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Reconnaissance geology of the Harrat Hutaymah quadrangle, sheet 26/42A, Kingdom of Saudi Arabia

by

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ABSTRACT

The Harrat Hutaymah quadrangle is underlain mostly by Proterozoic rocks that are intruded and partly covered in the north by the Quaternary extrusive products of the Harrat Hutaymah basalt field. The Proterozoic basement of the quadrangle may be broadly divided into the older (circa 650 Ma and older) Laban dioritic complex in the east and the younger (to possibly coeval) Kilab monzogranite batholith in the west. The dioritic complex is overlain by a monoclinal section of mostly intermediate composition volcanic and sedimentary rocks in the southeast (the Hibshi formation - dated at circa 632 Ma). The source plutons for the Hibshi volcanic rocks are not well constrained; the volcanics may be comagmatic with late phases of the Kilab batholith. All of these rocks are intruded by a younger (post-orogenic and circa 600 Ma) suite of more evolved granitic plutons and dikes. Several of these evolved granites may represent the root-zones of volcanic caldera complexes.

The Hibshi formation is divided into several members that are described in detail based on data from measured sections at the type section (Jibal Hibshi). There is considerable variation in composition and facies within the formation; individual members thicken and thin laterally, and some pinch out entirely over distances of only a few kilometers. Volcanic members at Jabal Hibshi are mostly andesitic to dacitic pyroclastic rocks, but at Jabal Aba al Liqah, basaltic and rhyolitic flow rocks predominate. The Hibshi formation consists of clastic sediments of volcanic and plutonic provenance intertonguing with the varied products of multiple subaerial volcanic centers. For these reasons, regional correlation based only on lithology is discouraged.

The Harrat Hutaymah basalt field contains abundant basaltic tephra as well as alkali olivine basalt flows. Tuff rings formed by explosive eruptions above mantle diatremes. Peridotite nodules are common in the basaltic tuff and in some flow rocks. Basaltic volcanism in the region began at a later time (circa 1.8 Ma) than at the other Saudi Arabian harrats; probably due to progressive mantle underflow related to Red Sea rifting.

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Areas having mineral resource potential include the ancient Samirah gold mine, a quartz-vein deposit in Laban complex dioritic rocks, and areas with tin-tungsten potential in the evolved plutons. Aggregate and pozzolan deposits occur in the basaltic tephra of the Harrat Hutaymah volcanic field and unusually deep groundwater reservoirs are present in the filled tuff-ring craters of the volcanic field.

INTRODUCTION

The Harrat Hutaymah quadrangle, sheet 26/42 A, encompasses an area of 2780 km^2 between lat 26°30' and 27°00' N. and long 42°00' and 42°30' E. (fig. 1) in the northeastern Najd province (Brown, 1960). The quadrangle is underlain mostly by Proterozoic rocks that are intruded and partly covered in the north by the Quaternary basaltic extrusive products of Harrat Hutaymah. The Proterozoic basement of the quadrangle may be broadly divided into the older Laban dioritic complex in the east and the younger to possibly coeval Kilab monzogranite batholith in the west. The dioritic complex is overlain to the southeast by the Hibshi formation that forms a monoclinal succession of mostly intermediate composition volcanic and sedimentary rocks in the southeast. The Hibshi formation and Laban complex are intruded by a younger (post-orogenic) suite of more evolved granitic plutons and dikes.

The dioritic and monzogranite basement forms an extensive high pediplane (average elevation about 1000 m) that is punctuated by inselbergs within the evolved granitic plutons and by the Jabal Salma and Jibal Hibshi mountain ranges, which reach about 1370 and 1300 m., respectively. The central area of the quadrangle, extending from Jibal Hibshi through Jabal Shurmah to Harrat Hutaymah, forms a broad gentle divide between the southwesterly drainages of Wadi Samirah, Wadi al Gusal, and Wadi al Khillah, and the northeasterly drainages of Wadi Hibshi and Wadi Aba al Kurush.

The quadrangle is accessible via the new paved highway that extends south from Hail to the Al Madinah - Al Qasim highway and traverses the western part of the quadrangle. Most areas of the quadrangle are easily accessible via the paved highway, major dirt roads that parallel new power lines between Al Uzaym and the west and north quadrangle boundaries, and via numerous desert tracks that criss-cross the pediplane surface. A network of desert tracks parallel the ancient Darb Zubaydah that traverses the quadrangle from southwest to northeast. The remains of a pilgram rest stop are preserved at the village of Al Birka.

The principal settlement and commercial center is the small village of Samirah, located astride the southern quadrangle boundary. Other small villages include Al Birka, Uglat al Laban, Al Ghumrah, and Al Uzaym in the south, and Uglat bin Klab, Murayyah, As Safrah, and Ubdah in the north. In addition, numerous settlements of a few houses each, and many Bedouin camps are scattered throughout the quadrangle, but both are more densely clustered in the western half.

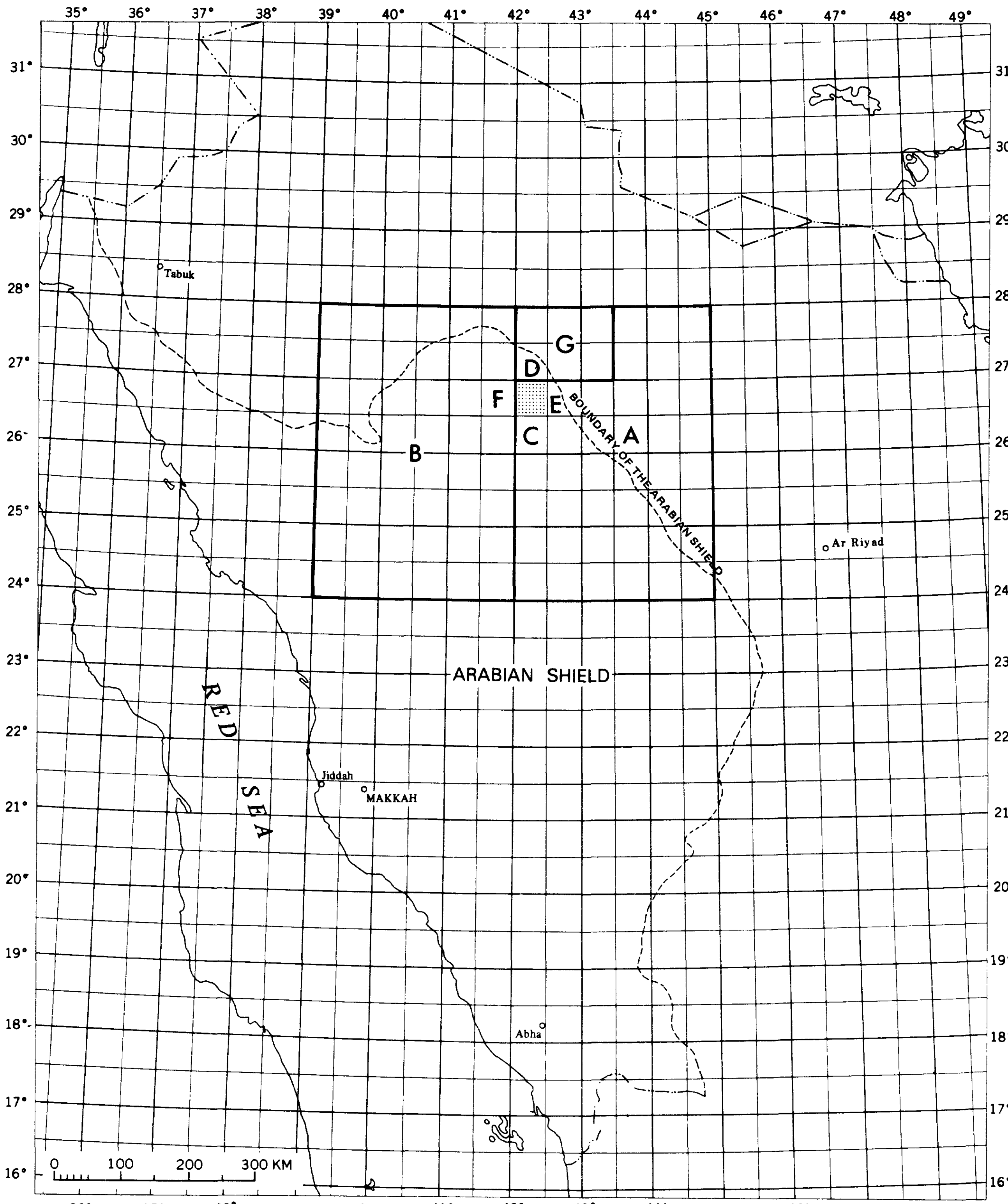


Figure 1.—Index map of western Saudi Arabia showing location of the Harrat Hutaymah quadrangle (shaded) and other quadrangles referred to in this report: A, Wadi Ar Rima (Bramkamp and others, 1963); B, Northeastern Hijaz (Brown and others, 1963); C, Samirah (Williams, 1983); D, Rak (Kellogg, 1983); E, Al Makhul (du Bray, 1984); F, Al ,Awshaziyah (Leo, 1984).

The geology of the Harrat Hutaymah quadrangle was first mapped in broad reconnaissance scale by Bramkamp and others (1963). These authors mapped a basement complex of gray granite intruded by several small bodies of diorite and by red (locally peralkaline) granite at Jabal Salma and Al Hudub. They also defined the Hibshi formation for the rocks at Jibal Hibshi and Jabal Aba al Liqah and they mapped the Quaternary basaltic rocks of Harrat Hutaymah. They did not recognize the distinction between the Laban dioritic complex and the Kilab monzogranite batholith, nor did they recognize several of the evolved granite plutons.

The Harrat Hutaymah 1:100,000-scale map shows additional map units in far more detail than is possible at 1:500,000 scale. It is, however, also a reconnaissance-scale map, based on a rapid, albeit relatively intensive survey of the area. Detailed mapping might result in the definition of individual plutons and subunits within both the dioritic complex and the monzogranite batholith; however, the relatively poor exposure of these two units and the internal complexity of the dioritic unit made such a project impossible during the present study.

This report is the result of geologic mapping during 12-26 March and 16 April-1 May, 1983; including 5 days of helicopter support. Petrographic and geochemical results reported herein are based on approximately 500 thin sections, modal analyses of approximately 250 stained slabs, 27 major element X-ray flourescence (XRF) analyses, 7 rare-earth element (REE) analyses, and 8 atomic absorption (AA) and semi-quantitative spectrographic analyses. A mobile lab was constructed and used in the field for the preparation and modal analysis of stained slabs.

Plutonic and volcanic rocks are classified according to the recommendations of the International Union of Geological Sciences (Streckeisen, 1973, 1976, 1978; Schmid, 1981).

Geologic mapping of the adjacent Samirah (Williams, 1983), Rak (Kellogg, 1984a), Al Makhul (du Bray, 1984a), and Al 'Awshazyah (Leo, 1984) quadrangles were underway during 1982-1983. Work was also underway during 1983-1984 on geologic compilation (Johnson and Williams, 1984) and mineral resource assessment (Richter and others, 1984, unpub. data) of the Jabal Habashi 1:250,000-scale quadrangle of which the Harrat Hutaymah quadrangle forms the northwest one-sixth. Discussions with the various investigators involved in these projects were very useful in making correlations and in establishing areas of mineral resource potential. Discussions and collaboration with C. R. Thornber form the basis for an ongoing study of the basalts and mantle nodules from Harrat Hutaymah, and discussions with J. C. Cole, D. B. Stoeser, C. E. Hedge, and R. T. Gregory have aided in regional correlations and petrologic interpretations.

The author wishes to thank and acknowledge Ahmed Hamdan El Bazli for assistance in the field and for modal analyses. Thanks are also extended to Ibrahim Hassan and Emad Tahir who maintained and operated the mobile stained-slab lab in the field and to the members of the USGS Field Services Section who made fieldwork in the quadrangle both very efficient and most entertaining.

The work for this report was performed by the U. S. Geological Survey in accordance with a work agreement with the Saudi Arabian Ministry of Petroleum and Mineral Resources.

PROTEROZOIC SEDIMENTARY AND VOLCANIC ROCKS AND METAMORPHIC EQUIVALENTS

The Proterozoic sedimentary, volcanic, metasedimentary, and metavolcanic rocks of the Harrat Hutaymah quadrangle occur in one of two settings and age groups: 1) amphibolite-grade metamorphic rocks forming highly deformed roof-rock septa in the Laban dioritic complex, 2) slightly deformed and lower greenschist or zeolite-facies metamorphosed volcanic and sedimentary rocks overlying the dioritic complex and probably partly coeval with granitic bodies in the quadrangle. The former class of rocks make up the Ghumrah amphibolite unit, the latter comprise the Hibshi formation and the Samirah dacite and rhyolite units.

Ghumrah amphibolite

The Ghumrah amphibolite (am) consists mostly of dark-green-gray to black plagioclase-hornblende porphyroblastic amphibolite and hornfels. Other rock types include interlayered epidote quartzite, epidote-amphibole hornfels or quartzite. The amphibolites and quartzites are typically very fine to fine grained, and weakly to moderately foliated. Relict porphyritic and diabasic textures in some of the amphibolites indicate basalt and diabase protoliths. The quartzites were probably derived from interbedded sandstones.

A northerly plunging lineation was observed in the foliation plane at the easternmost exposure near Jibal Hibshi. At this outcrop, the amphibolite has a foliation produced by the superposition of cm- to mm-scale isoclinal folds. The lineation is parallel to these fold axes.

The Ghumrah amphibolite forms three prominent north-trending ridges within Laban dioritic complex host rocks northwest of Jibal Hibshi. Foliation attitudes and an apparent vergence of the ridges to the north toward Al Ghumrah suggest an antiformal structure of the roof rock septum. However, a central ridge of amphibolite, and vergence of the central and eastern belts near relict diabasic texture, and may represent a metadiabase dike keel to the structure. The unit is cut by and extended along the left lateral northwest-trending fault that also offsets the Hibshi formation.

Rocks of the Ghumrah amphibolite unit are probably among the oldest rocks exposed in the quadrangle. They are interlayered with rocks of the dioritic complex and are intruded by prominent granodiorite dikes that are probably coeval with the Kilab monzogranite batholith. Apparent diabase-dike protoliths for some of the amphibolite and hornfels suggests that parts of the unit may be younger than, and intrusive into, the dioritic complex. However, the Ghumrah amphibolite unit may also be roughly coeval with parts of the dioritic complex and may represent the volcanic products of mafic plutons in the dioritic complex. Interlayered quartzose rocks may represent sediments interbedded with the volcanics. Subsequent deformation of the dioritic complex and its volcanic and sedimentary roof rocks could have lead to infolding of the roof rocks to produce the observed complex structures.

Hibshi formation

The Hibshi formation was defined by Bramkamp and others (1963) as:

> Conglomerate of pebbles and boulders of gray granite, fine-grained igneous rocks, red ripple-marked slate or shale, wacke, and arkose; welded agglomerate at top; possible equivalent of Fatimah and Abla formations of Southern Hijaz quadrangle. Type locality at Jabal Hibshi where exposure is 750 meters thick.

Bramkamp and others (1963) considered the Hibshi to be younger than the Halaban and Murdama formations. The strike ridge of Hibshi formation extends southeast from Jibal Hibshi across 42^0 E. lat. into the Northeastern Hijaz 1:500,000-scale quadrangle (Brown and others, 1963). During 1:100,000-scale mapping of the area west of 42^0 by BRGM in the late 1960's and early 1970's, the Murdama was elevated to group status and the Hibshi was assigned as its basal formation (see 1:250,000-scale compilation by Delfour (1977)). This led to use of the term Hibshi for conglomerates and related sedimentary and volcanic rocks exposed at the base or at the margins of sequences of rocks assigned to the Murdama in widely separated parts of the northeastern and east-central Arabian Shield (see compilations by Delfour, 1977, 1979; and Delfour and others, 1982).

The description of the Hibshi formation in this report is based mostly on data from the type locality. Jibal Hibshi is a monoclinal succession of southeast-dipping sedimentary and volcanic rocks. Measured sections through the Hibshi at several localities along the Jibal Hibshi strike-ridge are presented in figure 2, and the lower part of the section at the northeast end of Jibal Hibshi is shown in figure 3. There is considerable

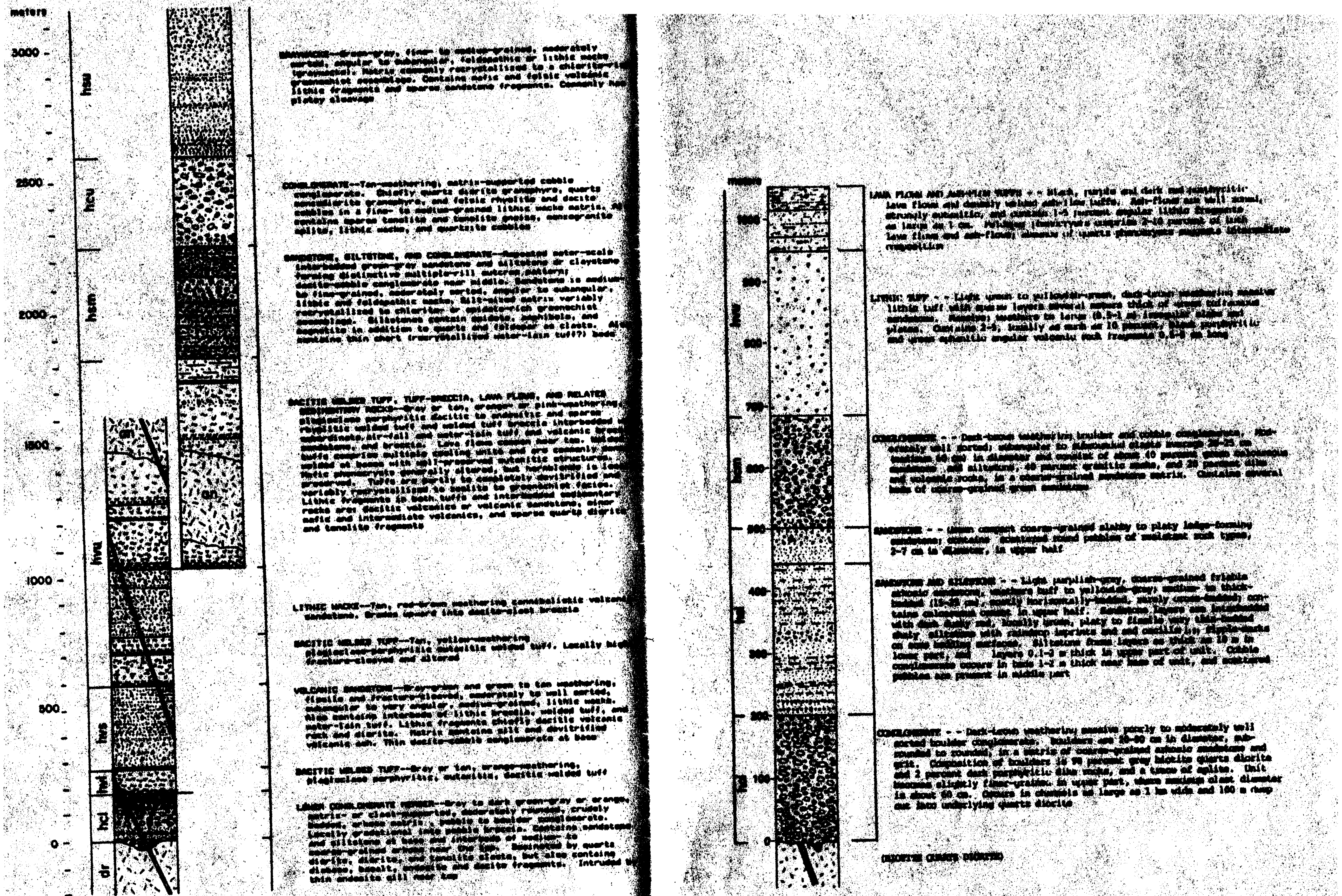


Figure 2.—Columnar sections of the Hibshi formation. Column on left is from Jibal Hibshi north of the Al Ghumrah fault and is a composite of two overlapping measured sections. Column on right is from the southern part of Jibal Hibshi and is adapted from a section measured by P. L. Williams (written commun., 1983). Cross-cutting dikes are diabase. Member symbol-designations given to left of each column.

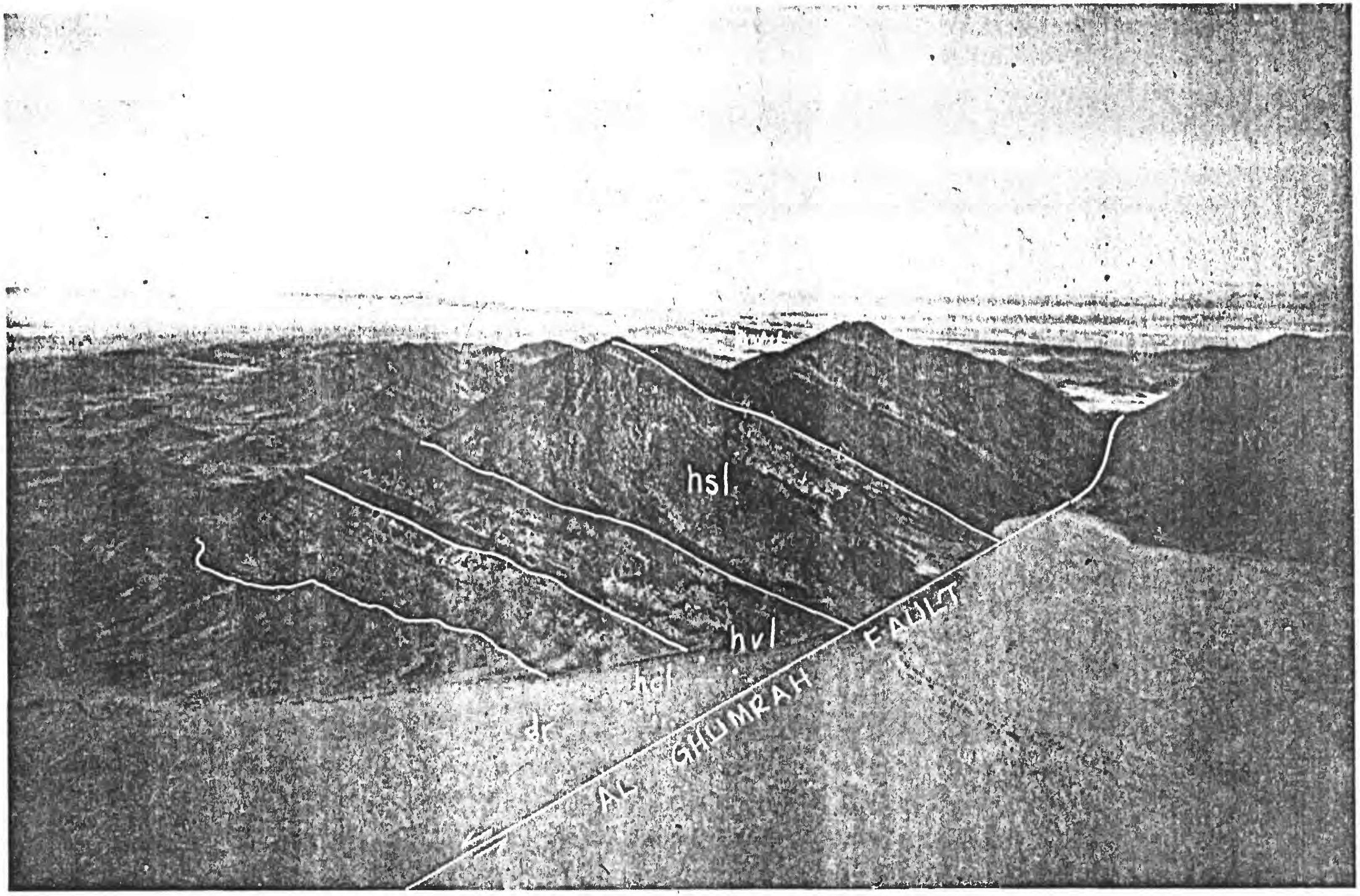


Figure 3.—Oblique aerial photograph of the north end of Jabal Hibshi, viewed from the southwest. Lower members of the Hibshi formation and the Laban dioritic complex are indicated by map symbol and the trace of the Al Ghumrah fault is shown.

variation along strike in the formation. Individual members pinch and swell in thickness and some pinch out entirely over a strike distance of only a few kilometers (pl. 1). There is also considerable variation in the composition of the volcanic members of the Hibshi. At the type sections at Jibal Hibshi the volcanic rocks are mostly dacitic to andesitic welded tuffs. However, about 20 km to the northeast at Jabal Aba al Liqah, volcanics in the Hibshi are dominantly basaltic. These facts illustrate the danger in regional correlation of the formation based on lithology. The Hibshi formation clearly represents the intertonguing of clastic sediments of volcanic and plutonic provenance with the varied products of local subaerial volcanic centers. Simple layer-cake stratigraphic models cannot be applied to such a formation. The Hibshi typically has a basal conglomerate that is dominated by clasts from the underlying Laban dioritic complex, but, in some localities a thin zone of volcanics (included in the lower conglomerate member in plate 1) underlies the conglomerate.

In this report, the Hibshi formation is considered to be a marginal facies of the Murdama group, following the usage of Williams (1983). This correlation is tentative, pending determination of the age of the Murdama south of the quadrangle. Zircon from the upper volcanic member of the Hibshi at the type locality was dated by the U-Pb method at 632 ± 5 Ma (C. E. Hedge, written commun., 1983). The Hibshi is intruded by the Hudub monzogranite at Jabal Aba al Liqah, by the Nimriah and Shuwayman monzogranites in the southeast corner of the quadrangle, and by an andesite sill and sparse diabase dikes at Jibal Hibshi. The Nimriah monzogranite is dated by the U-Pb zircon method at 621 ± 5 Ma and the basement dioritic complex is dated at 650 ± 5 Ma (C. E. Hedge, written commun., 1983). Therefore, the age of 632 ± 5 Ma is consistent with regional geologic relations. The Murdama group is currently being studied using the techniques of basin analysis and additional radiometric determinations are underway (P. D. Rowley, oral commun., 1984).

It is the intention herein to present a detailed description of the Hibshi formation at the type area (Jibal Hibshi) and propose elevation of the unit to formal status, following review by the Saudi Arabian Deputy Ministry for Mineral Resources (DMMR) Stratigraphic Committee. However, correlation of the Hibshi formation with other volcano-sedimentary successions at the base or margins of the Murdama group is discouraged unless there is good reason to believe that these successions were once contiguous with the type Hibshi.

The members of the Hibshi are described below; additional discussion of age relations and possible tectonic setting during deposition is presented in the geologic history section of this report. All of the members of the Hibshi have undergone zeolite or lower greenschist metamorphism, however, primary sedimentary and volcanic structures and textures are locally very well preserved. Deformation is generally locallized along faults and shear zones and produces regions of fissile parting or fracture cleavage. A more detailed account of the metamorphism and deformation is given in the metamorphic and structural geology section.

Lower conglomerate member

Conglomerate beds occur at several different stratigraphic positions within the Hibshi formation. Typically the lower conglomerate member (hcl) is the basal unit in the sections at Jibal Hibshi, but, in the section north of the Al Ghumrah fault (fig. 2), sandstone and siltstone beds within the member directly overlie diorite complex basement. The conglomerate is gray to dark green gray, or orange where iron-oxide stained, and is composed of pebble- to boulder-size clasts in an arkosic matrix (fig. 4). Clasts average about 20 cm diameter, but range from a few cm to 1-2 m diameter. Elongate clasts within the conglomerate are sometimes aligned within the bedding plane.

Most of the conglomerate is moderately rounded, is matrix or clast supported, and crudely bedded at meter-scale. Upward gradations were observed from pebble-size, matrix-supported, angular to subrounded breccia to matrix-supported subrounded cobble to boulder conglomerate. Interbeds, about 10 cm to 1 m thick, of medium- to coarse-grained arkose are common, especially near the top of the member.

Thickness of the member varies from about 200 m at the north and south ends of Jibal Hibshi to 0 m in central Jibal Hibshi, where the member pinches out on an apparent basement high. This variation in thickness suggests that the conglomerate was deposited in broad channels developed on the basement surface.

Clast populations for the lower, middle, and upper conglomerate members are given in figure 5. Note that the lower conglomerate is dominated by quartz diorite, diorite, and tonalite clasts. An approximately $10 m^2$ area in the lower conglomerate member near the northern end of Jibal Hibshi yielded the following clast distribution (based on field identifications): about 70% tonalite, diorite, quartz diorite, and about 15% diabase and basalt; about 10% fine-grained granitoids; about 5% dacite. Petrographic examination of these and other clasts in the member led to identification of biotite tonalite gneiss, allotriomorphic granular biotite tonalite, and plagioclase porphyritic andesite or dacite. The compositions and textures of the mafic plutonic rocks are identical to those of rocks in the immediately underlying Laban dioritic complex. There is little doubt that these clasts were locally derived. The arkose matrix to the conglomerate is tonolitic in composition and was also derived primarily from the basement dioritic complex (and by disaggregation of the clasts in the conglomerate).

Andesitic to dacitic clasts in the conglomerate are similar to those in the Hibshi volcanic member and indicate that felsic volcanism locally predated the lower conglomerate member. True granitic clasts have not been positively identified in the member; possible granite clasts examined in thin section to date

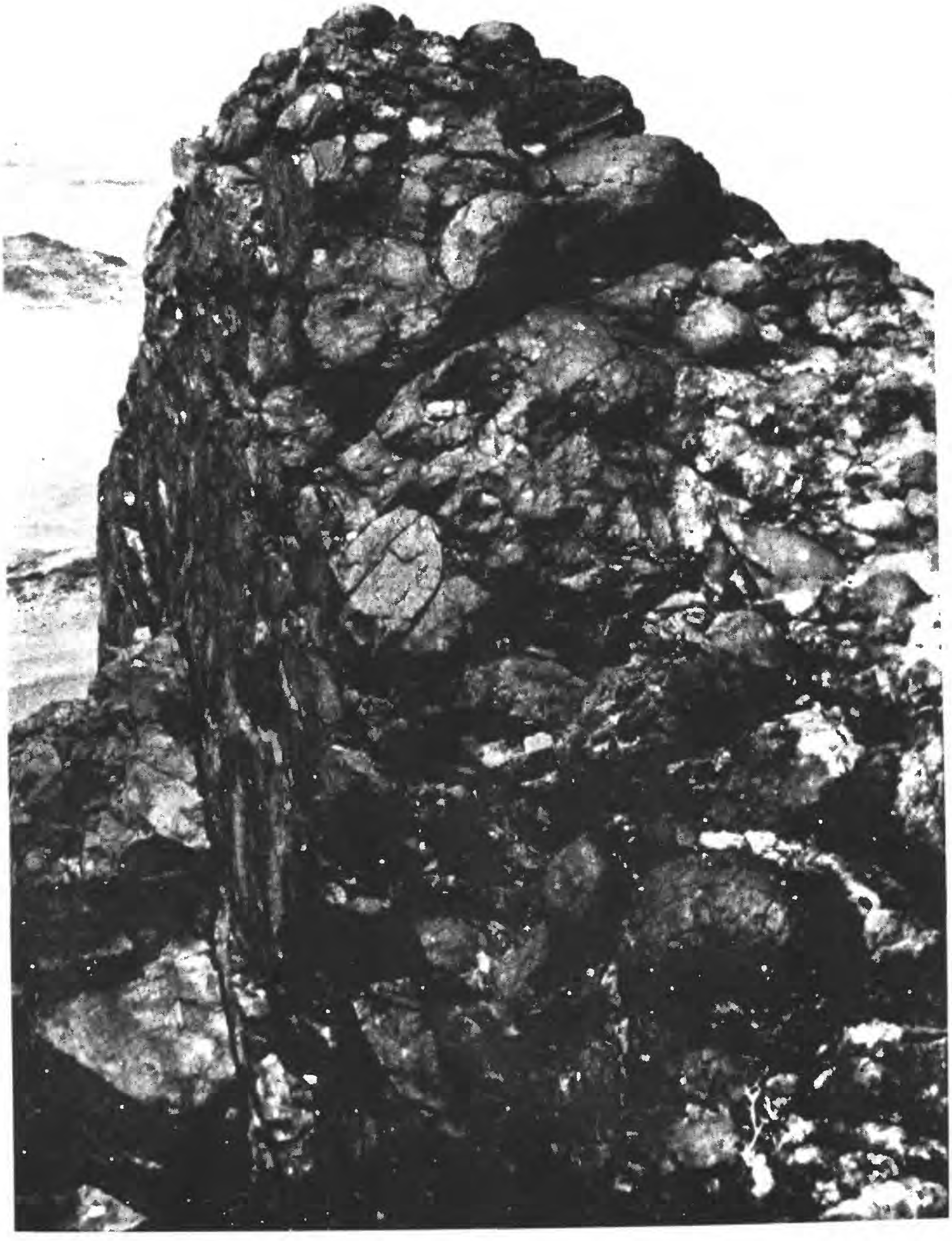


Figure 4.—Outcrop photograph showing the lower conglomerate member of the Hibshi formation near the northern end of Jibal Hibshi. Hammer (upper right) is about 25 cm long for scale.

Clast rock type	Lower conglomerate member		Middle conglomerate member		Upper conglomerate member	
quartz diorite	Ẋ		CCCC	CS		
quartz diorite gneiss						
quartz diorite granophyre			C		X	
tonolite	XXẊLLL	XL	S	C	X	
tonolite gneiss	XXXẊL				X	
tonolite granophyre	Ẋ		C			
qz. mozodiorite granophyre					X	
mozonite gneiss			S			
quartz monzonite			SSS			
granodiorite	X		CSS			
monzogranite			C		XX	
syenogranite gneiss			S			
alk. feld. granite granophyre			C			
diabase or basalt	Ẋ			CC		X
andesite			S			
andesite-dacite	XXẊ		C	CS	X	X
rhyolite					XX	
amphibolite	Ẋ					
quartzite					X	
	blocks	matrix frags.	blocks	matrix frags.	blocks	matrix frags.

EXPLANATION

X Sample from northern Jabal Hibshi; thin-section identification

Ẋ Sample from northern Jabal Hibshi; field identification

L Sample from Jabal Aba al Liqah; thin-section identification

C Sample from central Jabal Hibshi; thin-section identification

S Sample from southern jabal Hibshi; thin-section identification

blocks = cobbles and boulders

matrix frags. = pebbles and granules identified in matrix sandstone

Figure 5.—Histograms showing clast-type distribution in the lower, middle, and upper conglomerate members of the Hibshi formation.

are either fine-grained alaskitic tonalite or potassium metasomatized tonalite. This is in contrast to the presence of sparse granodiorite, quartz monzonite, and monzogranite clasts in the middle and upper conglomerate members. This may indicate a geographic as well as a temporal control, because the sample suites examined from the lower conglomerate come only from the northern part of Jibal Hibshi and from Jabal Aba al Liqah. Sample suites have not been examined from the southernmost outcrops of the member near the quadrangle boundary.

Lower sandstone member

The lower sandstone member (hsl) conformably overlies the lower conglomerate member in southern Jibal Hibshi. Similar sandstone overlies the lower Hibshi conglomerate member at Jabal Aba al Liqah and is shown as lower sandstone member on plate 1; however, it is not clear that the two deposits were ever contiguous.

The sandstone is tan to gray or maroon arkose and lithic graywacke and is fine to medium grained, poorly to moderately sorted, and angular to subangular. It is medium bedded (15-25 cm); typically planar-, but locally cross-bedded, and locally calcite cemented. Detrital grains are plagioclase, quartz, minor hornblende and epidote, and lithic fragments. The lithic fragments include dacitic welded tuff, chloritic very fine grained mafic volcanics, siltstone, and fine-grained tonalite or quartz diorite. The abundance of plagioclase and the lithic assemblage indicate derivation from a mixed mafic plutonic-volcanic and felsic volcanic source area. Possible sources are the underlying Laban dioritic complex and lower conglomerate member, and earlier compositional equivalents of the overlying Hibshi volcanics.

The contact with the underlying conglomerate is locally gradational with interbedded sandstone and conglomerate within a few meters of the mapped contact. The conglomerate interbeds are typically less than 2 m thick and are lensoidal in cross-section. They probably represent channel-fill deposits.

Maroon and green siltstone, claystone, and shale interbeds are common in the lower half or the member. These rocks typically consist of silt- to clay-sized clasts of quartz and variably oxidized magnetite in a chlorite-epidote-hematite-clay matrix. The interbeds are typically 10 cm to 2 m thick, but, bedded sequences as much as 10 m thick are locally present (fig. 2). The siltstone, claystone, and shale locally contain well-preserved raindrop imprints (fig. 6) and cm-wavelength oscillation ripple-marks on bedding surfaces. This interbedded sequence produces a characteristic multiple-bedded outcrop appearance where exposed on the northwest flank of Jibal Hibshi (fig. 7).

Thickness of the member ranges from greater than 240 m in the southwest to 0 m, where it pinches out between the lower and middle conglomerate members in central Jibal Hibshi.

Figure 6.—Photograph showing the lower sandstone member of the Hibshi formation; northwest flank of south-central Jibal Hibshi.

Figure 7.—Photograph showing rain-drop imprints in shale of the lower sandstone member of the Hibshi formation; northwest flank of south-central Jibal Hibshi.

Basalt member

The basalt member of the Hibshi (hb) crops out only at Jabal Aba al Liqah and in the adjacent Al Makhul quadrangle (du Bray, 1984a). In this area the basalt member is interbedded and interfingers with the lower sandstone and upper volcanic members of the Hibshi formation.

The member is composed mostly of fine-grained, dark weathering, intergranular basalt flows and subordinate diabase dikes. The basalt is locally porphyritic with plagioclase and subordinate clinopyroxene phenocrysts. Although it is metamorphosed to greenschist facies, primary volcanic textures are well preserved. The plagioclase is saussuritic and the clinopyroxene is pseudomorphed by uralite+chlorite+magnetite+carbonate. Relict phenocrysts of hornblende are described in some flows in the Al Makhul quadrangle by du Bray (1984a).

Basalt flows (5-10 m thick) are interbedded near the base of the member with thin cooling units of rhyolitic welded tuff correlated with the upper volcanic member of the Hibshi. This accumulation of basalt at Jabal Aba al Liqah is a likely source for basaltic debris found in the conglomerates, sandstones, and tuffs at Jibal Hibshi.

Lower volcanic member

The lower volcanic member (hvl) crops out only at the northeast end of Jibal Hibshi (pl. 1). It consists of a succession approximately 110 m thick of plagioclase-porphyritic dacitic welded ash-flow tuff. This tuff pinches out a few kilometers to the northeast; it also pinches out southwest of the Al Ghumrah fault. It overlies the lower conglomerate and is overlain by the volcanic sandstone member of the Hibshi. The tuff has a densely welded (formerly vitrophyric) base and an amygdaloidal top. It appears to be a single cooling unit.

The tuff is eutaxitic and is densely to partially welded. In addition to mm-scale plagioclase phenocrysts, it contains phenocrystic iron-titanium oxides, xenocrystic quartz, and pumice lapilli in a devitrified groundmass of glass shards and dust. Devitrification formed either a matrix of very fine grained microlites and opaque dust, or in the interior of the ash flow, a magnetite-rich granophyric intergrowth of quartz and feldspar.

The ash flow is very similar to those in the upper volcanic member of the Hibshi and probably erupted from the same volcanic field prior to eruption of the much thicker succession of multiple cooling units in the upper volcanic member. The apparent similarity in composition of the various welded tuffs in the Hibshi formation is discussed in the geochemistry and petrogenesis section.

Volcanic sandstone member

The volcanic sandstone member (hvs) conformably overlies the lower conglomerate or disconformably overlies the lower volcanic member of the Hibshi near the northeastern end Jibal Hibshi. The member underlies the upper volcanic member of the Hibshi.

The sandstone is green gray or green tan on weathered surfaces. It is typically fissile, with bedding-parallel fracture cleavage, and produces platy outcrops and scree-flanked slopes. The sandstone is medium grained, moderately to well sorted, and subangular to very angular. It consists of medium- to thick-bedded (10 cm- 10 m) lithic wacke with common interbeds of lithic breccia. Detrital grains are mostly plagioclase (typically about 90%) and minor quartz and epidote-rich (epidote+chlorite+carbonate or smectite) pseudomorphs after hornblende. Lithic fragments are mostly cm-scale fragments of plagioclase porphyric dacitic volcanic rock and dioritic plutonic rock. The matrix of the sandstone consists of silt and devitrified, altered, or recrystallized volcanic ash. The member also contains thin (less than 5 m) plagioclase-porphyritic dacitic welded tuff flows and dacitic water-lain tuff beds.

The abundance of dacitic lithic fragments, volcanic ash, and interbedded dacitic tuffs indicates that the volcanic sandstone member was deposited during the early stages of volcanism that produced the overlying upper volcanic member of the Hibshi. The member was probably deposited in a basin adjacent to a caldera-forming volcanic center and received ash flows intertongued with their reworked derivatives, as well as subordinate detritus from the surrounding dioritic basement complex.

A thin (less than 10 m) basal conglomerate composed mostly of dacite clasts in a lithic wacke matrix is developed where the member disconformably overlies the lower volcanic member northeast of the Al Ghumrah fault. This conglomerate is included in the volcanic sandstone member and indicates limited reworking of the underlying volcanic member prior to deposition of the sandstone.

Thickness of the member ranges from about 300 m northeast of the Al Ghumrah fault to 0 m where it pinches out in the central part of Jibal Hibshi. The sandstone is replaced at the same stratigraphic position by the middle conglomerate member in the southwestern part of Jibal Hibshi. As noted previously, this suggests a local facies change from channel deposits in the southwest to open-basinal deposits in the northeast during this interval of Hibshi time.

Middle conglomerate member

The middle conglomerate member (hcm) crops out in the central and southwestern parts of Jibal Hibshi, where it is separated from the lower conglomerate member by the lower sandstone member. The middle conglomerate pinches out and is replaced at the same stratigraphic position by the volcanic sandstone member of the Hibshi in the central part of Jibal Hibshi (pl. 1). This suggests a facies change from conglomerate to volcanic sandstone from southwest to northeast. However, the transition area has not been studied in sufficient detail to determine if a gradation exists.

The middle conglomerate is similar in color, outcrop appearance, clast size and distribution, and bedding to the lower conglomerate. However, the clast-type population is distinct (fig. 5). The middle conglomerate is dominated by both quartz diorite and tonalite clasts, in contrast to the dominance of tonalite clasts observed in the lower conglomerate. This probably reflects a slightly different source area of the dioritic complex basement. Tonalite is common in the diorite complex immediately northwest of Jibal Hibshi, but quartz diorite is more common farther to the west and to the northeast.

Plutonic clast types examined in thin section include: hornblende-biotite quartz diorite, alaskitic tonalite granophyre, biotite granodiorite, biotite-hornblende quartz monzonite, alaskitic or mylonitic quartz monzonite, hornblende monzonite gneiss, biotite syenogranite gneiss, and alkali feldspar granite granophyre. All of these rocks could have been derived from the Laban dioritic complex except the syenogranite gneiss and the alkali feldspar granite granophyre. The latter is an altered biotite(?)-altered amphibole-microperthite-quartz granophyre (fig. 8) that is petrographically similar to the Gusal alkali feldspar granite granophyre. The presence of these granite clasts in the Hibshi demonstrates that some evolved granites were exposed in the northeastern Shield prior to deposition of the Hibshi formation. However, evolved granite magmatism is generally thought to have only occurred late in the history of the region.

In addition to plutonic clasts, a cobble from the middle conglomerate was identified as clinopyroxene-hornblende-plagioclase porphyritic andesite. The conglomerate matrix is medium- to coarse-grained lithic wacke with quartz and plagioclase clasts and lithic fragments in an epidote-rich recrystallized quartzofeldspathic matrix. Lithic fragments include: tonalite, quartz diorite, diabase, fine-grained chloritic mafic volcanics (metabasalt?), and fine-grained felsic volcanics. Clearly, the middle conglomerate member was derived from a mixed plutonic-volcanic source area which, although dominated by mafic plutonic rocks, also contained evolved granite dikes or plutons and basaltic to andesitic volcanics (see geologic history section).

Figure 8.—Microphotograph of alkali-feldspar granite granophyre clast from the middle conglomerate member of the Hibshi formation (sample 197408). Photograph represents a height of 7.0 mm.

Thickness of the middle conglomerate member varies from about 200 m in the southwest part of Jibal Hibshi to 0 m where it pinches out in the central part of the jibal.

Upper volcanic member

The upper volcanic member (hvu) overlies the middle conglomerate member in the southwest part of Jibal Hibshi and overlies the volcanic sandstone member in the northeast part of Jibal Hibshi. The upper volcanic member forms the resistant crest of Jibal Hibshi. The member is intruded by an andesitic sill north of the Al Ghumrah fault and is overlain by the middle sandstone member along the southeastern flank of Jibal Hibshi, except in the central and southwest parts of the jabal, where the upper member sandstone is thrust over the upper volcanic member.

The member is made up of multiple cooling units of dacitic to andesitic and sparse rhyolitic welded ash-flow tuff and tuff-breccia, interbedded with subordinate air-fall and water-laid tuff and cannibalistic volcanic siltstone, sandstone, breccia, and dacitic lava flows. The welded tuffs are gray or tan on fresh surfaces, weather tan or orange, and are ubiquitously plagioclase porphyritic. Most of the cooling units are densely welded at the base and grade upward into partly welded or unwelded tops. Eutaxitic texture is well-developed near the bases of many of the units (fig. 9).

Plagioclase phenocrysts are typically subhedral or broken, are sericitic or saussuritic, and 1-3 mm in size. Mafic phenocrysts are typically pseudomorphed by aggregates of biotite or epidote and chlorite; however, subhedral tan-green pleochroic hornblende phenocrysts are locally preserved. Microcline (inverted phenocrystic sanidine?) was observed in only two samples from the member. Minor quartz is present as broken and strained multidomain xenocrysts in some of the ash flows and with microcline as phenocrysts in at least one ash flow at Jabal Aba al Liqah. Xenocrystic hornblende is also locally present.

The fragment assemblage is dominated by pumice lapilli and dacitic volcanic or volcanic sandstone lithic fragments. Other rock fragments include minor mafic and intermediate volcanics, and sparse quartz diorite or tonalite. The dacitic volcanic and volcanic sandstone fragments are identical to rocks in the underlying part of the Hibshi and were probably derived by entrainment and intraformational reworking. The quartz diorite and tonalite fragments and the xenocrystic quartz and hornblende were probably derived from the dioritic complex basement. The presence of mafic (basaltic) volcanics is particularly interesting, as it indicates that a basaltic volcanic center was exposed throughout

Figure 9.—Microphotograph showing eutaxitic dacitic welded tuff from the upper volcanic member of the Hibshi formation (sample 197337). Photograph represents a height of 7.0 mm.

much of the Hibshi depositional period. This basaltic center may correlate with the basalt member of the Hibshi formation at Jabal Aba al Liqah. The presence of quartz and microcline as phenocrysts at Jabal Aba al Liqah and the more evolved chemical composition of these ash flows (see Geochemistry and petrogenesis section) suggests either a different source caldera or a different (earlier) phase of volcanism than that which produced most of the volcanics at Jibal Hibshi.

The welded tuffs typically have matrices composed of partly to completely devitrified glass shards and dust. They are variably altered and recrystallized to zeolite or greenschist facies. Pumice lapilli commonly show axiolitic devitrification to zeolitic or quartzofeldspathic assemblages. The matrices of some of the ash flows are replaced by microcrystalline quartz, feldspar, and magnetite dust.

Interbedded volcanic sandstones (lithic wackes) and breccias are common and were produced by cannibalistic reworking of the underlying ash flows and sediments. These sandstones are similar to those in the volcanic sandstone member. They are dominated by plagioclase grains and dacitic volcanic clasts, but they also contain mafic volcanic and quartz diorite or tonalite fragments, and multidomain quartz grains. They are fine to coarse grained, poorly to well sorted, and subangular to angular. The matrices of these rocks are commonly tuffaceous.

Individual cooling units in the member range from a few meters to greater than 50 m. Interbedded sandstones and breccias range from less than 1 m to greater than 10 m. The total thickness of the member ranges from about 1200 m at the northeastern end of Jibal Hibshi to less than about 100 m at Jabal Aba al Liqah. The member apparently pinches out to the northeast in the Al Makhul quadrangle (du Bray, 1984a).

Upper conglomerate

The upper conglomerate member (hcu) crops out in a poorly exposed belt southwest of Jabal Aba al Liqah and as a discontinuous channel-fill deposit at the top of the middle sandstone member along the southeast flank of Jibal Hibshi northeast of the Al Ghumrah fault. The upper conglomerate overlies the upper volcanic member at Jabal Aba al Liqah and is overlain throughout the region by the upper sandstone member.

The upper conglomerate is a tan-weathering, matrix-supported cobble conglomerate. In the best exposures on the southeast flank of Jibal Hibshi, it is composed of about 10% cobbles in a fine- to medium-grained lithic wacke matrix. The clast-type population is distinct from the middle and lower conglomerate members. The most common clast type is resistent fine-grained biotite quartz diorite granophyre or biotite-quartz monzodiorite granophyre; rocks probably derived from sills or dikes within or near the roofs of plutons. In contrast to the lower and middle conglomerates, the upper conglomerate contains abundant felsic volcanic cobbles. These include: sanidine (inverted)-quartz porphyritic, pilotixitic rhyolite (flow rock), and biotite-plagioclase porphyritic dacite. Other less abundant clast types include: biotite tonalite and tonalite gneiss, alaskitic monzogranite aplite, fine-granied lithic wacke, and banded, green, fine-grained quartzite. The conglomerate matrix contains angular (broken) quartz and plagioclase grains and felsic and mafic volcanic fragments in a chloritic matrix.

The clast assemblage and matrix composition indicates derivation from a mixed volcanic-plutonic source area. The source area was probably dominated by mafic plutonic rocks, but also contained sparse monzogranite. Again, the dioritic complex basement probably was the source for many of the clasts. The smaller clast size and finer grain size of the mafic granophyres that dominate the clast assemblage at the Jibal Hibshi exposure indicate greater transport and derivation from a more distant part of the basement. This is consistent with the position of the member high in the Hibshi stratigraphic succession. The occurrence of dacitic volcanic and lithic wacke clasts in the conglomerate and the composition of the conglomerate matrix reflects detrital contribution from the underlying volcanic member of the Hibshi. The presence of rhyolite clasts is anomalous with respect to the composition of the immediately underlying volcanics, but may have been derived from more evolved volcanics elsewhere in the Hibshi perhaps those at Jabal Aba al Liqah.

The conglomerate ranges from 0 to about 340 m at Jibal Hibshi and about 50-100 m southwest of Jabal Aba al Liqah. The member probably pinches out just across the boundary into the adjacent Al Makul quadrangle to the east (du Bray, 1984a).

Middle sandstone member

The middle sandstone member (hsm) crops out along the southeast flank of the northeastern part of Jibal Hibshi. It overlies the upper volcanic member and is overlain by the upper sandstone member. The middle sandstone member consists of repeated meter-scale interbeds of sandstone and siltstone or claystone beds, and sparse chert beds. The sandstone is more resistant than the siltstone and claystone, resulting in a distinctive ledge and swale outcrop. The ridges consist of resistent sandstone; the depressions between ridges consist of siltstone, claystone, or sheared sandstone. Exposures of the unit northeast of the Al Ghumrah fault form a monoclinal section, about 470 m thick, dipping to the southeast. However, exposures southwest of the Al Ghumrah fault are folded and block faulted (fig. 10), probably due to deformation produced by thrusting of this area to the northwest (see plate 1 and Structural geology section).

Figure 10.--Oblique aerial photograph showing folded and block-faulted middle sandstone member of the Hibshi formation southwest of the Al Ghumrah fault on the southeast flank of Jibal Hibshi.

The sandstones are green to gray, medium to fine grained, angular to subangular, moderately-sorted lithic and feldspathic wackes. They contain quartz and feldspar grains and mafic and felsic volcanic fragments in a variably recrystallized chlorite- and epidote-rich, and locally carbonate-rich, silty matrix. The siltstones contain mostly silt-sized quartz, feldspar, epidote, amphibole, and magnetite grains. Thin (less than 10 cm) black chert interbeds probably represent recrystallized water-lain tuff beds.

The middle sandstone member was probably deposited in a local basin, perhaps a closed basin, during the waning stages of Hibshi volcanism. Clast and matrix compositions indicate that detritus was derived from the underlying part of the Hibshi as well as from a more distant region of the diorite complex basement. The presence of mafic plutonic detritus indicates that basement highs penetrated the Hibshi-Murdama cover rocks at the time of deposition. Mafic and felsic rock fragments in the lithic wackes indicate a mixed volcanic source terrain.

Upper sandstone member

The upper sandstone member (hsu) crops out southeast of Jabal Hibshi and south of Jabal Aba al Liqah and underlies most of the Sha'ib al Uzaym. The upper sandstone overlies the middle sandstone and upper congolmerate members. It is also thrust over the upper volcanic member in the southwest part of Jibal Hibshi and is intruded by the Nimriah and Shuwayman monzogranite plutons. About 500 m stratigraphic thickness of the upper sandstone member is exposed in the section north of the Al Ghumrah fault (fig. 2) and the top of the member is not exposed.

The sandstone is green gray and outcrops appear distinctly dark green gray from a distance. The dominant rock type is very fine to medium-grained, moderately sorted, angular to subangular, feldspathic or lithic wacke. Common clast types are: quartz, plagioclase (and locally potassium feldspar), opaque oxides, epidote, mafic and felsic volcanic fragments, and sparse sandstone fragments. The matrix is typically silt sized and is variably recrystallized to a greenschist assemblage of quartz, feldspar, chlorite, epidote, fibrous amphibole, biotite, magnetite, and locally carbonate. The chloritic matrix and abundant volcanic lithic fragments are characteristic features of rocks described as graywackes. The upper sandstone member is undistinguishable from graywackes mapped in the Murdama group to the south in the Samirah quadrangle (P. L. Williams, oral commun., 1984).

It has been argued that the Hibshi formation is less metamorphosed and less deformed than typical Murdamah graywacke. This has been used as an argument that the Hibshi is younger than the Murdamah. However, as noted above, the degree of metamorphism and deformation within the Hibshi is variable. Local shear zones are common in the lower part of the Hibshi section and platy cleavage is developed there. Platy cleavage and greenschist metamorphism is characteristic of much of the upper sandstone member. The Hibshi within the upper thrust plate on the southeast flank of Jibal Hibshi is locally highly deformed (fig. 10) in a manner similar to many regions within the Murdama basin south of the quadrangle. The presence of quartz diorite from a 10 m-deep water well in Wadi Hibshi suggests that the main section of the Hibshi formation thins to the southeast and undergoes a facies change such that the upper sandstone member and the Murdama graywacke to the south (Maraghan formation of du Bray, in press, and Johnson and Williams, 1984) represent lateral equivalents of the thick volcanic-dominated section at Jibal Hibshi (see cross-section, plate 1).

Samirah dacite and rhyolite

Discontinuous outcrops of dacite and rhyolite (dc) crop out in a belt along the eastern margin of the Gusal alkali feldspar granite pluton northwest of the village of Samirah. The member contains eutaxitic welded tuff that is intruded by hornblende-biotite-plagioclase porphyritic dacitic dikes which also cut the margin of the Gusal pluton in the northern part of the belt.

In the southern part of the belt the member is not well exposed but appears to unconformably overlie the Kilab monzogranite batholith. In this area, both the Samirah volcanics and the Kilab monzogranite may be intruded by the Gusal pluton. In the southern outcrops, the unit consists of plagioclase-sanidine (inverted) porphyritic rhyolite tuff and biotite-hornblende plagioclase porphyritic dacite.

The Samirah dacite and rhyolite may represent volcanics related to the Hibshi. If this were the case, it would indicate that the Kilab monzogranite is older than the Hibshi (see the geologic history section). However, the rhyolitic composition of some of the Samirah volcanics is chemically equivalent to samples of the Gusal alkali-feldspar granite (Table 1). The presence of pilotaxitic and granophyric groundmass textures indicates a lava-flow origin for some of the dacites, and the presence of dacitic dikes with similar phenocryst mineralogy to the flows suggests a local origin. For these reasons, the Samirah dacite and rhyolite are tentatively correlated with the Gusal pluton. The area of the Gusal pluton may have formerly been a small volcanic center, characterized by ash- and lava-flow eruptions from dike feeders (perhaps a ring dike formed and limited caldera collapse ensued). This volcanic phase would have been followed by resurgence of the main Gusal pluton. The Samirah volcanics and the Gusal pluton may be analagous to the Qarfa formation (intracaldera volcanics) and the Salma granophyre (resurgent dome) in the Baq'a quadrangle as interpreted by Kellogg (in press).

Table 1.—Chemical and normative analyses of rocks of the Harrat Hutaymah quadrangle and volcanic field

Sample	197061	197085	197089	197099	197146	197224	197110	197124	197151	197163
Symbol	Qb	Qb	Qb	Qb	dc	hvu	mg(d)	mg(d)	mg(d)	gag(d)
Lat.	27 09.2'	26 43.1'	26 52.3'	26 49.0'	26 31.4'	26 34.6'	26 38.3'	26 36.3'	26 33.1'	26 31.0'
Long.	42 11.0'	42 15.9'	42 12.9'	42 15.1'	42 03.7'	42 22.5'	42 01.3'	42 09.3'	42 06.8'	42 03.4'
SiO2	46.46	46.19	46.48	44.51	71.34	62.86	71.59	53.14	49.63	67.90
Al2O3	14.54	14.52	13.87	12.51	14.41	16.60	14.02	15.94	17.32	15.78
Fe2O3	3.78	4.14	3.64	3.54	1.87	2.31	1.55	3.09	2.68	1.91
FeO	8.12	7.87	7.12	8.26	.39	2.41	.10	4.89	6.64	.86
MgO	9.57	8.55	10.53	14.15	.44	1.76	.49	5.16	4.78	1.10
CaO	9.17	9.64	9.23	9.79	.66	3.46	1.26	6.55	8.15	2.43
Na2O	4.03	3.43	3.05	2.72	5.68	4.38	4.29	4.06	3.56	5.05
K2O	1.27	1.46	1.46	.97	4.09	4.22	4.81	1.53	1.39	3.39
LOI	-	.71	1.64	.64	.47	.77	1.47	3.24	4.11	.70
TiO2	2.26	2.62	2.12	2.00	.37	.80	.21	1.58	1.17	.41
P2O5	.46	.51	.51	.53	.07	.20	.07	.54	.28	.14
MnO	.18	.18	.18	.18	.13	.09	.06	.10	.15	.08
Cr2O3	.42	.37	.65	.81	.03	.04	.01	.23	.07	.03
Total	100.26	100.19	100.48	100.61	99.95	99.90	99.93	100.05	99.93	99.76
Q					20.818	11.547	25.434	3.500		19.503
C										.042
Or	7.465	8.644	8.702	5.723	24.191	25.035	28.801	9.317	8.563	20.150
Ab	19.547	20.389	21.299	13.646	48.106	37.207	36.783	35.403	31.405	42.967
An	17.739	19.949	20.015	19.030	1.745	13.222	4.856	21.384	28.330	10.331
Ne	7.787	4.707	2.602	5.056						
Ac										
Ns										
Wo	10.240	10.283	9.525	10.858	.449	1.127	.370	3.535	4.975	
En	7.045	7.167	6.953	7.918	1.097	4.400	1.237	13.243	8.900	2.756
Fs	2.372	2.261	1.680	1.926		1.334		3.920	6.179	
Fo	11.678	9.928	13.664	19.109					2.460	
Fa	4.334	3.452	3.639	5.122					1.882	
Mt	5.452	6.014	5.323	5.124	.564	3.362		4.617	4.051	1.773
Cm	.615	.546	.966	1.191	.044	.059	.015	.349	.107	.044
Hm					1.483		1.571			.698
Il	4.270	4.985	4.061	3.792	.703	1.525	.334	3.092	2.317	.783
Ap	1.084	1.210	1.218	1.253	.166	.476	.168	1.318	.691	.334

Table 1.—Chemical and normative analyses of rocks of the Harrat Hutaymah quadrangle and volcanic field continued

Sample	197187	197087	197226	197206	155168	197209	198208	197101	197144	197160
Symbol	hcl(d)	sgr	sgr	qs	ga	ga	ga	gag	gag	gag
Lat.	26 35.6'	26 52.3'	26 38.2'	26 54.5'	26 58.9'	26 55.3'	26 54.8'	26 34.4'	26 31.7'	26 30.3'
Long.	42 20.3'	42 12.7'	42 12.8'	42 06.6'	42 05.5'	42 04.3'	42 05.7'	42 03.0'	42 03.1'	42 02.4'
SiO2	45.99	72.90	75.84	72.90	77.80	74.70	76.00	73.30	73.40	76.80
Al2O3	14.05	12.60	11.70	14.10	11.90	13.00	12.40	13.60	13.40	12.20
Fe2O3	3.91	2.29	1.47	0.85	1.05	0.90	0.76	1.38	1.04	0.30
FeO	8.48	0.50	0.30	0.40	0.11	0.50	0.50	0.30	0.20	0.40
MgO	3.45	0.29	0.15	0.42	0.05	0.23	0.18	0.50	0.35	0.15
CaO	8.46	0.66	0.45	1.36	0.41	0.59	0.37	0.67	0.71	0.18
Na2O	2.80	4.42	4.06	4.62	3.64	4.27	4.48	5.46	5.28	4.82
K2O	1.50	5.04	4.69	4.40	4.71	5.16	4.71	4.13	4.35	4.31
LOI	6.77	.93	0.93	0.51	0.21	0.47	0.39	0.16	0.62	0.31
TiO2	2.40	.27	0.13	0.16	0.06	0.18	0.10	0.36	0.25	0.14
P2O5	1.84	.04	0.02	0.05	0.05	0.03	0.03	0.08	0.05	0.03
MnO	.21	.07	0.02	0.04	0.01	0.02	0.02	0.11	0.10	0.06
Cr2O3	.01									
Total	99.86	100.01	99.72	99.84	100.00	100.05	99.94	100.05	99.75	99.76
Q	3.672	27.219	34.036	26.337	37.870	29.075	31.402	24.326	25.044	32.638
C					0.189					
Or	9.456	30.059	28.059	26.184	27.891	30.620	27.958	24.432	25.931	25.625
Ab	25.275	37.092	34.487	39.369	30.865	36.284	37.729	46.252	45.070	38.995
An	22.763			4.774	1.711	1.070		0.403	0.016	
Ne										
Ac		0.578	0.254				0.309			0.873
Ns										0.244
Wo	3.835	1.270	0.888	0.706		0.698	0.688	1.002	1.339	0.293
En	9.166	0.729	0.378	1.053	0.125	0.575	0.450	1.247	0.879	0.376
Fs	9.345						0.251			0.619
Fo										
Fa										
Mt	6.048	1.067	0.663	0.963	0.214	1.160	0.952	0.283	0.249	
Cm	.016									
Hm		1.375	0.943	0.192	0.905	0.104		1.186	0.878	
Il	4.863	0.518	0.250	0.306	0.114	0.343	0.191	0.684	0.479	0.268
Ap	4.649	0.096	0.048	0.119	0.119	0. 71	0.071	0.190	0.199	0.071

Table 1.—Chemical and normative analyses of rocks of the Harrat Hutaymah quadrangle and volcanic field continued

Sample	197257	197267	197239	197244	197207	197088	197127	197156
Symbol	gah	gah	mg	mg	dr	dr	dr	dr
Lat.	26 40.0'	26 28.7'	26 43.0'	26 32.3'	26 54.5'	26 52.3'	26 33.7'	26 36.1'
Long.	42 22.1'	42 42.4'	42 08.4'	42 15.0'	42 06.4'	42 12.7'	42 15.7'	42 19.9'
SiO2	74.80	75.60	77.00	68.00	69.50	59.60	64.20	70.50
Al2O3	13.60	13.40	12.30	14.80	15.70	16.10	17.40	15.90
Fe2O3	0.43	0.44	0.43	1.54	3.66	1.91	1.95	0.84
FeO	0.10	0.10	0.20	1.40	3.80	4.60	1.60	0.70
MgO	0.19	0.14	0.16	1.75	1.35	3.02	1.32	0.60
CaO	0.44	0.37	0.17	2.84	3.33	5.77	4.46	2.63
Na2O	5.19	5.17	2.95	4.48	5.69	3.73	5.49	5.20
K2O	4.43	4.46	6.13	3.58	3.01	2.37	1.57	2.70
LOI	0.47	0.23	0.54	0.54	0.16	1.16	0.70	0.62
TiO2	0.07	0.07	0.05	0.42	1.14	0.83	0.55	0.18
P2O5	0.01	0.01	0.05	0.14	0.27	0.19	0.19	0.08
MnO	0.05	0.07	¼0.01	0.05	0.19	0.11	0.07	0.06
Total	99.78	100.06	99.98	99.54	97.80	99.39	99.50	100.00
Q	26.946	27.877	36.123	20.580	6.928	11.668	15.790	23.686
C			0.626					
Or	26.360	26.400	36.428	21.369	18.217	14.257	9.390	16.055
Ab	44.221	43.822	25.103	38.291	49.311	32.131	47.019	44.275
An	0.734	0.185	0.520	9.799	8.611	20.552	18.418	12.144
Ne								
Ac								
Ns								
Wo	0.584	0.663		1.465	2.715	3.059	1.136	0.191
En	0.476	0.349	0.401	4.402	3.443	7.657	3.327	1.504
Fs				0.705	2.484	5.806	0.556	0.390
Fo								
Fa								
Mt	0.285	0.348	0.502	2.255	5.435	2.819	2.862	1.226
Hm	0.237	0.200	0.086					
Il	0.134	0.133	0.095	0.806	2.217	1.605	1.057	0.344
Ap	0.024	0.024	0.119	0.335	0.655	0.458	0.455	0.191

Table 1.—Chemical and normative analyses of rocks of the Harrat Hutaymah quadrangle and volcanic field continued

Map symbols

Qb = Quaternary basalt
dc = Samirah dacite
hvu= Upper volcanic member of Hibshi formation
hcl= Lower conglomerate member of Hibshi formation
sgr= Shurmah alkali-feldspar granite ring
qs = Salma alkali-feldspar quartz syenite
ga = Salma alkali-feldspar granite
gag= Gusal alkali-feldspar granite
gah= Hudub alkali-feldspar granite
mg = Klab monzogranite
dr = Laban dioritic complex
(d)= dike (within indicated host rock)

Normative minerals

Q = quartz
C = corundum
Or = orthoclase
Ab = albite
An = anorthite
Ne = nepheline
Ac = acmite
Ns = sodium metasilicate
Wo = wollastonite
En = enstatite
Fs = ferrosilite
Fo = forsterite
Fa = fayalite
Mt = magnetite
Hm = hematite
Il = ilmenite
Cm = chromite
Ap = apatite

PROTEROZOIC INTRUSIVE ROCKS

Older pultonic series

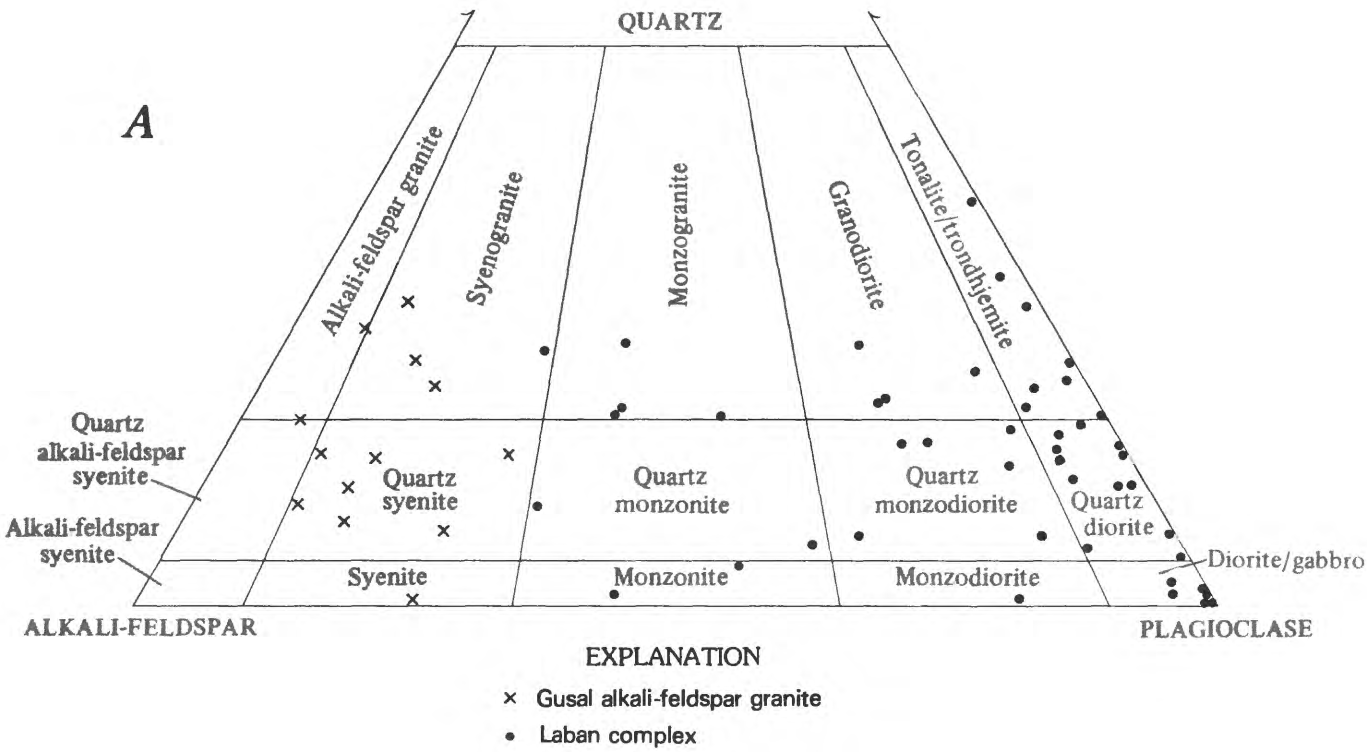
A basement complex underlies the central and eastern parts of the quadrangle. It consists of variably metamorphosed and deformed mafic plutonic rocks of the Laban dioritic complex and the Birka gabbro. The Laban dioritic complex is intruded by the Birka gabbro; however, it also contains smaller areas of more deformed gabbro and both map units are considered to be part of a relatively old basement complex. The Birka gabbro is not in contact with any of the younger rocks in the quadrangle, therefore its assignment to the older plutonic series is somewhat arbitrary. Of the rocks exposed in the quadrangle, only the Al Ghumrah amphibolite is demonstrably older than the older plutonic series.

The Laban dioritic complex contains a variety of mafic plutonic rocks that have undergone variable degrees of metamorphism and deformation. Clearly, the complex is composite with respect to age; however, the absolute range in age is unknown. Quartz diorite from just across the southern quadrangle boundary is dated by the U-Pb method on zircon at 650 $\pm$ 5 Ma (J. C. Cole and C. E. Hedge, written commun., 1984).

Laban dioritic complex

The Laban dioritic complex (dr) is an intrusive complex of biotite quartz diorite, biotite and(or) hornblende diorite and tonalite, hornblende and pyroxene gabbro, gabbronorite, monzodiorite or monzogabbro, and subordinate granodiorite and quartz monzodiorite. Minor amounts of monzonite, quartz monzonite, and monzogranite are locally present as small bodies or as extreme variants (figure 11A). The most common rock types in the complex are tonalite and quartz diorite, with either igneous (hypidiomorphic) or metamorphic (gneissic) textures. Transitions from hypidiomorphic to gneissis textures take place over narrow (less than 10 m) intervals and the distribution of gneissic rock within the complex is locally complicated. Small bodies of gneiss are intricately mixed with homogeneous quartz diorite or tonalite or vice versa over areas of a few km^2. Other regions are characterized by undeformed quartz diorite or tonalite over areas of tens of km^2.

The Laban complex weathers to a low-relief pediplain characterized by isolated outcrops in small wadi channels and on low-relief exfoliation surfaces. Consequently, intrusive relations within the complex are difficult to document. The best outcrops in the quadrangle for observing the internal characteristics of the complex are in the near-vertical outcrops within the crater of Harrat Hutaymah.



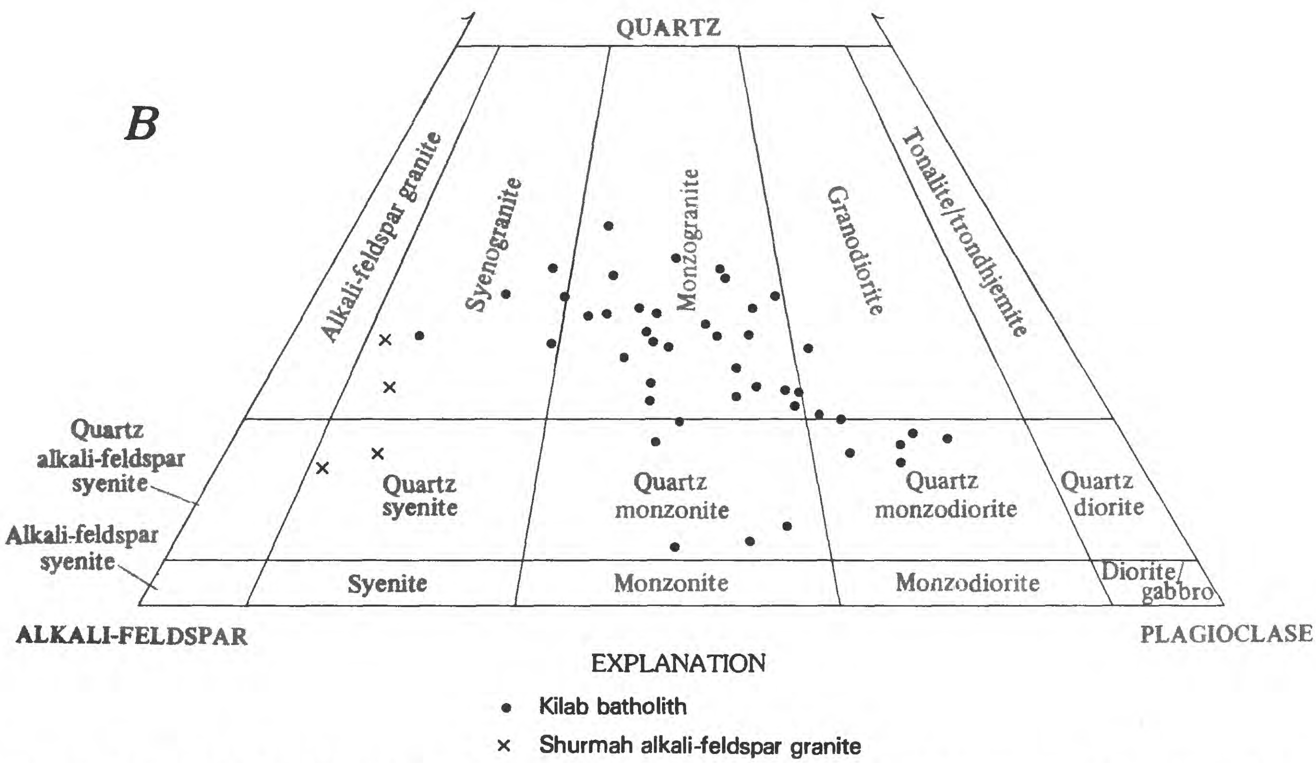
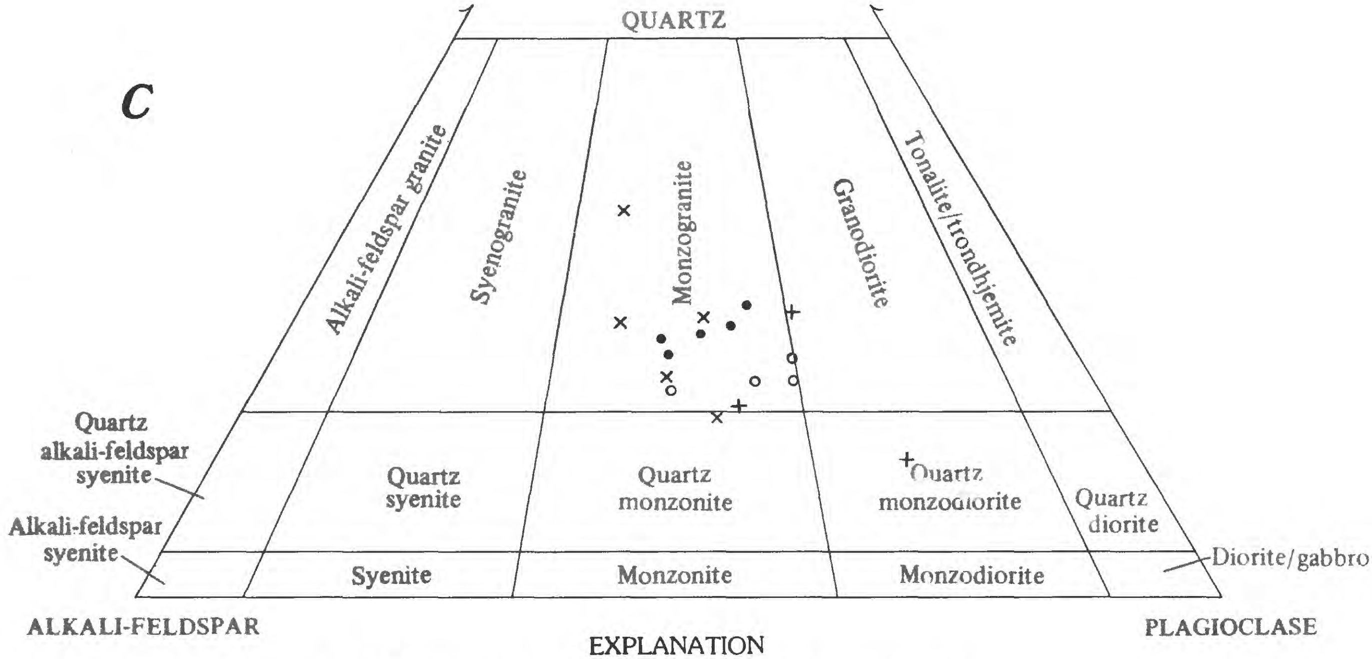
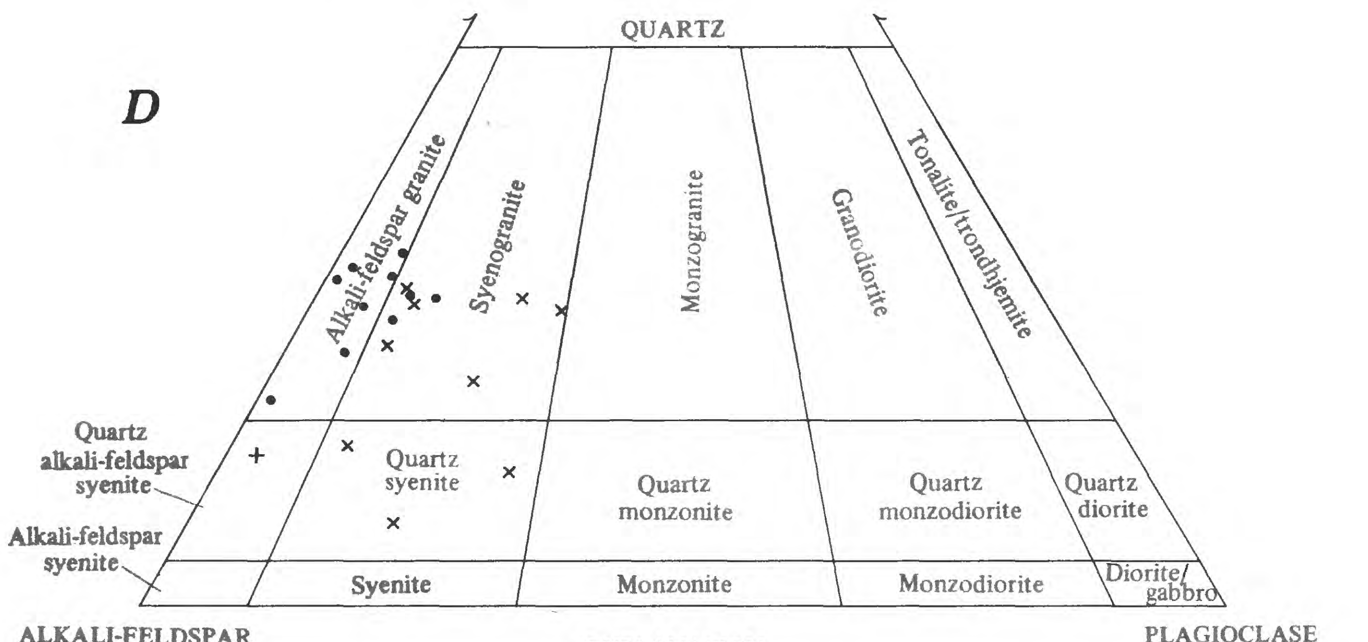


Figure 11.—Modal classification ternary diagrams for plutonic rocks (Streckeisen, 1976) of the Harrat Hutaymah quadrangle. Lower apices are defined as K-feldspar and plagioclase, rather than alkali-feldspar and non-albitic plagioclase (as in the IUGS system), to show variation in alkali-feldspar granites. This is significant for the sgr, qs, gap, ga, gag, and gah units, all of which contain albitic plagioclase and are accordingly classified as alkali-feldspar granites and alkali-feldspar quartz syenites.



EXPLANATION

- ● Ubdah monzogranite
- × Hudub alkali-feldspar granite
- ○ Nimriah monzogranite
- + Shuwayman monzogranite



EXPLANATION

- ● Salma alkali-feldspar granite
- + Salma alkali-feldspar quartz syenite granophyre
- × Salma alkali-feldspar quartz syenite

Figure 11.—Continued

Quartz diorite and tonalite from the complex are typically medium grained and hypidiomorphic granular. Biotite and hornblende are commonly pseudomorphed by fibrous amphibole (tremolite-actinolite), chlorite, and epidote and zoned intermediate to calcic plagioclase is variably saussuritized. Mafic minerals (mostly biotite, hornblende, and opaques) average about 15% in these rocks. Microcline or microcline perthite, titanite, and titanomagnetite are common minor or trace minerals. The rocks are locally recrystallized and have granoblastic or gneissic textures; cataclastic textures are common along faults.

A sample of saprolitic biotite-hornblende-clinopyroxene quartz diorite was recovered from a water well in Wadi Hibshi. The sample is coarse grained and hypidiomorphic granular. The biotite is oxidized and the clinopyroxene is rimmed by hornblende. The sample is probably from less than 10 m depth and it is likely that quartz diorite underlies the alluvium in this area. A small outcrop of Laban complex is shown on plate 1 in the immediate vicinity of the well. The presence of quartz diorite in this area has important consequences for the stratigraphy of the Hibshi formation. If this is truly Laban complex rock and not a later intrusion, which cannot be ruled out with the present data, a major intraformational thinning is required within the Hibshi section between Jibal Hibshi and the sample locality.

Abundant mafic (metadiabase) and felsic (metarhyolite to metaandesite and granophyre or granite) dikes intrude the complex. In addition, vuggy quartz-limonite breccia dikes and veins intrude the complex and are mineralized at the ancient Samirah gold mine. These dikes and veins were probably derived from the Gusal alkali-feldspar granite. Most of the felsic dikes also intrude the Kilab monzogranite batholith and are related to plutons of the younger plutonic series. In contrast, mafic dikes are more common in the Laban complex than in the younger units and some are probably only slightly younger than the Laban. Younger diabase and metadiabase dikes were intruded along northwesterly trending faults and fractures and are similar to dikes cutting the Hibshi formation.

Rocks of the Laban complex intrude amphibolite and quartzite of the Ghumrah formation northwest of Jibal Hibshi. The Hibshi formation is unconformably deposited on Laban quartz diorite and tonalite. The Kilab batholith, the Hudub and Ubdah plutons, and the Shurmah ring dike intrude the Laban complex.

Birka gabbro

The Birka gabbro (gb) forms small plutons that intrude the Laban complex near the village of Al Birka, at Jabal Uraynibah, and near Wadi aba al Kurush. Other smaller and less distinct bodies are present in the Laban complex, but are not differentiated on plate 1.

The Birka gabbro unit is made up of gray- to black-weathering, fine- to coarse-grained, hypidiomorphic granular hornblende gabbro, hornblende-clinopyroxene gabbro, and clinopyroxene gabbro and melagabbro, and cumulus plagioclase wehrlite, olivine-clinopyroxene gabbro, and hornblende-clinopyroxene gabbro. Heteradcumulus hornblende gabbro (poikilitic) is locally present. The ultramafic rocks (wehrlites and melagabbro) are exposed mostly at Jabal Uraynibah.

The Birka gabbro is intruded by Proterozoic aplite and rhyolitic dikes and at Jabal Uraynibah by a peridotite-xenolith bearing basalt dike of probable Tertiary or Quaternary age.

Granodiorite dikes

Granodiorite dikes (-++++-) intrude the Al Ghumrah amphibolite and the Laban quartz diorite. They are alaskitic biotite granodiorite aplite and pegmatite and are tentatively correlated in relative age with the Kilab batholith.

Kilab monzogranite batholith

The Kilab monzogranite batholith (mg) is a composite batholith of mostly monzogranite, but also contains small bodies or local variations to granodiorite, syenogranite, alkali-feldspar granite or granophyre, quartz monzonite, and quartz monzodiorite (fig. 11B). The monzogranite is light gray to pinkish gray, medium grained, and allotriomorphic granular to granoblastic. It is composed of microcline or microcline perthite, zoned plagioclase, quartz, green hornblende, and minor titanite. The rock is locally plagioclase or microcline porphyritic and has an average color index of about 5.

Local variations in grain size (from fine to coarse grained) are present, but most of the monzogranite is medium grained. Alteration and metamorphism is also variable. The cores of plagioclase grains are commonly saussuritized and biotite and hornblende are locally chloritized or uralitized, however, most outcrops are moderately fresh. The degree of protoclastic and subsolidus deformation is variable. Quartz is commonly strained or recrystallized into multi-domain grains; locally it is recrystallized into gneissic seams.

Centimeter- to meter-scale bull quartz and quartz-feldspar pegmatite veins and pods are locally common. The larger veins and pods produce prominent white-weathering quartz lag aprons. Such veins and pods near the southwestern part of the Shurmah ring dike are associated with a small zone of peraluminous zinwaldite(?) granite.

The granite weathers to a low-relief grus-covered plain with the only prominent outcrop at the Jabal al Hamrah inselberg. It is therefore difficult to work out the internal structure of the batholith in detail.

The batholith extends into the adjacent Rak (Kellogg, in press), Qufar (Kellogg, 1983), Al ,Awashazyah (Leo, 1984), and Samirah (Williams, 1983) quadrangles and is exposed over a total area of several thousand km^2. It probably contains many individual plutons and may have a significant age range. U-Pb dating of zircon from a phase of the batholith in the Qufar quadrangle (J. C. Cole and C. E. Hedge, written commun., 1984) yielded 651 $\pm$ 5 Ma; the batholite is therefore considered to be partly coeval with some plutons in the Laban complex and only about 20 Ma older than the Hibshi formation.

The batholith is intruded by numerous 1-10 m thick mafic and felsic dikes and by quartz-limonite breccia dikes associated with the younger plutonic series. The quartz-limonite breccia dikes were probably derived in part from the Gusal alkali-feldspar granite and are not mineralized where the country rock is Kilab monzogranite. However, similar dikes and veins in the Laban dioritic complex are mineralized. The felsic dikes are: red- or pink-weathering biotite (chlorite)-plagioclase-quartz rhyolite, K-feldspar-plagioclase-quartz rhyolite, quartz and(or) plagioclase dacite, and quartz-K-feldspar granophyre. Gray or dark-gray trachyte(?) dikes are present near the Shurmah alkali-feldspar granite ring dike and dark-gray weathering diabase dikes are present throughout the batholith. Thick (10-15 m wide) hornblende monzodiorite dikes were also observed near the Shurmah ring dike. Intrusive relations of the dike swarms of Jabal Shurmah and their relations to the Shurmah ring dike are discussed in a subsequent section of this report.

Younger plutonic series

A series of largely undeformed, commonly oval or circular-outline plutons and ring complexes composed mostly of monzogranite or alkali-feldspar granite were intruded at a late stage in the development of the Arabian shield. These "post-orogenic" or "pan-African" granites occur throughout the Arabian Shield and range in age from about 670-550 Ma (Stoeser and Elliott, 1980). Those in the northeastern Shield are mostly in the 550-600 Ma age range based on recent radiometric dating reported by J. C. Cole and C. E. Hedge (written commun., 1984), J. S. Stacey (oral commun., 1984) and Stuckless and others (1984).

The Hudub, Gusal, Salma, and Shurmah granites are considered as members of the post-orogenic suite. The Nimriah and Shuwayman monzogranites are somewhat older (the Nimriah is dated at 621 $\pm$ 5 Ma), but both intrude the Hibshi formation and are accordingly classified in the younger plutonic series. Relative ages of several of the plutons within the younger plutonic series are unknown. However, recent geochronological studies of the post-orogenic granites in the northern Shield (Cole and Hedge, written commun., 1984; Stuckless and others, 1984) suggest that the alkali-feldspar granites are commonly younger than the monzogranites. On this basis, the Ubdah and Shuwayman monzogranites are shown on plate 1 as approximate age equivalents to the dated Nimriah monzogranite, and the Hudub, Gusal, and Shurmah alkali-feldspar granites are shown as members of a younger group; roughly coeval with the dated (apparent age 580 ± 5 Ma; Stuckless and others, 1984) Salma alkali-feldspar granite.

Another line of evidence that there are two age groups within the younger plutonic series is the difference in topographic expression of the plutons. The monzogranite plutons (Nimriah and Shuwayman) are eroded to the same level as the Kilab batholith and Laban dioritic complex - the regional pediplane surface. Exposures are consequently poor in these plutons. The monzogranites are not obviously less resistant to erosion than the alkali-feldspar granites; in fact, the Hudub pluton is composed of particularily crumbly, easily weathered, alkali-feldspar granite. This difference in topographic expression was first noted by Cole(unpublished) in the Uglat As Suqur quadrangle. Cole pointed out that several of the late alkali-feldspar granites are exposed at topographically higher levels than the regional projection of the base of the Paleozoic sedimentary rocks that form the eastern margin of the Shield. This indicates that they were topographically high during the Cambrian and(or) Ordovician, and either were not yet emplaced, or were not as completely eroded during the late Proterozoic erosional epoch (peneplaination) that took place prior to deposition of the Cambro-Ordovician Saq Sandstone.

Andesite sill

An andesite sill (an), approximately 320 m thick, intrudes the upper volcanic member of the Hibshi formation at the northeast end of Jibal Hibshi. A thin (3 m) andesite sill intrudes the lower conglomerate member, also at the northeast end of Jibal Hibshi.

The sill is composed of gray to greenish-gray, fine-grained, plagioclase and hornblende-plagioclase porphyritic andesite. The rock has an intergranular groundmass texture and is variably altered to a greenschist facies assemblage of fibrous amphibole, chlorite, and albite. Smectite alteration of the groundmass is also locally common. The hornblende phenocrysts are typically pseudomorphed by uralite and chlorite or by smectite and chlorite, and plagioclase phenocrysts are commonly saussuritic. The rock also contains minor phenocrysts and microphenocrysts of Ti-Fe oxides and interstitial quartz. The rock has not been chemically analyzed, therefore the designation as andesite is based only on petrography.

Ubdah monzogranite

The Ubdah monzogranite (mgu) intrudes the Laban complex and is covered by Quaternary volcanic rocks of Harrat Awaied and Harrat Hutaymah in the northeastern part of the quadrangle. The Ubdah pluton is poorly exposed and can be shown to intrude only the Laban complex; therefore, its age is not well constrained. It is included with the younger plutonic series in this report, however, it could be an apophysis of the Kilab monzogranite.

The Ubdah pluton is composed of light-gray to pinkish-gray, fine- to medium-grained, biotite and hornblende-biotite monzogranite with a color index of about 4. It is allotriomorphic to hypidiomorphic granular and locally granoblastic. The feldspars are subequal zoned plagioclase (oligoclase-andesine) and microcline microperthite. Modal analyses indicate an ideal monzogranite composition (fig. 11C). The quartz grains are recrystallized to a mosiac of small extinction domains and in some samples quartz is sheared into lensoidal multi-domain grains, defining a weak foliation in the rock.

Shuwayman monzogranite

The Shuwayman monzogranite (mgs) is exposed in the southeast corner of the quadrangle. It forms a large pluton that extends into the adjacent Jabal as Silsilah, Al Makhul (du Bray, in press, 1984a), and Samirah (Williams, 1983) quadrangles. The pluton intrudes the upper sandstone member of the Hibshi formation southeast of Wadi Hibshi and is intruded by west- and northwest-trending plagioclase porphyritic andesitic dikes.

Outcrops of the Shuwayman pluton in the Harrat Hutaymah quadrangle are composed of pale-orange, fine- to medium-grained, hypidiomorphic to allotriomorphic granular biotite monzogranite, biotite quartz monzonite, and biotite granodiorite (fig. 11C). In other areas the granite is peraluminous (corundum normative) and a few samples contain traces of muscovite (du Bray, 1984b, unpub. data). The feldspars are microcline perthite, microperthite, nonperthitic microcline, and zoned oligoclase-andesine. Biotite is commonly pseudomorphed by chlorite and the quartz shows undulatory extinction. The color index is typically about 3. Opaque oxides and titanite are the most common accessory minerals.

Nimriah monzogranite

The Nimriah monzogranite (mgn) forms a small (4.5 X 7.5 km) oval pluton that intrudes the upper sandstone member of the Hibshi formation east of Jibal Hibshi. The Nimriah pluton is dated at 621 ± 5 Ma by the U-Pb method on zircon (J. C. Cole and C. E. Hedge, written commun., 1984) from a sample located just south of the quadrangle boundary in the Samirah quadrangle. A preliminary date of 616 ± 10 Ma was reported by Williams (1983) for the monzogranite, which he regarded as part of the Shuwayman pluton. It cannot be demonstrated that the Nimriah body is not related to the Shuwayman; it may be an apophysis that is continuous at depth below a septum of Hibshi formation. However, the Nimriah monzogranite does form a discreet, oval outcrop area and although the few samples available overlap in modal abundance of quartz and feldspars (fig. 11C), the Nimriah samples have a higher color index (see below). For these reasons, a separate pluton is defined.

The Nimriah pluton is composed of pink, recessive weathering, biotite and hornblende-biotite monzogranite and granodiorite (fig. 11C). It is medium to coarse grained and hypidiomorphic to allotriomorphic equigranular or locally plagioclase porphyritic. Feldspars are zoned oligoclase-andesine and microperthite. Common minor and trace minerals are biotite, green hornblende, titanite, and opaque oxides.

Hudub alkali-feldspar granite

The Hudub alkali-feldspar granite (gah) forms a 12 km diameter circular-outline pluton that intrudes the Laban complex and the Hibshi formation at Jabal Aba al Liqah. A chilled border phase is present where the pluton intrudes the Hibshi. The prominent inselbergs at Jabal al Hammr and Jabal al Kanhar are composed of the granite. The pluton is shown as correlative in age with the Salma and Gusal plutons. This correlation is somewhat arbitrary; the relative age of the Hudub pluton within the younger plutonic series cannot be demonstrated with intrusive relations. The granite is hypersolvus, in contrast to the partly subsolvus Salma alkali-feldspar granite. However, both hypersolvus and subsolvus alkali-feldspar granites are among the youngest granites of the northern Shield (D. B. Stoeser and E. A. du Bray, oral commun., 1984).

The core of the pluton is light-gray to pinkish-gray biotite- and magnetite-bearing hypersolvus alkali-feldspar granite. It is medium to coarse grained, typically alaskitic (color index less than 1) and has an allotriomorphic or hypidiomorphic granular texture. It is composed mostly of subequal twinned albite, microcline (locally perthitic or microperthitic), and quartz with minor amounts of biotite and magnetite, and locally with a trace of muscovite. The modal mineral composition (fig. 11C) overlaps with the true monzogranites of the region (the Klab, Ubdah, Nimiriah, and Shuwayman monzogranites), however, the chemical composition of the Hudub rocks (Table 1) and a few optical determinations of plagioclase composition indicate that the plagioclase is albite and the rock is accordingly classified as alkali-feldspar granite according to IUGS guidelines (Streckeisen, 1976).

Magnetite is more abundant than biotite in the pluton and is commonly altered to hematite and(or) limonite. The hemitite and limonite pseudomorphs are weathered out in many of the rocks, leaving a characteristic pitted appearance and crumbly outcrop.

The chilled border phase adjacent to the Hibshi formation at Jabal Aba al Liqah is a biotite-bearing alkali-feldspar granite with phenocrysts of quartz, microcline, and plagioclase (albite) in a very fine grained intergranular quartzofeldspathic groundmass. The Hibshi sandstone and conglomerate is recrystallized within 5 m of the contact.

The pluton is intruded by several 1-5 m thick K-feldspar (inverted sanidine?) porphyritic quartz trachyte(?) or comendite (?) dikes. These dikes are probably cogenetic with the pluton.

Gusal alkali-feldspar granite

The Gusal alkali-feldspar granite (gag) forms a small (about 8 X about 15 km) pluton in the southwest corner of the quadrangle and extending to the south into the Samirah quadrangle (Williams, 1983). The Gusal pluton intrudes the Klab monzogranite batholith and may also locally intrude the Samirah dacite and rhyolite (the contact is not well exposed). Dacite dikes intrude the margin of the Gusal pluton and some exposures of the Samirah dacite and rhyolite. Rhyolite of the Samirah formation is chemically equivalent to parts of the Gusal pluton (Table 1) and may represent early volcanic products of the pluton. The granophyric phase of the Gusal pluton may represent the resurgent phase of a pluton that intruded its cogenetic volcanic cover.

The pluton is composed of pink to gray, fine-grained, alkali-feldspar granite granophyre, alkali-feldspar quartz syenite granophyre, and alaskitic alkali-feldspar granite. The granophyre is either alaskitic, or hornblende- and(or) biotite-bearing and commonly microcline and quartz porphyritic. The microcline phenocrysts in some samples are perthitic; in others the potassium feldspar appears optically to be transitional orthoclase-microcline, with grid-iron twinning not well-developed. A sample of the alaskitic alkali-feldspar granite is peralkaline (acmite normative, Table 1).

Salma alkali-feldspar granite

The Salma alkali-feldspar granite (ga) forms the core of the southern lobe of an elongate (50 km long) northeast-trending dumbell-shaped pluton. The pluton consists of two about 15 km X about 20 to about 25 km diameter oval bodies or lobes (long axes trending north-south) of alkali-feldspar granite and syenogranite containing granophyre sheets at either end of an about 7 km wide northeast-southwest trending biotite quartz syenite septum. The southern lobe is exposed in the northwest corner of the Harrat Hutaymah quadrangle. The northeastern part of the pluton crops out in the Rak quadrangle (Kellogg, 1984a). The southwestern part of the pluton may be exposed at a slightly deeper erosional level than the northeast. Alkali-feldspar granite of the southern lobe passes upward into granophyric sheets (sills) of alkali-feldspar quartz syenite granophyre (gap) near the northern quadrangle boundary. A cogenetic ring dike and related volcanic rocks are mapped bordering the northeastern oval body of the pluton by Kellogg (1984a, in press). A marginal zone of alkali-feldspar quartz syenite (qs) is mapped as a separate unit in the southwestern part of the pluton (see below).

The core-phase of the southern lobe of the pluton is composed of light-gray, medium- to coarse-grained, hypidiomorphic granular, biotite alkali-feldspar granite. Some samples are hypersolvus (1-feldspar), with perthitic orthoclase or optically incipient microcline, however, minor primary albite is present in other samples. The quartz shows variable deformation, is unstrained and has good crystal form in some rocks and is slightly to moderately strained or recrystallized into multi-domain grains in others. The alkali-feldspar granite has an average color index of about 3. Biotite and(or) opaque oxides are the most common mafic minerals. An opaque oxide (titanomagnetite) is the only mafic phase in some of the true hypersolvus granite.

The pluton was dated at about 590 Ma by K-Ar on biotite and at about 575 Ma by Rb-Sr (Aldrich and others, 1978; errors not cited). The pluton was also dated by a two-point isochron at 580 ± 5 Ma by Stuckless and others (1984).

Salma alkali-feldspar quartz syenite granophyre

The Salma alkali-feldspar quartz syenite granophyre (gap) forms a series of sills in and above the core phase of the southern lobe of the Salma pluton. The granophyre forms moderately dipping 10-100 m thick sheets in deep exposures in the south that become more gently dipping upward and to the north. Similar granophyre sheets form most of the exposed rock in the northern lobe of the pluton (Kellogg, 1984a, in press). The granophyre sheets are regarded as the upper border-phase of an oval resurgent body (the southern lobe) within the southern part of the Salma pluton, following the model proposed by Kellogg (in press) for the northern lobe of the pluton.

The sheets are composed of light-gray, fine-grained, biotite alkali-feldspar quartz syenite granophyre (fig. 11D) and alkali-feldspar granite granophyre. The granophyre is biotite-bearing and has a color index less than 5. It contains millimeter-scale phenocrysts of subhedral microperthitic orthoclase, subhedral to anhedral quartz, and subhedral to anhedral albite in a granophyric groundmass of intergrown microperthitic orthoclase and quartz and minor albite and quartz.

Salma alkali-feldspar quartz syenite

The Salma alkali-feldspar quartz syenite (qs) forms a marginal zone adjacent to the alkali-feldspar granite of the southern lobe of the Salma pluton. The alkali-feldspar quartz syenite intrudes the Kilab monzogranite and the Laban complex and is intruded by dikes of the Salma alkali-feldspar quartz syenite granophyre. It is probably also intruded by the Salma alkali-feldspar granite, but the contact is obscured by a septum of quartz diorite hornfels derived from the Laban complex on the east and is covered by Quaternary alluvium to the south. The alkali-feldspar quartz syenite is thought to represent an older phase of the pluton, into which resurgent bodies (the north and south lobes) were intruded.

The alkali-feldspar quartz syenite is light gray, medium to fine grained, allotriomorphic granular or locally granophyric. It is composed of microperthitic orthoclase and minor microcline, albite, quartz, biotite, and(or) hornblende, and(or) opaque oxides. Rocks in the unit range in modal composition from alkali-feldspar quartz syenite to alkali-feldspar granite (fig. 11D). Subsolvus and hypersolvus varieties are present. The rock has a color index of 5-10. The hornblende is pleochroic in shades of green to brown or dark blue-green to tan (subcalcic amphibole?); the latter in a subsolvus amphibole alkali-feldspar granite. The biotite is variably altered to chlorite. Trace minerals are typically titanite, allanite, and zircon. The quartz is typically interstitial and is variably strained and(or) recrystallized into multidomain grains.

Shurmah alkali-feldspar granite

The Shurmah alkali-feldspar granite (sgr) forms an oval 8 X 13.5 km subvertical ring dike in the center of the quadrangle. The ring dike intrudes the Kilab monzogranite and the Laban complex. It is offset locally up to about 0.5 km along a series of right-lateral faults and dike-intruded faults, including the Al Ghumrah fault. The ring dike intrudes many dikes of the Shurmah dike swarm, but is intruded by some of the dikes in the swarm. Much of the ring-dike rock is granophyric and likely fed volcanic eruptions, although no related volcanic rock is exposed in the vicinity of the ring dike. The ring dike probably outlines the extent of a shallow alkali-feldspar granite pluton.

The ring dike is composed of pinkish-gray to pink, fine-grained, alaskitic and biotite- or amphibole-bearing alkali-feldspar granite and orthoclase-quartz porphyritic alkali-feldspar granite or rhyolite. The alkali-feldspar granite is allotriomorphic granular, graphic, or granophyric. Orthoclase and quartz phenocrysts in the porphyry are euhedral to subhedral. The orthoclase is pervasively sericitized. The ring dike locally contains sub-calcic amphibole (arfvedsonite?).

Dikes and Quartz veins

Mafic and felsic dikes of various ages intrude the rocks of the quadrangle. Dikes were probably intruded from all of the plutons in the quadrangle. A large number of the dikes (both mafic and felsic) can be shown to be at least as young as the younger plutonic series; therefore, most of the dikes are shown within this series on the correlation chart (plate 1). There was probably a period of mafic dike intrusion related to formation of the Laban dioritic complex, but no attempt was made to differentiate these diabase dikes from later diabase dikes. Dikes of both ages are similar in outcrop appearance, and they are both far too common to attempt discrimination on plate 1. In contrast, most of the felsic dikes are probably cogenetic with the younger plutonic series, especially with the alkali-feldspar granite plutons.

Local intrusive relations between dikes within the Klab batholith indicate that there is no systematic relation in age between post-Kilab mafic and felsic dikes. In addition, both mafic and felsic dikes are intruded by and intrude the Shurmah ring dike. A prominent east-west to northwest-southeast trending swarm of dikes are present in Jabal Shurmah (fig.< 12). The Shurmah dike swarm contains rhyolite, trachyte, and diabase dikes as well as quartz-orthoclase porphyry dikes derived from the Shurmah ring dike. Some of the dikes in the swarm are cut by the ring dike whereas others (including diabase) intrude the ring. These dikes were intruded during a period of north-south tension preceeding and following ring-dike intrusion.

The felsic dikes (-•••-) are red- or pink-weathering rhyolite or alkali-feldspar granophyre, and light-gray or tan- to red-weathering altered dacite to andesite and rare trachyte dikes. Some rhyolite dikes, probably intruded from the Gusal pluton, grade laterally or vertically into, or have border-zones of, vuggy quartz-limonite breccia. Similar quartz-limonite dikes and veins are mineralized where they intrude the Laban dioritic complex at the Samirah gold prospect. The mafic dikes (-×-×-) are light- to dark-gray metabasalt and metadiabase.

In addition to the east-west to northwest-southeast trending Shurmah dike swarm, many dikes have northwesterly trends paralled to or intruding the prominent northwesterly faults in the quadrangle.

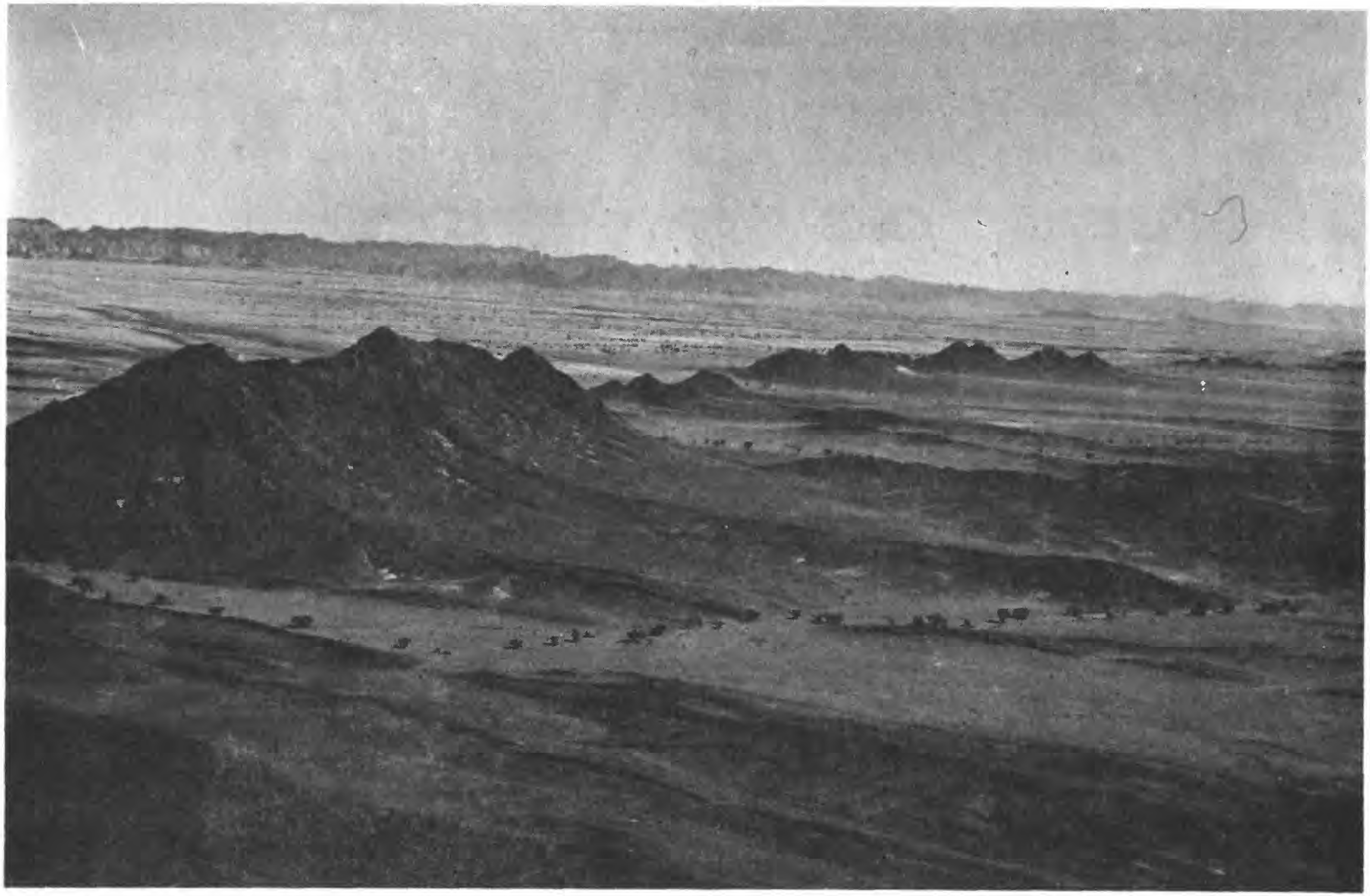


Figure 12.—Oblique aerial photograph showing the Shurmah dike swarm and Shurmah alkali-feldspar granite ring dike. View is to the northwest.

QUATERNARY VOLCANIC AND HYPABYSSAL ROCKS AND QUATERNARY SEDIMENTS

Rocks of the Harrat Hutaymah volcanic field

The Harrat Hutaymah volcanic field discontinuously covers parts of the northern half of the Harrat Hutaymah quadrangle and parts of the southern half of the Rak quadrangle (Kellogg, 1984a). The field was named by Bramkamp and others (1963) for the prominant tuff ring and crater at Harrat Hutaymah (sensu stricto) near the northern boundary of the Harrat Hutaymah quadrangle. The volcanic field covers about 900 km^2 and is one of a series of 13 mostly alkali flood-basalt plateaus (harra in Arabic) that collectively cover about 90,000 km^2 of the the Arabian Peninsula. These volcanic fields were produced between about 30 Ma ago and the present (several historic flows have been recorded in Saudi Arabia) and are related in time and space to Red Sea rifting (Coleman and others, 1983). The Harrat Hutaymah field is farthest from the Red Sea axis (550 km) and a compilation of radiometric age determinations plotted against distance from the axis indicates that volcanism in the field probably began at a later time (circa 1.8 Ma) than at the other Arabian fields (M.E. Gettings, written commun., 1983).

An alkali basalt flow (dated at 1.80 $\pm$ 0.5 Ma - Table 2) conformably overlies a thin deposit of Tertiary or Quaternary sand and gravel, which in turn unconformably overlies Precambrian basement. The flow is also cut by the Harrat Hutaymah tuff-ring crater. Based on the degree of preservation of the vents and the degree of weathering, it is considered likely that most of the volcanics are less than 5 Ma in age or younger. It is possible that all are less than 1.8 Ma (the Quaternary-Tertiary boundary (Palmer, 1983); and accordingly all are arbitrarly symbolized as Quaternary.

In contrast to the other basalt fields of Arabia, the Harrat Hutaymah field contains a large proportion of tephra deposits relative to lava flows. Aa and subordinate pahoehoe alkali olivine basalt flows issued from cinder cones and fissure vents and cover small areas (typically less than 100 km^2) however, 22 tuff rings occur in the field and their tephra deposits comprize a significant proportion of the exposed volcanic rocks. At least 57 relatively small (typically less than 2 km in diameter) cinder and(or) spatter cones are present in the field.

Table 2.—Potassium-argon data for a sample of olivine alkali basalt from Harrat Hutaymah

Sample	Lat.	Long.	%K	$^{40}Ar^{*}$ ($x10^{-10}$ moles/g)	$^{40}Ar^{*}/^{40}Ar_{total}$	Date (Ma)
175363	26°59.5'	42°14.4'	1.230 1.231	0.03847	0.306	1.80+0.05

Constants: 40K = 0.01167 atom %; $\lambda_{\beta} = 4.962 \times 10^{-10} \gamma^{-1}$; $\lambda_{\varepsilon} = 0.5811 \times 10^{-10} \gamma^{-1}$

The vents (cinder and(or) spatter cones, tuff rings, and fissure vents) are aligned along a series of northerly or northeasterly trending lineaments. Kellogg (1984a) plotted vent lineaments for the part of Harrat Hutaymah in the Rak quadrangle. This method was extended over the remainder of the volcanic field and is shown in figure 13. Individual vents or vent clusters are sometimes also elongated in the north-south dimension, as in the fissure lined with cinder cones at Harrat ad Dahamah. Locally, as at Harrat ad Dahamah, eruptions were probably characterized by coalesence of a "wall-of-fire" fissure eruption from a feeder dike.

The northerly or northeasterly vent alignment is anomalous with respect to the fabric of the Precambrian rocks and indicates a significant shift in orientation of the Quaternary stress field relative to the Precambrian and relative to the northwesterly trend of the Red Sea axis. The shift from northwesterly to northerly alignment of vents in the volcanic fields of Saudi Arabia is consistent with a two-stage spreading history in the Red Sea and is related by Coleman and others (1983) to Miocene left-lateral motion on the Dead Sea rift and slight counter-clockwise rotation of the Arabian plate

Olivine alkali basalt

Olivine alkali basalt (Qb) forms aa and subordinate block or pahoehoe flows fed from vents within breached cinder cones or from fissure vents associated with, or overlain by, cinder cone deposits at Harrat ad Dahamah, Jabal abu Rawadif, Jabal Ubdah, Najfat umm Harruj, Harrat Awaied, and Harrat ar Rushayd. Similar basalt is overlain by the tuff-ring deposits of Harrat Hutaymah. The basalt flow at Harrat Hutaymah is dated by the K-Ar whole-rock method at 1.80 ± 0.05 Ma (Table 2). Basalt flows from each of the vent areas, except Nafat Umm Harruj were tested in the

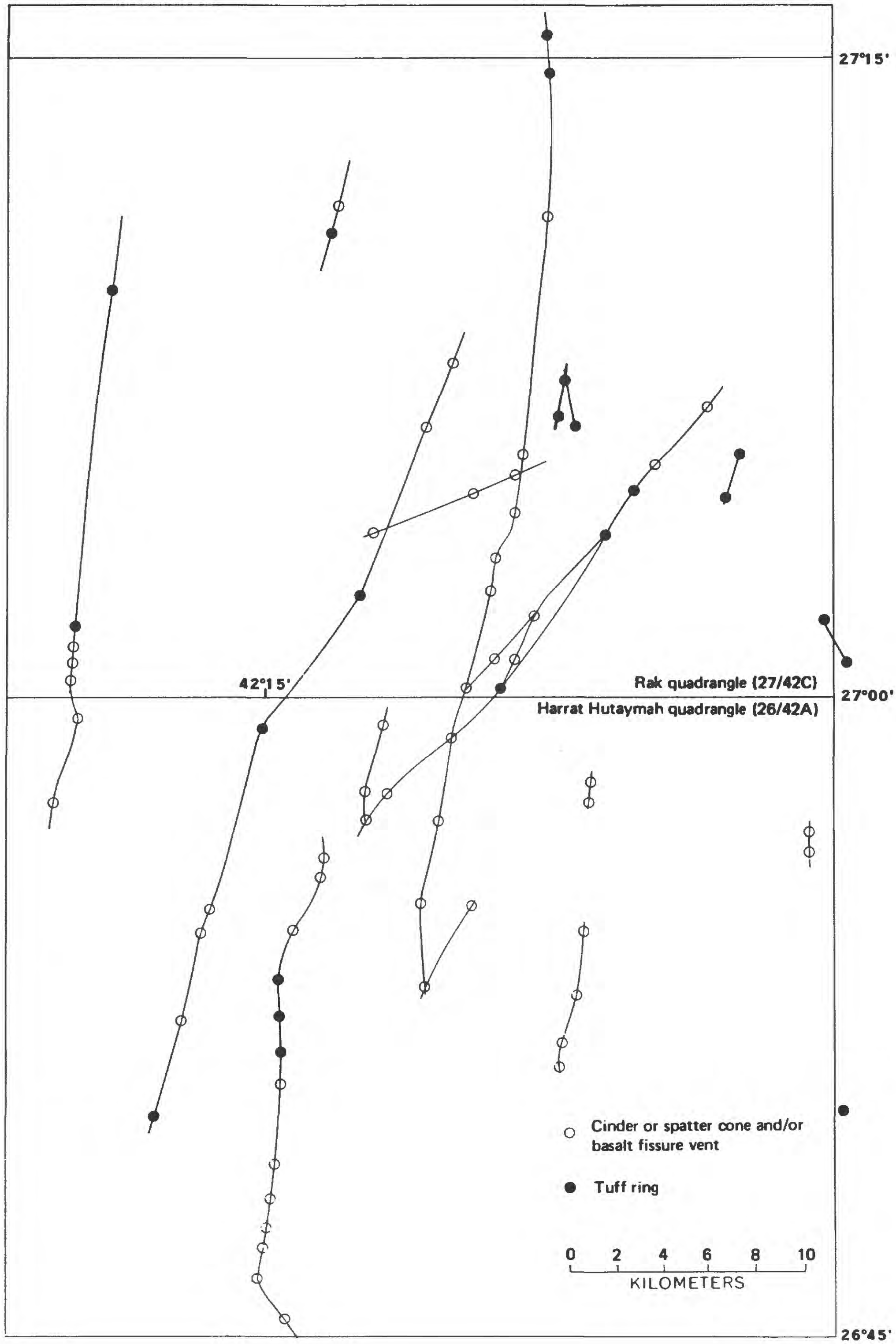


Figure 13.—Distribution of volcanic vents of the Harrat Hutaymah volcanic field. Apparent lineaments are shown with lines. Data from Rak quadrangle (Kellogg, 1984).

field for magnetic polarity using a portable flux-gate magnetometer. Except for rotated blocks (common in many aa or block flows) all are apparently normally magnetized. It is somewhat surprising that no negatively polarized flows were found as the Matuyama reversed polarity epoch exists between 0.7 (end of the Brunhes normal period) and 2.5 Ma. However, a short normal period exists between about 1.7 and about 2.0 Ma (anomaly "2", Palmer, 1983). This may explain the results, but as no detailed sampling or paleomagnetic work was done, this explanation is unsubstantiated.

The basalt is dark gray, nonvesicular or poorly vesicular and ubiquitously olivine-porphyritic. Many flows are also clinopyroxene-porphyritic and some contain spinel phenocrysts. Most contain less than 15% phenocrysts in an intergranular or intersertal groundmass. Microphenocrysts include olivine, clinopyroxene, and plagioclase. Most flows contain sparse peridotite xenoliths and olivine or pyroxene xenocrysts derived from peridotite and, these are more common in tuff-ring deposits and are described in a following section. Orthopyroxene xenocrysts derived from peridotite, and quartz xenocrysts derived from the crustal country rock occur in some flows and are surrounded by fine-grained reaction halos indicating disequilibrium with the silica-undersaturated alkali basalt melt.

The basalt is classified as olivine alkali basalt of the sodic alkaline series of Irvine and Baragar (1971) (figure 14). It is chemically similar to the alkali basalts that characterize the many Tertiary and Quaternary flood basalt fields of Arabia (Table 1 and Coleman and others, 1983). Rare-earth element patterns have large negative slopes, consistent with derivation from a relatively undepleted mantle source.

Basaltic cinder and spatter

Basaltic cinder and spatter (Qc) forms small (typically less than 2 km diameter) constructional cones throughout the Harrat Hutaymah volcanic field. The cones are typically composed of lapilli-sized fragments of oxidized basaltic scoria containing centimeter- to meter-scale alkali basalt basalt bombs and sparse accidental xenoliths of the plutonic country rock (granitic, dioritic, or gabbroic). Peridotite xenoliths are extremely rare in the cinder and spatter cone deposits of the Harrat Hutaymah quadrangle. The apparent absence of peridotite xenoliths in the cinder deposits of the Rak quadrangle was also noted by Kellogg (1984a).

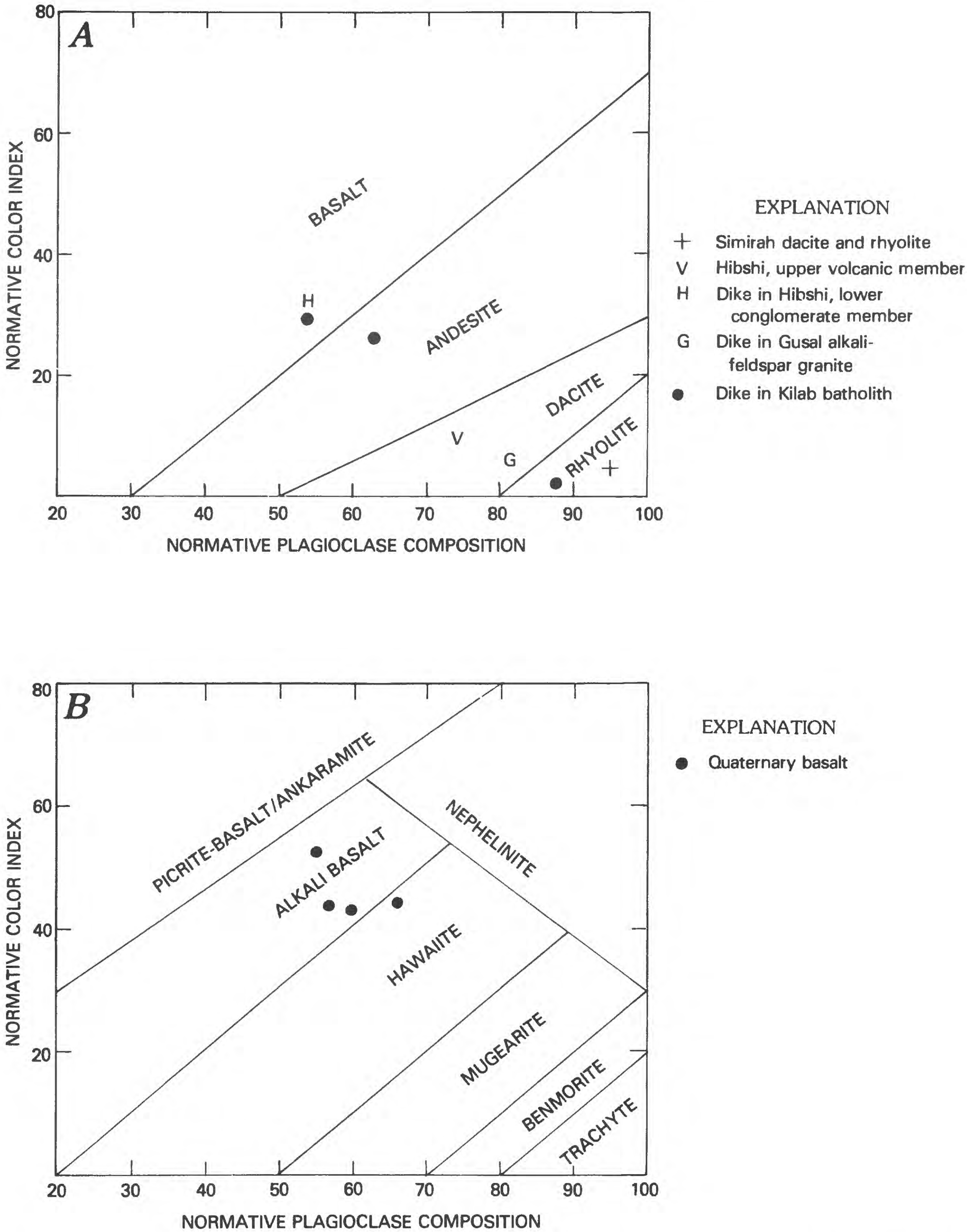


Figure 14.—Volcanic rock classification diagrams for (A) sub-alkaline rocks and (B) sodic alkaline rocks based on the method of Irvine and Baragar (1971).

The cinder deposits have classic cinder cone morphology with central craters and both outward-dipping marginal bedding and inward-dipping crater wall bedding. The ratio of crater diameter to cone diameter and the angle of bedding is variable between individual cones, suggesting various stages of morphologic maturity. The cinder cone at Harrat ad Dahamah is composite, indicating repeated eruption from nearly coaxial vents. Some of the cones are breached by olivine alkali basalt flows that were erupted from the same vents following degassing and consequent cinder-cone formation.

Cinder cones at Harrat ad Dahamah and north of Samrah as Safrah and Jabal Dilham are elongate and form north-trending chains parallel to the regional vent-alignment trends. This supports the argument made above for fissure or "chain of fire" eruptions along north-trending feeder dikes.

Basaltic tuff-ring deposits

Basaltic tuff rings are a common volcanic form in the Harrat Hutaymah volcanic field. The basaltic tuff ring deposits (Qtf) are annular bedded deposits of mostly basaltic tuff and dis-aggregated country rock that surround craters that were excavated into the basement rocks by explosive eruptions. The tuff deposits were produced by fall-back and base surge eruptive and depositional processes. The deposits also contain variable amounts (typically less than 1%, but individual beds are richer) of peridotite and country rock xenoliths.

The deposits are oxidized and weather to various shades of red brown and tan. Commonly, peridotite xenolith-rich beds weather to yellow-brown or tan hues. Lag deposits of xenoliths are common in channels weathered into the outboard flanks of the deposits.

The Harrat Hutaymah tuff ring, located near the northern boundary of the quadrangle may be used as a type example for the other deposits. This tuff ring is only slightly eroded and the central crater is not filled with Quaternary sediments, in contrast to the other tuff rings in the volcanic field. For these reasons it is considered to be one of the youngest of the tuff rings in the field. An apron of radially dipping (10^0-15^0) basaltic tuff surrounds a central pit crater about 1 km in diameter that is floored by Quaternary sand, silt, and evaporite deposits (figures 15 and 16). The pit crater penetrates 275 m into the basement Laban dioritic complex. The crater is probably underlain at depth by a basaltic breccia pipe or diatreme.

Figure 15.—Oblique aerial photograph showing Harrat Hutaymah tuff ring and crater. View is to the north-northwest.

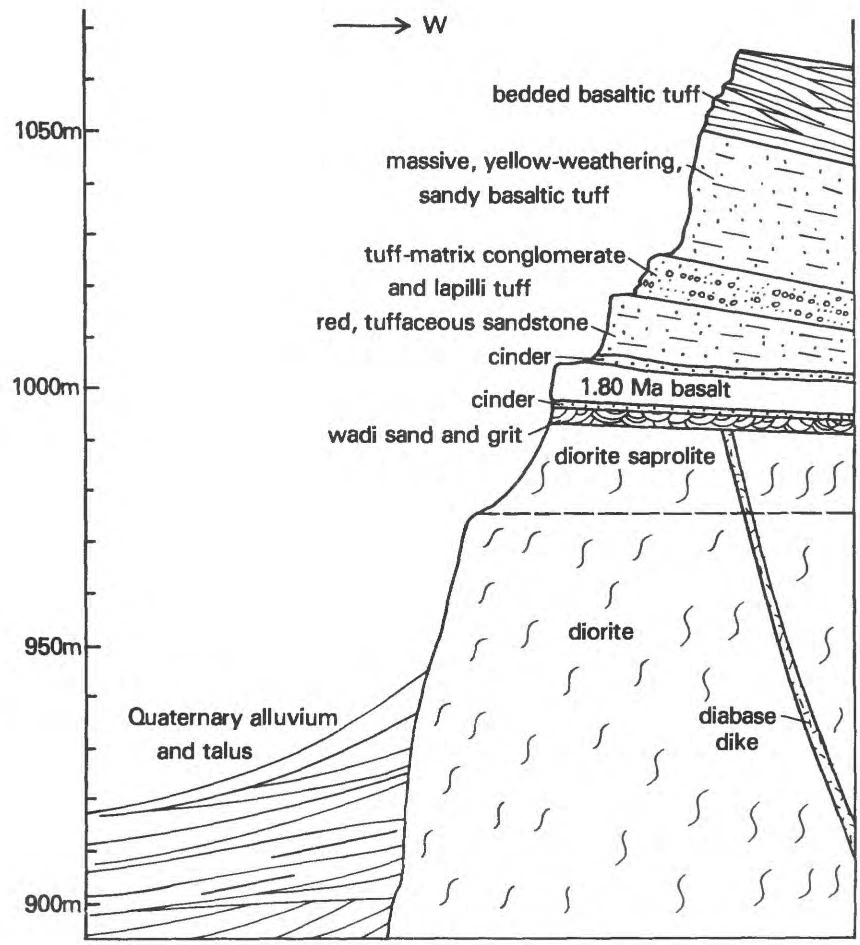


Figure 16.—Diagramatic cross-section of the west wall of the Harrat Hutaymah crater and tuff ring.

Figure 17.—Oblique aerial view showing the west wall of the Harrat Hutaymah crater.

A section measured up the west wall of the crater (figures 16 and 17) shows the following sequence from bottom to top: fresh quartz diorite and dioritic gneiss that grades upward into about 25 about 70 m of quartz diorite saprolite, a 5 m-thick section of partly consolidated gritstone and sandstone, a 4 m thick olivine alkali basalt flow and thin basaltic cinder deposits, and about 225 m of basaltic tuff, The basaltic tuff is compiled as a formation on plate 1; it is divided into 4 members, as described below.

The gritstone and sandstone is channel cross-bedded, moderately sorted and weakly to moderately calcite cemented. It contains angular quartz and red-stained feldspar fragments and sparse fine-grained silicic volcanic or hypabyssal rock fragments, but no basalt or cinder clasts. It is Quaternary to Tetiary alluvium formed by reworking of the Proterozoic basement rocks and deposited on the underlying quartz diorite saprolite. The overlying basalt consists of a basal zone of spatter and cinder about 50 cm thick overlain by an about 4 m thick composite basalt flow. The flow locally has an internal rubble zone that probably marks the contact between two flow lobes or pulses of extrusion. A sample from the upper part of the flow was dated at 1.80 ± 0.05 Ma (Table 2). It is mapped as part of the Quaternary olivine alkali basalt unit where it crops out to the east of the Harrat Hutaymah tuff ring. The basalt flow is overlain by 1-2 meters of agglutinated cinder and spatter that was probably deposited on the flow as is moved away from a nearby vent. This suggests that a cinder and spatter cone may have existed in the immediate area prior to destruction by explosive formation of the tuff ring.

As shown in figure 16, the basal member in the tuff ring section is a punky-weathering, red tuffaceous sandstone with abundant quartz, feldspar, and lithic fragments in a basaltic ash matrix. The ratio of juvenile to exotic fragments is locally as low as 1:3. The tuffaceous sandstone contains sparse (1-2%) floating centimeter-scale basalt clasts and is massive or faintly bedded except for sparse decimeter to meter thick discontinuous interbeds of matrix supported conglomerate with clasts of peridotite and basement dioritic rocks.

The basal sandstone is overlain by interbedded basaltic-tuff matrix conglomerate and coarse-grained basaltic lapilli tuff (basaltic tephra sandstone). This member consists of beds 1-2 m thick of massive tuff separated by intervals 1-5 m thick of well-bedded and cross-bedded conglomerate composed of centimeter- to decimeter-scale blocks of basalt, peridotite, and basement rocks in a sandy basaltic tuff matrix (fig. 18). Bedding is lensoidal, and grading within the conglomerates is commonly inverse (fig. 18), as observed in base surge deposits (Wohletz and Sheridan, 1983).

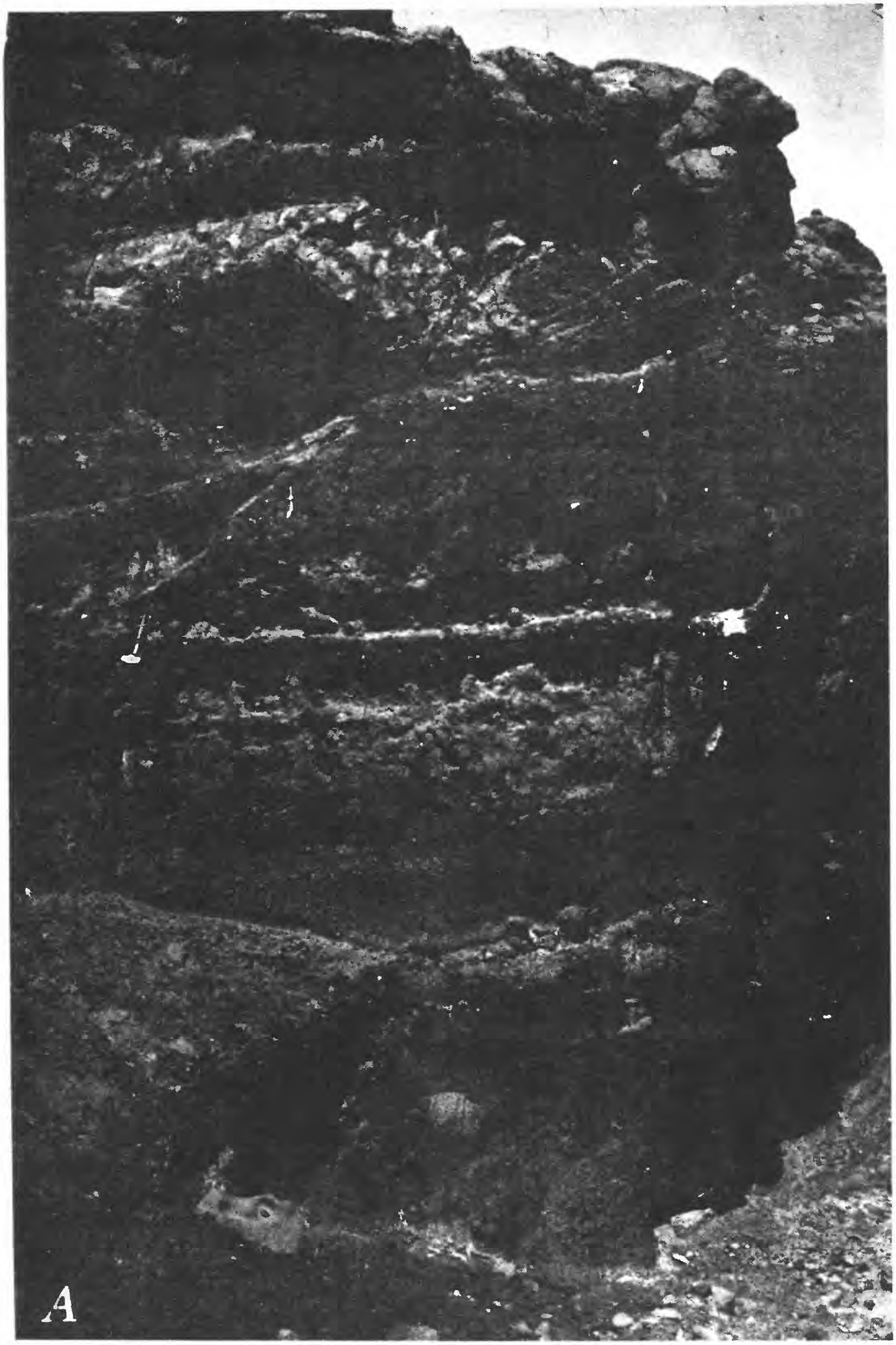


Figure 18.—A, Cross-bedding in basaltic tuff and conglomerate of the Harrat Hutaymah tuff-ring deposit.

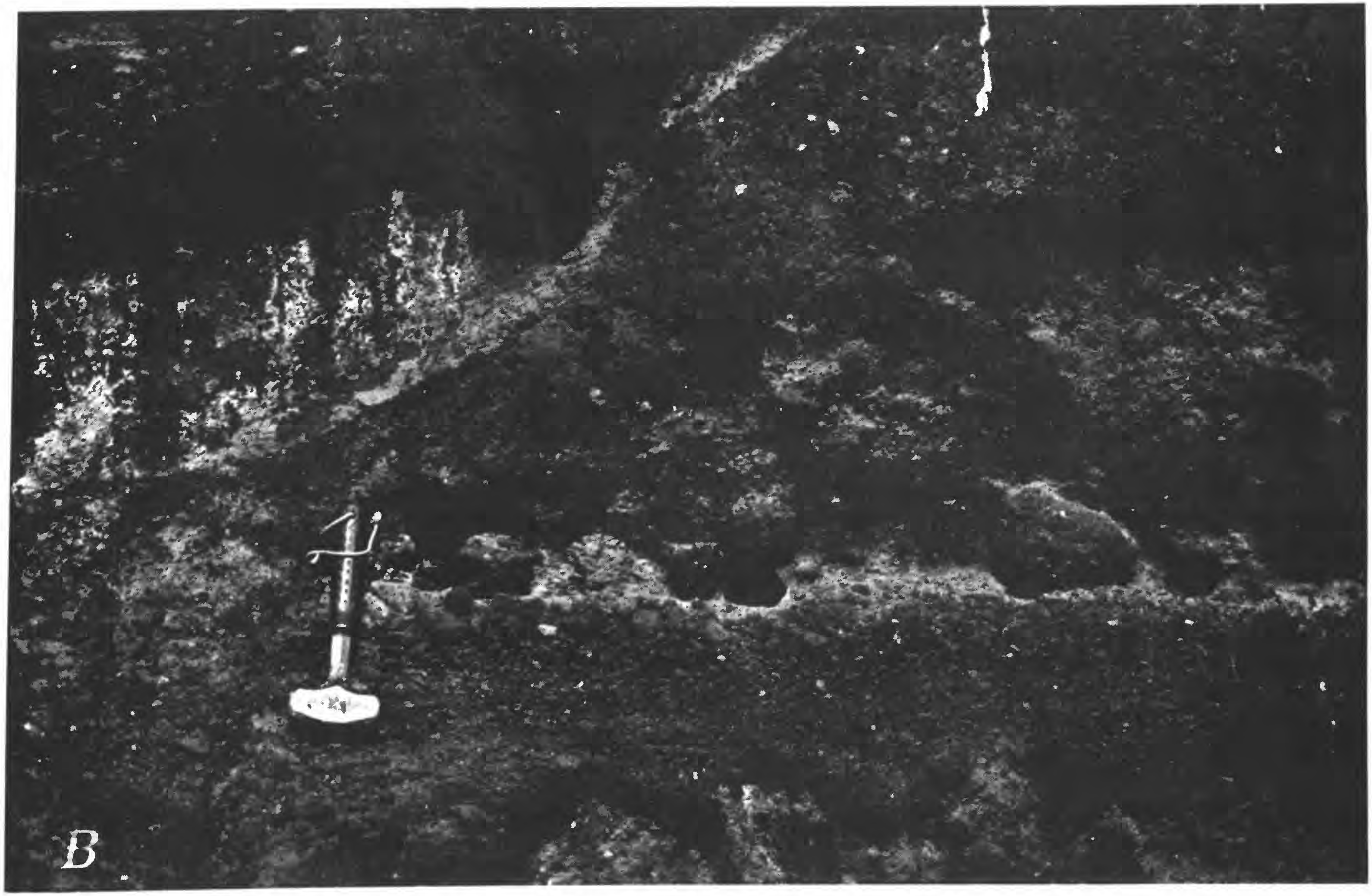


Figure 18.—Continued—B, Inverse graded beds in basaltic tuff and conglomerate of the Harrat Hutaymah tuff-ring deposit.

Overlying the conglomerate member is a thick (about 80 m; fig. 15) interval of light yellow weathering (palagonitic?) cliff-forming sandy basaltic tuff. This member is massive, except for lensoidal decimenter-scale conglomeratic interbeds containing interbeds of basaltic scoria and xenoliths (basalt, dioritic basement rocks, and peridotite) at 1-3 m intervals. The massive tuff also contains 2-10% floating centimeter-scale clasts of mostly basalt or basalt scoria. An interbed was observed to be tightly folded back over itself but without distortion of overlying bedding. The fold closure is in the direction of the crater center. These factors suggest deposition of the member by radially directed blasts with internal turbulent flow.

The uppermost member of the tuff ring deposit at Harrat Hutaymah is maroon, well-bedded basaltic tuff composed of cinder and scoria with abundant and locally clast-supported xenoliths. Most xenoliths are basalt, basalt scoria, or basalt spatter, but a few percent are peridotite or dioritic complex basement rocks. The member is well bedded at decimeter-scale, but poorly sorted. Graded beds are locally common; both normal and inverse grading were observed. Double sets of two decimeter-scale graded beds commonly occur together. Some beds are inverse graded within a coarse-grained or pebbly base and also show inverse size distribution of floating clasts within a finer-grained upper matrix; the net effect is to produce overall normal grading (fig. 19).

Maars (basaltic phreatomagmatic explosion craters and peripheral tephra deposits) and diatremes (breccia pipes, explosion craters and peripheral tephra deposits produced by volatile-charged mantle emissions) have similar surface morphologies and both produce tuff rings (Wohletz and Sheridan, 1983; Dawson, 1980). Maar deposits are typically palagonitic, due to hydrothermal alteration. Diatremes characteristically carry mantle (peridotite) nodules. Diatremes that penetrate thick continental crust (and(or) were derived from relatively fertile mantle) may contain kimberlite (carbonate-rich porphyritic garnet lherzolite), carbonatite, and diamonds.

Several factors favor a diatreme origin for the Harrat Hutaymah tuff rings. The occurrence of mantle nodules in the tuff-ring deposits indicates rapid rise of the melt from the mantle. The presence of mantle nodules in virtually all tuff-ring deposits, but few in cinder and spatter cones suggests a correlation between highly explosive eruptions and abundance of nodules. This is best accounted for by a diatreme origin for the tuff rings. However, sparse nodules also occur in some of the lava flows indicating that non-explosive eruptions also brought nodules to the surface (perhaps entrained in near-surface magma erupted shortly after an explosive eruption). The apparently random distribution of tuff rings along lineaments within the volcanic field (fig. 13) including an example within Jabal Salma, does not favor systematic interaction with ground water (maar origin). The Harrat Hutaymah tuff ring craters penetrate well into basement crystalline rocks; none appear to have been formed by basalt flowing over wet ground.

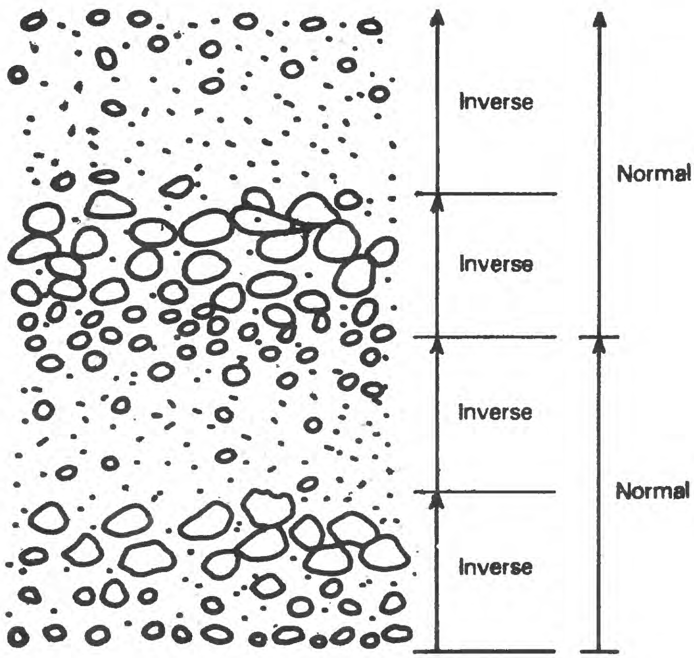


Figure 19.—Sketch showing types of grading observed in the uppermost member of the tuff-ring deposit at Harrat Hutaymah.

Despite evidence for a diatreme origin for the tuff rings, some degree of explosive interaction with groundwater cannot be ruled out, as is argued for the Peridote Mesa tuff ring in Arizona (Worlitz and Sheridan, 1983). The tuffs are altered (as would result in either mechanism of origin). Shallow groundwater is present in the region and probably was also present during eruption of the tuffs.

Xenoliths are present in all of the tuff rings of the Harrat Hutaymah quadrangle. Basement xenoliths of quartz diorite, diorite and quartz diorite gneiss, and gabbro are common and comprise the exposed country rocks for most of the tuff rings. Monzogranite or quartz monzonite xenoliths are also found in some of the deposits. Nodules of peridotite commonly have tectonite fabrics and were probably derived from a depth of about 60 km in the upper mantle (Ghent and others, 1980). Mantle nodules include lherzolite, harzburgite, dunite, clinopyroxene, and websterite. Cognate inclusions are mostly kaersutite bearing gabbro and minor cumulus dunite.

Reworked basaltic tuff

Alluvially reworked basaltic tuff (Qtr) blankets the bedded tuff deposits marginal to each of the tuff rings. The reworked tuff consists of tuffaceous sand and silt deposits in small channels developed in the flanks of the tuff rings and extending as a thin veneer over the surrounding country rocks. Unconsolidated tuffaceous sand and silt that is still in situ forms a disaggregated blanket over the bedded tuff ring deposits. Lag deposits of peridotite and basement xenoliths form on the surface of the tuff ring deposits and are concentrated into the reworked tuff; especially in small channels on the flanks of the tuff rings.

Basaltic dike

A single basalt dike of likely Quaternary age (-■-■-) was observed intruding the Birka gabbro at Jabal Uraynibah. The dike is thought to be Quaternary (or possibly Tertiary) due to the presence of peridotite xenoliths. The dike strikes northeasterly and dips to the southeast.

Eolian deposits

Unconsolidated eolian sheet and dune sand (Qe) forms deposits mostly on the west and southwest flanks of prominent mountains in the eastern half of the quadrangle. These areas are topographic traps on the windward sides of the mountains and indicate that the prevailing winds in the quadrangle during recent time has been from the west or southwest. The largest deposit is along the southwest margin the Hudub pluton at Jabal al Hammr.

Alluvial deposits

Unconsolidated sand, silt, and gravel deposits (Qal) occur along wadis and form extensive pediments throughout the quadrangle. These deposits are variably colored according to the composition of the source rocks. Alluvium near Jabal Salmah is tan to brown; near the Quaternary basaltic rocks it is dark gray; elsewhere it is light gray or light tan.

In addition small, but probably thick accumulations of unconsolidated to partly consolidated silt, sand, and evaporite deposits occur interbedded within the several tuff ring craters. Analysis of the prominent white evaporite pan deposit in the Harrat Hutaymah tuff ring crater (fig. 15) is mostly halite with minor (less than 5%) magnesium, calcium, and potassium salts. These interbedded alluvial and evaporite deposits are probably relatively thin in the Harrat Hutaymah crater, but they nearly fill the craters of the other tuff rings, probably to thicknesses in excess of several hundred meters. The almost-filled crater at the Tabah tuff ring in the Rak quadrangle to the north (Kellogg, 1984a) contains at least 150 m of similar deposits based on water well data and represents a significant local ground water reservoir. The tuff ring at Samrah as Safrah was being drilled for water in 1983.

Talus deposits

Small talus deposits (Qt) are differentiated on plate 1 along the northwest flank of Jibal Hibshi. These deposits consist of unconsolidated, angular, cobble- to boulder-sized blocks of Hibshi formation rocks that form locally steep (near angle-of-repose) blankets over the Hibshi outcrops.

METAMORPHIC GEOLOGY

Regional Metamorphism

All of the Proterozoic layered rocks in the quadrangle and most of the rocks in the older plutonic series have been affected by regional greenschist facies metamorphism. The degree of recrystallization and deformation varies considerably between and within individual units.

The Ghumrah amphibolite is recrystallized to greenschist or amphibolite facies and has undergone polyphase deformation. It was also contact metamorphosed by the host dioritic complex plutonic rocks in which it forms a septum. The Hibshi formation is typically recrystallized to greenschist facies assemblages, although local enclaves of partly preserved igneous mineralogy are present in some of the volcanic rocks. The Hibshi formation is commonly undeformed and delicate primary sedimentary and volcanic structures are preserved. Local zones of shearing or folding and development of fracture cleavage are present in the Hibshi, but these features are mostly associated with faults.

The Laban dioritic complex rocks are typically recrystallized at greenschist to amphibolite facies. This unit is made up of a complex of dioritic, tonolitic, and gabbroic plutons that probably span a considerable age range. Some of the bodies are highly deformed and locally converted to mafic gneiss; others preserve primary igneous textures and partly preserve primary mineral parageneses. Even the least recrystallized rocks in the unit have undergone limited conversion of pyroxene and hornblende to uralite and plagioclase to saussurite.

The Kilab batholith and the younger plutonic rocks are generally not recrystallized and preserve primary igneous mineralogy and textures. In contrast, the hypabyssal rocks are commonly altered. This alteration is probably mostly deuteric; some of the felsic dikes grade from granophyre to vuggy quartz breccia and obviously contained abundant volatiles.

The Samirah dacite is typically less recrystallized than the Hibshi volcanics, which is one reason for not correlating these rocks. It has been somewhat altered and recrystallized by intrusion of granophyre of the Gusal intrusion. The Samirah dacite is only exposed as an erosional remnant along the margin of the Gusal pluton. Pre-erosional extensions of the unit were probably not regionally metamorphosed to greenschist facies.

The thermal anomaly associated with intrusion of the Kilab monzogranite batholith was probably responsible for the regional greenschist metamorphism. The anomaly would have metamorphosed older rocks such as the Laban complex and Ghumrah amphibolite as well as roughly coeval and comagmatic roofrocks to the batholith, such as the Hibshi formation.

Contact Metamorphism

A metamorphic aureole is developed along the contact of the Hudub alkali-feldspar granite pluton with the Hibshi formation at Jabal Aba al Liqah. The lower sandstone and lower conglomerate members of the Hibshi are recrystallized to quartzites within a few meters of the contact.

Contact metamorphism of rocks of the Laban dioritic complex took place along the eastern contact of the Salma pluton. Dioritic rocks in these host-rock septa to the pluton were recrystallized to mafic hornfels.

STRUCTURAL GEOLOGY

The Harrat Hutaymah region has undergone several distinct periods and styles of deformation. An early period of high-temperature deformation is indicated by the development of gneissic fabric and amphibolite facies in the Laban dioritic complex and Ghumrah amphibolite. This deformational period was characterized by formation of steeply-dipping foliations and tight (locally recumbent) folding. The Laban is considerably deformed; linear zones of gneissic banding, tens to hundreds of meters wide, separate zones with relict igneous textures. Foliation attitudes also are regionally variable, but are steep and tend to be north trending. These factors suggest that this early (pre-Hibshi and pre-Kilab) deformation was dominantly compressional, and roughly east-west directed. A similar northerly to northeasterly grain is observed in the older mafic rocks throughout the northeastern Arabian Shield (the Urd and Hulayfah groups of Delfour, 1977; the Birka formation of Quick, 1984; and the Nuff formation of Kellogg 1984a, in press). This grain is deflected adjacent to late (post-orogenic) plutons.

A northwest-trend of faulting, diking, and jointing is superimposed on the older plutonic series and is well developed in the Kilab monzogranite as well as the Hibshi formation and the younger plutonic series. This northwest-trend is most obvious in the large, mostly strike-slip faults that offset the Hibshi formation, rocks of the older plutonic series, the Kilab monzogranite, the Shurmah ring dike, and the Salmah pluton. Thrusting of upper members of the Hibshi formation over lower members southwest of the Al Ghumrah fault is probably the result of near-horizontal compression of the southern plate of Hibshi formation due to differential strike-slip movement along the Al Ghumrah and related faults. Northwest-trending mafic and felsic dikes are common throughout all the rocks in the quadrangle except the younger plutonic series, from which many of the felsic dikes were probably derived.

The northwest-trending structures are probably an expression of the Najd orogeny of Schmidt and others (1979) that was characterized by development of northwest-trending strike-slip faults with major left-lateral offset and was attributed to collision of the partly accreted Arabian neocraton with a continental landmass to the east.

A dense swarm of and more west-trending felsic and subordinate mafic dikes occur at Jabal Shurmah. These dikes are roughly coeval, and partly comagmatic, with the Shurmah ring dike. Less-dense swarms are probably related to other plutons of the the younger plutonic series. The west-trending dikes cut some of the northwest-trending dikes and vice-versa. In addition, the Shurmah ring dike is offset by northwest-trending faults. Therfore, a simple temporal change in the regional stress-field is not indicated.

The intrusion of circular- to oval-outline plutons of the younger plutonic series suggests intrusion into a relatively homogeneous, unstressed medium. The field relations described above suggest that the west-trending dike swarms are the expression of local stress-fields developed above and adjacent to plutons of the younger series, and that these plutons were probably intruded after the major phase of Najd deformation (continental collision). However, northwest faulting and dike intrusion continued episodically, even after intrusion of plutons of the younger series.

The Quaternary tuff rings and basalt vents of Harrat Hutaymah are aligned along north- to northeast-trending lineaments (fig. 13). This is consistent with vent alignments in the younger Tertiary and Quaternary basalt fields in Saudi Arabia and is attributed by Coleman and others (1983) to the stress-field of the Arabian plate during second-stage (approximately 5 Ma to present) seafloor spreading in the Red Sea.

GEOCHEMISTRY AND PETROGENESIS

Major-chemical analyses of representative rocks from the quadrangle are listed in Table 1. This work was done to aid in classification of the various rocks and to constrain models of petrogenesis.

Proterozoic rocks

Chemical characteristics of the various rocks are noted in the Descriptions of Map Units (plate 1) section of this report. Several features bear repetition.

Only two analyses of the Proterozoic volcanic rocks in the quadrangle are available. A moderately fresh plagioclase-porphyritic lava flow from near the contact between the upper volcanic member and middle sandstone member of the Hibshi has an andesitic composition (Table 1, fig. 14). Petrographic examination suggests that most volcanic rocks of the Hibshi formation at the type area range from andesite through dacite. Basalt and rhyolite are locally identified, as at Jabal Aba al Liqah, on the basis of petrography. Additional major- and trace-element geochemistry on the Hibshi is needed to confirm the compositional range indicated by petrography and will aid in identification of individual volcanic centers. The greenschist facies alteration of most Hibshi rocks poses a potential problem with such a study, but careful selection of samples and correlation of major-element with immobile trace-element and mineral chemistry should allow discrimination of primary and secondary compositional trends.

A sample of a potassium feldspar-plagioclase porphyritic rhyolite tuff from the Samirah dacite was analyzed (Table 1, fig. 14). The chemical composition of the tuff is very similar to that of the Gusal alkali-feldspar granite, supporting geologic arguments that the pluton and the Samirah volcanic rocks are related.

The major-element chemistry of the plutonic rocks in the region, and its relation to mineral potential has been summarized by du Bray (1984b, unpub. data). The chemical analyses reported in Table 1 are a subset of the data reviewed by du Bray.

Most of the plutonic rocks in the quadrangle are metaluminous (fig. 20). Exceptions include the slightly peralkaline Shurmah alkali-feldspar granite ring, the locally slightly peralkaline Gusal and Salma alkali-feldspar granite plutons. The Salma pluton also contains local peraluminous zones (du Bray, 1984b, unpub. data), as does the composite Kilab monzogranite batholith. A few samples of the Salma, Gusal, and Kilab plutons plot near the experimentally determined granite-minimum trough in the normative quartz-albite-orthoclase system (du Bray, 1984b, unpub. data, fig. 3) and are probably eutectic melts at relatively low pressures (less than 150 mPa = less than 1.5 kb) corresponding to less than 5 km depth. Other samples of these and the other plutonic rocks are relatively enriched in albite component and probably do not represent eutectic melts.

Quaternary rocks

Four samples of basalt flows from Harrat Hutaymah are listed in Table 1. The basalts are classified as olivine alkali basalt of the sodic alkaline series of Irvine and Baragar (1971) (figure 14). All are nepheline normative and are chemically similar to many of the olivine alkali basalts from the other Saudi Arabian Harrat basalt fields reported by Coleman and others (1983).

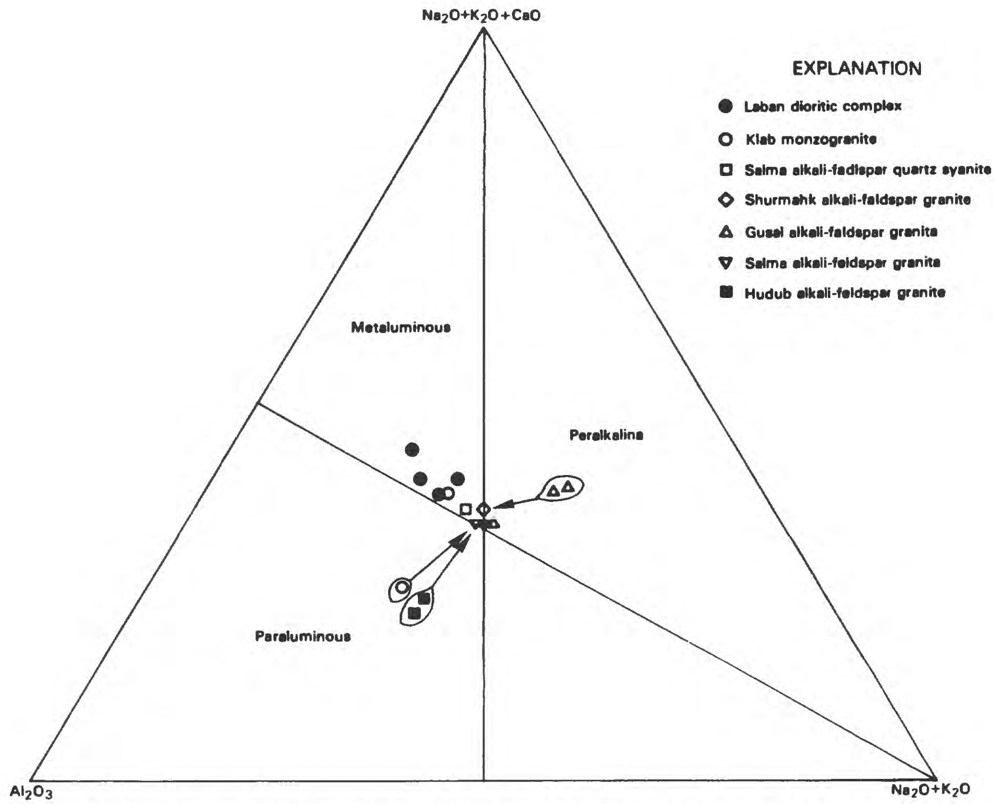


Figure 20.—Na_2O+K_2O+CaO - Al_2O_3 - Na_2O+K_2O ternary diagram showing the distribution of plutonic rocks from the Harrat Hutaymah quadrangle and the fields for peralkaline, peraluminous, and metaluminous rocks. Overlapping points shown with arrows.

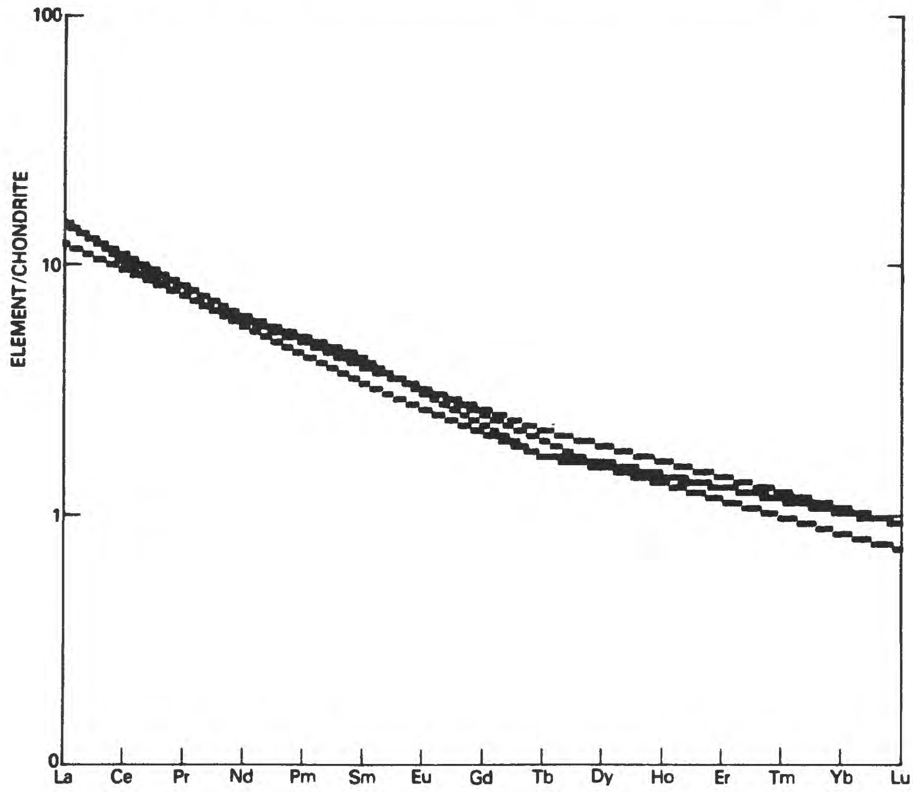


Figure 21.—Chondrite-normalized rare-earth element diagram showing patterns for olivine alkali basalts from the Harrat Hutaymah volcanic field

Several lines of evidence (reviewed by Coleman and others, 1983) indicate direct mantle derivation for the Saudi Arabian Harrat basalts: $^{87}Sr/^{86}Sr$ ratios for a small suite of the Harrat basalts are in the range 0.7030-0.7044; many of the Harrat basalts and tephra deposits contain peridotite nodules that record mantle (about 190 mPa = 19 kb) equilibration pressures; and the composition of alkali basalts and picrites from the Harrats are consistent with experimentally derived compositions for upper mantle partial melts.

Rare-earth element (REE) abundances for the basalts are listed in Table 3 and chondrite-normalized rare-earth patterns are shown in figure 21. The patterns are all light-REE enriched and form a tight linear band between 1 and 10 X chondrite. This suggests derivation from a relatively undepleted mantle source (as contrasted to light-REE-depleted oceanic mantle). Nodule suites from the basalts and tuff ring deposits include lherzolite as well as more depleted peridotites (harzburgite and dunite).

Table 3.—Rare-earth element abundances (ppm) in rocks of the Harrat Hutaymah quadrangle

Sample	197061	197085	197089	197099	197124	197151	197187
Symbol	Qb	Qb	Qb	Qb	mg(d)	mg(d)	hcl(d)
Lat.	26 09.2'	26 43.1'	26 52.3'	26 49.0'	26 36.3'	26 33.1'	26 35.6'
Long.	42 11.0'	42 15.9'	42 12.9'	42 15.1'	42 09.3'	42 06.8'	42 20.3'
La	48	40	48	49	32	13	69
Ce	84	77	86	79	69	30	147
Nd	35	34	35	32	35	18	82
Sm	7.2	7.4	7.8	6.3	7.8	4.7	18.9
Eu	2.2	2.2	2.1	1.8	2.0	1.4	5.3
Tb	0.9	1.0	0.8	0.8	0.8	0.7	2.1
Dy	4.7	5.8	5.0	4.8	3.0	3.7	12
Yb	2.2	2.2	2.1	1.7	1.0	1.6	5.1
Lu	0.32	0.32	0.31	0.25	0.14	0.25	0.73

GEOLOGIC HISTORY

The tonalite, diorite, and gabbro units comprise a mafic plutonic suite that forms the basement of the eastern half of the quadrangle. These are the oldest plutonic rocks exposed in the quadrangle. A sample from the quartz diorite just south of the quadrangle boundary was dated by the U-Pb zircon method at 650 Ma ± 5 Ma. In the generally accepted island-arc plate tectonic model for the developement of the Arabian Shield, this plutonic suite may represent the mafic basement to an immature arc complex.

The mafic plutonic suite was intruded by a monzogranite batholith that underlies most of the western half of the Harrat Hutaymah quadrangle and large areas of the adjacent quadrangles. The monzogranite is typically massive, indicating emplacement after deformation of the mafic suite. The monzogranite does not come into contact with the Hibshi formation. There are few monzogranite cobbles in the Hibshi conglomerates (especially the lower conglomerate member) suggesting that the monzogranite batholith is either younger or roughly coeval with the Hibshi.

Because of facies changes in the Hibshi formation to the northeast and southwest, the eruptive center for the Hibshi welded tuffs was either northwest or southeast of Jibal Hibshi. The occurrence of quartz diorite saprolite in a well in Wadi Hibshi and quartz monzodiorite and tonalite underlying the upper sandstone member of the Hibshi near Al Uzaym suggests that the Hibshi volcanic members pinch out abruptly and the basement contact locally rises to the east and southeast of the Hibshi strike ridge. This favors a source area for the Hibshi tuffs to the northwest.

Monzogranite that may be part of the batholith in the Qufar quadrangle (Kellogg, 1983) was dated by the U-Pb zircon method at 651 ± 5 Ma; dacite from the upper volcanic member of the Hibshi is dated at 632 ± 5 Ma (J. C. Cole and C. E. Hedge, written commun., 1984). Numerous andesite to rhyolite dikes intrude the monzogranite batholith but do not intrude the Hibshi and could represent feeders for some of the Hibshi volcanics. However, caldera-collapse structures or dacite-composition ring dikes of appropriate age, as might be expected to intrude the basement to the Hibshi welded-tuffs have not yet been described in the monzogranite. The caldera-root zones of the Salma, Gusal, Shurmah, and other "post-tectonic" plutons of the northeastern Shield are generally thought to be too young to have produced Hibshi volcanics.

The paucity of monzogranite cobbles in the Hibshi conglomerates is difficult to reconcile with a pre-Hibshi age for the batholith, unless it was largely covered by a carapace of tonalite and diorite roof rocks during Hibshi deposition. However, the batholith is composite, and may range considerably in age, even overlapping in age with the Hibshi. Following this reasoning, the batholith and its slightly older to coeval mafic

Laban complex host rocks could represent the core of a mountain range marginal to the Hibshi-Murdama depositional basin to the southeast. Cupolas developed over younger plutons within the batholith could have given rise to calderas and Hibshi ash-flow tuff eruptions. Additional chemical and geochronological data is needed on the Kilab batholith and Hibshi formation to test this hypothesis.

It is perhaps premature to define a plate tectonic model for the region. Available data suggest that in late Proterozoic time a northeast-trending volcanic highland bordered on the southeast by a basin floored with ocean crust existed in the Hutaymah region. Stoeser and others (1984) argue that the accretion of island arcs to form the Shield was completed by about 640 Ma by continental collision along the Nabitah mobile belt. The Hail area is thought to be underlain by the Afif type II lead isotopic province and by the Nabitah mobile belt by Stoeser and others (1984). Collision of an accreted arc terrane with the Afif province and interaction of subduction-derived melts with Afif crust may have generated the monzogranite batholith and the Hibshi volcanic rocks.

After deposition of the Hibshi formation, the oval Uzaym granodiorite pluton, the Ubdah monzogranite pluton, the Nimriah, and probably the Shuwayman monzogranite plutons were emplaced. The Uzaym granodiorite and Hudub monzogranite plutons clearly intrude the Hibshi. Intrusion of an andesite sill into the Hibshi section may have occurred at about this time. The Nimriah pluton is dated at 621 $\pm$ 5 Ma by the U-Pb zircon method (J. C. Cole and C. E. Hedge, written commun., 1984).

The final period of plutonism was characterized by intrusion of highly evolved potassic granitic magmas to form the Gusal syenogranite, the Salma alkali-feldspar granite to quartz syenite and granophyre, and the Shurmah alkali-feldspar granite to granophyre ring complex. These rocks are relatively undeformed except for development of prominent jointing and relatively small-scale offset along northwest- and northeast-trending faults.

The Shurmah ring complex may be slightly younger than the other potassic granite plutons because it represents a shallower level of exposure and forms a swarm of granophyre dikes that both pre- and post-date prominent northwest-trending faults and fault-parallel diabase dikes. Each of these plutons was emplaced at a relatively shallow level in the crust as indicated by the presence of granophyre sheets and dikes, and by the composition of apparent eutectic melts. The Shurmah ring dike may represent the subvolcanic level of a rhyolitic caldera complex. The east-west dike swarm through Jabal Shurmah consists mostly of rhyolite and granophyre dikes. Some of these dikes are fed by the ring granophyre, some cut the ring, and others intrude the ring. The dike swarm is therefore considered to be roughly coeval with the ring granophyre, and may represent the subvolcanic expression of a caldera axial graben system.

Some rhyolite dikes fed by these plutons are cored by limonitic vuggy-quartz breccia zones and extend laterally as quartz-breccia dikes. A quartz breccia dike that apparently emanates from the Gusal pluton is on trend with the ancient Samirah gold mines. Late-stage hydrothermal solutions related to the potassic plutons probably produced the quartz-breccia dikes, and in the case of the Gusal pluton, may have deposited gold and related metals where it intruded and reacted with the older diorite unit rocks.

Faulting along northwest trends and injection of fault-parallel diabase dikes began before intrusion of the potassic suite of plutonic and hypabyssal rocks. However, faulting and dike injection continued during and after emplacement as well. Northwest-trending left-lateral strike-slip faults offset the mafic plutonic suite and the Hibshi strike ridge approximately 5 km near Al Birka and near the southern quadrangle boundary, respectively. Compression in the block between the two northwest-trending strike-slip faults at either end of Jibal Hibshi was taken up by thrusting within the Hibshi section.

The Precambrian rocks were covered by Paleozoic sedimentary rocks that were stripped away during formation of the Hail arch and during erosion related to uplift accompanying the opening of the Red Sea. This erosion produced a nearly flat peneplane surface except for protrusions of resistant rock at Jabal Salmah and Jibal Hibshi.

About 2 Ma ago basaltic volcanism began in the quadrangle. A basalt flow that underlies basaltic tuff and is penetrated by the explosion crater at the Harrat Hutaymah tuff ring was dated by the K-Ar whole-rock method at 1.80 + 0.05 Ma. Vents formed along a series of north-trending lineaments. Various stages of erosion of the tuff rings and cinder cones are observed in the quadrangle and in the Rak quadrangle (Kellogg, 1984a) to the north. The Tabah tuff ring lies just to the north of the quadrangle boundary along the westernmost lineament. It is nearly filled with sediment and represents an older morphologic stage in the erosion of the tuff rings. In contrast, the Harrat Hutaymah tuff ring is only slightly eroded and penetrates about 100 m into basement diorite. The Harrat Hutaymah basalt field is the easternmost in a series of mostly basalt fields that cover an area of about 90,000 km^2 of the Arabian Shield. Eruption of alkali-olivine basalt is related to Red Sea rifting (Coleman and others, 1983). The distribution of radiometric ages for these Tertiary and Quaternary volcanic rocks relative to the spreading axis of the Red Sea shows a decrease in maximum ages with distance from the axis (M.E. Gettings, written commun., 1983). In this respect, the Harrat Hutaymah volcanic field is the youngest in Arabia. This may be related to the progressive underflow of the oceanic mantle below the Arabian plate (M. E. Gettings, oral commun., 1983).

ECONOMIC GEOLOGY

Mineral localities described in this report are identified by a unique five-diget number and are recorded in the Mineral Occurrence Documentation System (MODS) data bank at the office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah, Saudi Arabia.

The only MODS action generated by this study was updating entry 1264 (Samirah ancient gold workings).

Gold occurrences

The Samirah ancient workings (MODS 1264) consist of shallow (partly filled) trenches, tailings, and slag in a about 1 km^2 area of low relief about 6 km north of Samirah village. The workings were developed along quartz veins in deformed Laban complex tonalite and diorite. Mytton (1970) reports that the workings were inferred to be along two 055^{O}-trending quartz veins, based on the orientation of the ancient trenches. The veins are not easily distinguished at the surface because they are covered by tailings and slag. However, a west-northwesterly trending limonite-quartz breccia was observed about 500 m north of the principal workings and quartz-limonite vein rock is common in the ancient mine dumps.

Assay results for grab samples of quartz-vein rock from the ancient mine dumps reported by Mytton (1970) show 0.24 oz./ton (about 7 ppm) Au, negligable Ag, 0.1% Cu, 0.03% Zn and 0.1% Pb. Mytton also reported that the quartz-vein rock contains hematite, limonite, malachite, azurite, and possibly some chalcocite, and that one sample contained a trace of free gold. Additional assay results for samples of quartz-vein rock, limonite-rich ironstone or gossan, and slag from the dumps obtained during this study are reported in Table 4. The richest sample was a malachite-bearing gossan that contains about 5 ppm Au, 18 ppm Ag, 5% Cu, 1300 ppm Pb, and 600 ppm Zn. A sample collected from the mine site in 1982 yielded 28 ppm Au (P.L. Williams, written commun., 1984).

Similar hematite- and limonite-rich vuggy quartz veins or dikes occur in the western part of the quadrangle near the Gusal pluton and northwest of Uglat bin Kilab. These quartz veins occur within, or as lateral or vertical equivalents of, granophyric or rhyolitic dikes related to plutons of the younger plutonic series. Samples of these veins and dikes were also assayed, but proved barren. However, it is suggested that these veins may correlate with those at the Samirah ancient mine, and that a host-rock control on metallogenesis may exist. The interaction of the vein fluids with a mafic (Laban complex) host may have been necessary for metallic mineralization.

Table 4.—Metallic and pathfinder element abundances in quartz breccia and gossan from the Harrat Hutaymah quadrangle

Sample	197112	197112b	197112c	197112d	197113	197115	197173	197295
Lat.	26°32.7'	26°32.7'	26°32.7'	26°32.7'	26°33.1'	26°33.6'	26°33.6'	26°46.9'
Long	42°09.5'	42°09.5'	42°09.5'	42°09.5'	42°09.6'	42°10.4'	42°03.5'	42°02.4'
Au*	3.25	2.17	5.23	0.59	<0.05	<0.05	<0.05	<0.05
Ag*	2.0	2.8	17.5	1.3	1.3	1.3	<0.5	1.3
Cu*	480	1000	50000	700	46	270	11	47
Pb*	<10	15	1300	35	20	20	10	140
Zn*	15	120	600	130	30	75	15	150
As	-	-	5000	-	-	-	-	-
B	15	10	15	30	-	20	15	-
Ba	200	200	300	1000	300	1500	300	>5000
Be	-	-	-	-	-	-	-	2
Bi	-	-	-	-	-	-	-	-
Cd	-	-	-	-	-	-	-	-
Co	-	50	300	20	10	15	-	20
Cr	300	500	200	500	300	300	300	150
Mo	20	-	-	500	50	-	-	100
Nb	-	-	-	-	-	-	-	-
Ni	-	300	500	200	30	100	-	-
Sc	-	-	-	-	10	5	-	-
V	2000	700	200	500	100	200	30	50
Fe%	>20	>20	>20	20	1.5	3	1.5	10
Ti%	.5	.03	.05	.1	.15	.15	.15	.1
Mn	100	200	1000	150	500	1500	300	50

All values in ppm, except Fe and Ti. *Analysis by atomic absorption; all others by semi-quantitative spectrographic methods. Dash indicates at or below detection limit.

Tin-tungsten and rare-metal potential areas

The presence of tin-tungsten mineralization in the peraluminous Fawwarah alkali-feldspar granite and its association with the Silsilah alkali feldspar granite in the young (587 ± 8 Ma) root-zone of a caldera (du Bray, 1984b, unpub. data) indicates that several of the plutons of the younger plutonic series are potential targets for exploration. The Shurmah ring dike, and the Gusal and Salma plutons probably each represent root-zones of young calderas. Each of these plutons contains peralkaline alkali-feldspar granite or granophyre, and the Salma pluton also contains peraluminous rocks. The peralkaline granitic rocks are also potential mineralization targets for rare-earth elements, Zr, Nb, Ta, U, Th, Sn, and Y (du Bray, 1984b, unpub. data). To date, none of the plutons of the younger plutonic series have been carefully prospected for these types of mineralization.

Aggregate and pozzolan deposits

The cinder and basaltic tuff deposits of Harrat Hutaymah volcanic field are an obvious aggregate resource for local construction projects. Basaltic cinder is currently being exploited from Harrat ar Rushayd for road aggregate used in construction of the Saudi Arabian highway that passes nearby.

Samples of agglomerate and cinder from several sites in the volcanic field (MODS 2770, 3492, 3488, 2775) were tested for use as lightweight aggregate or pozzolan (Laurent and Al Nakhebi, 1979). Ten vent deposits tested by Laurent and Al Nakhebi showed pozzolanic properties (reacts with calcium hydroxide at room temperature to form cement or mortar and can be combined with Portland cement to extend the volume and enhance the chemical resistance, while reducing the permiability of the cement). The most favorable deposit was considered to be at Jabal al Thiniyah, about 6 km north of the central quadrangle boundary.

Positive pozzolinic results were also obtained for some of the deposits in the Harrat Hutaymah quadrangle, however, these were considered less favorable, and were studied in less detail because of the greater distance to the paved Hail-Buraydah highway. With the completion of the new paved Highway between Samirah and Hail many of the southern deposits are now easily accessible.

Water resources

An unusual type of groundwater reservoir exists in the Harrat Hutaymah quadrangle. The tuff rings of the Harrat Hutaymah field formed by explosive eruptions that excavated cylindrical craters into the relatively impermeable crystalline basement rocks. These craters locally penetrate at least 275 m into the basement rocks and are probably underlain by a permeable basaltic breccia pipe that extends to considerably greater depth. Most of the tuff-ring craters are filled with Quaternary alluvium and evaporite deposits. The village of Tabah is located in a filled tuff-ring crater just north of the quadrangle boundary. Wells drilled into the crater fill produce water for the village and for irrigation of farms within the tuff ring. In the past two years, accelerated ground-water withdrawal has apparently caused subsidence and ground cracking within the crater-fill deposits.

During mapping of the quadrangle in 1983, drilling for water was beginning in the Samrah as Safrah tuff ring crater. Similar deep cylindrical groundwater reservoirs probably exist in the craters of most of the filled tuff rings in the volcanic field.

Diatremes and diamonds?

Interest has recently been expressed in prospecting for kimberlitic mantle diatremes in Saudi Arabia (Legg, 1983). The Harrat Hutaymah tuff rings are morphologically similar to the surficial expressions of kimberlite pipes (see Dawson, 1980, fig. 10). Indeed, the tuff rings are thought to have been produced by mantle diatremes (see discussion in the geologic history section of this report). However, the apparent lack of kimberlite (alkalic garnet peridotite) and the evidence for relatively shallow (circa 60 km) mantle origin for the alkali basalts, including the presence of spinel rather than garnet in the peridotite nodule suites, suggests that the diatremes were probably not tapping a deep enough source to be diamondiferous. This is also consistent with the relatively shallow crustal thickness of about 40 km indicated for most of the Arabian Shield by seismic refraction studies (Healey and others, 1982).

The Hutaymah diatremes are apparently tapping a more fertile (lherzolitic) mantle source than that indicated by peridotite nodule suites in the other Harrat basalt fields of Saudi Arabia. However, distribution of Pb-isotopic types in the Arabian Shield indicates that the Harrat Hutaymah lies near the contact between a region of type I (oceanic) Pb and type II (continental) Pb (Stoeser and others, 1984). Kimberlite formation would probably be more likely in the region of type II Pb to the east and southeast (the Afif terrane). However, no alkali olivine basalt fields or diatremes are known in that region.

DATA STORAGE

Field and laboratory data, including field notes, petrographic data and other work materials, are archived as Data file USGS-OF-04-25 at the Jiddah office of the U.S. Geological Survey.

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