarhyolite. In the southern half of Jabal Aba al Liqah between 2 and 5 m of conglomerate intervenes between the metarhyolite and conglomerate; the conglomerate pinches out to the north. The conglomerate is poorly sorted and contains well-rounded, pebble- and cobble-size clasts, principally composed of quartz diorite, tonalite, and granodiorite but also includes clasts of the underlying metarhyolite. The metabasalt has no lithologic counterpart in the Hibshi formation (Williams, 1983) but its position between units that do have counterparts suggests that its deposition represents a localized event.

Graywacke

Medium-dark-gray to dark-greenish-gray graywacke (gw) crops out over about 45 km^2 along the west-southwest border of the quadrangle. The graywacke forms several hills and northeast-trending ridges that rise as much as 30 m above the level of the pediment; otherwise it weathers to a surface of low relief. Most outcrops of graywacke are massive and bedding is not apparent.

The graywacke is a medium- to coarse-grained poorly sorted lithic sandstone. Clasts are subangular and range from 0.4 mm to 1 mm in diameter but are predominantly about 0.5 mm in diameter. The matrix is a silt-sized intergrowth of subhedral, red-brown biotite and anhedral quartz and includes about 2 percent of subhedral opaque oxides and a trace of epidote. Petrographic features of the graywacke change in a regular fashion from north to south, that is, from base to top. The average clast size is greatest, and the degree of rounding and the matrix-to-clast ratio are least, in rocks at the base of the section. The matrix composes as much as 60 percent of the graywacke at the top of the section but accounts for less than 20 percent at its base. The clast population varies systematically throughout the section. Graywacke at the base of the section contains principally fragments of mafic volcanic rock and felsite, and only about a third of the clasts are monocrystalline or polycrystalline quartz, plagioclase, or potassium feldspar. Samples from higher in the section contain fewer volcanic clasts and more stable felsic grains, and at the top of the section most clasts are of monocrystalline quartz, and even feldspar is uncommon.

The graywacke rests depositionally on the metarhyolite and metabasalt exposed at Jabal Aba al Liqah and therefore is younger. The composition and texture of the graywacke in this section vary in a way that is consistent with its derivation from the underlying rocks. The graywacke is tentatively correlated with similar rocks included in the Hibshi formation by Williams (1983).

Turmus formation

A large elongate area that extends from near the center of the quadrangle toward its northwestern corner is underlain by meta-andesite and intimately interbedded meta-andesitic agglomerate and lithic graywacke, approximately 50, 30, and 20 percent, respectively. These medium-dark-gray rocks are here designated as the Turmus formation (tf) and are named for characteristic exposures located about 15 km west of Wadi at Turmus. The meta-andesite and agglomerate are massive whereas the graywacke is well bedded in most places; individual graywacke beds are 0.5 cm to 10 cm thick. The Turmus formation is locally intruded, concordantly in some places and discordantly in others, by hypabyssal dikes and sills of light-gray to pale-red rhyolite (mra). Conglomerate (cgl) was mapped in two places within the formation.

The meta-andesite is characteristically porphyritic. Subhedral to euhedral phenocrysts of locally sericitized, moderately zoned, albite-twinned plagioclase, 0.2 mm to 5 mm long, are set in an intergranular to felted matrix composed of very fine grained plagioclase, opaque oxides, chlorite, amphibole, and secondary calcite. Plagioclase laths display trachytic layering in some samples. Primary hornblende occurs as rounded or elongate, anhedral to subhedral phenocrysts as much as 1.5 mm long. Metamorphic epidote in isolated grains and in clusters is pseudomorphous after primary pyroxene. In some samples, vesicles as much as 0.5 mm in diameter are filled by calcite, epidote, and chlorite.

Massive meta-andesite flows grade upward into tuffaceous meta-andesite and meta-andesite agglomerate as the quantity and size of included rock fragments increase; all of these lithologies are intimately interbedded. Clasts are composed of meta-andesite; they are poorly sorted and subangular. These rocks may represent reworking and rapid redeposition of previously deposited andesite flows in a shallow marine environment.

Weakly metamorphosed lithic graywacke is a major component of the Turmus formation. The graywacke and meta-andesite are lithologically gradational into each other and are so closely interbedded that they cannot be separately mapped at the 1:100,000 scale. The graywacke is immature with respect to texture and composition. Its matrix is composed of turbid argillaceous material and accounts for 10 to 20 percent of most samples. The clast assemblage is poorly sorted. Most clasts are subangular to subrounded and are between 0.5 mm and 3 mm in diameter, although clasts as much as 1 cm in diameter were observed. Fragments of meta-andesite compose about 50 percent of the clast population. They consist of plagioclase microlites in a very fine grained matrix; in some samples they have a trachytic texture. Subangular clasts of albite-twinned plagioclase form 35 percent of the clast population, subangular to subrounded grains of monocrystalline quartz about 10 percent, and opaque oxides up to 1 mm in diameter about 5 percent. Trace amounts of secondary calcite and of metamorphic chlorite and epidote were identified.

Metarhyolite dikes and sills (mra) that intrude the rocks of the Turmus formation form hills as much as 40 m high and are most abundant in the northwest part of the quadrangle. Phenocrysts of quartz and feldspar are set in a very fine grained felsophyric matrix. Subangular to subrounded quartz phenocrysts are as much as 1 mm in diameter. Albite-twinned phenocrysts of albite are as much as 1.5 mm long and are sericitized in many samples. Trachytic layering of plagioclase is a feature common to samples of the metarhyolite that are phenocryst rich. Euhedral phenocrysts of potassium feldspar are as much as 2.5 mm long; most are completely altered to clay minerals. Small amounts of interstitial chlorite and biotite were identified in some samples. Trace amounts of apatite, epidote, muscovite, and secondary calcite were also identified.

Conglomerate (cgl) was mapped at a location 12 km south of Jabal al Ghumayq and at another in the northwest part of the quadrangle. The poorly sorted conglomerate appears to occur as very small lenses within the Turmus formation, but the contact relationships were not exposed. Clasts in the conglomerate are subangular to subrounded and are between 5 and 30 cm in diameter. Most of the clasts are composed of granodiorite or granite, although some are of metavolcanic rock. The matrix consists of well indurated grus.

The Turmus formation is tentatively considered to be contemporaneous with the metavolcanic rocks exposed in Jabal Aba al Liqah. Similarity of structural features, age relations with intrusive rocks, metamorphic grade, depositional style, and lithology are the basis for this correlation. These two units are not, however, in contact so it is not possible to make a definitive statement regarding their relative age. Like the metavolcanic rocks exposed at Jabal Aba al Liqah, the Turmus formation is intruded by and is older than most of the plutonic rocks. The contact between the Turmus formation and the quartz diorite is not well exposed but it is inferred that the Turmus formation rests unconformably on the quartz diorite.

PRECAMBRIAN INTRUSIVE ROCKS

Plutonic rock crops out extensively in the south part of the quadrangle. In addition, one pluton crops out midway along the west border of the quadrangle and another crops out a few kilometers to the east. Intrusive rocks were divided into plutons on the basis of mapped and inferred contacts, characteristic composition (fig. 2a-c), textural features, relations with adjacent rock, dikes, and structural features. Plutonic rock nomenclature follows the guidelines of Streckeisen (1976). The contents of plagioclase, quartz, and potassium feldspar given for each of the intrusive units are averages of modal data from several samples. Biotite-hornblende ratios are estimates and are based on petrographic study. Age relations between the plutons were difficult to determine because the contacts between most plutons are poorly exposed. Consequently, the indicated age relations, based on dike density and truncation of dikes by plutons, degree of pluton deformation, and geometric relations, are tentative.

Plutonic rocks in the Al Makhul quadrangle fall into three broad compositional categories. The first category consists of three mafic plutons composed of quartz monzodiorite, tonalite, and quartz diorite, respectively, and a complex composed of gabbro, diorite, quartz diorite, and granodiorite. Age relations indicate that these are the oldest plutons exposed in the quadrangle, and their primitive compositions suggest that they represent an early stage of plutonic activity in the area.

The second group of plutons comprises the bulk of the intrusive rock in the quadrangle and includes three monzogranite plutons. These plutons share similarities of lithology, composition, and plutonic style, which suggest that they are approximately coeval. They are lithologically and chemically similar to calc-alkaline intrusive rocks that underlie much of the Arabian Shield (Schmidt and Brown, in press).

The last category consists of a small alkali-feldspar granite pluton that represents the final intrusive episode in the Arabian Shield. This highly evolved rock is like those found at Jabal Qutn (Williams, 1983) and Jabal as Silsilah (du Bray, in press).

Quartz diorite

A large pluton composed of medium-greenish-gray quartz diorite (qd) (fig. 2b) crops out midway along the western boundary of the quadrangle. In most places this pluton weathers recessively and crops out in flat slabs but small inselbergs do occur on the pediment surface. The rock is cut by many rhyolitic and andesitic dikes and contains abundant amphibolitic xenolithic material.

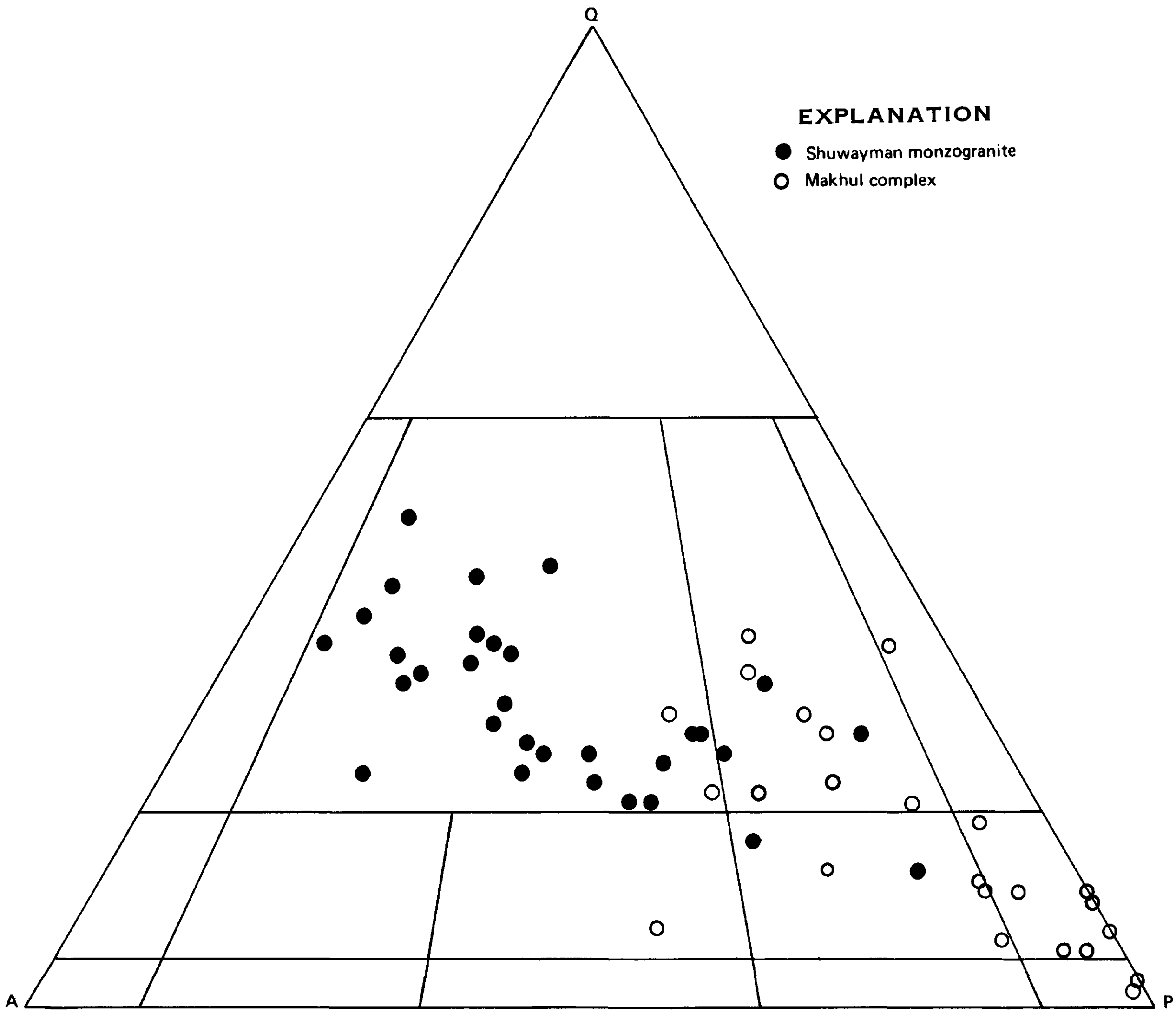

Figure 2a.--Quartz-alkali feldspar-plagioclase (QAP) ternary diagram (Streckeisen, 1976) showing the modal composition of intrusive rocks in the Al Makhul quadrangle; the sum of Q, A, and P is normalized to 100 percent. Each plotted point represents a modal analysis (between 400 and 700 points counted on a stained slab measuring at least 50 cm^2) for a single sample.

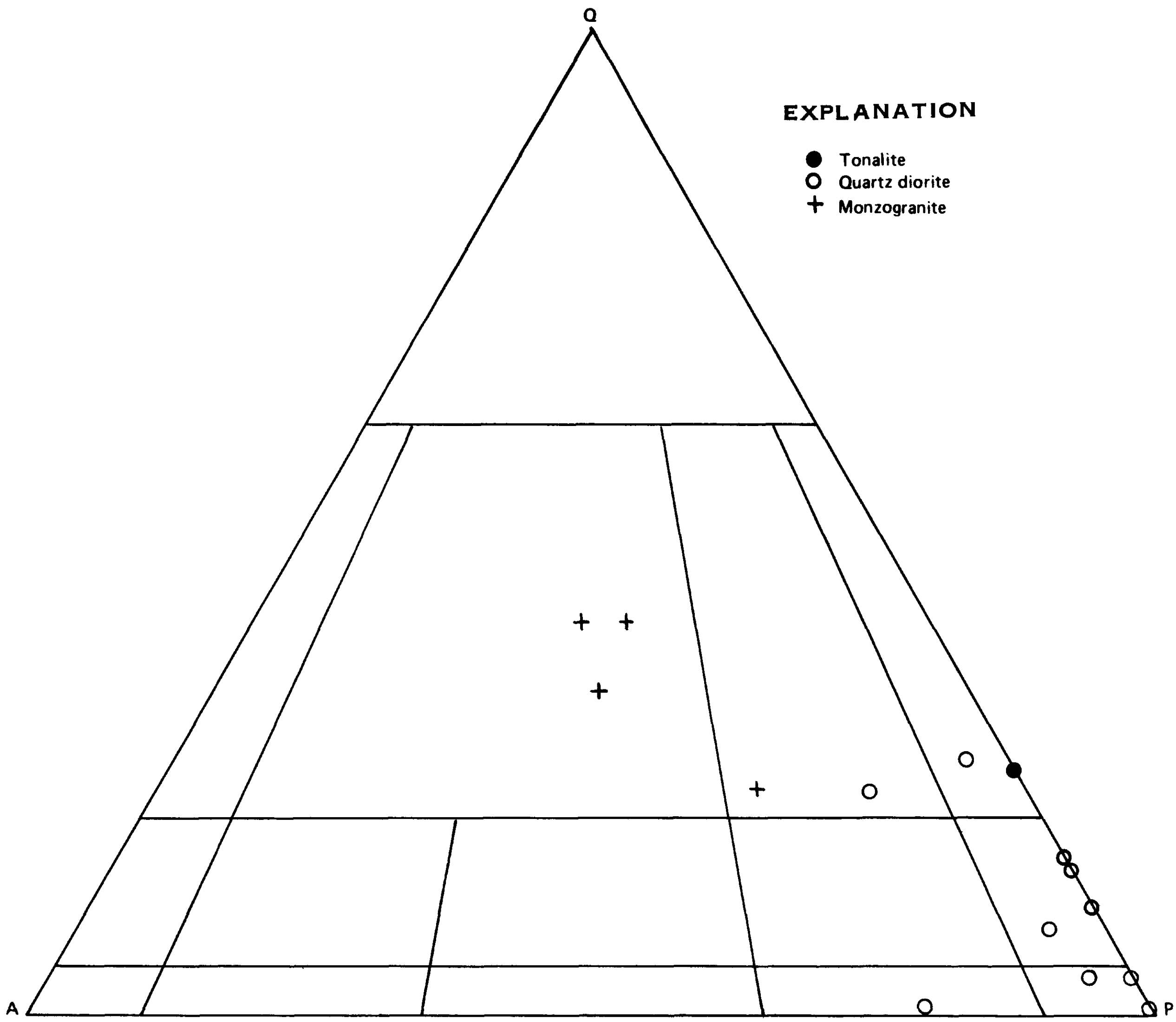

Figure 2b.--Quartz-alkali feldspar-plagioclase (QAP) ternary diagram (Streckeisen, 1976) showing the modal composition of intrusive rocks in the Al Makhul quadrangle; the sum of Q, A, and P is normalized to 100 percent. Each point plotted represents a modal analysis (between 400 and 700 points counted on a stained slab measuring at least 50 cm^2) for a single sample.

The quartz diorite is texturally and compositionally inhomogeneous, medium grained, and hypidiomorphic inequigranular. The felsic constituents are plagioclase, quartz, and potassium feldspar (53, 8, and 4, percent, respectively). Plagioclase occurs in anhedral to subhedral laths as much as 5 mm long and is strongly sericitized. Most grains are of a fairly homogeneous composition although some are strongly zoned; all grains are albite twinned. Quartz is anhedral and displays undulatory extinction. A trace of potassium feldspar is interstitial. Biotite and hornblende in varying proportions are the mafic minerals; color index is 35. Red-brown biotite is anhedral to subhedral and occurs in grains as much as 3 mm long; chlorite has partially replaced some grains. Pale-green hornblende occurs in anhedral laths as much as 4 mm long. Hornblende has been pseudomorphously replaced by chlorite and epidote in most samples. Where unaltered, hornblende is spongy and poikilitically encloses fine-grained quartz. Opaque oxides are the principal accessory minerals, and trace amounts of apatite, zircon, and sphene were identified. Interstitial calcite occurs as a secondary mineral.

The quartz diorite is considered to be the oldest intrusive unit in the quadrangle because it is the only one on which younger, layered rocks were deposited. The quartz diorite is characterized by a weak cataclastic texture, which also suggests its relatively old age.

Makhul complex

An intrusive complex composed of mafic plutonic rock (mc) (fig. 2a) underlies a large area in the south-central part of the quadrangle. Rocks of the Makhul complex are distinguished by their extreme textural and compositional variation. The rocks are grayish-black and weather very recessively; they are cut by dikes that also crop out very poorly. Some samples are weakly gneissic; postcrystallization deformation has created poorly defined mineral bands.

Samples of monzogranite, granite, tonalite, quartz monzonite, quartz monzodiorite, quartz diorite, diorite, poikilitic hornblende gabbro, and gabbro (fig. 2a) were collected within this unit. The rocks of the Makhul complex are hypidiomorphic inequigranular and medium grained. The felsic constituents are plagioclase, quartz, and potassium feldspar (50, 10, and 7 percent, respectively). Rare, gridiron-twinned potassium feldspar is interstitial and weakly perthitic. Quartz is also interstitial and characteristically displays undulatory extinction. In some samples the quartz has been moderately affected by cataclastic granulation. Stubby plagioclase laths as much as 1 cm long are anhedral to subhedral and are sericitized in many samples. Most grains of plagioclase are strongly and complexly zoned and albite-twinned. Hornblende, locally altered to chlorite and opaque oxides, is the dominant mafic mineral, although the biotite-hornblende ratio is highly variable; color index is 33. Hornblende occurs as anhedral to subhedral laths that are as much as 1 cm long and are pleochroic from pale-straw-yellow to pale-green. In several samples of hornblende gabbro, round, subhedral hornblende grains replaced by actinolite are as much as 2 cm in diameter and poikilitically enclose euhedral laths of plagioclase as much as 0.5 cm long. Anhedral grains of interstitial clinopyroxene as much as 0.5 mm long compose as much as 10 percent of the poikilitic hornblende gabbro. Clinopyroxene also forms the cores of some hornblende grains. Biotite is anhedral to subhedral and interstitial in most samples. Both pale-straw-yellow to deep-greenish-brown and pale-yellow to deep-reddish-brown pleochroic varieties were observed. The accessory minerals are principally opaque oxides and eudedral sphene, and trace amounts of apatite, allanite, zircon, and secondary calcite were observed.

The contact between the the Makhul complex and the Turmus formation is not well exposed but it appears that the Makhul complex intrudes, and is therefore younger than, the Turmus formation.

Tonalite

A recessive-weathering pluton of medium-gray tonalite (to) (fig. 2b) 4 km^2 in extent crops out 15 km east of the quadrangle's southwest corner, at the border of the Al Makhul and Jabal as Silsilah quadrangles. The rock is medium grained and hypidiomorphic inequigranular. It contains about two mafic inclusions per square meter of outcrop and its color index is 28. The felsic constituents are plagioclase and quartz (54 and 18 percent, respectively). Biotite and hornblende, in a 3:2 ratio, are the mafic silicates in this rock; both occur interstitially. Euhedral plagioclase laths up to 4 mm are weakly zoned. Apatite and sphene are the dominant accessory phases in this small pluton, and zircon and opaque oxides were also identified.

Quartz monzodiorite

An area of about 8 km^2 in the southeast part of the quadrangle is underlain by quartz monzodiorite (qmd) (fig. 2c). This medium-gray, medium-grained, hypidiomorphic inequigranular rock weathers recessively and crops out in flat slabs on the pediment surface; it is cut by numerous dikes. The quartz monzodiorite contains very few mafic inclusions.

The felsic constituents are plagioclase, quartz, and microcline (50, 11, and 18 percent, respectively). Biotite and hornblende occur in a 1:1 ratio; color index is 21.

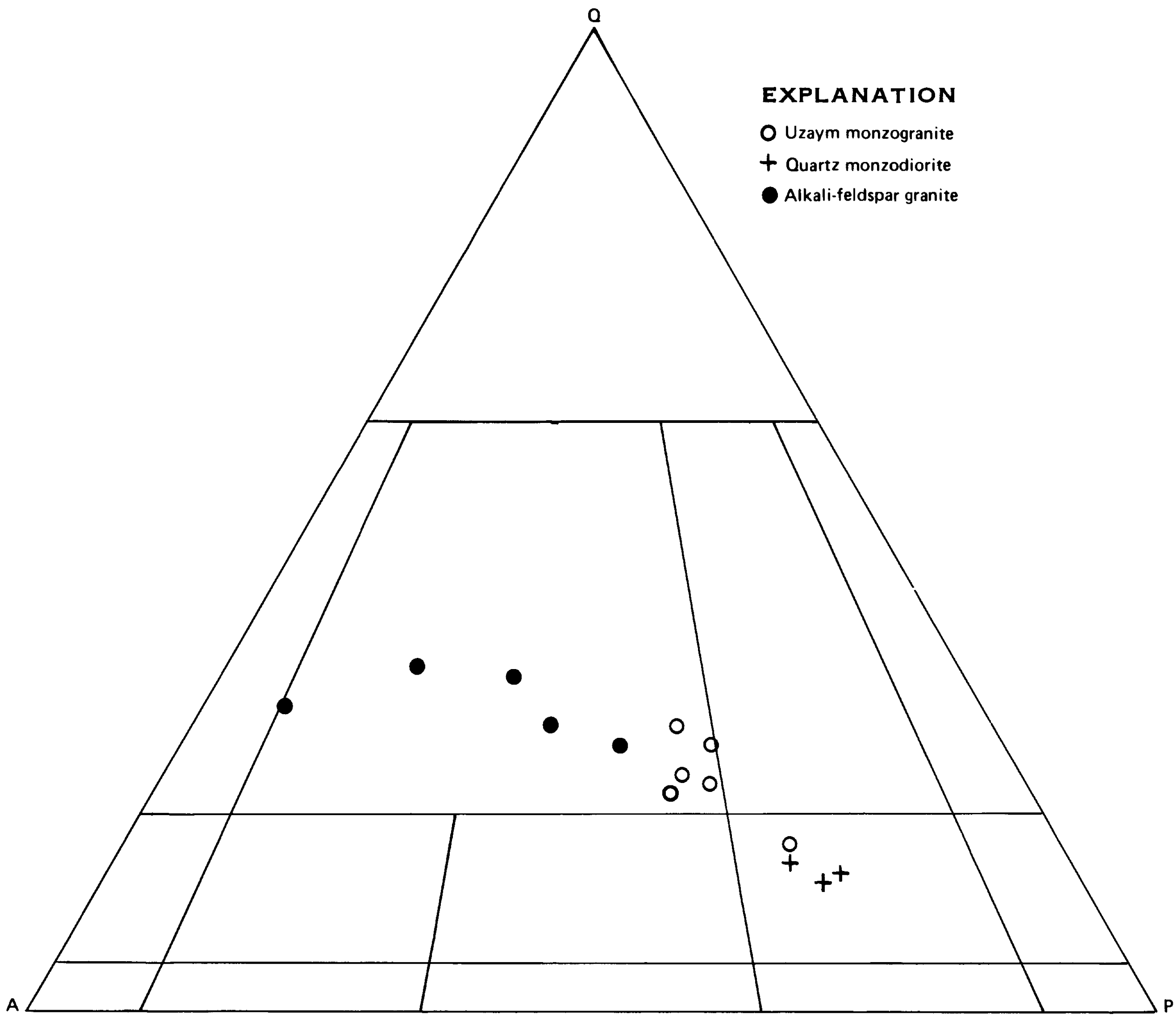

Figure 2c.--Quartz-alkali feldspar-plagioclase (QAP) ternary diagram (Streckeisen, 1976) showing the modal composition of intrusive rocks in the Al Makhul quadrangle; quadrangle; the sum of Q, A, and P is normalized to 100 percent. Each point plotted represents a modal analysis (between 400 and 700 points counted on a stained slab measuring at least 50 cm^2) for a single sample. Albite is counted as plagioclase for samples of the alkali-feldspar granite so that the ratio of albite to potassium feldspar is discernible. Properly plotted modes for these samples would fall on the quartz-potassium feldspar sideline of the ternary.

Moderately to strongly zoned plagioclase occurs as subhedral, albite-twinned laths as much as 4 mm long. Quartz is interstitial and characterized by undulatory extinction. Microcline is also interstitial and is weakly perthitic; albite has exsolved as stringers. Biotite is pleochroic from yellowish-brown to medium-reddish-brown and is anhedral and principally interstitial. Subhedral laths of hornblende are as much as 4 mm long and show yellowish-green to green pleochroism. Opaque oxides and sphene are the principal accessory minerals, and trace amounts of apatite and zircon, especially as inclusions in biotite, were identified.

The quartz monzodiorite, tonalite, and Makhul complex intrude the metamorphic rocks and are therefore younger than the quartz diorite. Age relations among these three plutonic units, however, are indeterminate.

Shuwayman monzogranite

A large area in the southern part of the quadrangle is underlain by the Shuwayman monzogranite (smg) (fig. 2a). The pluton is named for prominent outcrops near the village of Shuwayman in the Jabal as Silsilah quadrangle (fig. 1). This pinkish-gray, allotriomorphic equigranular, alaskitic monzogranite weathers recessively and crops out in flat slabs on the pediment surface. In the Al Makhul quadrangle the monzogranite is not as compositionally and texturally homogeneous as it is in the Jabal as Silsilah quadrangle; in particular, many samples contain more potassium feldspar than samples from the Jabal as Silsilah quadrangle and near its contacts the monzogranite tends to contain more plagioclase and mafic minerals and is finer grained. The pluton is cut by many north-northwest-trending dikes of mafic to intermediate composition.

The monzogranite is medium grained and equigranular. The felsic constituents are plagioclase, quartz, and microcline (30, 30, and 36 percent, respectively). Average color index is 4. Very few mafic inclusions were observed. Pale-yellow-brown to medium-reddish-brown pleochroic biotite is interstitial and is the only mafic phase in this granite. Trace amounts of interstitial primary muscovite were identified in some samples. Gridiron-twinned microcline is characterized by stringer and patch perthite. Microcline poikilitically encloses grains of plagioclase and biotite. Plagioclase is weakly zoned albite. Opaque oxides are the principal accessory minerals, and trace amounts of zircon, allanite, and sphene were also identified. The allotriomorphic equigranular character of this unit suggests simultaneous crystallization of the feldspars and quartz.

Felsic dikes that emanate from the Shuwayman monzogranite penetrate quartz monzodiorite, mafic rocks of the Makhul complex, and tonalite; aplitic and pegmatitic segregations were commonly observed in the Shuwayman monzogranite at its contacts with these rocks. The monzogranite is considered to be younger than all of these rocks.

Monzogranite

A small pluton composed of pinkish-gray monzogranite (mg) (fig. 2b) crops out over about 20 km^2 in the southeast part of the quadrangle. The monzogranite weathers recessively to flat slabs on the pediment surface and is cut by felsic dikes. No mafic inclusions were observed.

The monzogranite is medium grained, hypidiomorphic granular, and distinctly subporphyritic (phenocrysts are slightly smaller than the five-times-groundmass grain size--a criterion that is commonly used to define porphyritic rocks). The felsic constituents are plagioclase, quartz, and microcline (33, 31, and 26 percent, respectively). Strongly zoned laths of plagioclase as much as 4 mm long are albite twinned and anhedral to subhedral. Weakly perthitic microcline forms subphenocrysts as much as 8 mm long that display weak grid-iron twinning. Microcline poikilitically encloses all other minerals. Quartz is anhedral and displays undulatory extinction. Biotite is the principal mafic phase, and trace amounts of hornblende were identified; color index is 10. Yellowish-brown to reddish-brown pleochroic biotite occurs in interstitial grains as much as 2 mm long. Hornblende occurs in euhedral grains as much as 1 mm long. Opaque oxides and sphene are the principal accessory minerals and trace amounts of zircon and apatite were identified, especially as inclusions in biotite.

Poorly exposed contact relations and hydrothermal alteration of the monzogranite at its contact with the Shuwayman monzogranite suggest that the monzogranite is younger than the Shuwayman monzogranite.

Quartz

Quartz veins are not abundant in the quadrangle but two small bodies of massive, milky white quartz (q) were found. A small plug of apparently unmineralized quartz that intrudes the Shuwayman monzogranite crops out in a low mound near the southern boundary of the quadrangle and a few kilometers west of the amphibolite. A second low mound of quartz, located 6 km north of the first locality, is formed by massive quartz that intrudes mafic rock of the Makhul complex. Quartz at these mounds is probably related to final hydrothermal activity that accompanied emplacement and crystallization of the host pluton.

Uzaym monzogranite

The Uzaym monzogranite (umg) (fig. 2c) is distinctly porphyritic and is named for outcrops between 5 and 10 km east of Al Uzaym, which is in the Harrat al Hutaymah quadrangle (fig. 1). The Uzaym monzogranite is very light gray and weathers recessively to flat slabs on the pediment surface; it is cut by many dikes of intermediate to mafic composition.

The monzogranite is medium to coarse grained, hypidiomorphic granular, and contains phenocrysts of microcline. The felsic constituents are plagioclase, quartz, and microcline (46, 22, and 27 percent, respectively). Strongly and complexly zoned, albite-twinned plagioclase forms subhedral laths that are as much as 1 cm long. The cores and zone boundaries of some grains are dusted with sericite. Strongly perthitic, gridiron-twinned microcline forms anhedral phenocrysts as much as 1.5 cm long. Quartz is anhedral and displays undulatory extinction. Yellowish-brown to reddish-brown pleochroic biotite is the only mafic phase; color index is 5. Biotite occurs interstitially and is locally altered to chlorite. Opaque oxides and sphene are the principal accessory minerals and trace amounts of zircon and apatite were identified.

Like the Shuwayman monzogranite, the Uzaym monzogranite is slightly more mafic at its contacts; the presence of the mafic border phase at the contact with the Shuwayman monzogranite suggests that the Uzaym monzogranite cooled against the Shuwayman monzogranite, and therefore is younger.

Alkali-feldspar granite

An elliptical area underlain by alkali-feldspar granite (afg) (fig. 2c) is located about 10 km southeast of Ath Thuaylibi. This is the most recessively weathering rock type in the quadrangle; outcrop was found at only 5 places in the 45 km^2 area underlain by this unit; elsewhere the pluton is covered by a blanket of grus. Very few dikes transect this pluton. The alkali-feldspar granite is locally more than twice as radioactive as the average intrusive rocks of the Arabian Shield.

The grayish-orange-pink alkali-feldspar granite is allotriomorphic inequigranular and medium grained; this texture is characteristic of rocks that solidified by simultaneous crystallization of quartz and feldspar. The felsic constituents are plagioclase, quartz, and microcline (24, 30, and 44 percent, respectively). Plagioclase occurs as anhedral to subhedral, albite-twinned laths as much as 1 mm long. Anhedral microcline is gridiron-twinned and strongly perthitic. Anhedral quartz grains are as much as 4 mm in diameter. Most samples of this pluton contain no iron-bearing phase except hematite; color index is 2. One sample contains biotite that has been partly altered to chlorite. Trace amounts of zircon, sphene, apatite, and fluorite were identified.

The alkali-feldspar granite intrudes, and therefore is younger than, the Turmus formation and the metamorphic rocks exposed at Jabal Aba al Liqah, but age relations with the other intrusive rocks in the quadrangle are indeterminate. The plutonic style and composition of this pluton are similar to those of the alkali-feldspar granites at Jabal as Silsilah (du Bray, in press) and Jabal Qutn in the Samirah quadrangle (Williams, 1983) that are considered to represent the final period of pluton emplacement in the Arabian Shield. The alkali-feldspar granite is therefore considered to be the youngest pluton in the Al Makhul quadrangle.

Dikes

Several prominent swarms of dikes occur within the Al Makhul quadrangle. The Shuwayman monzogranite and the Uzaym monzogranite are cut by a northwest-trending dike swarm that includes both felsic and mafic dikes. Dikes that penetrate the remaining plutons are not characterized by such uniformity of trend, nor is the composition of these dikes consistent. No attempt was made to discriminate dikes on the basis of composition on the geologic map. The descriptions of mafic, intermediate, and felsic dikes that follow are based on a suite of samples that was collected to facilitate description of these arbitrarily constructed varietal classes.

Mafic dikes are abundant, and they occur mainly in a northwest-trending swarm in the southwest corner of the quadrangle. They weather dark-gray, and most are fine grained and porphyritic. A wide range of textures and mineralogy are represented but certain features occur in most samples. Felty, trachytic flow textures involving unzoned calcic plagioclase laths between 0.2 mm and 0.5 mm long set in a finer grained matrix of opaque oxides, biotite, chlorite, epidote, and secondary calcite are common. Opaque oxides compose as much as 10 percent of the mafic dikes. Euhedral phenocrysts of hypersthene were also identified in some of the mafic dikes.

Dikes of intermediate composition weather medium-gray to pale-red. Quartz is more abundant in these dikes than in the mafic dikes, and plagioclase and mafic silicates are more abundant than in the felsic dikes. The groundmass is typically a very fine grained allotriomorphic intergrowth of quartz and the feldspars, and fine-grained biotite and hornblende were also identified in the groundmass. Both equigranular and porphyritic dikes were observed. Subhedral to euhedral, perthitic potassium feldspar, rounded quartz grains, and sericitized laths of plagioclase commonly occur as phenocrysts. Devitrification textures were observed in several samples. Sphene, opaque oxides, and apatite are the principal accessory minerals. Many of the dikes that trend north are of intermediate composition.

Felsic dikes weather to a distinctive brick-red color. Like the dikes of intermediate composition, the felsic dikes have a groundmass composed of an allotriomorphic intergrowth of quartz and feldspar. Devitrification and micrographic textures are common. Mafic silicates are rare. Quartz in rounded grains and potassium feldspar in euhedral crystals are the common phenocryst minerals. Opaque oxides and trace amounts of muscovite, fluorite, zircon, and biotite are the accessory minerals. The felsic dikes have no particular trend.

PALEOZOIC ROCKS

The Saq Sandstone (OЄs) is a quartz arenite (Williams and others, 1954) that rests unconformably on a gently inclined erosional surface of Precambrian rocks in the east part of the quadrangle. A cross section constructed by Bramkamp and others (1963) suggests that the sandstone is approximately 600 m thick near its contact with the overlying Tabuk Formation. Local relief on the erosional surface appears to be small, probably not greater than 10 m. Powers and others (1966) provide a good regional description of the Saq Sandstone and indicate that it probably represents Early Cambrian through Early Ordovician sedimentation. The contact between the Saq Sandstone and the underlying rocks is concealed by alluvium in most places. The sandstone weathers to a surface of very low relief and crops out prominently only at Jabal al Ghumayq. The sandstone is massively bedded although small-scale cross bedding was locally observed.

Within the map area the Saq Sandstone is very homogeneous. Neither silty, conglomeratic, nor shaley beds were observed, although these are reported elsewhere in the formation (Bramkamp and others, 1963). A few beds that contain rounded milky quartz pebbles up to 2 cm in diameter were identified. The sandstone is a moderately well-sorted aggregate of medium to coarse, subangular to subrounded grains of monocrystalline quartz that show various degrees of strain and are cemented by carbonate. Polycrystalline quartz grains are sparse. The sandstone is relatively well compacted and is grain supported. Carbonate cement forms between 20 and 30 percent of most samples; it is locally replaced by ferruginous material that gives the sandstone its reddish-brown color.

QUATERNARY VOLCANIC ROCKS

Alkali basalt that crops out in the northwestern part of the Al Makhul quadrangle forms the southeast end of Harrat al Hutaymah, a basalt field composed principally of flow rocks, but also including cinder cone deposits, and explosive tuff ring deposits. The cinder cones are aligned along several north-trending axes, and basalt extrusion may have been fracture controlled. Harrat al Hutaymah is one of the smallest members of a set of harrats that cover much of the Precambrian rock in northwestern Saudi Arabia. These basaltic rocks are probably related to the ongoing process of rifting and vulcanism along the axis of the Red Sea. A single K-Ar date obtained from flow rocks in the Harrat al Hutaymah quadrangle (fig. 1) gives an age of 1.80±0.05 Ma (J.S. Pallister, written commun., 1983) but Kellogg (1982, unpub. data) considers that most of the Harrat al Hutaymah rocks are younger than this because the sample dated was collected from the base of the volcanic pile.

Parts of four isolated basaltic volcanoes, all located east of the main northerly-aligned chain of cinder cones, occur within the Al Makhul quadrangle. Northwest of the Al Makhul quadrangle the volcanoes and their basaltic extrusive products coalesce and form the Harrat al Hutaymah volcanic field that covers much of the Precambrian rock in this area. An explosion crater with a basaltic tuff ring is located 8 km southwest of Ath Thuaylibi at the western edge of the quadrangle; a single basalt flow that flowed northward out of the volcano is overlain by the tuff. Two basalt flows that emanated from volcanoes located west of the Al Makhul quadrangle occur in the northwestern part of the quadrangle. A volcano at the north boundary of the quadrangle emitted several flows that moved eastward; moderately welded, vent-facies basalt forms a tuff deposit peripheral to the volcano.

Basaltic tuff

Basaltic tuff (Qbt) is mapped at two places in the Al Makhul quadrangle; the lithology and mode of occurrence at each is somewhat distinct.

Poorly sorted, weakly cemented, pale brown lapilli tuff forms an unwelded blanket as much as 100 m thick at the periphery of the explosion crater on the western boundary of the quadrangle; thickness is greatest on the crater's northern edge. Layering in the the tuff is cyclically graded; coarse clasts are found at the base of each cycle and fine clasts at the top. The thickness of a single cycle varies between several centimeters and about one meter. Clasts in the tuff are angular and range between 2 mm and 5 m in diameter; most clasts are in the 2 mm to 10 cm range. The clasts include fractured xenocrysts of pale-green olivine and fragments of pumiceous basalt, of the quartz diorite that hosts the crater, and of biotite amphibolite that is not exposed elsewhere in the region but presumably represents unexposed Precambrian rock.

Basaltic tuff exposed at the volcano on the north edge of the quadrangle north of Ath Thuaylibi is a frothy vent facies of the basalt that forms flows in this area. This moderately welded material weathers medium-greenish-black to moderate-brown and locally contains fractured phenocrysts of diopside as much as 2 cm long. The tuff is vesicular and locally cavernous. Dark-yellowish-orange glass that exhibits weak compaction textures composes about 75 percent of this rock. Vesicles as much as 5 mm in diameter are irregularly shaped and compose about 5 percent of the rock. Moderately flattened pumice blocks as much as 5 mm long contain very fine grained olivine, are extremely vesicular, and compose about 15 percent of this tuff. Anhedral xenocrysts of olivine as much as 0.5 mm but more frequently 0.1 mm in diameter compose 5 per cent of the rock.

Alkali basalt

Flow rocks of alkali basalt (Qbf) crop out in the northwestern corner of the Al Makhul quadrangle. The flows are as much as 10 km long, several kilometers wide, a few meters thick, and are characterized by very flat tops. The basalt weathers brownish black and is vesicular although the degree of vesicularity is variable. Many vesicles, as much as 1 cm in diameter, are at least partially filled with calcite and most are stretched. The texture and composition of alkali basalt from different flows is variable, although some generalizations can be made. The basalt is holocrystalline, porphyritic, and very fine grained; trachytic orientation of elongate crystals was observed in most samples. Olivine, converted to iddingsite at grain margins, is anhedral to subhedral and forms phenocrysts as much as 3 mm in diameter; most olivine grains are 0.1 to 0.2 mm in diameter. Euhedral plagioclase laths as much as 0.2 mm long are trachytic. The groundmass is an intergranular mixture of plagioclase, opaque oxides, and augite.

QUATERNARY ALLUVIAL DEPOSITS

Alluvium

Alluvium (Qal) is predominantly composed of moderately well sorted sand-size material in active wadi channels but also includes silt, pebbles, fine windblown material, unconsolidated conglomeratic material in wadis, and minor amounts of colluvium, talus, and evaporite deposits. Colluvium forms poorly sorted inactive slope wash and occurs in areas of high relief. Talus deposits are restricted to areas underlain by blocky weathering bedrock and high relief. Evaporite deposits form in local depressions and in small blocked drainages; these deposits appear as bright white areas on aerial photographs and Landsat imagery. The saline encrustations are usually not more than several centimeters thick and are generally interbedded with fine silty material.

Alluvial fan deposits

Alluvial fan deposits (Qaf) are restricted to an apron around Jabal Aba al Liqah and the area north of Ath Thuaylibi; the fan deposits are poorly sorted. Coalescing alluviual fans, adjacent to mountain fronts and cut by major wadis, form aprons around the highlands. Laterally migrating distributary channels are incised as much as 5 m below the fan surface and are filled with poorly sorted material ranging from silt to boulder size.

STRUCTURE

Metarhyolite and metabasalt at Jabal Aba al Liqah and the superjacent graywacke have been tilted steeply to the southeast, and the section exposed there appears to be homoclinal. Rocks of the Turmus formation also dip steeply but the attitude of bedding is inconsistent; the rocks may be folded but no folds were recognized either on the ground or in aerial photographs. The amphibolite is massive and does not display distinctive structural features. The plutonic rocks in the quadrangle are devoid of flow features and most are undeformed; cataclastic textures are weakly developed in rocks of the Makhul complex and in the quartz diorite.

Several major lineaments, identified either on aerial photographs or on the aeromagnetic map of the area (Consortium aeromagnetic survey of the Arabian Shield, flown 1966-1967), are shown on plate 1 as faults. Lineaments mapped in the Jabal Aba al Liqah area have demonstrable offset and bring rocks of contrasting lithologies into contact. Offsets along lineaments mapped in the Turmus formation are unknown because no marker beds were found. A major northwest-trending aeromagnetic lineament parallels the trend of the Najd fault system and is shown on plate 1 as a fault crossing the souhwest corner of the quadrangle. Movement along this fault represents the only structural event that postdates emplacement of the plutonic rocks; the Shuwayman monzogranite, Makhul complex, tonalite, Uzaym monzogranite, and the amphibolite are truncated and/or displaced along this fault.

METAMORPHISM

Most metamorphic rocks in the Al Makhul quadrangle were metamorphosed at very low grades during burial, but higher grade contact metamorphism was observed adjacent to some plutons, and one small area of amphibolite-facies rocks was found. The Precambrian sedimentary and volcanic rocks were metamorphosed in lower greenschist facies conditions, as indicated by the presence of biotite, actinolite, chlorite, epidote, and magnetite. Argillaceous material in the groundmass of sedimentary rocks was locally converted to biotite, but in other places remains as turbid, silt-size, clayey material. Primary sedimentary and volcanic textures are entirely preserved.

Contact metamorphism is well developed adjacent to several plutons and is especially apparent in Landsat imagery and on conventional photomosaics. In particular, a darkened zone as much as 2 km wide is distinguishable in the graywacke adjacent to the Shuwayman monzogranite south of Jabal Aba al Liqah. The rock in this zone is characterized by a hornfelsic texture and contains abundant biotite and lesser magnetite formed during metamorphism.

Some of the amphibolite unit has the assemblage hornblende-clinozoisite-plagioclase-biotite characteristic of amphibolite facies metamorphism. This mineral assemblage and the weakly developed metamorphic foliation of the amphibolite suggest that it has been subjected to a medium-grade metamorphic event that the other metamorphic rocks in the quadrangle have not experienced.

GEOCHRONOLOGY

Radiometric dating studies are just beginning in the northeast Arabian Shield and no data exist for rocks in the Al Makhul quadrangle. Episodes of magma genesis in the northeastern Arabian Shield are bimodally distributed; magmas were principally generated approximately 680 Ma ago and 620 Ma ago, although a few highly evolved magmas that solidified to plutons composed of alkali-feldspar granite, such as the one exposed in the Al Makhul quadrangle, were probably generated about 580 Ma ago (C. E. Hedge, oral commun., 1982). Field evidence in the northeast Arabian Shield indicates that the oldest intrusive rocks predate deposition of metasedimetary rocks of the Murdama group and Hibshi formation whereas magmas generated approximately 620 Ma ago postdate deposition of these rocks.

The quartz diorite in the Samirah quadrangle (fig. 1; Williams, 1983) crystallized 646 Ma ago (C. E. Hedge, oral commun., 1982). Lithologic similarity and map relations suggest that this pluton, on which the Hibshi formation was deposited, is correlative with the quartz diorite exposed below the metarhyolite, metabasalt, and graywacke at Jabal Aba al Liqah in the Al Makhul quadrangle. These rocks are therefore younger than 646 Ma but are older than the remaining plutonic rocks because they are intruded by them. Since the Turmus formation is considered to be coeval with the rocks exposed at Jabal Aba al Liqah, these same age constraints must also apply to it. The age relations between the amphibolite, considered to be the oldest metamorphic rock in the quadrangle, and the quartz diorite, the oldest plutonic unit, are indeterminate.

GEOCHEMISTRY AND PETROGENESIS

Metamorphic rocks

Major element chemical analyses and CIPW normative compositions obtained for 6 samples of metavolcanic rock collected in the Al Makhul quadrangle are presented in table 1. The metavolcanic rocks were analyzed to document their chemical composition and to aid in their classification; the system of Irvine and Baragar (1971) was used to classify the metavolcanic rocks. The samples analyzed are subalkaline as determined by Na_2O+K_2O versus SiO_2. They contain about 4.5 percent Na_2O+K_2O at 55 percent SiO_2, about 6 per cent Na_2O+K_2O at 60 percent SiO_2, and about 9.5 percent Na_2O+K_2O at 72.5 SiO_2, all in weight percent. Al_2O_3 versus normative plagioclase composition and a ternary AFM plot (fig. 3), on which $A=Na_2O+K_2O$, F=total iron as FeO, and M=MgO, all in weight percent, indicate that most samples are calc-alkaline and not tholeiitic. Lithologic names applied to samples of metavolcanic rock are based on a plot of normative color index versus normative plagioclase composition (fig. 4). The relative proportions of normative an, ab, and or indicate that the metavolcanic rocks are not part of either K_2O- or Na_2O-enriched volcanic series. The chemistry of the metavolcanic rocks displays trends on silica variation (not shown) and AFM (fig. 3) diagrams that are characteristic of calc-alkaline igneous rocks (Carmichael and others, 1974). Total alkalis, Na_2O, and K_2O increase with increasing SiO_2, whereas Al_2O_3, CaO, MgO, TiO_2, P_2O_5, and total iron decrease with increasing SiO_2.

The source(s) of the metavolcanic rocks, including the metarhyolite and metabasalt exposed at Jabal Aba al Liqah and the meta-andesite that forms a major part of the Turmus formation, is not known. Felsic volcanic rocks compose a major part of the Hibshi formation in the Harrat al Hutaymah and Samirah quadrangles (fig. 1). The ultimate source of these extrusive rocks is not well known either, but the large volume of volcanic rocks suggests the existence of a large,

Table 1.--Major element analyses and CIPW norms (calculated for analyses normalized to 100 percent, anhydrous) for selected metavolcanic rocks in the Al Makhul quadrangle

[Analyses by X-ray Assay Laboratories Ltd., Ontario, Canada. All determinations by X-ray fluorescence except FeO, which was determined by wet chemistry. FeO/Fe_2O_3 ratio adjusted using guidelines proposed by Irvine and Baragar (1971) prior to norm calculation; chemical analyses given below are pre-adjustment values. All values in weight percent]

Unit	Metarhyolite		Metabasalt		Meta-andesite	
Sample number	181596	181631	181593	181630	181670	181674
Latitude (26° N.)	44'11"	46'23"	44'07"	45'57"	52'08"	50'17"
Longitude (42° E.)	31'36"	33'35"	32'40"	34'53"	36'19"	40'00"
			Chemical analyses			
SiO_2	67.9	72.3	52.2	51.0	61.2	55.9
Al_2O_3	15.0	13.4	15.9	18.8	16.1	17.9
Fe_2O_3	4.04	2.72	5.05	4.86	2.54	4.41
FeO	.20	0	3.20	3.20	2.60	2.10
MgO	.22	.08	5.58	4.22	3.32	3.26
CaO	.80	.34	7.87	7.58	4.11	6.34
Na_2O	4.85	5.44	3.67	3.20	4.49	4.24
K_2O	4.45	3.89	1.12	.86	1.93	1.96
H_2O*	1.23	.62	1.93	2.93	1.08	1.00
TiO_2	.55	.27	1.19	1.02	.74	.88
P_2O_5	.12	.05	.26	.31	.24	.24
MnO	.03	.06	.13	.14	.13	.10
Total	99.4	99.2	98.1	98.1	98.5	98.3
			CIPW norms			
Q	20.9	25.6	2.5	5.1	14.0	5.6
C	1.1	0	0	0	0	0
or	26.8	23.3	6.9	5.4	11.7	11.9
ab	41.9	46.8	32.4	28.5	39.0	36.9
an	3.3	.7	24.6	36.2	18.6	24.7
wo	0	.3	6.0	.5	.3	2.5
en	.6	.2	14.5	11.1	8.5	8.4
fs	1.1	0	6.1	6.6	2.5	4.1
mt	3.0	2.2	4.1	3.8	3.3	3.6
hm	0	.3	0	0	0	0
il	1.1	.5	2.4	2.0	1.4	1.7
ap	.3	.1	.6	.8	.6	.6

* H_2O is loss on ignition

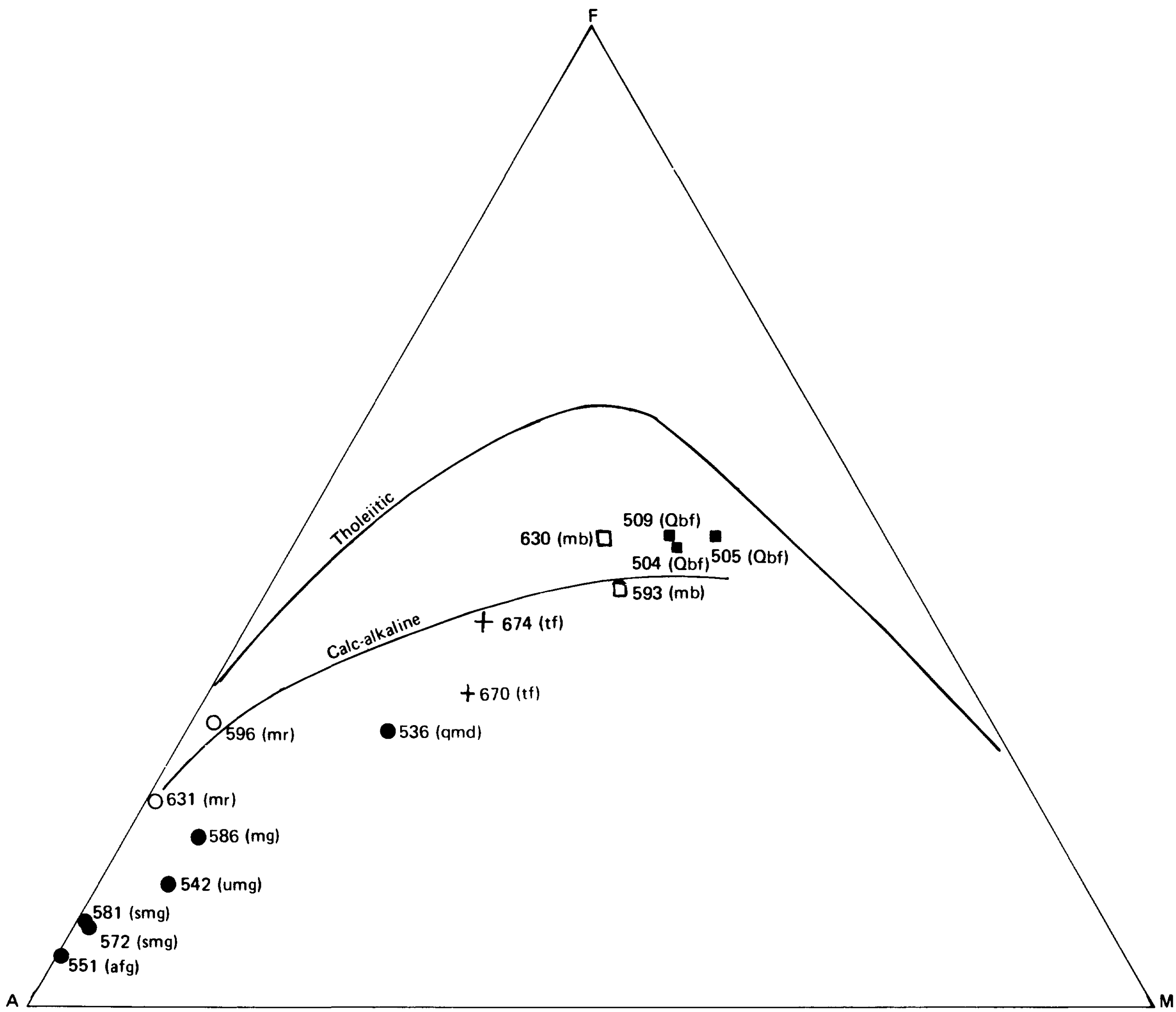

Figure 3.--Alkali-iron-magnesium (AFM) ternary diagram in weight percent for rocks of the Al Makhul quadrangle: $A=Na_2O+K_2O$, $F=FeO+0.8998 \times Fe_2O_3$, $M=MgO$; trend lines are from Irvine and Baragar (1971). Numbers next to data points should be prefixed by 181 to obtain sample number. Sample locations are given in tables 1 and 2. Unit symbols are explained on plate 1.

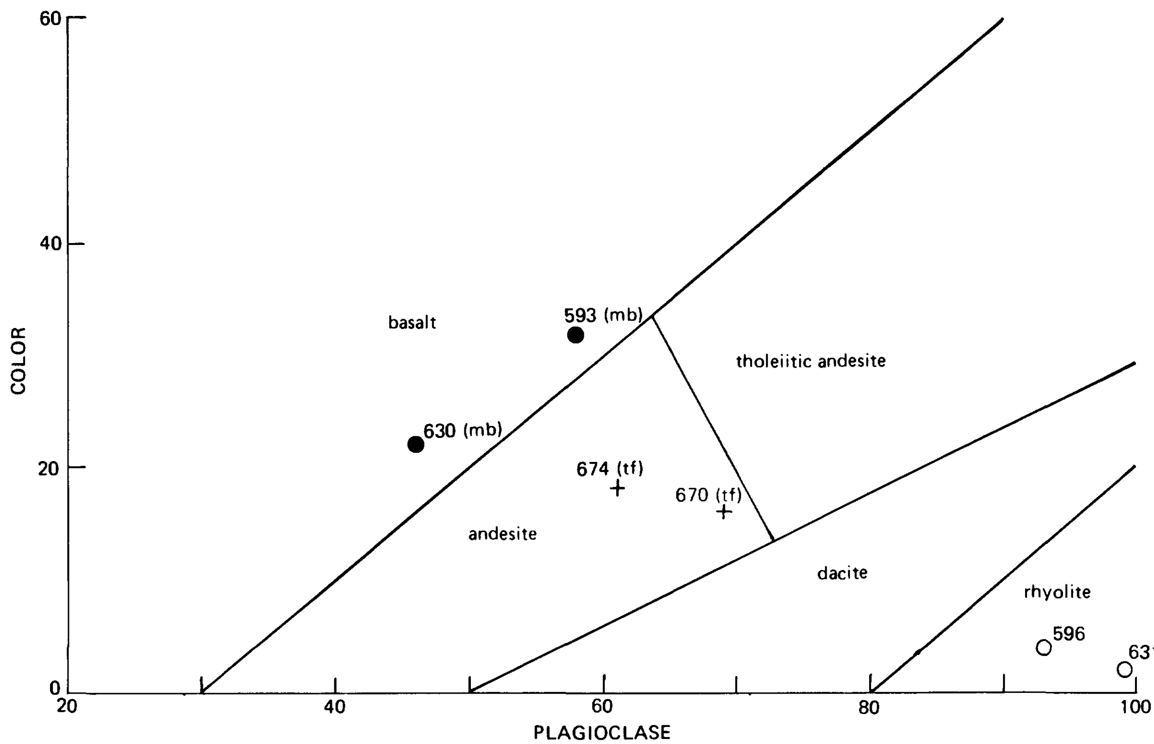

Figure 4.--Normative color index (=ol+hy+di+mt+il+hm) versus normative plagioclase composition (=an x 100/(an+ab+5/3ne)) variation diagram for classification of the metavolcanic rocks (Irvine and Baragar, 1971). Numbers next to data points should be prefixed by 181 to obtain sample number. Sample locations are given in table 1. Unit symbols are explained on plate 1.

nearby volcanic center. The conglomerate that marks the base of the metarhyolite and the metabasalt exposed at Jabal Aba al Liqah and the weakly to moderately welded character of the pyroclastic rocks suggests that these rocks were subaerially deposited. The large volume of volcanic rock in the Turmus formation again suggests the existence of a large nearby volcanic center. The fact that meta-andesite of the Turmus formation is intimately interbedded with andesitic agglomerate and finely laminated, volcanic graywacke suggests that these rocks were deposited in a shallow marine setting.

Intrusive rocks

The major element chemistry of the principal intrusive rocks in the quadrangle is given in table 2. The chemical trends exhibited by these plutons are similar to those defined by calc-alkaline igneous rocks throughout the world (Carmichael and others, 1974). Total iron, CaO, Al_2O_3, MgO, TiO_2, and P_2O_5 contents decrease with increasing silica content, whereas the K_2O content increases with increasing silica. Na_2O and MnO show no consistent co-variation with silica. All of the plutons are metaluminous except the alkali-feldspar granite, which is mildly peralkaline (Shand, 1947).

Results of the analyses are plotted on the Q-ab-or triangle and compared to minimum melting compositions in the experimental system SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-H_2O (fig. 5). The diagram facilitates comparison of the relative proportions of normative quartz, albite, and orthoclase in rocks from the Al Makhul quadrangle to one another and to other intrusive rocks. Phase relations displayed on figure 5 are not applicable to rocks having differentiation indices less than about 90 because such rocks contain significant amounts of components not considered on this ternary diagram. The effects of varying amounts and combinations of the other components are currently only partly known and are of such complexity that they are beyond the scope of this study.

Much of the chemical variation between the more evolved plutons (fig. 5) could be a consequence of polybaric crystallization and different conditions of $P(H_2O)$, which in turn are related to depth of emplacement and water content of the magmas. Compositions of the most chemically evolved rocks, the Shuwayman monzogranite and the alkali-feldspar granite, are nearly coincident with compositions on the eutectic minimum trend for $P(H_2O)$ in the range between 50 and about 200 mPa (0.5 to 2 kbar), which is equivalent to between 2 and 7 km of overburden. Petrographic features suggest that these rocks are the result of eutectic crystallization.

Table 2.--Major element analyses and CIPW norms (calculated for analyses normalized to 100 percent, anhydrous), for selected intrusive rocks in the Al Makhul quadrangle

[Analyses performed by X-ray Assay Laboratories Ltd., Ontario, Canada. All determinations by X-ray fluorescence except FeO, which was determined by wet chemistry. All values in weight percent]

Pluton	Alkali-feldspar granite	Shuwayman monzogranite		Monzogranite	Quartz monzodiorite	Uzaym monzogranite
Sample number	181551	181572	181581	181586	181536	181542
Latitude (26° N.)	49'33"	32'59"	34'00"	32'10"	34'55"	37'09"
Longitude (42° E.)	39'01"	45'02"	43'17"	50'47"	32'22"	32'59"
Chemical analyses						
SiO_2	76.2	75.0	74.9	69.6	62.8	70.5
Al_2O_3	12.7	13.0	13.4	14.5	16.2	14.8
Fe_2O_3	.61	.70	.83	1.40	1.72	1.03
FeO	0	.20	.10	.70	2.60	.40
MgO	.03	.19	.16	.77	2.63	.64
CaO	.19	.48	.50	1.84	4.04	2.23
Na_2O	5.24	4.81	4.84	4.27	4.37	4.57
K_2O	4.25	4.43	4.40	4.29	3.59	3.97
H_2O*	.54	.31	.39	.70	.70	1.54
TiO_2	.05	.14	.13	.32	.71	.21
P_2O_5	.02	.05	.04	.09	.22	.07
MnO	.02	.03	.03	.04	.07	.03
Total	99.9	99.3	99.7	98.5	99.7	100.0
CIPW norms						
Q	30.3	29.5	29.0	24.2	11.8	24.1
or	25.3	26.4	26.2	25.9	21.4	23.8
ab	42.0	41.1	41.2	36.9	37.4	39.3
an	0	.8	1.9	7.9	14.1	8.3
ac	1.8	0	0	0	0	0
ns	.2	0	0	0	0	0
wo	.3	.5	.2	.3	2.0	1.0
en	.1	.5	.4	2.0	6.6	1.6
fs	0	0	0	0	2.3	0
mt	0	.3	0	1.5	2.5	.8
hm	0	.5	.8	.4	0	.5
il	0	.3	.2	.6	1.4	.4
tn	.1	0	0	0	0	0
ap	0	.1	.1	.2	.5	.2

* H_2O is loss on ignition

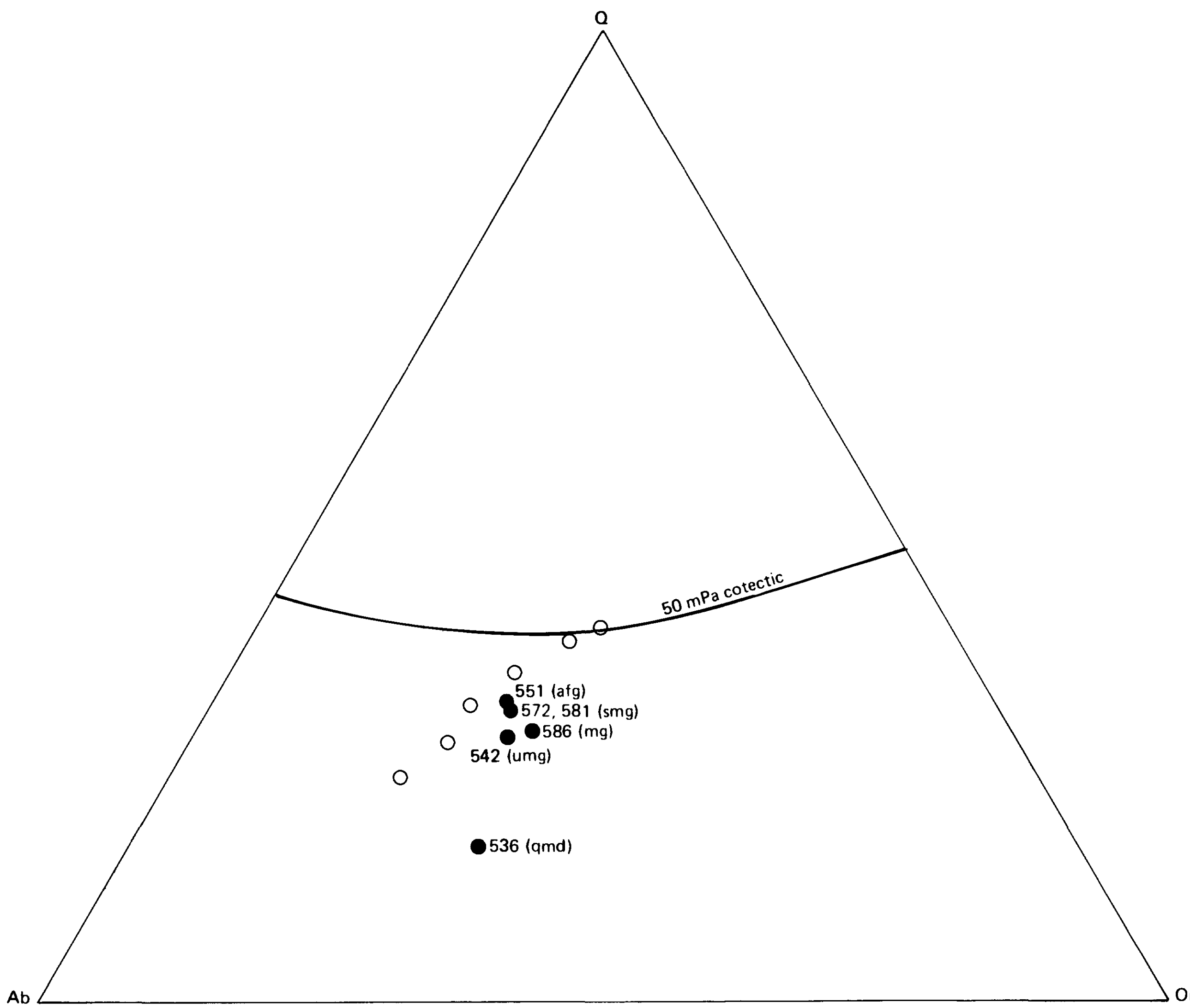

Figure 5.--Normative quartz-albite-orthoclase (Q-Ab-Or) ternary diagram showing the chemical composition of selected intrusive rocks. Numbers next to data points should be prefixed by 181 to obtain sample number. Sample locations are given in table 2. Unit symbols are explained on plate 1. Open circles, from top right to bottom left, represent the minimum melting compositions in the experimental system SiO_2-$KAlSi_3O_8$-$NaAlSi_3O_8$-H_2O for P_{H_2O} = P_{Total} = 50, 100, 200, 400, 500, and 1,000 mPa (0.5, 1, 2, 4, 5, and 10 kbar, respectively) (Winkler and others, 1975).

Rocks whose compositions depart markedly from the minima trend, the quartz monzodiorite, the monzogranite, and the Uzaym monzogranite, may have been generated by noneutectic melting that caused refractory components to be increasingly incorporated. Noneutectic melting in which quartz was consumed would cause an increase in the relative proportion of normative ab and or if they had not yet been consumed; the normative composition of these latter three plutons may reflect this process. Fractional crystallization of these magmas could have caused the remaining liquids to become more evolved.

White and Chappell (1977) have defined I- and S-type granitoid clans on the basis of major element chemistry. They distinguish those plutons thought to represent partial melts of igneous material (I-type) from melts thought to have been derived from sedimentary material (S-type). A line separating I- and S-type composition fields on the ACF ternary diagram (fig. 6) has been defined for the Berridale batholith, Australia (White and Chappell, 1977). Tin, tungsten, and rare-metal mineralization is commonly associated with S-type granites, whereas porphyry copper and molybdenum mineralization is commonly associated with I-type granites. Compositions for the plutons in the Al Makhul quadrangle plot in the I-type field.

The chemistry of the plutonic and metavolcanic rocks in the Al Makhul quadrangle follows a calc-alkaline trend (fig. 3). That alkali-feldspar granite, trondhjemite, and tonalite are rare indicates that the rocks in this area are not end products of alkaline or tholeiitic series. Major element compositions of the metabasalt, meta-andesite, and quartz monzodiorite are consistent with their genesis in a calc-alkaline island arc complex (fig. 3) and in the subjacent plutonic terrane. The more evolved plutonic and metavolcanic rocks may represent a later, more mature phase of arc development and may have been generated during final cratonization of the Arabian Shield (Greenwood and others, 1976, 1983; Schmidt and others, 1979; Pallister, in press). These rocks may represent modified partial melts derived from the mantle or subduction-related remelting of basal island-arc material.

Alkali basalt

Major element analyses were obtained for three samples of Quaternary basalt (table 3). The samples represent three separate basalt flows in the Al Makhul quadrangle. These basalts are alkaline, as defined by Irvine and Baragar (1971); in particular the sum of Na_2O and K_2O is between 4 and 5 weight percent. They are alkali basalts as defined by a plot of normative color index versus normative plagioclase composition (fig. 7). In addition, they tend to be

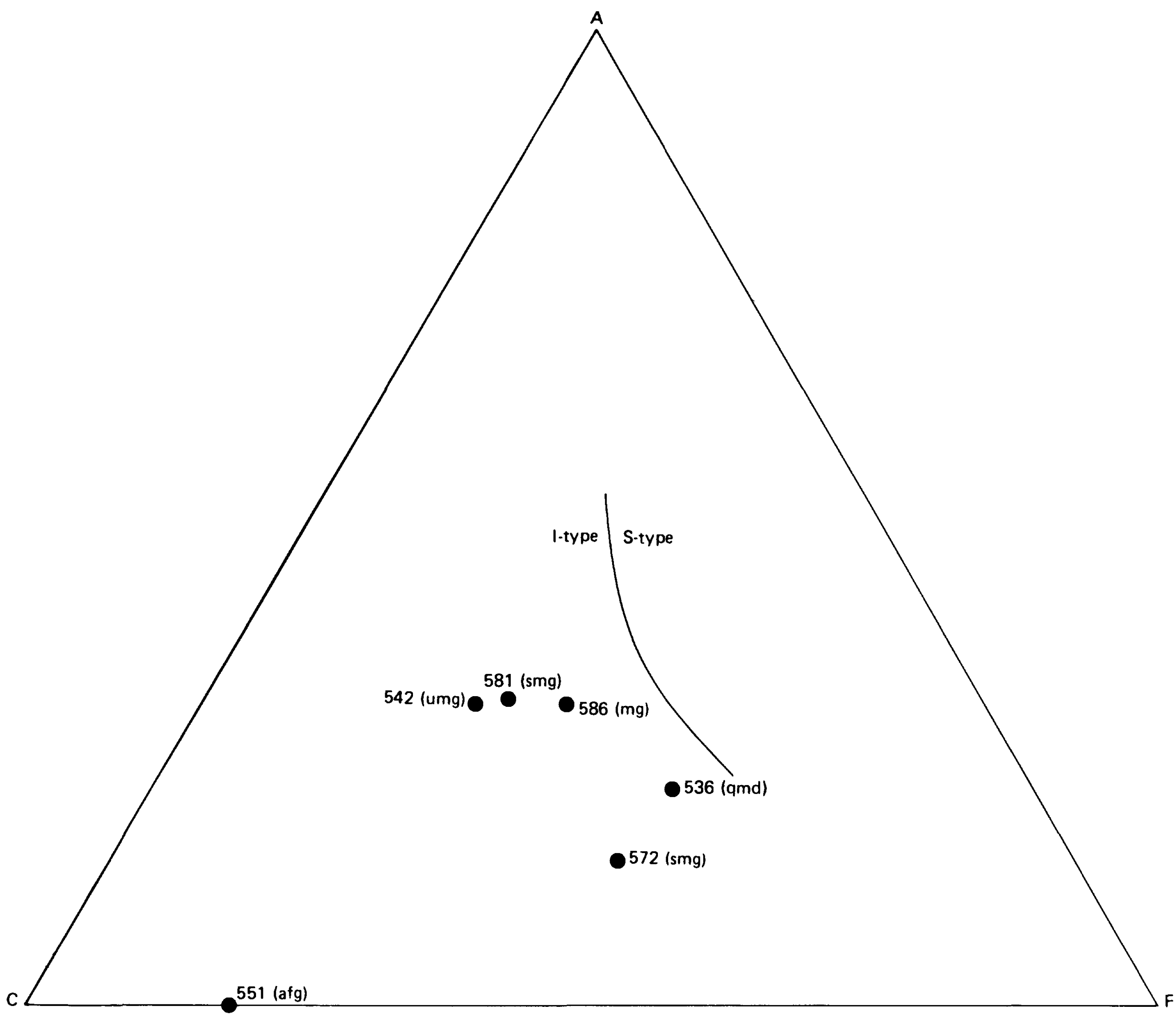

Figure 6.--Molar, $A=Al_2O_3-Na_2O-K_2O$, $C=CaO$, $F=FeO+MgO$ (ACF) ternary diagram showing the chemical composition of selected intrusive rocks. Numbers next to data points should be prefixed by 181 to obtain sample number. Sample locations are given in table 2. Unit symbols are explained on plate 1. The curve represents the boundary suggested by White and Chappell (1977) between I-and S-type granite compositions.

Table 3.--Major element analyses and CIPW norms (calculated for analyses normalized to 100 percent, anhydrous) for selected samples of alkali basalt in the Al Makhul quadrangle

[Analyses performed by X-ray Assay Laboratories Ltd., Ontario, Canada. All determinations by X-ray fluorescence except FeO, which was determined by wet chemistry. FeO/Fe_2O_3 ratio adjusted using guidelines proposed by Irvine and Baragar (1971) prior to norm calculation; chemical analyses given below are pre-adjustment values. All values in weight percent]

Sample number	181504	181505	181509
Latitude (26° N.)	59'12"	59'30"	55'01"
Longitude(42° E.)	37'16"	31'49"	31'13"
		Chemical analyses	
SiO_2	43.7	45.5	43.2
Al_2O_3	13.8	14.1	13.9
Fe_2O_3	6.85	4.00	5.38
FeO	5.80	8.10	7.40
MgO	8.73	9.04	8.28
CaO	10.3	10.6	10.3
Na_2O	3.25	3.08	3.42
K_2O	1.42	.77	1.46
H_2O*	.70	.31	.69
TiO_2	2.79	1.72	2.80
P_2O_5	.55	.42	.58
MnO	.18	.17	.19
Total	98.1	97.8	97.6
		CIPW norms	
or	8.6	4.7	8.9
ab	14.4	19.7	13.1
an	19.4	23.0	18.9
ne	7.5	3.8	9.1
wo	12.3	11.8	12.5
en	8.5	7.4	8.5
fs	2.8	3.6	3.1
fo	9.7	11.0	9.0
fa	3.5	5.9	3.6
mt	6.4	4.8	6.4
il	5.5	3.4	5.5
ap	1.3	1.0	1.4

* H_2O is loss on ignition

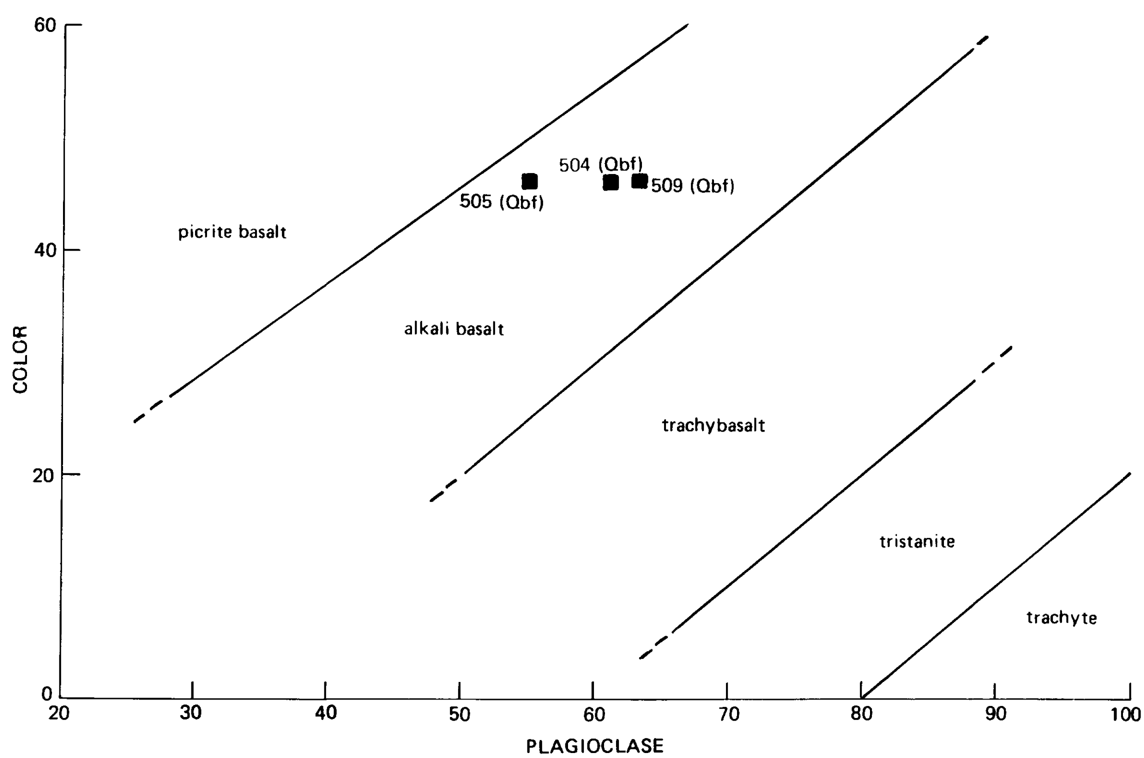

Figure 7.--Normative color index (=ol+hy+di+mt+il+hm) versus normative plagioclase composition (= an x 100/(an+ab+5/3ne)) variation diagram for classification of the alkali basalt (Irvine and Baragar, 1971). Numbers next to data points should be prefixed by 181 to obtain sample number. Sample locations are given in table 3. Unit symbols are explained on plate 1.

slightly potassic (Irvine and Baragar, 1971). The composition and tectonic settings of these rocks suggest that their genesis is related to ocean floor spreading that is presently taking place along the axis of the nearby Red Sea (J. S. Pallister, written commun., 1983).

ECONOMIC GEOLOGY

Economic potential in the Al Makhul quadrangle seems to be minimal. A small prospect pit, approximately 5 m in diameter and 0.5 m deep, was found in rocks of the Turmus formation. Exposed in the pit are several veins of massive, milky-white quartz, locally coated by thin films of copper oxides and carbonates. No ore minerals were identified. The smallness of the prospect and the apparent absence of ore minerals preclude incorporation of this occurrence in the Mineral Occurrence Documentation System (MODS) and indicate that no further investigations at this locality are warranted.

Mytton (1970) indicated an ancient mine site named Gerthemi in the southeast corner of the Al Makhul quadrangle near the contact between Precambrian and Paleozoic rocks; however, the prospect is not mentioned in the text of his report. A grid search of this area was conducted by helicopter but the site was not relocated. The inability to relocate Gerthemi and the nonavailability of data on the occurrence suggest that, at best, the extent of the workings is minimal; no additional work seems merited.

Approximately 180 samples of wadi sediment were collected in the quadrangle as part of a regional geochemical reconnaissance program conducted in the northeastern Arabian Shield, by the U.S. Geological Survey (Allen and others, 1983). As the result of this study several areas in the Jabal Hibshi 1:250,000-scale quadrangle (sheet 26F) were recommended for further work but none of these were in the Al Makhul quadrangle.

Several geochemically distinctive regions were identified by R-mode factor analysis of the geochemical data. A magnesium-nickel association is coincident with the Quaternary alkali basalt and with meta-andesite of the Turmus formation. Examination of plots showing the distribution of anomalous single-element concentrations show that cobalt, chromium, and titanium are also present in concentrations that are anomalous relative to average values for the region. Concentrations of magnesium, nickel, cobalt, chromium, and titanium in basalt and andesite are much greater than in other rock types (Krauskopf, 1967). It is predictable, therefore, that samples of sediment collected from wadis draining areas underlain by these rock types would contain high concentrations of these elements.

Allen and others (1983) identified one other geochemically distictive region. R-mode factor analysis of the data indicates that a strontium-barium-calcium association is coincident with outcrops of amphibolite. They suggest that this association of elements may be indicative of hydrothermal alteration. In the Shiaila and Buqaya regions in the Jabal as Silsilah quadrangle (fig. 1), geologic features characteristic of hydrothermal alteration correlate with the strontium-barium-calcium association; in the Al Makhul quadrangle, however, no hydrothermal alteration is apparent in rocks from the area of the strontium-barium-calcium association. Allen and others (1983) indicate a correlation between this association and amphibolitic rocks exposed in the Samirah quadrangle (fig. 1). Perhaps the strontium-barium-calcium association in the Al Makhul quadrangle, like the magnesium-nickel association, is lithologically controlled.

DATA STORAGE

Documents relating to this project have been archived in data file USGS-DF-03-10 (du Bray, 1983b). This file contains all of the geochemical data accumulated during this study.

No mineral localities in the Al Makhul quadrangle merit incorporation in the Mineral Occurrence Documentation System (MODS) data bank. Inquiries regarding the MODS data bank may be made through the Office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah.

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