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Reconnaissance geology of the Ghazzalah quadrangle, sheet 26/41 A, Kingdom of Saudi Arabia

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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ABSTRACT

The Ghazzalah quadrangle is located in the northern Precambrian shield of Saudi Arabia between lat 26°30' and 27°00' N. and long 41°00' and 41°30' E. The area is underlain by two lithologically distinct, Precambrian volcano-sedimentary units and a wide range of dioritoid and granitoid plutonic intrusive rocks. The only Phanerozoic rocks consist of one outcrop of Tertiary(?) basalt and widespread but thin deposits of Quaternary detritus.

The Banana greenstone, the oldest rock in the quadrangle, consists of intermediate volcanic and subvolcanic rocks and minor interbedded marble, which have been metamorphosed to greenschist-facies assemblages. Volcanic rocks mainly range in composition from basalt to andesite, and subvolcanic rocks consist of diorite and diabase.

The Banana greenstone is unconformably overlain by silicic volcanic rocks and minor arkosic sandstone and breccia of the Hadn formation. Preservation of delicate volcanic textures suggests that the rocks have been only incipiently metamorphosed. Unpublished rubidium/strontium isotopic data for the Hadn formation suggest an age of 620 to 610 Ma.

Intrusive rocks are separable according to their ages relative to the Hadn formation. Those that are unconformably overlain by the Hadn formation consist of hornblende quartz diorite and gabbro, which may be consanguineous with the Banana greenstone, and younger tonalite, biotite-hornblende granodiorite, syenogranite, and monzogranite. Plutons of monzogranite, alkali-feldspar granite, syenogranite, peralkaline granite, and hypabyssal intrusions of granophyre were probably emplaced during a period coincident with and (or) following Hadn volcanism. Uranium-lead and rubidium/strontium isotopic data for two plutons in the adjacent Al Qasr quadrangle suggest that plutonic activity persisted in the region until about 580 to 570 Ma.

Faulting appears to postdate all of the plutonic rocks. The dominant faults belong to a northeast-trending system of right-lateral shears; a subordinant system consists of mainly north- to northwest-trending faults.

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The peralkaline-granite plutons underlying Jibal Ba'gham and Jibal ar Rumman have the most economic potential. Wadi samples from these areas show anomalous concentrations of tin, lead, niobium, and yttrium. Localized, intense radiometric anomalies in the Ba'gham intrusive complex are associated with high concentrations of thorium, uranium, and rare-earth elements.

INTRODUCTION

Geographic setting

The Ghazzalah quadrangle, sheet 26/41 A, occupies 2760 km^2 between lat 26°30' and 27°00' N. and long 41°00' and 41°30' E. in north-central Saudi Arabia (fig. 1). Ha'il, the nearest city with an airport, is located about 100 km northeast of the center of the quadrangle. The principal access to the study area is by a major highway that connects Ha'il and Al Madinah. From the highway, it is possible to drive within 1 km of most outcrops via secondary paved roads, dirt roads, and desert tracks.

The topography is subdued; two-thirds of the area is underlain by pediments, peneplains, and alluvial fans and plains that have an average altitude of approximately 1000 to 1100 m. The most rugged terrain is along the eastern and northern margins of the quadrangle, where young granites and silicic-volcanic rocks crop out; Jibal ar Rumman has a maximum altitude of 1350 m, and Jibal Ba'gham and Jabal Ma'a have maximum altitudes of about 1265 m. Elsewhere, most of the inselbergs and ranges of hills are less than 100 m higher than the surrounding plains. The drainage is dominated by Wadi Sha'bah, which crosses the center of the quadrangle toward the southeast. All streams are intermittent and belong to the Wadi ar Rimah drainage system.

Most of the permanent settlements in the quadrangle are located near Jibal ar Rumman or Jibal Ba'gham, where ground water is available for agriculture.

Previous investigations

The only published geologic map that includes the Ghazzalah area is the 1:500,000-scale Northeastern Hijaz quadrangle by Brown and others (1963), which is based on field investigations conducted prior to 1963. However, a recent increase in geologic investigation in the northern shield has resulted in a number of studies that are relevant to the geology of the Ghazzalah area (fig. 1). The adjacent quadrangles of Al Qasr (27/41 C) to the north, Qufar (27/41 D) to the northeast, and Al Awshaziyah (26/41 B) to the east

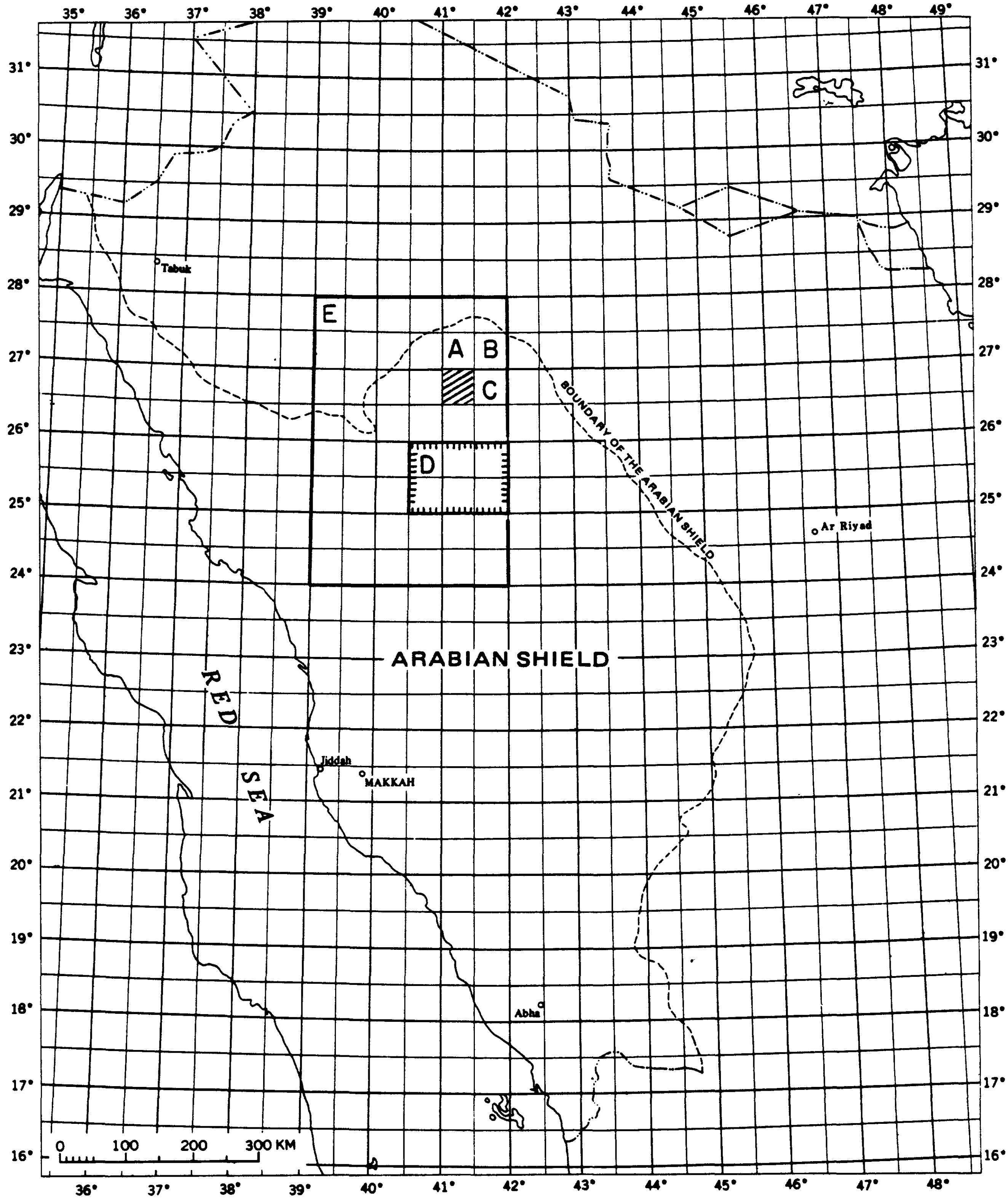

Figure 1.--Index map of western Saudi Arabia showing location of the Ghazzalah quadrangle (shaded) and other quadrangles referred to in this report: A, Al Qasr (Stoeser, unpublished data); B, Qufar (Kellogg, unpubl data); C, Al Awshaziyah (Leo, unpublished data); D, Nuqrah (Delfour, 1977); E, Northeastern Hijaz (Brown and others, 1963).

have been mapped at a scale of 1:100,000 by D. B. Stoeser, K. S. Kellogg, and G. W. Leo, respectively, of the U.S. Geological Survey. Chevremont (1982) has presented a geologic reconnaissance and mineral evaluation of the volcanic and mafic plutonic rocks in the area between Ha'il and Ghazzalah. Delfour (1977) has published a 1:250,000-scale geologic map of the Nuqrah quadrangle 50 km to the south.

Present investigation

The Ghazzalah quadrangle was mapped by helicopter and surface vehicle during 34 days of field work from March through June 1982. A total of about 10 days was spent performing a geologic reconnaissance of the adjacent Al Qasr, Qufar, and Al Awshaziyah quadrangles during March, September, and October 1982. An additional 10 days were spent performing reconnaissance geologic mapping of quadrangles 26/41 C and 26/40 B during November 1982. The geology in the Ghazzalah quadrangle is shown on plate 1.

The work on which this report is based was performed in accordance with a work agreement between the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia and the U.S. Geological Survey (USGS) for systematic mapping of 1:100,000-scale quadrangles in western Saudi Arabia.

In this report, rocks are classified according to guidelines of the International Union of Geological Sciences (Streckeisen, 1976, 1979) and Fisher (1961). Units were named for the most abundant lithology in cases where the rock composition varies.

Rock descriptions include measurements of radioactivity using a Geometrics GR-101A portable, total-count scintillometer. This instrument measures the total intensity of all gamma rays above 0.05 MeV energy. Results are reported in counts per second (cps), which reflects the total abundance of potassium (K), uranium (U), thorium (Th), and the radioactive daughter products of U and Th. The instrument, however, is not calibrated for quantitative determination of abundances of these elements, and the results are reported for qualitative comparison only.

Abundances of uranium, thorium, and selected rare-earth elements were measured in highly radioactive samples by X-ray fluorescence. Semiquantitative spectrographic analyses for 30 elements were performed on 14 samples that contained quartz veins or showed evidence of alteration. All analyses were made by the DGMR/USGS laboratories, Jiddah, Saudi Arabia. Sample localities along with geographic and cultural features in the Ghazzalah quadrangle are shown on plate 2.

Acknowledgments

The author is indebted to J. C. Cole, K. S. Kellogg, and D. B. Stoeser, all of USGS, for an introduction to and a continuing dialogue on the geology of the northern Arabian Shield. Kellogg also provided useful comments in the field, and Cole provided a very helpful review of this report. Ahmed El Bazli performed the stained-slab point count analyses.

GEOLOGIC OVERVIEW

The Ghazzalah quadrangle is located near the crest of a broad, north-trending, regional upwarp of late Proterozoic rocks known as the Ha'il arch (Greenwood, 1973). This basement passes under the sands of An Nafud approximately 50 km to the north and is covered by Cenozoic basalts of Harrat Khaybar and Harrat Ithnayn approximately 50 km to the west. About 125 km to the east, the basement rocks are overlain by Paleozoic sedimentary rocks.

The fundamental lithologies in the Ghazzalah quadrangle were identified by Brown and others (1963) in their 1:500,000-scale reconnaissance. Two groups of metamorphosed volcanic and sedimentary rocks were recognized; an older sequence, containing abundant andesitic volcanic rocks, was correlated with the "Haliban formation", and a younger sequence of silicic flows, tuffs, and breccias was assigned to the "Shammar rhyolite". Essentially two episodes of granite emplacement were identified. An older association of hornblende-bearing granodiorite and calc-alkaline granite was interpreted to be a crystalline basement upon which the two volcano-sedimentary units were deposited. Younger alkalic to peralkaline granites were interpreted to intrude the "Haliban formation" but to predate the "Shammar rhyolite".

The present investigation confirms that the Ghazzalah quadrangle is underlain by a wide variety of Precambrian metavolcanic, metasedimentary, and intrusive rocks. However, the relative ages of the rocks differ significantly from the original sequence proposed by Brown and others (1963). Also, the fact that extreme lithologic variations over short distances characterize the volcanic and sedimentary rocks suggests that regional correlations are tenuous in the absence of geochronologic constraints. Therefore, the original stratigraphic terminology of Brown and others (1963) has been abandoned in this report in favor of locally defined formation-rank units.

A metamorphosed sequence of basaltic to intermediate volcanic and subvolcanic rock with minor interbedded marble and clastic rock was named the Banana greenstone for representative outcrops in the western part of the quadrangle near the settlement of Al Banana. A younger sequence of rhyolitic to dacitic volcanic rock with interbedded arkose was named the Hadn formation for a representative section at Jabal Hadn (lat 27°02' N., long 41°08' E.) in the southern part of the Al Qasr quadrangle (Chevremont, 1982; D. B. Stoeser, written commun., 1982). The Hadn formation unconformably overlies some plutonic rocks but is intruded by others, and, therefore, provides a basis for dividing the plutonic rocks into two age groups.

VOLCANIC AND SEDIMENTARY ROCKS

Banana greenstone

The Banana greenstone (bg) is composed of metamorphosed volcanic and subvolcanic rocks and minor amounts of interbedded marble (bm). Exposures of these rocks form a discontinuous, north-trending belt, which is as much as 13 km wide along the western edge of the quadrangle, and underlie smaller (1-2 km), isolated areas near the northern and southern edges of the quadrangle.

The outcrop terrain is distinctive. Volcanic and subvolcanic rocks of the Banana greenstone form low, rolling, dark hills or pediments with a blue-green coloration to the regolith. The rocks weather to small, subangular blocks that rarely exceed 1 m in size. The terrain is dotted with white patches from mechanical weathering of small quartz veins in the greenstone. Marble is more resistant than the volcanic and subvolcanic rocks and forms local, buff to light-blue promontories.

The greenstone consists of flows and flow breccias that range in color from dark gray-green and black to light gray. The more mafic rocks are commonly vesicular, and, in the southwestern corner of the quadrangle, locally have pillow structures. In hand specimen, the rocks are aphanitic to plagioclase- and (or) pyroxene-phyric. Rare volcanic wackes crop out northwest of Jabal Qa'iyah and contain clasts of flow-laminated volcanic rock, plagioclase-phyric volcanic rock, felsite, mafic aphanite, and diorite. Layering is undiscernable except where thin beds of marble or wacke crop out.

The volcanic rocks are locally intruded by dikes and sills of diabase and microdiorite too small to map as separate units. These rocks are postulated to have formed as subvolcanic intrusions that were comagmatic with the Banana volcanic rocks because they are compositionally similar to them and display the same degree of metamorphism and deformation.

In most places, the mineralogy and textures reflect greenschist-grade metamorphism. Aphanitic volcanic rocks and the matrices of porphyritic rocks have recrystallized to an extremely fine grained (0.01-0.15 mm) intergrowth of acicular actinolite and mosaic-textured albite, chlorite, ± biotite, sphene, and opaque minerals. Relict vesicles are filled with albite, quartz, and actinolite. Veins composed of quartz and (or) epidote are abundant. Pyroxene phenocrysts have been almost completely replaced by green actinolitic amphibole, and plagioclase phenocrysts are intensely saussuritized; a similar alteration of primary pyroxene and plagioclase has occurred in the microdiorite and diabase.

Relics of the primary mineralogy have survived in some of the coarser-grained rocks. In the microdiorite, diabase, and plagioclase-phyric volcanic rock, intensely saussuritized plagioclase preserves primary igneous morphology (blocky to tabular euhedra), concentric zoning, and twinning. In the microdiorite, primary plagioclase compositions are An_{50-60} in the phenocrysts and An_{30-35} in the groundmass. Plagioclase compositions in the mafic volcanic rock are An_{30-60} with the smaller grains tending to be less calcic. Compositions of the plagioclase phenocrysts in the clinopyroxene- and plagioclase-phyric rocks are An_{40-50}.

Higher grade assemblages occur in a broad valley 1 to 3 km northwest of the town of Al Banana, where the rocks are metamorphosed to at least epidote-amphibolite grade. The primary mineralogy and textures have been replaced by a very fine grained (0.05-0.15 mm) mosaic-textured intergrowth of green hornblende, epidote, untwinned plagioclase, and minor amounts of pink garnet. The garnet could be spessartine-rich and, therefore, could have been stablilized under conditions of greenschist-grade metamorphism by local high concentrations of manganese in the rocks (Hyndman, 1972). Alternatively, the garnet may indicate local attainment of almandine-amphibolite-grade metamorphism.

The degree of deformation in the greenstone is variable. The volcanic and subvolcanic rocks have a faint to well developed metamorphic foliation and lineation in outcrops west of Jabal al Banana, near Jabal Qa'iyah, and in the southeastern corner of the quadrangle. The fabrics are defined principally by preferred orientation of actinolite, although some coarser-grained rocks display fine-scale, metamorphic, compositional banding. A sedimentary breccia having stretched clasts crops out about 3 km northwest of Jabal Qa'iyah. In contrast, however, the rocks are essentially undeformed in the southwestern corner of the quadrangle and southeast of Jabal Ma'a.

The bulk composition of the rock may be inferred from phenocryst composition, modal mineralogy, and radioactivity level. Compositions that range from basalt to andesite are suggested by the composition of plagioclase phenocrysts. Furthermore, point counts were made on four thin sections of aphanitic rock to calculate the whole-rock silica concentration from the modal mineralogy and reasonable estimates of mineral composition and density. Calculated whole-rock silica concentration ranged from 50 to 60 percent, which is the range of basalt and andesite. Additional information was supplied by scintillometer readings, which ranged from 5 to 20 cps in most places but locally were as high as 25 to 30 cps. The lower range of measurements suggests low-potassium concentrations and overlaps with the range found for gabbro and hornblende quartz diorite (table 1). The higher readings are similar to those measured for monzogranite (table 1). Therefore, the scintillometer data suggest that a continuum of composition exists from basalt through basaltic andesite to andesite and, perhaps, rhyodacite.

Minor amounts of marble (bm), in beds less than 0.5 m thick and isolated lenses up to 100 m across, are interbedded with the volcanic rock. The largest bodies crop out immediately west of Jabal al Banana. Most of the marble is pure and devoid of internal structure although some laminated marble and iron- and magnesium-rich calc-silicate beds crop out in the south-central part of the quadrangle. Marble does not appear to be restricted to any particular stratigraphic interval within the Banana greenstone.

Age and thickness

The Banana greenstone is the oldest rock in the quadrangle. The stratigraphic thickness of the unit is unknown because its base is not exposed and because structural controls are few.

Hadn formation

The Hadn formation was named for exposures of volcanic and sedimentary rocks underlying Jabal Hadn in the southern part of the Al Qasr quadrangle (Chevremont, 1982; D. B. Stoeser, written commun., 1982). Continuous exposures of Hadn formation extend southward into the Ghazzalah quadrangle, where it is composed of predominantly silicic volcanic rock and subordinate amounts of arkosic sedimentary rock and rare concretionary chert. The principal exposures crop out in a west-trending belt along the northern margin of the quadrangle. Isolated outcrops of silicic-volcanic rock also crop out in the southern two-thirds of the quadrangle and are assigned to the Hadn formation on the basis of similarities in mineralogy, inferred composition, and metamorphic grade. The largest outcrops are located in a broad, highly alluviated zone in the central part of the quadrangle. Smaller outcrops are located near the southeastern and southwestern corners of the quadrangle and in the interior of Jibal ar Rumman.

The topography of the Hadn outcrops is distinctly more rugged than that associated with the Banana greenstone. The rock is resistant to erosion, commonly underlies steep-sided hills, and forms talus slopes with large (>1 m), angular boulders. The color of the regolith ranges from red to tan to olive green.

Undivided volcanic rock

Most of the Hadn formation is composed of volcanic rock (hu) that displays a range in bulk composition from rhyolite to rhyodacite. Most of the rock is crystal-lithic tuff having phenocrysts ($\leq$5 mm) of quartz, feldspar, and biotite, and lithic fragments ($\leq$5 mm to 20 cm) that are dispersed in a gray, red, or purple aphanitic matrix. The relative abundances of matrix, phenocrysts, and lithic fragments are locally variable. Phenocrysts constitute from 10 to 25 percent of the rock, and, in most places, lithic fragments from 0 to 20 percent. Locally, the rock is composed of 20 to 80 percent lithic clasts and is more properly termed lapilli tuff, tuff breccia, and pyroclastic breccia (Fisher, 1961). The rock is locally eutaxitic and, in some places, extreme welding and compaction have produced a well-laminated rock; lamina range from 0.2 to [illegible] mm in thickness. In general, however, the rock appears more massive in outcrop, and individual layers, if discernable, range from about 1 m to 50 m in thickness.

The phenocryst populations show considerable variation. The following phenocryst assemblages were observed: plagioclase in about 30 percent of the rocks; potassium feldspar in about 30 percent; quartz, potassium feldspar, and plagioclase in about 20 percent; potassium feldspar and plagioclase in about 10 percent; and plagioclase and amphibole in about 10 percent. Plagioclase phenocrysts show a total range in composition from $An_{<10}$ to An_{30}, but tend to be predominantly An_{20} to An_{30}. It is impossible to assign unequivocal lithologic names to these rocks in the absence of bulk-composition data. However, the phenocryst populations suggest that the rocks span a range in composition that could extend from rhyolite to dacite.

The lapilli range from less than 5 mm to 20 cm in size and are relatively equant and angular to rounded in shape. Feldspar-phyric rock fragments are present in minor amounts, but most fragments are crystal-lithic tuff that are only distinguished from the matrix tuff by slightly darker color, the presence of lamellae or fiamme, or differences in phenocryst abundance. The agglutinates, and some of the structureless fragments of crystal-lithic tuff, may have formed as quenched blobs of essential melt. However, the presence of lamellae and fiamme in some fragments suggests they were derived from pre-existing volcanic rock that had been compacted and welded prior to incorporation.

Accidental fragments are rare and mostly occur near the base of the Hadn formation. Angular clasts of granodiorite and medium-grained syenogranite are incorporated in well-laminated and locally crossbedded tuff at the base of the Hadn on the southern side of Jabal Ma'a and in an outlier of Hadn in the northwestern corner of the quadrangle. These fragments are identical to the locally underlying crystalline rocks. Accidental fragments of fine-grained, red, alkali-feldspar granite constitute less than 1 percent of the clast suite but do not seem to be confined to any stratigraphic horizon.

Lithic fragments and phenocrysts are typically set in an extremely fine grained (10-100 μm) mosaic of quartz, alkali feldspar, chlorite, and opaque minerals, ± brown amphibole, ± fayalite, ± diopside, ± aegirine. Fiamme structures and lamellae have devitrified to a somewhat coarser grain size (0.05-0.1 mm) and commonly contain spherulitic aggregates of quartz and feldspar. Vugs are filled by quartz, alkali feldspar, ± fayalite, ± opaque minerals, and in one rock rare lithophysae are lined with aegirine. In some rocks, the matrix contains acicular microlites (50-150 μm) of albite, which define a pilotaxitic fabric that wraps around phenocrysts. In other rocks, microphenocrysts of sanidine are abundant.

Concretionary chert (hcc) crops out over an area of about 0.25 km^2 east of Jabal Qa'iyah. The chert is a lensoidal mass of close-packed, rounded, siliceous concretions that are 5 to 10 cm in diameter. Although contacts are poorly exposed, the outcrop pattern suggests that the chert was deposited over a limited area at the base of the Hadn formation and directly on a pre-Hadn metagabbro. The deposit may have been formed by precipitation of silica in a hot spring or fumarole environment in early Hadn time.

For the most part, the Hadn volcanic rocks have been only incipiently recrystallized. Some amphiboles and pyroxenes are partially replaced by chlorite. Potassium feldspar phenocrysts and, to a lesser extent, plagioclase phenocrysts are replaced by a cryptocrystalline intergrowth of hematite, albite, and clay(?) minerals. Vugs are commonly filled by chlorite, epidote, and stilbite. However, primary igneous textures are widely preserved, including fiamme structures, extremely fine (0.2 mm) lamellae, lithophysae, and spherulites. Locally, original shapes of glass fragments appear to be preserved, and there are possible relics of perlitic fractures. The extent to which these primary igneous textures and structures are preserved is in sharp contrast to the more profound recrystallization of the Banana greenstone.

Rhyolite member

Two sequences of rhyolite (hr), located north and northwest of Al Qa'iyah, are thick enough to map as separate units. The rock is rhyolitic crystal-lithic tuff that contains abundant quartz phenocrysts. The rhyolite is easily distinguished from the other Hadn volcanic rocks by its brick-red color. The more extensive of the two sequences occurs within the undivided Hadn volcanic rock and appears to wedge out along strike; the less extensive sequence appears to overlie undivided Hadn volcanic rock.

Arkose member

Arkosic sandstone and sedimentary breccia (ha) crops out at Jabal Ma'a and north of Jibal Amrass. On Jabal Ma'a, a poorly sorted arkosic sandstone locally constitutes the basal 10 to 30 m of the Hadn formation. The sandstone is composed of angular fragments (0.02-5 mm) of quartz, microcline, plagioclase (An_{30-40}), granite, and minor silicic volcanic rock. Interstices are filled by white mica and opaque minerals. The plagioclase compositions are consistent with derivation from the underlying, pre-Hadn monzogranite or granodiorite (table 1). About 2 km north of Jibal Amrass, interbedded sandstone, silicic flow rock, and massive sedimentary breccia underlie one small hill. The breccia contains locally derived fragments of pre-Hadn monzogranite and volcanic clasts from the Hadn. The limited extent of these clastic rocks and the presence of Hadn and pre-Hadn clasts suggest that the clastic rocks were deposited in channels in early Hadn time.

Age and thickness

The Hadn formation is known to unconformably overlie the Banana greenstone, although the contact is not exposed within the Ghazzalah quadrangle. About 2 to 3 km north of the northwestern corner of the quadrangle, the basal unit of the Hadn formation consists of a cobble-to-boulder conglomerate that overlies volcanic rocks of the Banana greenstone and contains clasts of basalt and andesite.

The thickness of the Hadn formation within the Ghazzalah quadrangle is uncertain because of discontinuous exposure, generally poor definition of layering, and extensive erosion that has removed much of the section. Minimum thicknesses are inferred to be on the order of 1 to 2 km in cross section A-A' based on available exposures and attitudes of bedding. This estimate is consistent with a minimum thickness of 3 to 5 km determined for the Hadn formation by Chevremont (1982) about 5 to 10 km west of the Ghazzalah quadrangle on Jibal ar Rumman.

INTRUSIVE ROCKS

Most of the intrusive rocks of the Ghazzalah quadrangle can be divided into two main groups based on their ages relative to the Hadn formation. Pre-Hadn intrusive rocks include metagabbro, hornblende quartz diorite, tonalite, biotite-hornblende granodiorite, and magnetite syenogranite. Intrusive rocks that postdate the Hadn formation are gabbro, alkali-feldspar granite, hornblende-feldspar porphyry, granophyre, diorite, and plutons of syenogranite and peralkaline granite. The age relationships between the Hadn formation and intrusions of monzogranite, diabase, and felsic-dike rock are less straightforward; locally, individual bodies of these rocks are unconformably overlain by the Hadn formation, and, elsewhere, similar rocks intrude the Hadn formation.

To facilitate comparison of the plutonic rocks, salient petrographic features are summarized in table 1.

Metagabbro

Medium- to coarse-grained metagabbro (gbm) crops out in the southern part of the quadrangle. The outcrops have a blue-green sheen similar to that of the Banana greenstone and underlie low hills and pediments that are covered with subrounded, nonfriable boulders less than 2 m in diameter. Faint cumulate layering, defined by variations in color index, is present locally.

The primary texture is a hypidiomorphic intergrowth of plagioclase (An_{55-70}), olivine, clinopyroxene, minor orthopyroxene, and equant opaque minerals. Plagioclase constitutes 50 to 60 percent of the rock, clinopyroxene about 10 percent, and olivine as much as 30 percent. Pyroxene fills interstices between plagioclase laths and large individual grains of olivine. The primary mineralogy has been extensively altered. Olivine and orthopyroxene are rimmed by serpentine, talc, and magnetite, and plagioclase is saussuritized. Chlorite is abundant in interstices between primary minerals. Clinopyroxene has been replaced by green amphibole.

The age of the metagabbro relative to most of the other units is obfuscated by poor exposures. In the south-central part of the quadrangle, the fact that the contact between the

Table I.—Petrographic properties and radioactivity of intrusive rocks in the Ghazzalah quadrangle

Rock type & unit symbol	Texture	Color index	Mafic minerals	Feldspars	Accessory minerals	Radioactivity level (cps)
Metagabbro (gbm)	m.g. to c.g. hypidiomorphic-granular; highly altered	40-65	oliv cpx opx	plag An_{55-70}		8-12
Hornblende quartz diorite (hqd)	m.g. hypidiomorphic-granular	15-30	hb ± biot	plag An_{30-50} trace ksp, interstitial	zircon apatite	12-20
Tonalite (ton)	c.g. hypidiomorphic-granular	10-20	hb biot	plag An_{25-30} trace ksp, interstitial	zircon apatite	15
Biotite-hornblende granodiorite (gd)	m.g. to c.g. hypidiomorphic-granular	<15	hb biot	plag An_{20-40} trace ksp, interstitial	zircon apatite	15
Magnetite syenogranite (sgm)	c.g. xenomorphic-granular to protoclastic	<2	biot	microcline minor plag An_{25-35}	zircon	30-55
Pre-Hadn monzogranite (mga)	m.g. to c.g. hypidiomorphic-granular to porphyritic	<5	biot	plag An_{20-30} microcline	zircon apatite sphene allanite	25-35
Post-Hadn monzogranite (mgb)	c.g. hypidiomorphic granular to porphyritic; local rapikivi	<5	biot ± hb	plag An_{25-35} microcline anorthoclase	zircon apatite sphene	29-46
Gabbro (gb)	m.g. to c.g. hypidiomorphic-granular	40-50	cpx ol opx	plag An_{60-70}		8-12
Alkali-feldspar granite (afg)	f.g. to m.g. xenomorphic-granular	<2	biot ± hb	microcline minor plag, An_{25-30}	sphene zircon apatite	30-55
Hornblende-feldspar porphyry (phf)	f.g. porphyritic; locally graphic matrix	3-5	hb biot	Plag An_{30-35} microcline	sphene apatite zircon	
Granophyre (gph)	f.g. granophyric; locally porphyritic	1-5	biot	mostly ksp minor plag		30-40
Diorite (dr)	f.g. hypidiomorphic-granular to ophitic	10-20	hb biot	plag An_{25-45}	sphene zircon apatite	
Jufayfah syenogranite (sgf)	f.g. to m.g. hypidiomorphic granular	<2	biot ± hb	microcline plag An_{25-35}	zircon apatite	55-80
Rumman granite (pgr)	c.g. hypidiomorphic-to xenomorphic-granular	5	kataph aenig aegir	microcline	zircon apatite	35-40
Arfvedsonite granite (pga)	f.g. to m.g. xenomorphic-granular	1-2	aegir arfv ± biot	microcline	sphene ± zircon ± apatite	40-70
Ba'gham granite (pgb)	c.g. hypidiomorphic-to xenomorphic-granular	5-10	arfv ± biot	microcline	zircon allanite	70-150
Ba'gham granophyre (gphb)	f.g. granophyric, locally porphyritic	<2	biot	kspar		50-120
Diabase (di)	f.g. intersertal	>30				10
Felsic dikes (ry)	aphanitic	<3	biot amph	kspar plag		30-70

f.g. fine-grained; m.g. medium-grained; c.g., coarse grained

ol, olivine; cpx, clinopyroxene; opx, orthopyroxene; biot, biotite; hb, hornblende; kataph, kataphorite; aenig, aenigmatite; aegir, aegirine; arfv, arfvedsonite; amph, amphibolite; plag, plagioclase; ksp and kspar, potassium feldspar metagabbro and the overlying Hadn formation appears to be concordant with layering in the Hadn suggests that the volcanic rocks and local concretionary chert were deposited on the gabbro. A pre-Hadn age is tentatively extended to the other metagabbro bodies. The age of the metagabbro relative to the other pre-Hadn plutonic rocks is unknown because no contact relations are exposed. However, the primitive chemical composition and high degree of alteration of the metagabbro suggest that it may be the oldest pre-Hadn plutonic rock and that it could be cogenetic with the Banana greenstone.

Hornblende quartz diorite

Hornblende quartz diorite (hqd) crops out over a total area of about 15 to 20 km^2 in the northwestern and central parts of the Ghazzalah quadrangle. From a distance, the rock appears similar to the Banana greenstone. Outcrops form low-lying hills covered with gray-green regolith and small (<1 m), rounded to subangular, dark-gray boulders.

The rock shows a complete gradation between diorite and quartz diorite (fig. 2). Textures range from hypidiomorphic-granular to intersertal. Color indices range from 15 to 30, and brown, magmatic hornblende is the dominant mafic mineral; minor amounts (2-5 percent) of biotite are present in only two of the samples examined. Plagioclase ranges in composition from An_{30} to An_{50}. Alteration has resulted in saussuritization of plagioclase and chloritization of amphibole and biotite. Calcite veins are locally abundant.

Northwest of Saqf, the hornblende quartz diorite appears to be unconformably overlain by the Hadn formation, and, as discussed in the subsequent two sections, the hornblende quartz diorite is intruded by rocks that clearly predate the Hadn formation. The hornblende quartz diorite is mineralogically similar to, and therefore may be cogenetic with, some of the small diorite dikes in the Banana greenstone.

Tonalite

Tonalite (ton) crops out in two areas comprising about 10 km^2 in the northwestern and southwestern corners of the quadrangle. The rock weathers to low hills and pediments, which are distinctly lighter colored than the hornblende quartz diorite.

The tonalite is composed of a coarse-grained, hypidiomorphic-granular intergrowth of more than 60 percent plagioclase euhedra and subhedra (An_{25-30}), and lesser amounts of interstitial quartz, brown hornblende, and biotite. Opaque minerals and zircon are present in minor amounts. Plagioclase is intensely saussuritized, biotite is almost completely

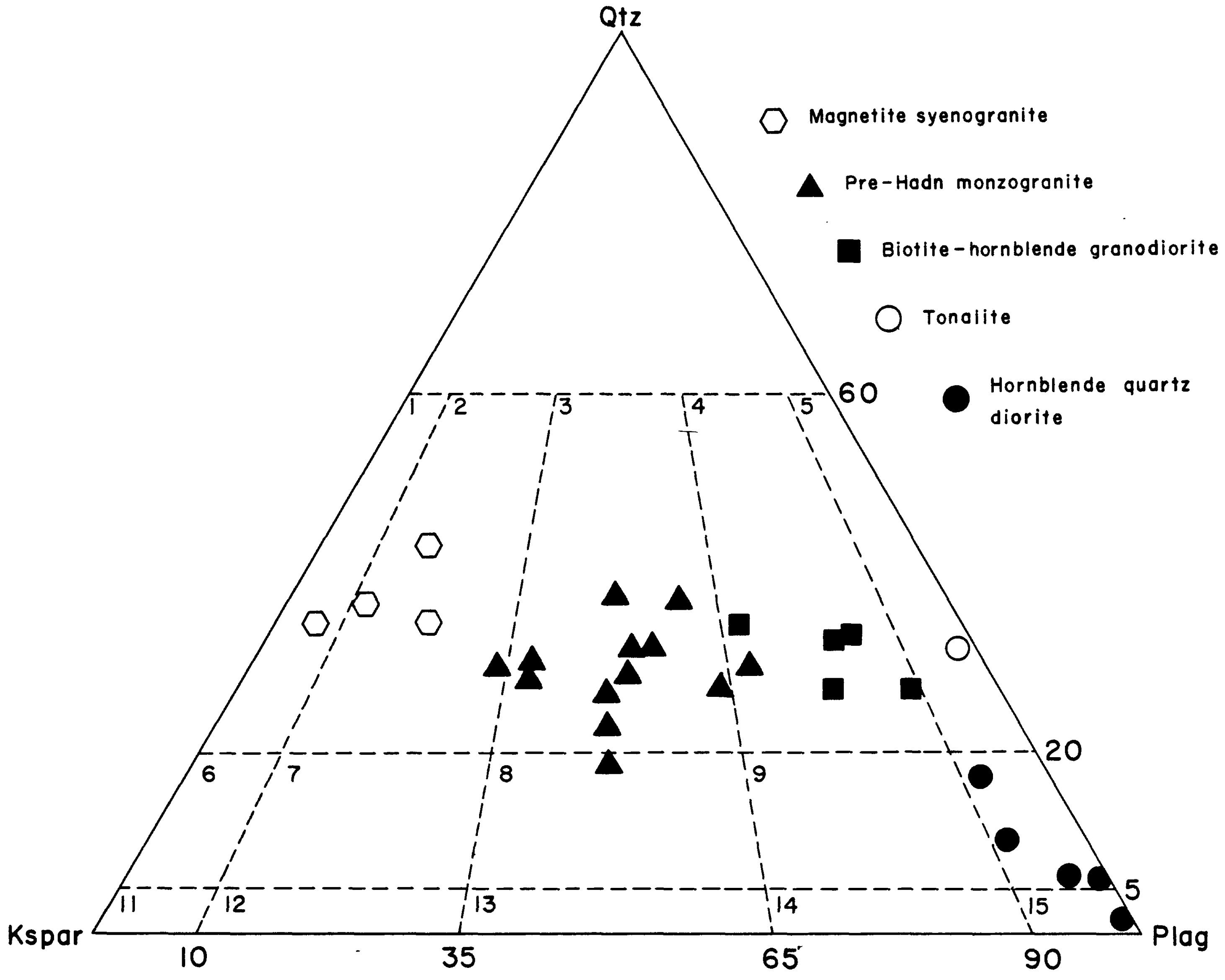

Figure 2.--Ternary diagram showing the relative modal abundances of quartz (Qtz), potassium feldspar (Kspar), and plagioclase (Plag) in pre-Hadn granitic rocks. Fields in figures 2 to 4 are drawn according to Streckeisen (1976) and are as follows: 1, alkali-feldspar granite; 2, syenogranite; 3, monzogranite; 4, granodiorite; 5, tonalite; 6, quartz alkali-feldspar syenite; 7, quartz syenite; 8, quartz monzogranite; 9, quartz monzodiorite; 10, quartz diorite; 11, alkali-feldspar syenite; 12, syenite; 13, monzonite; 14, monzodiorite; 15, diorite.

replaced by chlorite and opaque minerals, and the primary brown hornblende is partially converted to green actinolitic amphibole. Compared to the hornblende quartz diorite, the tonalite has a lower color index, is coarser grained (0.5-10 mm), and contains more zircon and less-calcic plagioclase (table 1).

The fact that the tonalite body at the western end of Jibal Wagadeem contains angular xenoliths of hornblende quartz diorite clearly indicates that the tonalite is younger. The tonalite appears to be unconformably overlain by the Hadn formation. Contact relationships are not exposed, but parallelism between the inferred contact and layering in the overlying Hadn over several hundred meters suggests that the contact is depositional rather than intrusive.

Biotite-hornblende granodiorite

Medium- to coarse-grained biotite-hornblende granodiorite (gd) crops out over a total area of about 60 to 70 km^2 in the northern part of the quadrangle. The outcrops typically underlie low, gray hills having abundant boulders and gray-green regolith. These outcrops are distinguished from the tonalite and hornblende quartz diorite by the greater abundance of large subrounded boulders.

The rocks are composed of subequal amounts of quartz, plagioclase, and potassium feldspar (fig. 2) and generally less than 15 percent mafic minerals. The texture is distinctly hypidiomorphic-granular with potassium feldspar and quartz filling interstices between more euhedral plagioclase. Plagioclase ranges in composition from An_{20} to An_{40}, and individual grains show strong concentric zonation. Both biotite and amphibole are ubiquitous. Alteration has made feldspars turbid and replaced the mafic minerals with fine-grained clots of chlorite and magnetite.

The biotite-hornblende granodiorite clearly postdates the Banana greenstone and the hornblende quartz diorite, but predates the Hadn formation. Eight to 10 km. north of Jabal al Banana, outcrops of granodiorite contain rounded xenoliths of hornblende quartz diorite. Xenoliths of greenstone are present in the granodiorite near its contact with the Banana about 5 km southeast of Jabal Ma'a. On the southern side of Jabal Ma'a, and on smaller hills to the northeast, the Hadn formation rests unconformably on the biotite-hornblende granodiorite. The depositional nature of the contact is indicated by: (1) the conformity of layering in the Hadn with the Hadn-granodiorite contact; (2) the presence of angular clasts of biotite-hornblende granodiorite in the basal ash-flow tuff of the Hadn; and (3) the presence of plagioclase fragments and mafic-rich detrital lenses, which have been derived chiefly from the granodiorite, in a locally exposed, basal sandstone (ha).

Magnetite syenogranite

Coarse-grained magnetite syenogranite (sgm) is exposed over about 100 to 110 km^2 in the northwestern corner of the quadrangle and over 2 to 3 km^2 on the southeastern side of Jabal Ma'a. The rock is highly friable and forms subdued, red outcrops with broad, slightly convex faces. The unit is distinguished from the other pre-Hadn plutonic rocks by a pervasive red staining, abundant hematite-filled fractures, and the presence of small (1-2 mm) magnetite-rich clots.

The rock is mostly composed of a xenomorphic-granular intergrowth of quartz and microcline perthite with well-developed exsolution lamellae (30-100 μm). The interstices between the quartz and microcline are filled with minor plagioclase (An_{25-35}), myrmekitic intergrowths of quartz and feldspar, and clots of magnetite, ± muscovite, ± biotite, ± quartz, ± albite, ± zircon. The relative abundance of plagioclase is low, and the rock actually grades from syenogranite to alkali-feldspar granite in modal composition (fig. 2). The rock is locally cataclastic; interstices between large, angular fragments of quartz and microcline are filled by comminuted fragments (0.02-0.5 mm) from the primary mineralogy and by veins of secondary hematite.

The magnetite syenogranite is considered to be possibly one of the youngest pre-Hadn intrusive rocks based on its evolved, felsic composition. It is clearly younger than the hornblende quartz diorite because dikes of magnetite syenogranite intrude that unit on the southeastern flank of Jabal Ma'a. There are no contacts with the other pre-Hadn plutonic rocks. A pre-Hadn age for the magnetite syenogranite was established in the northwestern corner of the quadrangle (lat 26°59.5' N., long 41°01' E.), where clasts of the granite are included in the basal laminated tuff of the Hadn formation. Furthermore, the magnetite syenogranite is mineralogically identical to clasts that are present within a basal boulder conglomerate of the Hadn formation 3 to 5 km north of the quadrangle.

Monzogranite

Monzogranite forms plutons that underlie large parts of the quadrangle. Exposed contact relationships demonstrate that some monzogranite bodies predate the Hadn formation while others intrude the Hadn formation. However, all of these rocks are similar in terms of mineralogy, texture, and outcrop terrain. Therefore, it is not possible to unequivocally state the age of every monzogranite body relative to the Hadn formation, and monzogranite plutons that are not in contact with the Hadn formation are assigned tentative (queried) pre- or post-Hadn ages based on their proximity to monzogranite of known age.

Pre-Hadn monzogranite

Pre-Hadn monzogranite (mga) crops out in the vicinity of Ghazzalah and Ghazwar. The rock is extremely friable and decomposes readily by mechanical weathering. As a result, the outcrops are typically low lying, cavernous weathering, relatively free of boulders, and surrounded by a distinctive white grus.

The rock is composed mostly of quartz, plagioclase (An_{20-30}), and microcline (fig. 2), which form a medium- to coarse-grained (0.3-10 mm), hypidiomorphic-granular to protoclastic intergrowth. Locally, microcline forms equant phenocrysts as large as 10 mm. Plagioclase is typically euhedral to subhedral, rimmed by albite, and shows weak concentric zoning. Biotite forms interstitial clusters (<1.5 mm) of grains associated with opaque minerals, albite, quartz, and zircon. Biotite has been largely replaced by chlorite, and microcline has been replaced by dusty, red, disseminated hematite and clay minerals. These rocks are distinguished from the other pre-Hadn plutonic rocks by: (1) the presence of two feldspars that are discernable in handspecimen; (2) locally abundant, potassium feldspar phenocrysts; (3) low color index (generally <5); and (4) biotite as the principal mafic mineral.

The evidence relative to the age of these rocks is as follows: Rounded xenoliths of hornblende quartz diorite are abundant in the pre-Hadn monzogranite, and thin (1 m wide) dikes of biotite monzogranite cut hornblende quartz diorite about 10 km northwest of Ghazzalah. A pre-Hadn age is indicated by cobbles and boulders of biotite monzogranite present in a sedimentary breccia (ha) near the base of the Hadn formation about 1 to 2 km north of Jibal Amrass. About 10 km east of the quadrangle, a basal conglomerate (50 m thick) of the Hadn rests unconformably on a monzogranite that in handspecimen is identical to the rocks mapped as pre-Hadn monzogranite nea- Ghazzalah.

A pre-Hadn age assignment is supported by the relationship of these monzogranites to the biotite-hornblende granodiorite. On a small hill immediately east of Jabal Ma'a, the biotite-hornblende granodiorite grades into monzogranite, and both are unconformably overlain by the Hadn formation. About 6 km southeast of Ghazwar, where the two rock-types are in contact, the granodiorite contains xenoliths of biotite monzogranite indicating that, at that locality, it postdates the monzogranite. It is suggested, therefore, that the monzogranite and biotite-hornblende granodiorite may be slightly different facies of a single suite of pre-Hadn felsic plutonic rocks.

Post-Hadn monzogranite

Medium- to coarse-grained monzogranite (mgb) that clearly postdates the Hadn formation crops out in plutons concentrated in the southern part of the quadrangle. The general terrain associated with this unit is similar to that of the pre-Hadn monzogranite. The monzogranite crops out in narrow ridges where it is intruded by felsic dikes. Red-weathering inselbergs rise as much as 50 m above a highly eroded plain covered with white grus.

Although the dominant lithology is monzogranite, the rocks display a wide variation in modal composition within a given pluton, ranging from quartz monzonite to syenogranite (fig. 3); in general, the potassium-feldspar content of the rock appears to increase toward the margins of the plutons. Most of the rocks have a hypidiomorphic-granular texture, but locally the rocks are markedly porphyritic. Plagioclase (An_{25-35}) forms subhedral to euhedral laths with oscillatory zoning. Phenocrysts of anorthoclase antiperthite occur locally. Microcline forms blocky phenocrysts as much as 15 mm across, and smaller subhedral to euhedral grains, and graphic intergrowths with quartz. Rapikivi texture is developed in some of the porphyritic rocks. Biotite is ubiquitous and forms large (0.1-2 mm) interstitial grains; clusters of tiny, interstitial grains are not as common as in the pre-Hadn monzogranite. Green hornblende is present in about 30 to 40 percent of the rocks. Equant opaque minerals and accessory zircon, sphene, and apatite are in close spatial association with biotite. Biotite has commonly been replaced by chlorite. Potassium feldspar and plagioclase are incipiently altered, and locally both biotite and hornblende are oxidized to magnetite.

The post-Hadn monzogranite clearly intrudes the Hadn formation at several locations. Xenoliths of Hadn volcanic rocks are incorporated within the monzogranite on the southern side of Jabal Qa'iyah. The monzogranite between Wadi Mudaysis and Wadi Braina is inferred to postdate the Hadn formation because the apparent contact crosscuts the strike of the Hadn. The large monzogranite pluton southeast of Wadi Sha'bah Drassi extends into the quadrangle to the south, where it intrudes and includes rocks that correlate with the Hadn formation. Similarly, the large monzogranite body along the southwestern margin of the quadrangle is contiguous with a large pluton to the west that intrudes and includes rocks that correlate with the Hadn.

Tentative age assigments

The pre- and post-Hadn monzogranites are difficult to distinguish in the field on the basis of mineralogy and texture. The pre-Hadn monzogranite appears to contain a

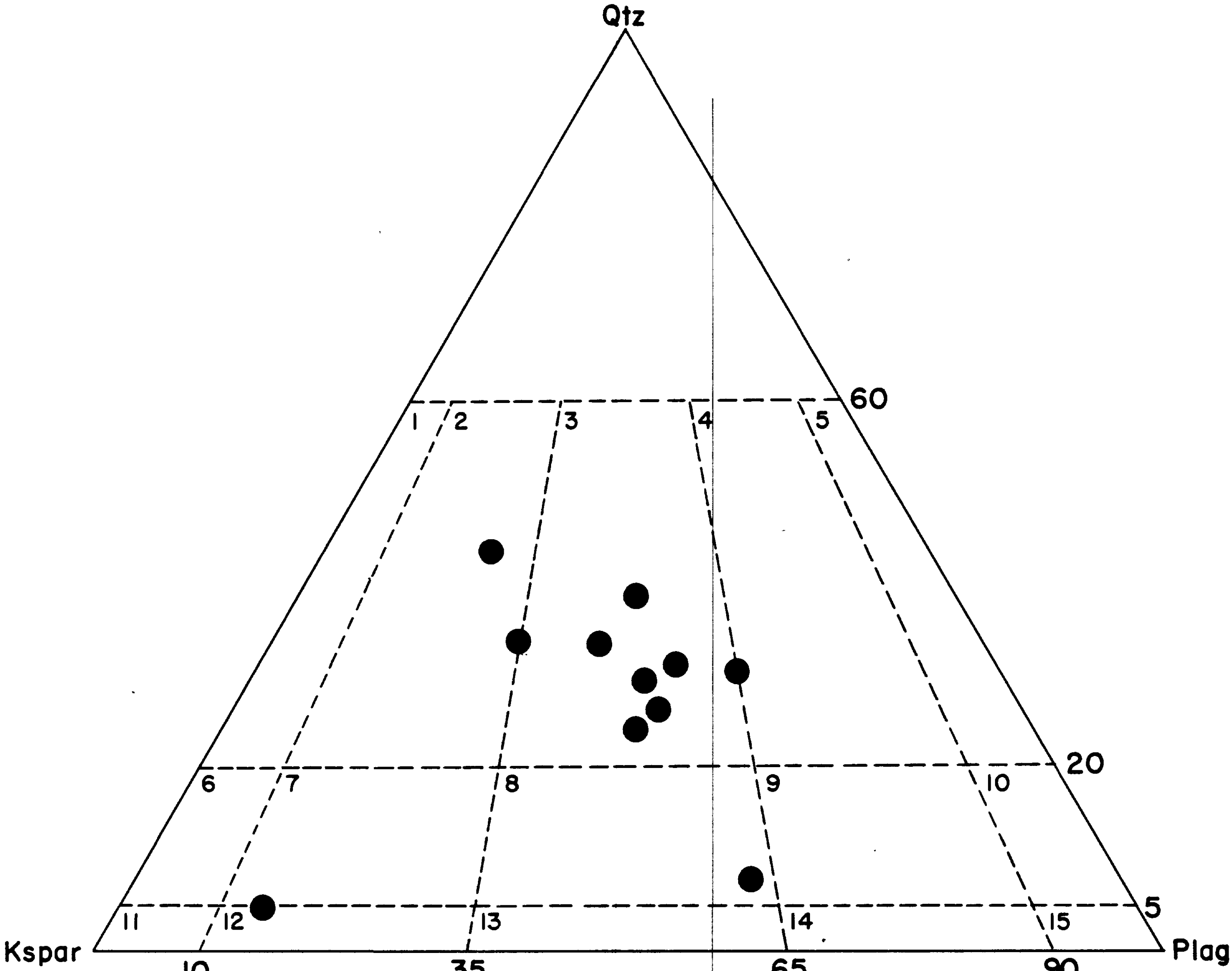

Figure 3.--Ternary diagram showing the relative modal abundances of quartz (Qtz), potassium feldspar (Kspar), and plagioclase (Plag) in post-Hadn monzogranite. Fields are drawn and labelled as in figure 2.

lower abundance of potassium feldspar and hornblende and displays more complete recrystallization of biotite into fine-grained clots. However, these apparent differences are based on a small sample population from rocks that display large lithologic variation, and petrographic discrimination between the two units remains equivocal at best.

Gabbro

Unmetamorphosed gabbro (gb), mapped east of Jabal al Banana and northwest of Al Qa'iyah, crops out as black, bouldery hills that lack the blue-green regolith of the metagabbro. Cumulate layering is locally present.

The mineralogy of the gabbro is variable. Typically, clinopyroxene constitutes 30 to 45 percent of the rock and plagioclase (An_{60-70}) 50 to 60 percent. Black spinel is present in minor amounts, and olivine and orthopyroxene are generally present in minor amounts or are absent. Locally, however, olivine or orthopyroxene may compose up to 30 percent of the rock. Olivine and pyroxene are partly replaced by talc, serpentine, chlorite, and magnetite, and plagioclase is saussuritized. In general, however, the degree of alteration is substantially less than in the metagabbro.

The gabbro is assigned a post-Hadn age based on the outcrop east of Jabal al Banana. The fact that the body is located just east of an easterly dipping section of Hadn volcanic rocks suggests that the gabbro has intruded the Hadn. A fault contact between the two units cannot be ruled out on the basis of available evidence, and the post-Hadn age assignment is, therefore, tentative. However, post-Hadn gabbro bodies are well documented in the adjacent Al Qasr and Qufar quadrangles (D. B. Stoeser, written commun., 1982; Kellogg, unpub. data). There are no contacts with the post-Hadn monzogranite, and so the relative ages of the two units are unknown.

Alkali-feldspar granite

Stocks and plutons of fine- to medium-grained alkali-feldspar granite (afg) crop out over a total area of 100 to 120 km^2 in the quadrangle. The rock weathers to a low-lying, white pediment above which project scattered, red-weathering inselbergs. From a distance, the red inselbergs are the principal feature that distinguishes the alkali-feldspar granite from the other intrusive rocks. The contrast in color between the inselbergs and the pediment appears to reflect different amounts of staining from secondary hematite rather than major differences in primary mineralogy.

In most places, the rocks are composed of a xenomorphic-granular intergrowth of microcline and quartz (fig. 4). Color indices are typically less than 2. Opaque and mafic minerals and sphene, ± zircon, ± apatite are clustered together in fine-grained ($\leq$0.2 mm) clots. Biotite is the most common mafic mineral, but hornblende is present in some rocks. Locally, the texture is porphyritic with potassium-feldspar phenocrysts as much as 8 mm across. Although most of the rocks are true one-feldspar granites, laths of plagioclase (An_{25-30}) locally make up as much as 5 percent of the rock (fig. 4). About 10 km north of Al Mahash, an alkali-feldspar granite appears to grade into syenogranite or monzogranite (not separately mapped) in the core of a large pluton.

A post-Hadn age for the alkali-feldspar granite is certain because it intrudes the Hadn formation south of Jabal al Banana and about 13 to 14 km north of Al Mahash. The alkali-feldspar granite also intrudes the post-Hadn gabbro east of Jabal al Banana.

Hornblende-feldspar porphyry

A fine-grained porphyry (phf), containing distinctive acicular amphibole phenocrysts, forms dikes and small ($\leq$1 km^2) stocks located 4 to 5 km west of Jabal al Banana, 5 to 10 km northwest and west of Al Mahash, and at the southwestern end of Jibal Ghatat. Outcrops form low-lying hills that are covered with well-rounded, white to light-pink boulders.

The rock is composed of phenocrysts (0.5-3 mm) of plagioclase (An_{30-35}), microcline microperthite, and brown acicular amphibole set in a very fine grained (0.05-0.3 mm) matrix. The matrix is a hypidiomorphic-granular intergrowth of plagioclase, potassium feldspar, quartz, amphibole, biotite, and opaque minerals. Locally, quartz and potassium feldspar are graphically intergrown. Sphene, apatite, and zircon are all present as accessory minerals. Quartz constitutes 10 to 25 percent of the rock, and plagioclase and potassium feldspar are present in subequal amounts. Biotite and amphibole are partially replaced by chlorite, plagioclase is saussuritized, and potassium feldspar is partially replaced by disseminated hematite and clay minerals.

The hornblende-feldspar porphyry is a young intrusive rock that is coeval, and possibly cogenetic, with the alkali-feldspar granite. Small stocks of the porphyry intrude the Hadn volcanic rocks at the southern end of Jibal Ghatat. West of Jabal al Banana, the outcrop pattern of the porphyry suggests that it intrudes the Banana greenstone. Northeast of Al Mahash, the hornblende-feldspar porphyry appears to grade into the alkali-feldspar granite as the matrix grain-size increases.

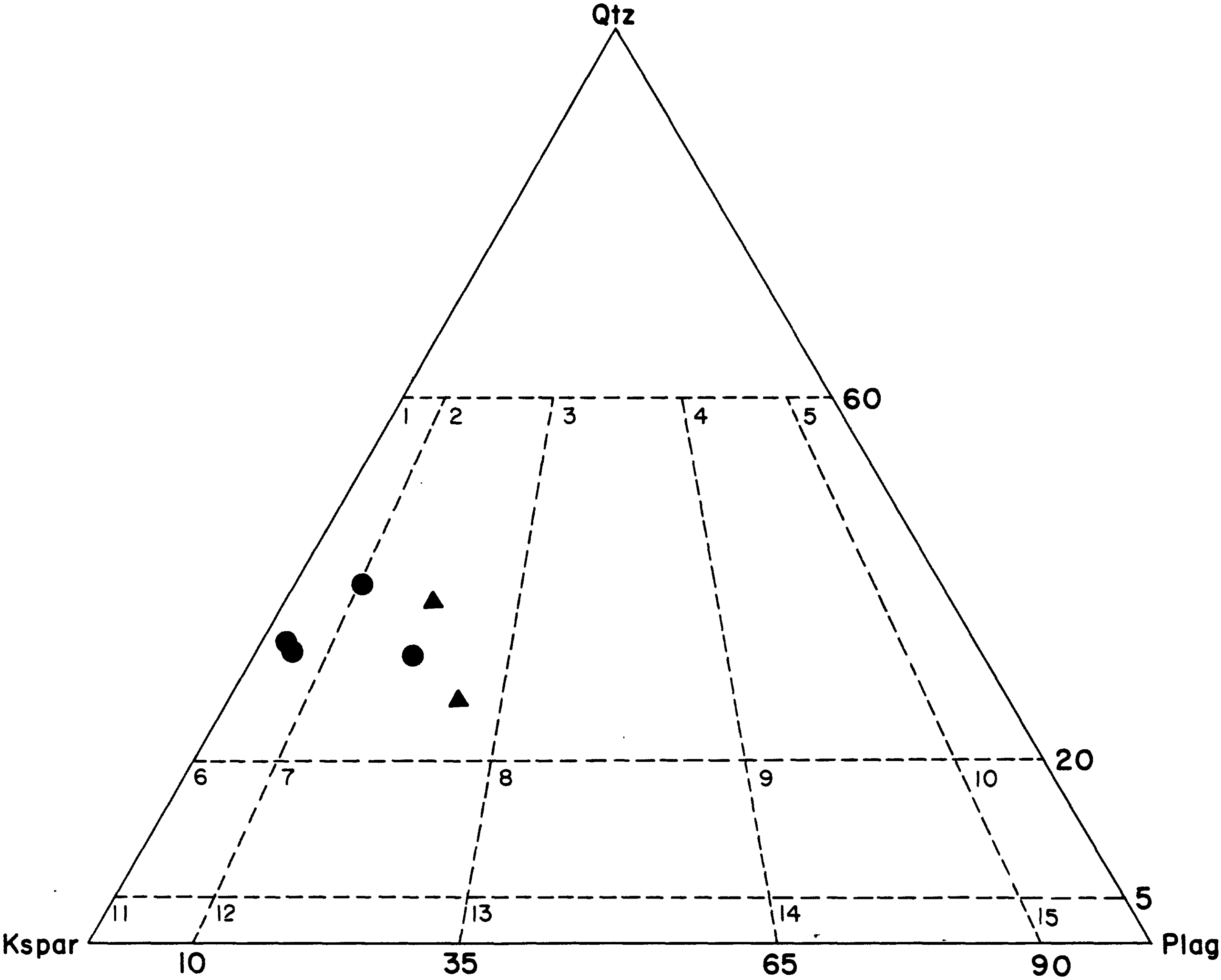

Figure 4.--Ternary diagram showing the relative modal abundances of quartz (Qtz), potassium feldspar (Kspar), and plagioclase (Plag) in alkali-feldspar granite (circles) and the Jufayfah syenogranite (triangles). Fields are drawn and labelled as in figure 2.

Granophyre

Discrete intrusions of granophyre (gph) crop out in the quadrangle over a total area of about 40 km^2. The largest and best exposed bodies are located about 5 km northwest of Al Mahash and about 5 km west of Jabal al Banana.

The granophyre is resistant to erosion and, with the exception of bodies in the south, tends to form prominent, brick-red mountains and ridges. The appearance of the rocks from a distance is variable. In the two largest bodies, the consistent orientation of the joints and (or) flow-banding gives the outcrops a layered appearance that superficially resembles the Hadn rhyolites. Elsewhere, the rock is structureless and weathers to large, smooth, convex rock faces that more closely resemble outcrops of the alkali-feldspar granite.

All of the granophyre bodies are porphyritic with phenocrysts (1-10 mm) set in a very fine grained (0.03-0.3 mm) granophyric matrix of quartz and alkali feldspar. The phenocryst population is variable. Orthoclase phenocrysts are ubiquitous in all of the bodies. Oligoclase (An_{25-30}) forms phenocrysts in the intrusion northwest of Al Mahash. The most common mafic mineral is biotite. The feldspars in all of the granophyre bodies have been pervasively altered to hematite, clay minerals, and epidote, and the mafic phenocrysts are partly replaced by chlorite.

The granophyre intrusions are clearly young. Where they are in contact with the Hadn formation, they intrude it. The relationship between the granophyre and the alkali-feldspar granite is more complex. Northwest of Al Mahash, both gradational contacts between the two rock types and clear intrusive contacts where alkali-feldspar granite intrudes the granophyre are present. It is suggested that much of the granophyre is broadly contemporaneous with the alkali-feldspar granite and may be genetically related. However, multiple episodes of granophyre emplacement cannot be ruled out.

Diorite

Small (1-2 km^2), crescent-shaped dikes of fine-grained diorite (dr) crop out in the southeastern corner of the quadrangle near the confluence of Wadi Sha'bah and Wadi Sha'bah Drassi and in the northern part of the quadrangle about 5 km northwest of Al Mahash. Smaller intrusions are present at Jibal Ghatat. The rock is not resistant to erosion and crops out only as low-lying clusters of gray boulders.

The intrusions are slightly different in mineralogy and texture. The diorite body farthest to the southeast is composed of a hypidiomorphic-granular to ophitic intergrowth of 60 to 65 percent plagioclase (An_{35-45}), 20 percent brown hornblende, 10 percent clinopyroxene, 5 percent equant opaque minerals, and 2 to 3 percent quartz. Sphene, zircon, and apatite are all present as accessory phases. Plagioclase forms a network of 0.1- to 2-mm-long laths. Interstices are filled with hornblende, clinopyroxene, quartz, and opaque minerals that are generally less than 0.5 mm in size. Locally, plagioclase, clinopyroxene, and opaque and accessory minerals are enclosed by poikilitic amphibole about 5 mm in diameter. Plagioclase is only slightly saussuritized, and amphibole and clinopyroxene are partially replaced by chlorite. The diorite bodies farther to the north are composed of 70 to 80 percent plagioclase (An_{25-30}), about 10 percent brown hornblende and (or) biotite, about 5 percent quartz, and 5 percent opaque minerals. Zircon, sphene, and apatite are accessory minerals. Clinopyroxene is absent, and poikilitic texture is not developed. Instead, amphibole forms only small (0.1-1 mm) euhedra and subhedra that fill interstices between blocky plagioclase grains.

The only constraints on the age of these intrusions are that they intrude the Hadn formation and the post-Hadn alkali-feldspar granite west of Al Mahash.

Jufayfah syenogranite

The Jufayfah syenogranite (sgj) was named for outcrops of post-Hadn syenogranite in the southern part of the Al Qasr quadrangle (D. B. Stoeser, written commun., 1982). The intrusion extends southward into the Ghazzalah quadrangle, and syenogranite is exposed over about 20 km^2 in the vicinity of the town of Saqf. The topography is distinct from all other plutonic rocks. Numerous, white to tan granite pinnacles project as much as 100 m above very flat pediment and alluvial plains. The rock is distinguished from the alkali-feldspar granite by its light color and from the monzogranites and all pre-Hadn rocks by a more rugged topography and a high level of background radioactivity (table 1).

The intrusion is composed of fine- to medium-grained, hypidiomorphic-granular syenogranite. The modal mineralogy (fig. 4) is 35 to 40 percent quartz, 40 percent microcline, 15 to 20 percent plagioclase (An_{25-35}), and minor amounts of biotite and opaque minerals, $\pm$ green/brown hornblende. Grain size rarely exceeds 1.5 mm. Tiny (0.05 mm) apatite and zircon grains are the only accessory minerals. Interstitial muscovite is present in some rocks but may be a secondary subsolidus phase. The potassium feldspars have been pervasively altered to hematite, clay minerals, and muscovite, and biotite has been largely replaced by opaque minerals and chlorite.

The Jufayfah syenogranite postdates the Hadn formation. Contacts with the Hadn, the hornblende granodiorite, and the Banana greenstone are clearly exposed, and dikes of syenogranite penetrate all three units. Fragments of all three units are incorporated as xenoliths within the Jufayfah syenogranite. The age of the syenogranite relative to the other post-Hadn plutonic rocks is uncertain because of the absence of contact relationships.

Rumman granite

The Rumman granite (pgr) crops out in a nearly circular pluton underlying about 300 km^2 in the eastern part of the quadrangle and in the western part of the adjacent Al Awshaziyah quadrangle. The rock is readily distinguished from the surrounding granites by its topography, which is the most rugged in the area. Medium-gray, steep-sided mountains are separated by deep (100-300 m) valleys littered with large (1-10 m), angular boulders. General radioactivity levels are 35 to 40 cps, which is somewhat above the range measured for the alkali-feldspar granite and the monzogranite units (table 1).

The rock is composed of a hypidiomorphic- to xenomorphic-granular intergrowth of 50 to 70 percent microcline microperthite, 20 to 40 percent quartz, 3 to 5 percent amphibole, minor amounts of aenigmatite, aegirine, and equant opaque minerals, and trace amounts of zircon and apatite. The amphibole is tentatively identified as kataphorite based on its dark-green to brown pleochroism, small optic angle, and negative interference figure. The rock shows a seriate grain size distribution, ranging from less than 0.5 to 15 mm. Alteration of the rock has partially replaced microcline by a disseminated intergrowth of hematite and clay minerals.

The Rumman granite intrudes the Hadn formation, the hornblende quartz diorite, the alkali-feldspar granite, and the granophyre. Along the southeastern margin of the pluton, rhyolite of the Hadn formation has been recrystallized to a sugary-textured hornfels and has been invaded by dikes of Rumman granite. North of Al Mahash, xenoliths of red granophyre and Hadn rhyolite are present within the marginal 10 m of the pluton. A large roof pendant of Hadn and hornblende quartz diorite is preserved in the southern one-third of the Rumman pluton. About 3 to 4 km southeast of Ghazzalah, the granite becomes finer-grained toward the contact with an alkali-feldspar granite and forms dikes that intrude the alkali-feldspar granite.

The age of the Rumman granite relative to the Jufayfah syenogranite cannot be determined from field relationships. Both granites are typical of highly evolved felsic plutonic rocks of the northern Shield (Stuckless and others, 1982/1983), and it is suggested that they may have been emplaced penecontemporaneously.

Arfvedsonite granite

Fine- to medium-grained, arfvedsonite-bearing granite (pga) is exposed in three main clusters of outcrops near the Rumman pluton and forms steep hills that weather white to light gray. Fresh surfaces are light purple to pink. Compared to the Rumman granite, the rocks are finer grained, color indices are lower (1-2), and mafic minerals tend to be confined to small interstitial clots. General radioactivity levels are relatively high (40-70 cps; table 1).

The rock is composed of 55 to 70 percent microcline perthite, 30 to 40 percent quartz, 1 to 2 percent mafic and opaque minerals, and minor amounts of sphene, ± zircon, ± apatite. The mafic minerals are most commonly arfvedsonite and aegirine, although locally yellow to brown biotite is the principal mafic mineral. Microcline forms subhedral to euhedral grains that are commonly concentrically zoned. Small (0.01-1 mm) grains of mafic minerals, sphene, zircon, and apatite occur in clusters that are interstitial to larger (0.5-5 mm) quartz and microcline. In contrast to the Rumman granite, kataphorite is absent. The effects of subsolidus recrystallization are also more obvious in the arfvedsonite granite, where quartz and locally microcline are recrystallized to a mosaic texture. Along grain boundaries, microcline is typically recrystallized to discrete, fine grains (0.03-0.1 mm) of albite and potassium feldspar. Subsequent alteration partially replaced feldspar by disseminated hematite and clay minerals and produced chlorite from biotite.

The arfvedsonite granite is interpreted to be essentially the same age as the Rumman pluton. Immediately south of Ghazzalah, the fact that arfvedsonite granite intrudes red, alkali-feldspar granite indicates that it, like the alkali-feldspar granite, is younger than the Hadn formation. On the southwestern margin of Jibal ar Rumman, the arfvedsonite granite appears to grade into the Rumman granite with increasing grain size, color index, and euhedral shape of mafic minerals. The gradation is not completely traceable from one unit to the other because of intervening faults but nevertheless suggests that the arfvedsonite granite may be a finer-grained border facies and (or) marginal intrusion of the main Rumman pluton.

Ba'gham intrusive complex

The Ba'gham intrusive complex is composed of coarse-grained, dark-gray peralkaline granite (pgb) that is rimmed on the eastern side by a shell of fine-grained, brick-red granophyre (gphb). Collectively, these two units underlie 40 km^2 in the northwestern corner of the quadrangle. The outcrops define a narrow, bifurcating belt along the eastern margin of the large magnetite syenogranite pluton. Two lobes, separated by a mass of magnetite syenogranite, project to the south.

The topography is rugged and similar to that of the Rumman granite. Dark-gray peralkaline granite forms high hills with steep walls and cliffs, and talus slopes with large (1-5 m) angular boulders. Valleys have been eroded along westerly and northerly trending fracture zones. The complex is distinguished from all other intrusive bodies in the quadrangle by its high level of radioactivity (table 1).

Peralkaline granite member

The peralkaline granite (pgb) in the interior of the pluton is composed of a coarse-grained (2-15 mm), hypidiomorphic- to xenomorphic-granular intergrowth of 50 to 70 percent microcline microperthite, 30 to 45 percent quartz, 5 to 10 percent arfvedsonite, minor amounts of equant opaque minerals and zircon, and trace amounts of yellow biotite.

The mineralogy and textures along the western contact of the pluton near the older syenogranite reflect extensive late-stage magmatic recrystallization and oxidation. In outcrop, the rock is cut by ubiquitous hematite veins and weathers red due to pervasive hematite staining; mafic minerals are replaced by dark, hematite-rich clots. Ellipsoidal, pegmatitic segregations, as much as 20 cm in diameter, are locally abundant and probably crystallized from late-stage, volatile-rich fluids. Hematite veinlets (10-100 mm wide) are present along grain boundaries and within microcline grains parallel to exsolution lamellae. Locally, incipient protoclastic texture is evident from interstitial secondary hematite and crushed primary grains between large quartz and feldspar grains. Amphibole has been completely replaced by intergrowths of magnetite, quartz, calcite, and potassium feldspar, but the primary amphibole morphology and cleavage are preserved by trails of opaque minerals.

Granophyre member

The granophyre (gphb) is composed of about 40 to 55 percent potassium feldspar, 30 percent quartz, 10 percent albite microphenocrysts, and minor amounts of biotite and opaque minerals. The granophyre is typically fine grained (<0.3 mm), although locally it is porphyritic with phenocrysts of potassium feldspar and quartz as large as 15 mm. Near the eastern rim of the complex, fine-grained granophyric dikes appear to originate from the granophyric shell and cut the coarser grained peralkaline granite. Gradational contacts between most dikes and the host granite suggest that the two rock types are comagmatic. However, the presence of two feldspars in the granophyre and the crosscutting relationships suggest that the granophyre may have formed from a late-stage, volatile-rich magma left over after the bulk of the peralkaline granite had crystallized.

Age of the complex

The Ba'gham intrusive complex is considered to postdate the Hadn formation because dikes of granophyre are emplaced in the Hadn volcanic rocks immediately to the east. Rhyolite xenoliths, which may be fragments of Hadn, are present within the peralkaline granite. There is no direct evidence to establish the age of the Ba'gham intrusive complex relative to the other post-Hadn plutonic rocks, although chemical similarity suggests the complex may be broadly coeval with the other peralkaline rocks in the Ghazzalah area, and, therefore, may postdate the young alkali-feldspar granite and granophyre.

Diabase

Dikes and small stocks of diabase (di) intrude tonalite, hornblende quartz diorite, pre-Hadn biotite monzogranite, hornblende-biotite granodiorite, Hadn formation, Jufayfah syenogranite, and Rumman granite. Many of the diabase intrusions are located along a system of northeasterly trending faults that are described in the Structure section. Most of the diabase intrusions are of limited extent and only locally exceed 2 m in thickness. Consequently, only the largest bodies were mapped.

There are no constraints on the lower age limit of diabase intrusion. In the Al Awshaziyah and Qúfar quadrangles, the Hadn formation unconformably overlies a north-northeast-trending swarm of diabase dikes (G. W. Leo, written commun., 1982; Kellogg, unpubl. data). However, the presence of diabase dikes that cut the Jufayfah syenogranite and the Rumman granite indicates that diabase was also emplaced in post-Hadn time.

Felsic dikes

Felsic dikes are ubiquitous throughout the quadrangle and cut all other map units. The dikes are red to black on fresh surfaces but tend to weather black because of a thick desert varnish. In most places the dikes are less than 2 m wide.

Dikes that are thick enough to map as separate units (ry) crop out in the northeastern corner of the quadrangle southwest of Jabal al Banana.

The topographic expression of the dikes depends on the nature of the host rock. The dikes tend to weather at the same rate as the host rock in the Hadn formation, the Banana greenstone, the granophyre, and the peralkaline and alkali-feldspar granites. These dikes are difficult to detect from a distance. In the diorite, granodiorite, monzogranite, and syenogranite, the dikes are more resistant than the host rocks and tend to form the spines of long, low ridges.

Regardless of color, all the felsic-dike rocks are extremely fine grained and composed mainly of quartz and potassium feldspar $\pm$ phenocrysts. Two principal types of textures are present: (1) porphyritic with felty, granophyric, or hypidiomorphic-granular matrices; and (2) very fine grained hypidiomorphic- to xenomorphic-granular intergrowths of quartz and feldspar. Excluding phenocrysts, matrix grain size is typically less than 0.3 mm. Phenocrysts range in size from 0.5 to 5 mm and vary in type and abundance from dike to dike: microcline microperthite and plagioclase (mostly An_{25-30}) are the most common, followed by deeply embayed quartz, and brown hornblende and opaque minerals. Some of the dikes have sodium-bearing mafic phases that suggest a peralkaline bulk composition. Aegirine and aenigmatite occur in a dike cutting the arfvedsonite granite south of Jibal ar Rumman. Aegirine and kataphorite are abundant in a black rhyolite dike that crops out discontinuously for 25 km between Jibal ar Rumman and Jibal al Banana.

The variations in phenocryst populations and quartz abundance suggest that the dikes may vary greatly in bulk composition. No attempt was made to estimate bulk compositions from petrography, but dike rocks were tentatively classified in the field according to their phenocrysts (plate 2). Rocks containing abundant quartz phenocrysts were classified as rhyolite, those containing abundant plagioclase phenocrysts were classified as dacites, and those containing abundant microcline phenocrysts and subordinant numbers of quartz and plagioclase phenocrysts were classified as rhyodacites.

The dikes appear to have been emplaced episodically over a long span of time, and many of the dikes may be endogenous to the plutons they cut. The younger rocks, especially peralkaline granite, alkali-feldspar granite, and Hadn formation, tend to be cut by fewer dikes than the pre-Hadn rocks. This tendency suggests that many of the dikes were emplaced prior to and (or) contemporaneously with Hadn volcanic activity. Certainly, a consanguineous origin for some of the dikes and the Hadn volcanic rocks is suggested by similarities of phenocryst populations.

CENOZOIC ROCKS

Basalt

Basaltic flows and lapilli tuff (Tv) crop out over 2 km^2 about 5 km south of Jibal ar Rumman. Dense, black flows are interbedded with poorly indurated lapilli tuff. Lapilli consist of mostly blocks of vesicular to massive basalt. Deep erosion of the basalt suggests that the present outcrop is an erosional remnant of a more extensive deposit. The unit is tentatively assigned a Tertiary age because Kellogg (1983) reports potassium-argon ages of 15 to 20 Ma for remnants of basaltic flows that have undergone similar amounts of erosion.

Undifferentiated Quaternary deposits

Undifferentiated Quaternary deposits (Qu) are composed of colluvium, talus, flood plain and terrace deposits, and alluvium in channels too small to map. These deposits are extensive and completely cover the bedrock in large parts of the quadrangle.

Alluvium

Alluvium (Qal) consists of unconsolidated sand and silt that is actively being moved in large wadi channels. These sediments are generally lighter colored, better sorted, and more mature than the undifferentiated Quaternary deposits.

Playa lake deposits

Playa lake deposits (Qp) consist mostly of clay and fine silt deposited in small playa lakes. All of these deposits are less than 1 km^2 in size, and most are located in depressions along major wadi channels.

STRUCTURE

Structures in large parts of the Ghazzalah quadrangle are obscured by thin veneers of Quaternary deposits. To aid the following discussion, the inferred bedrock geology beneath the Quaternary and Tertiary units is shown on a simplified structural map (plate 3). Bedrock contacts are drawn through areas of extensive cover based on projections from well-exposed areas and on an interpretation of the aeromagnetic map produced under the supervision of the Bureau de Recherches Geologiques et Minieres (Consortium members, 1967). Hypothetical faults, entirely covered by surficial units and therefore not mapped on plate 1, are shown on the simplified map. Small dikes and intrusions have been omitted, and some units have been grouped for simplicity and clarity. With the cover subtracted, the distribution of basement units shows some order with respect to both age and lithology.

The structure of the quadrangle is dominated by intrusions of plutonic to hypabyssal granitic rocks. About 80 percent of the bedrock is inferred to be composed of plutonic or hypabyssal bodies. A weak correlation exists between the ages of the plutons and their shapes. The fact that some of the older granitic rocks (hqd, gd, mga) are irregular in shape and appear sandwiched between the younger units suggests that their outlines have been modified by the younger intrusions. In contrast, the younger granitic rocks (mgb, afg, pgr, and pga) tend to crop out as discrete, relatively equant plutons with outwardly convex contacts, or, in the case of the granophyre (gph), as elongate, arcuate, dike-like bodies. The Jufayfah syenogranite is a major exception, because, although it is one of the youngest granites, its shape is extremely irregular.

The oldest rock in the quadrangle, the Banana greenstone, is preserved as narrow, steeply dipping septa between and as inclusions within the granitic plutons. The greenstone locally contains a foliation, but exposures are too poor to accurately determine its extent, general trend, and continuity. The fact that available attitudes appear to roughly parallel contacts with large intrusions suggests that formation of the foliation was related to the emplacement of those plutons and is not regional in extent.

The Banana greenstone may be thought of as one component of a pre-Hadn basement, which also includes the hornblende quartz diorite, tonalite, biotite-hornblende granodiorite, pre-Hadn monzogranite, metagabbro, and magnetite syenogranite. The major unconformity at the base of the Hadn indicates that the "basement" was regionally uplifted and extensively eroded prior to Hadn time. Local irregularities along the unconformity and rapid lateral facies changes at the base of the Hadn suggest that the depositional surface was uneven with at least tens of meters of relief.

The Hadn formation is preserved as isolated fault blocks and roof pendants. Considered together, the attitudes in these separate blocks suggest a regional pattern of deformation. The Hadn dips generally to the north along the northern edge of the quadrangle; however, south of Jabal Ma'a, both the internal layering of the Hadn and its basal unconformity have a strong tendency to dip toward the southwestern flank of Jibal ar Rumman. A similar tendency for the Hadn formation to dip toward Jibal ar Rumman was noted by G. W. Leo (written commun., 1982) in the Al Awshaziyah quadrangle to the east.

All the Precambrian rocks are cut by an extensive network of faults. The network is dominated by northeast-trending faults designated the Saqf fault system after the best documented break, the Saqf fault, located in the northwestern corner of the quadrangle. Displacements along these faults appear to have involved large right-lateral components. The Saqf fault system has a well-developed topographic expression in the younger plutonic rocks, where the faults are marked by deep, linear valleys. A subordinate system of faults has a north to northwest trend. Offsets suggest that movement on these faults was more complex and had both dip-slip and possible left-lateral components. The two trends may represent a single conjugate set, but this possibility is difficult to assess, given the uncertainties in the inferred slip on the subordinate fault system. It should be noted that the Saqf fault system has both the appropriate orientation and sense of movement to be a conjugate system to the Najd faults (Schmidt and others, 1979), although the nearest major fracture that is correlated unequivocally with the main Najd zone is located 70 km southwest of the southwestern corner of the Ghazzalah quadrangle (Delfour, 1977).

METAMORPHISM

The effects of metamorphism are strikingly more pronounced in the Banana greenstone than in the Hadn formation. Mineral assemblages in the Banana greenstone indicate that those rocks were exposed to a regional, greenschist-grade metamorphic event. Although chlorite and epidote are present in minor amounts in the Hadn formation, the preservation of fine volcanic features suggests that the Hadn formation was only incipiently recrystallized in most places. Rather than being products of regional metamorphism, the epidote and chlorite in the Hadn may have been produced by autometamorphism during the volcanic activity that formed those rocks. The contrast in metamorphism between the two formations is consistent with their separation by a major unconformity.

GEOLOGICAL HISTORY AND GEOCHRONOLOGICAL CONSTRAINTS

The major late-Precambrian events in the Ghazzalah area are summarized as follows. (1) The Banana greenstone was formed during a period of dominantly basaltic to intermediate volcanism in an environment that was locally to entirely marine. The hornblende quartz diorite and metagabbro may have been the plutonic equivalents of some of the greenstone. (2) Large volumes of granodiorite, monzogranite, and syenogranite intruded the Banana greenstone and hornblende quartz diorite possibly during a prolonged magmatic episode. (3) The region was then uplifted and eroded, and (4) the Hadn volcanic and sedimentary rocks were subsequently deposited in a subaerial environment. (5) Magmatic activity, which continued during and after deposition of the Hadn, formed plutons and hypabyssal intrusions that range in composition from monzogranite to alkali-feldspar granite and peralkaline granite, and included minor amounts of gabbro. (6) After the cessation of most of the igneous activity, the region was deformed by the northeast-trending Saqf fault system and a subordinant system of northwest-trending faults.

No isotopic ages have been determined for any rocks from the Ghazzalah quadrangle. Therefore, ages must be inferred by correlation with rocks and events in nearby quadrangles where geochronologic constraints exist.

Three field trips to the Qufar and Al Qasr quadrangles have confirmed that the Banana greenstone is petrologically similar to the oldest rocks there, which have been termed the Nuf formation by Chevremont (1982) and Kellogg ( ). Chevremont (1982) suggests that the Nuf formation is a Hulayfah-age unit based on similarities to the Hulayfah group defined by Delfour (1977) in the Nuqrah quadrangle about 150 km southwest of Ghazzalah. The Banana greenstone is lithologically similar to the upper member of the Afna formation of the Hulayfah group, which is composed of andesitic and (or) basaltic flows and subordinate intercalations of andesitic tuff, breccia, agglomerate, and marble (Delfour, 1977). Delfour (1977) estimates an age of about 740 Ma for the Afna formation based on the oldest potassium-argon age from three different determinations made on those rocks.

Age estimates may be made for the tonalite, the Hadn formation, the Jufayfah syenogranite, and the peralkaline rocks by comparison to similar rocks in the Al Qasr quadrangle for which R. J. Fleck (written commun., 1982) has produced preliminary rubidium/strontium isotopic data. Data for a tonalite body in the southern part of the Al Qasr quadrangle suggest an age of about 630 Ma, although the data also allow interpretation of an age greater than 700 Ma. Therefore, the tonalite bodies in the Ghazzalah quadrangle may be on the order of 630 to more than 700 Ma in age. The data for the Hadn formation in the Al Qasr quadrangle yield a "best-fit" isochron corresponding to an age of about 613 Ma and an initial $^{87}Sr/^{86}Sr$ of 0.7034. The data for the Jufayfah syenogranite consist of five points that show some scatter; an isochron fitted to three points from one locality yields an age of 580 Ma. Fleck also reports that rubidium/strontium data for the Aja granite, which is mineralogically and chemically similar to the peralkaline granites in the Ghazzalah quadrangle (Stuckless and others, 1982/1983), yield an age of 583 ± 8 Ma. Stacey and others (1980) report a zircon age date of $\overline{5}70$ Ma for the Aja granite. Therefore, based on a correlation with the Aja granite, it seems likely that the peralkaline granite in the Ghazzalah quadrangle was emplaced at about 580 to 570 Ma.

The only records of Phanerozoic events are the Quaternary deposits and the Tertiary(?) basalts. Potassium-argon (K-Ar) ages of about 15 and 19 to 20 Ma are reported for two basaltic plugs in the Al Qasr quadrangle (R. J. Fleck, written commun., 1982). A similar K-Ar age of 23.4 Ma is reported by Kellogg (1983) for a remnant of a basaltic flow in the Qufar quadrangle.

COGENETIC IGNEOUS SUITES

Four suites of cogenetic rocks are tentatively proposed in the Ghazzalah quadrangle on the basis of field observations, petrography, and relative ages.

The oldest suite is made up of the Banana greenstone, metagabbro, hornblende quartz diorite, and tonalite. All of these units crop out in close association, and all are demonstrably pre-Hadn in age. Petrographic examination and radioactivity measurements suggest that the metagabbro and hornblende quartz diorite have appropriate bulk compositions to be plutonic equivalents of the Banana greenstone. Contacts between the hornblende quartz diorite and the greenstone locally are gradational in grain size. Textures and plagioclase compositions suggest that the tonalite could be a more leucocratic, though somewhat younger, phase of the hornblende quartz diorite. The available evidence, however, does not rule out the possibility that the plutonic rocks were intruded into a much older terrane of basalt and andesite.

A second, pre-Hadn suite is composed of the biotite-hornblende granodiorite and monzogranite (mga). A consanguineous origin for these rocks is strongly suggested by similar texture, similar mineralogy, similar age, and gradational mutual contacts. The magnetite syenogranite could be the most evolved member of this suite, but, in the absence of contact relationships and chemical data, that possibility cannot be evaluated.

The Hadn formation contains an enormous volume of volcanic rock that must have been associated with a major plutonic event. Primarily based on two arguments, it is suggested that the Hadn volcanic rocks, the granophyre, the alkali-feldspar granite, and the post-Hadn monzogranite may compose a single cogenetic suite. First, the phenocryst assemblages in the Hadn formation suggest that the bulk compositions of the different layers range from rhyolite to dacite, and that a volume-weighted plutonic equivalent might approximate syenogranite or monzogranite. Indeed, the compositions of plagioclase phenocrysts in the Hadn overlap with the compositions of plagioclase in the monzogranite. Second, gradational relationships appear to exist locally between some of these units. The fact that the monzogranite and alkali-feldspar granite both show variations in modal mineralogy suggests that they may grade into one another. The granophyre and alkali-feldspar granite are mutally intrusive. Rhyolite, which may be part of the Hadn formation, grades downward into granophyre at lat 26°34' N., long 40°59' E. The granophyre, in turn, grades downward into a coarse-grained granite.

A four-part model is suggested to relate the above units. First, some of the granophyres are the hypabyssal equivalents of the Hadn volcanic rocks. Second, the alkali-feldspar granite and monzogranite constitute the plutonic equivalents of the Hadn. Third, the intrusion of monzogranite and alkali-feldspar granite into the Hadn occurred as those rocks advanced upward into their own volcanic pile. Fourth, the mineralogic variations in the plutonic rocks may reflect changes in melt composition due to fractional crystallization or, in some cases, may reflect differences in H_2O concentration and confining pressure during crystallization. It is well documented experimentally that the one-feldspar crystallization field for melts of granitic composition decreases in size with increasing P_{H_2O}. Therefore, starting with the similar magma compositions, the two-feldspar granite may have crystallized under conditions of high P_{H_2O}, while the one-feldspar alkali-feldspar granite may have crystallized under conditions of low P_{H_2O}.

The Ba'gham intrusive complex, the Rumman granite, and the arfvedsonite granite may constitute a post-Hadn cogenetic suite. All of these rocks are young, highly radioactive (table 1), and have a similar mineralogy that indicates peralkaline affinities. The Jufayfah syenogranite could belong to this suite; this association would be consistent with its young age and its high radioactivity.

ECONOMIC GEOLOGY

The only demonstrated zones of potential economic significance in the Ghazzalah quadrangle are associated with peralkaline granite plutons. If the Banana greenstone correlates with the Hulayfah group (Delfour, 1977), then it may have potential for volcanogenic sulfide deposits. However, in the absence of ancient workings and gossanous rock (Hummel and others, 1966; C. W. Smith, oral commun., 1982), this potential seems limited.

Jibal Ba'gham radiometric anomalies

The vicinity of Jibal Ba'gham shows the greatest potential for mineralization in the quadrangle. The airborne magnetometer-scintillation counter survey of sheet 61 (Consortium members, 1967) delineates several radiometric anomalies near Jibal Ba'gham that range from 2 to 3 times background level. More recently, a number of small but intense radiometric anomalies were discovered by the author in the Jibal Ba'gham peralkaline granite.

Approximately 3 days were spent by the author and C. W. Smith (USGS) studying the size and distribution of the Jibal Ba'gham radiometric anomalies and collecting samples for geochemical analysis. An additional 3 days were spent by the author with J. S. Stuckless (USGS) collecting samples for isotopic and geochemical analysis. Anomalies were located by a helicopter-borne scintillation counter survey, using an uncalibrated Geometrics GR-101A total-count scintillometer flown at an elevation of about 10 to 15 m above ground level. The results of the survey and the locations of rock and soil samples are shown in figure 5. Geochemical analyses for uranium (U), thorium (Th), and rare-earth elements (REE) are presented in table 2. The origin of the radioactive anomalies appears to be complex; at least 4 different types of anomalies were apparently produced by several different processes.

Field relations

Ground investigation discovered radiometric anomalies that ranged from 150 to 20,000 cps. All of the anomalies greater than 300 cps are small, isolated zones that rarely exceed a few meters in size.

Brick-red, irregular granophyric zones contain anomalies with radioactivity levels in the range of 150 to 2,000 cps (192341 and 147879). Broad highs of 150 to 250 cps extend over tens to hundreds of square meters near the eastern margin of the pluton. Intense anomalies of 1,000 to 2,000 cps are associated with small (0.5-2 m) pegmatitic zones in the granophyre that contain abundant, red, euhedral zircon. These anomalies appear to be primary igneous features that formed during crystallization of the granophyric zone late in the magmatic evolution of the complex.

Rare pegmatite pods (147872) have radioactivity levels of less than 400 cps. Pods are elliptical to irregular in shape, generally less than 0.5 m across, and composed mostly of quartz and amphibole with minor hematite ± fluorite. The pods occur in clusters rather than uniformly throughout the pluton. Pods are commonly surrounded by radiating fractures. The textures and mineralogy suggest that these anomalies are late-stage magmatic features that may be similar to the thorium-rich pegmatitic dikes in the Jabal Aja pluton about 50 km to the north (Matzko and Naqvi, 1978).

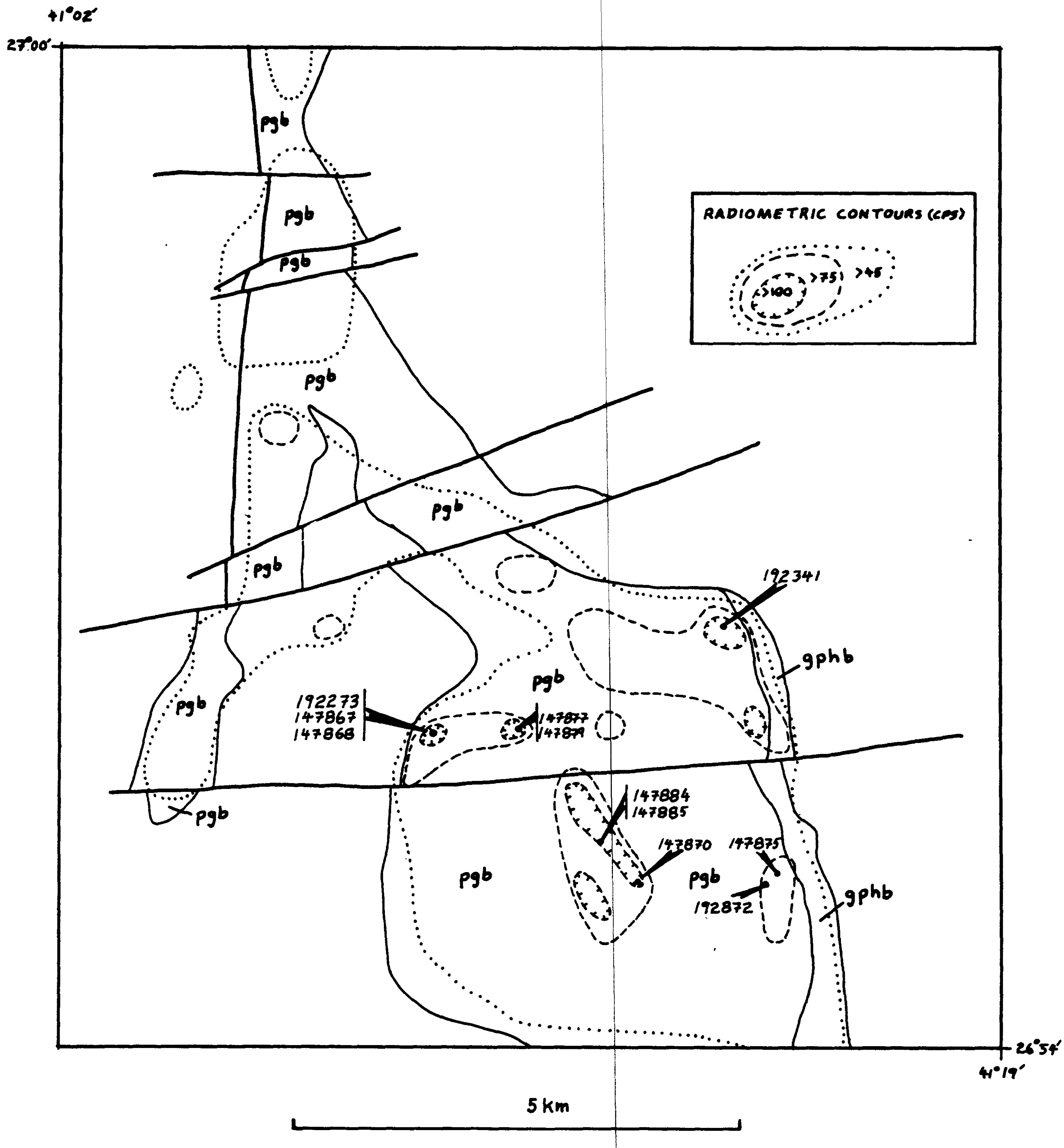

Figure 5.--Geologic sketch map showing the contacts (solid lines) of the Jabal Ba'gham peralkaline granite (pgb) and granophyre (gphb), faults (heavy lines), radiometric contours, and the locations of samples listed in table 2. See text for explanation of radioactivity levels. Sample prefix 192-, collected by the author; prefix 147-, collected by C. W. Smith (USGS).

Table 2.--Radioactivity in counts per second (cps) and concentrations of uranium, thorium, and rare-earth elements in the Jibal Ba'gham peralkaline pluton [Leaders (--), not recorded. Sample locations shown on figure 5]

Sample no. (cps)	192273 10k+	192341 1000	147867 1600	147868 1600	147870 1200	147872 400	147875 2000	147877 >10k	147879 --	147884 400	147885 500
Elements (in ppm)											
U	519	62	177	242	181	<10	200	578	477	225	250
Th	44,317	734	385	1,114	3,263	97	778	51,352	225	<20	244
La	21	97	110	47	150	2,425	135		40	130	120
Ce	232	148	170	40	270	4,254	280	1,195	160	160	160
Pr			70	40	90	920	70		35	100	70
Nd			98	42	150	1,940	108		36	119	116
Sm			40	20	60	430	42		20	55	45
Eu			51	36	54	226	104		14	82	45
Gd			73	34	133	860	80		26	165	90
Tb			217	92	272	684	220		24	769	260
Dy			329	194	436	1,175	595		77	791	334
Ho			46	25	57	17	42		24	132	53
Er			169	71	255	697	178		37	541	201
Tm			43	17	65	186	46		<10	55	55
Lu			<10	<10	16	75	<10		<10	<10	<10

Sample descriptions

192273--Ferruginous, red cake of amorphous material within a red granite. Pod is located in a N- to N10E-trending hematite-rich fracture system about 10 cm wide; cut by hematite-coated fractures with a dominant trend of N to N10E

192341--Red granophyre

147867--Coarse-grained red granite cut by numerous hematite-rich fractures

147868--Zone of bleached granite about 40 m across. Radioactivity 800 to 1,000 cps with local highs of about 1,600 cps

147870--Granite cut by hematite-rich fractures trending S10E; fracture set about 1 to 2 m wide and 30 m long

147872--Pegmatite pod about 1 m across in coarse-grained granite; pod is about 70 percent quartz and 25 percent amphibole with minor hematite and fluorite

147875--Red soil; apparently a lag deposit in a small depression located at the convergence of a radiating hematite-rich fracture set

147877--Dark-brown to black, organic-rich(?) soil; apparently a lag deposit in a small depression on the granite. Granite in vicinity contains scattered pegmatic pods similar to 147872

147879--Red granophyre

147884--Hematitic quartz vein up to 10 cm wide and trending about N75W; appears to predate jointing

147855--Fine-grained, granophyric zone trending E-W and containing moderate hematite staining

Hematite-rich fractures and veins in the granite (192273, 147867, 147870, and 147884) locally have radioactivity levels in the range of 250 to more than 10,000 cps. Anomalies range in size from meters to tens of meters, and commonly are elongate parallel to a fracture system. Fractures are typically less than 1 mm wide, whispy, and coated with a thin layer of dark-red hematite(?). The orientations of the fractures are locally variable, but a northerly trend is common. Less abundant veins are as much as 10 cm wide and filled by quartz and hematite. One especially intense anomaly (192273) was associated with a 7- to 8-cm-wide cake of amorphous, ferruginous material within one of these fracture systems. The cake was located within a 10-cm-wide zone of predominantly north-trending joints. Small fractures in the granite radiate from the cake in a manner that is similar to the fractures associated with many pegmatite pods. This relationship suggests that the cake may be an intensely oxidized and metasomatized pegmatite pod. The association with hematite veins and the petrographic evidence for replacement of amphibole by magnetite and (or) hematite suggest that the above anomalies were formed by highly oxidizing fluids. The fluids may have been late-stage magmatic fluids or, alternatively, meteoric in origin.

Intense radioactive anomalies in the range of 2,000 to more than 10,000 cps are associated with rare, small (<1 m), soil-filled depressions in the granite bedrock (147875 and 147877). The source of the radiation is a red to dark-brown or black soil. The black soils appear to be rich in organic matter. In the case of sample 147875, the fact that the deposit formed at the intersection of a set of radiating ferruginous fractures suggests that it may have been an erosional lag deposit above either a pegmatitic pod or ferruginous cake. Indeed, sample 147877 was collected in an area where pegmatitic pods are relatively abundant. This type of anomaly may be Quaternary in age.

Chemistry

The data in table 2, taken at face value, indicate that there is wide variation in uranium (U), thorium (Th), and rare-earth element (REE) abundances in the Ba'gham intrusive complex. All analyses indicate subeconomic concentrations of these elements in view of the sizes of the anomalies (Nash and others, 1981; C. W. Smith, oral commun., 1982).

Several observations about the data that warrant consideration. During normal igneous processes, U and Th have similar geochemical behavior, and the Th/U ratio tends to be restricted to a narrow range of about 3 to 15 in most igneous rocks (Larsen and Phair, 1954; Nash and others, 1981). Obviously, the two elements must be separated geochemically to form thorium-free pitchblende ores (Larsen and Phair, 1954), and, if such a process has occurred, then the Th/U of the rocks must be disturbed. In Jibal Ba'gham, U is not correlated with Th and, in fact, there is an extreme range in the Th/U ratio. Extremely high Th/U ratios of 80 to 100 were found for the pegmatitic pods, the ferruginous cake, and the lag deposits. In contrast, low Th/U ratios of less than 1 were found in some of the granophyres and hematite-rich veins. Neither U nor Th appear to correlate with REE. This last observation is disconcerting and could reflect major analytical error. With this caveat in mind, the following discussion is presented.

The separation of U and Th could be explained by localized nucleation of phases, which exclude one or the other element, during the crystallization of the granite. For example, crystallization of thorite in the pegmatitic pods may have excluded U and concentrated Th. More complete documentation of the mineralogy of the complex is required to evaluate this possibility. This process does not, however, account for the fact that the rocks with the highest U and U/Th (147867, 147879, 147884, and 147885) have rather mundane concentrations of REE.

It is suggested that the peculiar distributions of U and Th in the Jibal Ba'gham granite reflect extremely oxidizing conditions late in the magmatic history of the complex. The presence of abundant hematite-rich veins and the replacement of amphibole by magnetite suggest late-stage oxidation. It is hypothesized that U was oxidized from the tetravalent to the hexavalent state and separated from Th and REE late in the magmatic history of the complex (Larsen and Phair, 1954). This oxidation and separation would explain the apparent correlation of anomalous U-concentration with late-stage granophyre and hematite-rich veinlets.

Jibal ar Rumman pluton

The airborne magnetometer-scintillation counter survey (Consortium members, 1967) identified several radiometric anomalies within the Rumman granite. All of the anomalies are two times background. No geological evaluation of the anomalies has been performed. The source of the anomalies may be similar to those in the Ba'gham granite.

Spectrographic analyses

Fourteen samples of quartz veins, concretionary chert from the Hadn formation, and granite that showed evidence of alteration were submitted for semiquantitative spectrographic analysis. The only results of economic interest were from samples from the vicinity of Jibal Ba'gham. A vein composed of coarse-grained hematite and quartz (192281) contained about 2,000 ppm zinc and 150 ppm tin. A hematite-free quartz vein (192285) and a hydrothermally altered and sheared outcrop of Ba'gham peralkaline granite (192269) both contained about 1,500 ppm zinc.

Wadi sediment samples

Jibal Ba'gham and Jibal ar Rumman also appear to be the sources of base metal and other elemental anomalies in the wadi sediment samples. M. D. Fenton and C. W. Smith (written commun., 1983; USGS, unpub. data) report anomalous amounts of tungsten, tin, lead, zinc, niobium, lanthanum, beryllium, yttrium, and zirconium in heavy mineral concentrates from wadi sediments in the Jibal Ba'gham area. Smith (written commun., 1983) reports anomalous concentrations of tin, lead, niobium, and yttrium in heavy mineral concentrates from Jibal ar Rumman.

Gravel

Gravel was being mined for local use about 6 km northeast of Al Mahash during 1982.

DATA STORAGE

The Jibal Ba'gham radioactive anomalies and the gravel deposit northeast of Al Mahash have been reported to the Mineral Occurrence Documentation System (MODS) data bank and will be assigned unique five-digit numbers. Inquiries regarding this data bank may be made through the Office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah.

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