DEPARTMENT OF THE INTERIOR
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# Reconnaissance geology of the Rak quadrangle, 27/42 C, Kingdom of Saudi Arabia

by

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RECONNAISSANCE GEOLOGY OF

THE RAK QUADRANGLE, 27/42 C,

KINGDOM OF SAUDI ARABIA

by

Karl S. Kellogg [1]

## ABSTRACT

The Rak quadrangle, located along the margin of the northern Precambrian Shield of Saudi Arabia, about 30 km southeast of the city of Ha'il, is underlain by rocks of three distinct geological provinces. Under the central and western portion of the quadrangle are upper Proterozoic volcanic and intrusive rocks of diverse composition. The northern third of the quadrangle is underlain by the Cambrian and Ordovician Saq Sandstone. A Quaternary and possibly Tertiary alkali-olivine basalt field, consisting of flows, tuff rings and cinder cones, crops out prominantly in the southeastern part of the quadrangle.

The oldest rocks comprise the Nuf formation, a layered and deformed sequence of metabasalt, meta-andesite, metadacite and metarhyolite and minor marble that may correlate with rocks mapped as Hulayfah group (approximately 740 Ma old) to the southwest. Gabbro and minor ultramafic rock intrudes probably genetically related rocks of the Nuf formation. The emplacement of large quartz diorite plutons probably commenced about 680 Ma ago. Large volumes of plutonic rocks of approximately monzogranite composition, probably about 620 Ma old, intruded and partially dismembered the Nuf formation, gabbro and diorite, which were subsequently metamorphosed to greenschist facies and internally deformed.

Sometime after about 590 Ma ago, rhyolitic ash flow tuffs of the Qarfa formation were deposited in response to the rise of a highly evolved alkali magma under what is now Jabal Salma. Caldera collapse resulted in generally inward dips on the rhyolite and the intrusion of peralkaline granite along the ring fracture. Rise of a metaluminous magma under the central region of the caldera resulted in the emplacement of a large body of biotite syenogranite, which comprises most of the rugged mountain massif of Jabal Salma. Venting of the partially crystallized magma chamber was probably responsible for quenching the residual liquid, producing sheets and masses of granophyre. A diabase dike swarm and a small monzogranite stock mark the last Proterozoic intrusive events in the quadrangle.



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Apparent right-lateral faulting along north-east trends (Saqf fault system) displaced rocks of the Salma granite complex. These faults may form a conjugate set with the northwest trending, left-lateral Najd faults that are prominantly developed to the southwest of the quadrangle.

North- to northwest-trending faults also cut both Precambrian rocks and the Saq Sandstone, and follow older structural trends in the Nuf formation.

No economic mineral occurrences were observed in the Rak quadrangle, although the Akash granite in the extreme northwest corner of the quadrangle is identified as containing higher than normal amounts of a tin, tungsten, and zinc. The Salma granite complex has also been noted as containing anomalously high concentrations of tungsten, molybdenum, uranium, thorium, niobium, and rare earth elements.

# INTRODUCTION

## Geographic setting

The Rak quadrangle occupies a 2750 $km^2$ area bounded by lat 27°00'N and 27°30'N and long 42°00'E and 42°30'E in the northeastern part of the Precambrian Shield of Saudi Arabia. The most striking geographic feature in the area is the granite complex of Jabal Salma, an arc of rugged mountains in the southwest and central parts of the quadrangle. The southeastern part of the quadrangle is notable for a north trending line of cinder cones, tuff rings, and basalt flows. Wadi al 'Ish, which drains northeast along the northwest side of Jabal Salma, is the largest drainage in the quadrangle, and occupies a wide sandy channel.

Ha'il, 30 km to the northwest of the quadrangle, is the nearest city, although a number of villages occur in the region. The largest villages in the quadrangle are Al Jihfah and Ash Shinan. Two other villages, An Na'i and Tabah, occupy the crater floors of large tuff rings (pl. 2). The district of Rak encompasses seven villages (including the village of Rak) in the central part of the quadrangle, on the north side of Jabal Salma. Numerous water wells are tapping a rapidly lowering water table (Ha'il Regional Planning Office, oral commun.) and the area under cultivation is increasing yearly. During 1982, the drawdown on the water table underlying the villiage of Tabah caused subsidence and minor earthquake activity, a matter of some concern to the local inhabitants.

The major highway between the cities of Ha'il and Buraydah crosses the center of the quadrangle, and in 1983, several other highways in or near the quadrangle were being paved. Numerous unpaved desert tracks provide access to large parts of the quadrangle area.

## Previous investigations

The first and only previously published geological map of the area was produced by Bramkamp and others (1963) at a scale of 1:500,000. Most subsequent geological work in the area has been of a topical nature. Mytton (1970) performed a reconnaissance geochemical study of the area in which anomalous tungsten and molybdenum values associated with the Salma granite complex were identified. Chevremont (1982) has prepared a preliminary report of the Jabal Nuf area, just west of the quadrangle, with a sketch map which straddles the quadrangle's northwest boundary. Chevremont's report describes a mafic and ultramafic complex which locally includes chromium- and nickel-bearing serpentinite. Stuckless and others (1982) have assessed the uranium favorability of post-orogenic granites of the northeastern shield, including those of the Salma granitic complex. They include 15 whole rock chemical analyses from granites in the Rak quadrangle.

Dating of the Salma granitic complex has been undertaken by Aldrich (1978), who reports a rubidium-strontium model biotite age of 575 Ma and a potassium-argon biotite age of 590 Ma.

Greenwood (1972) points out that the northeastern Shield occupies the axis of a broad north-south trending arch (the "Ha'il arch") that initially developed in pre-Permian time. Subsequent deformation along the same axis occurred in Late Cretaceous and Tertiary time, and outpourings of Tertiary alkali-olivine basalt, with vents oriented also along north-south trends, reflect this period of tensional stress.

Mapping at 1:100,000 scale in the region of Rak did not begin until 1981. The Qufar quadrangle (27/41 D), to the west of the Rak quadrangle, was mapped by Kellogg (1983). Leo (unpub data) mapped the Al 'Ashaziyyah quadrangle (26/41 B) to the southwest, and Pallister (unpub data) mapped the Harrat Hutaymah quadrangle (26/42 A) to the south.

## Present investigations

Field work for this report was done during April and May, 1983, using surface vehicles from a camp located at 27°15'N and 42°15'E. Two days of field checking were done by helicopter. For correlation purposes, a Scintrex hand-held scintillometer was used to measure gamma radiation at each outcrop. Classification of plutonic and volcanic rocks is according to the systems of Streckeisen (1976, 1979). Special thanks is extended to J. S. Pallister for his comments in the

field and in the office, and to A. H. Al Basli for his help in making modal counts of stained slabs of granitic rocks. R. G. Greene and E. H. Pampayan made very useful and thoughtful reviews of the manuscript.

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## GEOLOGIC SETTING

The Raq quadrangle is in the extreme northeastern corner of the Precambrian Arabian Shield (fig. 1), and straddles the contact between Precambrian rocks and the Cambrian and Ordovician Saq Sandstone. The first map of the area (Bramkamp and others, 1963) recognized the existence of north-south belts of "felsitic andesite" of the Halaban formation in the northwest part of the Rak quadrangle. They also recognized that the "felsitic andesites" were intruded by a large volume of highly dike-injected, biotite-hornblende granite. In addition, they determined that the large, oval-shaped late granites in the area, such as the granite underlying Jabal Salma, were at least in part peralkaline. Although recent mapping has refined and improved the geologic picture of the northeastern Shield, this early work of Bramkamp and others (1963) provides a good general setting for the geology of the region.

Extensive terranes of moderately metamorphosed mafic to intermediate volcanic, volcaniclastic and carbonate rocks of the Hulayfah group, which include rocks formerly mapped as Halaban formation by Brown and others (1963), exist within 200 km southwest of the Rak quadrangle, and have been dated at approximately 740 Ma (Delfour, 1977). Mapping in the northeastern Shield has shown that Bramkamp and other's (1963) "felsitic andesites" consist of a generally north-south belt of predominantly metabasaltic to metadacitic rock (the Nuf formation of this report). These rocks crop out in a region to the west of the Rak quadrangle (Kellogg, 1983), extend into the area for this report, and are the oldest in the region.

Large quantities of calc-alkaline monzogranite and granodiorite were emplaced in the northeastern Shield about 620 Ma ago (C. E. Hedge, oral commun.). In the Rak quadrangle, the Dhiyyab granite, a probable member of this assemblage, clearly postdates metagabbro and dioritoid rocks, and underlies extensive pediments both north and south of the Salma granite complex.

The northern Shield has long been noted for thick sequences of rhyolites and rhyolitic hypabyssal rocks

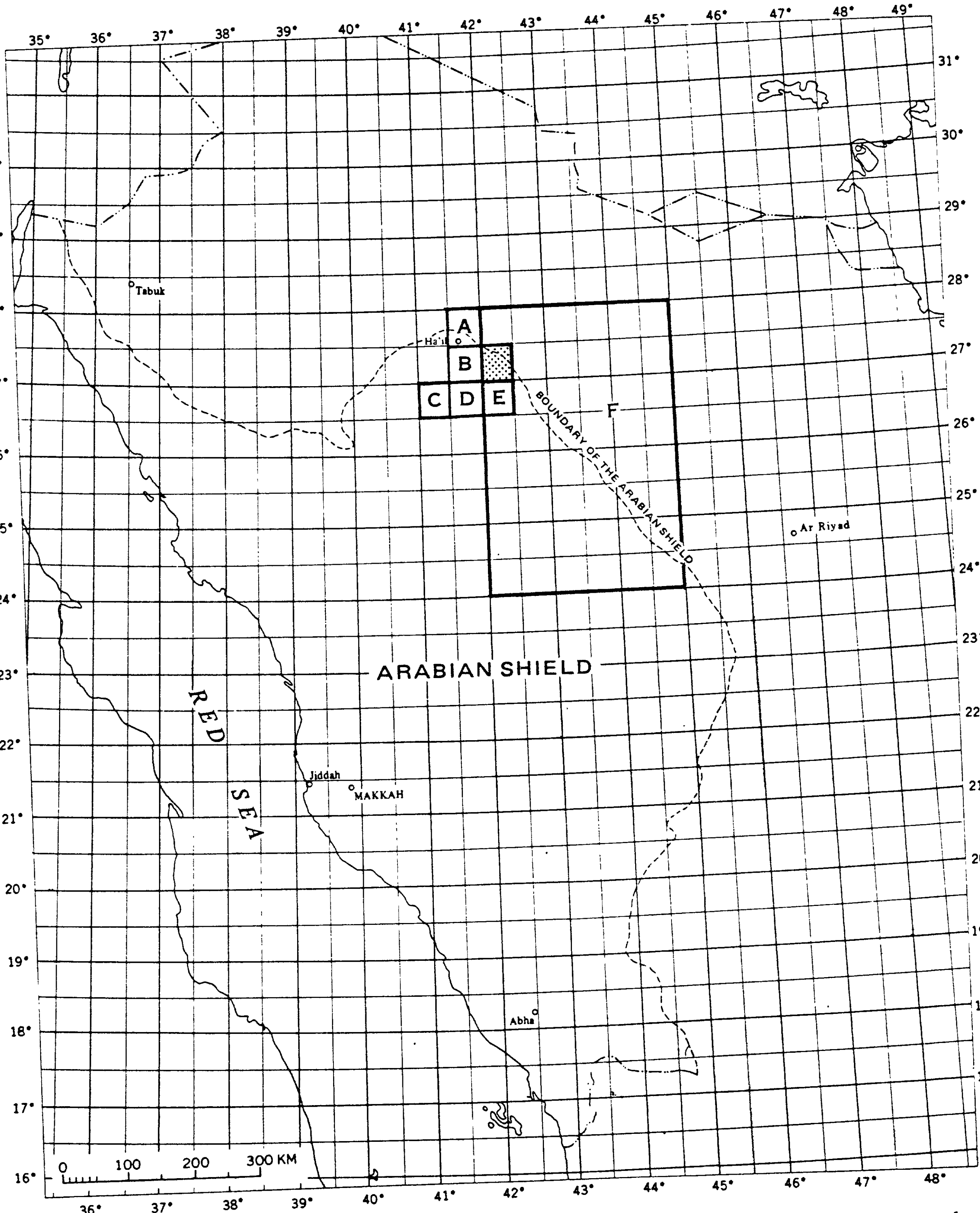


Figure 1.--Index map of western Saudi Arabia showing location of the Rak quadrangle (stippled) and other quadrangles referred to in this report: A, Ha'il (Kellogg and Stoeser, unpub. data); B, Qufar (Kellogg, 1983); C, Ghazalah (Quick, 1983); D, Al 'Awshaziyah (Leo, unpub. data); E, Harrat Hutaymah (Pallister, 1983); F, Wadi ar Rimah (Bramkamp and others, 1963).

iginally named the "Shammar rhyolite" (Brown and Jackson, 60; Brown and others, 1963; Bramkamp and others, 1963), and nce referred to as the "Shammar group" (Hadley, 1973). etailed mapping during 1981 and 1982 has revealed that many f these rhyolites are intimately associated with the calc-lkaline granites. Quick (1983) and Kellogg (1983) have hown that rhyolitic volcanic and sedimentary sequences of he Hadn formation, suspected to be about 613 Ma old on the basis of a Rb-Sr isochron established from rather scattered data (R. J. Fleck, written commun.), postdate some of the calc-alkaline granites but predate others. Mapping for the Rak quadrangle has also demonstrated the existence of a thick sequence of rhyolitic ash-flow tuffs and minor trachytes and conglomerates named the Qarfa formation, on the east side of Jabal Salma. It is evident, however, that the rocks of the Qarfa formation are considerably younger than those of the Hadn formation.

Beginning sometime after about 590 Ma ago, large oval alkalic to peralkalic granite complexes, including the Salma granite complex, were emplaced in the northeastern shield. The largest of these in the region underlie the rugged mountain massifs of Jabal Aja, near Ha'il, and Jabal Salma. Granite from the core region of Jabal Salma has been dated at about 580 Ma (Aldrich, 1978). The emplacement of these large granite complexes marked the last major intrusive event before the onset of extensive erosion, peneplanation and platform sedimentation.

The opening of the Red Sea in the middle Tertiary Period commenced with a broad uplift of the whole Arabian-Nubian region, and the thick cover of Cambrian and younger sediments were eroded from much of the area. In the northeastern Arabian Shield, a broad north-trending upwarp (the "Ha'il arch") produced the prominent embayment into the overlying Paleozoic and younger rocks (Greenwood, 1974). Late Tertiary to early Quaternary alkali-olivine basalts erupted along the crest of the Ha'il arch in response to extensional stress, producing numerous flows, cinder cones, and tuff rings.

## PRECAMBRIAN METAVOLCANIC, VOLCANIC, AND SEDIMENTARY ROCKS

### The Nuf formation

The Nuf formation was named by Chevremont (1982) to describe a sequence of metamorphosed mafic volcanic rocks ("amphibolites") that occur in the vicinity of Jabal Fitiq, a mountain which had been incorrectly named Jabal Nuf on the map of Brown and others (1963). Jabal Fitiq is a prominent peak that occurs about 5 km west of the quadrangle boundary, just south of the Ha'il-Buraydah highway, while Jabal Nuf is a prominent peak that occurs about 12 km further west of al Fitiq. Kellogg (1983) retained the name Nuf formation his description of the rocks in the Qufar quadrangle. It here proposed that the type locality for the Nuf formation along the northwest side of Jabal Fitiq, north to the 'il-Buraydah highway.

The Nuf formation comprises the oldest rocks in the Rak adrangle, and is composed of metamorphosed basalt (locally llowed), meta-andesite, metadacite, metarhyodacite, and inor marble. Sparse metagraywacke within the rocks of the uf formation has been mapped in the Qufar quadrangle Kellogg, 1983), but has not been observed in the Rak uadrangle. The environment of deposition for these rocks as probably subaqueous. The Nuf formation is intruded by numerous basaltic to rhyolitic dikes and sills that are not indicated on plate 1. Quartz veins and pods, some of which are shown on plate 1, are also common.

The Nuf formation defines a northerly-trending belt in the northwestern part of the quadrangle. Steeply dipping, weak to moderate foliation is generally parallel to this trend, and a well-developed fracture cleavage, probably representing an axial-plane cleavage, is commonly parallel to the foliation. Bedding planes are too poorly preserved to define mappable folds. The lack of recognizable bedding and the presence of numerous faults (most of which are oriented north, parallel to the trend of foliation) makes it almost impossible to estimate the thickness of the Nuf formation, although it is suspected to be in excess of several kilometers.

Metamorphic grade among the rocks of the Nuf formation is predominantly greenschist facies, although it has locally reached upper greenschist facies or lower amphibolite facies, as demonstrated by assemblages of secondary epidote, coarse green amphibole and calcium-bearing plagioclase.

Gabbro and ultramafic rock intrudes the Nuf formation, but petrologic similarities, and the spatial proximity of the gabbro to the Nuf formation suggust that the intrusive rocks may represent the intrusive equivalent to the Nuf formation.

Two members of the Nuf formation have been mapped, a metabasalt and meta-andesite member (nab) and a metadacite and metarhyodacite member (ndc).

### Metabasalt and meta-andesite member

The metabasalt and meta-andesite member (nab) contains massive to moderately foliated, black and dark-gray to dark greenish gray, aphyric to plagioclase- and rarely quartz-phyric, fine-grained metabasalt and meta-andesite. Pillow structures are common in the metabasalts, although layering is rarely visible. Primary mineralogy includes plagioclase, clino- and orthopyroxene, hornblende, and opaques. Upper greenschist facies metamorphism is indicated by the secondary growth of actinolite, ±biotite, ±quartz, ±epidote, and ±calcite. The secondary actinolite defines prisms up to 0.5 cm, and biotite, where present, is aligned parallel to foliation. Primary pyroxene is almost completely altered to fibrous actinolite. Secondary quartz stringers and lenses are common, and the rock has been locally sheared along predominantly north-south directions. More common than shearing, however, is a weak to moderate foliation defined by the alignment of metamorphic minerals. The rocks of the metabasalt and meta-andesite member weather to areas of low to moderate relief, and form a distinctive gray to black regolith, commonly scattered with lag quartz from eroded quartz veins.

No evidence has been found in the Rak quadrangle which suggests the relative age of the metabasalt and meta-andesite member to the metadacite and metarhyodacite member, although to the west of the Rak quadrangle, on Jabal Fitiq, a metadacite sequence appears to overlie the metabasalt and meta-andesite member (Kellogg, 1983). The metadacite and metarhyodacite member is therefore placed stratigraphically above the metabasalt and meta-andesite member.

### Metadacite and metarhyodacite member

The metadacite and metarhyodacite member (ndc) of the Nuf formation consists of a light- to dark-gray and tan to dark-brown, fine-grained, porphyritic meta-andesite, metadacite and metarhyodacite. These rocks contain plagioclase and local quartz phenocrysts, typically to 3 mm long. The groundmass contains plagioclase, quartz, biotite, opaques, sericite, apatite, ±potassium feldspar, and ±epidote. Lithic fragments and shard structures can rarely be identified in hand specimen, and are conspicuous in some thin sections, indicating that many of these rocks are tuffs. The rock is weakly to moderately foliated, although bedding attitudes are rarely observed. The rock weathers to a light tan to gray, highly fractured and cleaved rock that crops out in low relief. Numerous basaltic to rhyolitic dikes and sills intrude this unit.

### Nuf formation, undivided

A few areas underlain by undetermined rocks of the Nuf formation are mapped as Nuf formation, undivided (nu).

## Qarfa formation

The Qarfa formation is named after the village of Al Qarfa, which lies at the foot of a hill composed mostly of rhyolitic flows. The type locality for the Qarfa formation is proposed for a homoclinal sequence of rhyolitic flows that crop out on a prominent hill immediately east of the village of Al Jihfah.

The Qarfa formation consists predominantly of a thick sequence of porphyritic rhyolite (qr), subordinate trachyte (qt), and sparse volcanogenic conglomerate (qc). A steeply dipping, probable basal contact is exposed 3 km west of the village of Qarfa, where rhyolite porphyry overlies a silicified hornblende-biotite monzogranite grus, which is correlated with the Dhiyyab granite.

All rocks of the Salma granite complex intrude the Qarfa formation, although textural and lithologic similarities, as well as an intimate spatial association, of the porphyritic rhyolite and the quartz syenite porphyry (syp) indicate that the latter unit is in part the intrusive equivalent to the porphyritic rhyolite.

The thickness of the Qarfa formation is unknown, as the stratigraphic top of the unit has not been observed. A minimum thickness of approximately 0.7 km has been measured in the ridge just east of Al Jihfah, although the total thickness may be considerably greater than this. Except in the north, near the villiage of Qarfa, layering in the Qarfa formation is conspicuous, and flow units vary in thickness from several meters to greater than 25 m.

Rhyolite porphyry

The rhyolite porphyry (qr) is somewhat variable in composition and texture, and includes massive rhyolite porphyry, rhyolitic agglomerates, and rhyolitic ash-flow tuffs with well-preserved eutaxitic structures. The rock is pinkish-brown to brown ("chocolate"), and contains between 10 and 50 percent phenocrysts of potassium-feldspar, albite and quartz. The potassium feldspar is pink, euhedral, and up to 0.5 cm long, equant quartz is subhedral and up to 0.3 cm long, and the albite, where it occurs, is distinctive as gray, subhedral to euhedral phenocrysts up to one cm long. The groundmass is aphanitic to fine-grained hypidiomorphic granular, and contains potassium feldspar, quartz, magnetite, ±albite, ±green to dark blue green amphibole, ±clinopyroxene, and traces of zircon and apatite. The presence of opaque-rimmed arfvedsonite and aegerine-augite distinguishes at least some of the flows (notably on the ridge just east of Al Jihfah) as comenditic (peralkaline rhyolitic). Biotite is absent in all observed flows. Alteration is minimal, and consists of spongy intergrowths and rims of opaques after ferromagnesian minerals, and traces of epidote, calcite and an unidentified fibrous orange mineral (hematite-stained chlorite?).

The rhyolite porphyry weathers to a reddish-brown, ledgy, fractured rock that locally acquires a black desert varnish.

### Clinopyroxene trachyte

One isolated hill composed of steeply south-dipping dark-brown (reddish-brown weathering) clinopyroxene trachyte (qt) flows occurs in the south-central part of the quadrangle. The rock is fine-grained, holocrystalline, and slightly porphyritic. Cloudy plagioclase has developed as lath-shaped phenocrysts to 8 mm and as microlites in the matrix. Approximately half of the feldspar microlites, which comprise about 70 percent of the rock, are potassium feldspar. The rest of the rock is composed of 10 to 20 percent clinopyroxene, 5 percent opaque, and trace amounts of epidote and quartz.

### Conglomerate

One 100 m section of steeply dipping volcaniclastic conglomerate (qc), interbedded with rhyolite porphyry, is mapped 3 km south of the village of An Na'i. The clasts are well-rounded, matrix supported, up to 70 cm in diameter, and consist entirely of rhyolite porphyry derived from the erosion of the Qarfa formation rhyolites. The 70 to 80 percent matrix is grayish-green, poorly sorted, medium to coarse-grained lithic graywacke (Pettijohn, 1957).

## PRECAMBRIAN INTRUSIVE ROCKS

### Samra intrusive suite

Chevremont (1982) coined the term "Ha'il mafic-ultramafic complex" to describe an assemblage of serpentinite, metagabbro ("amphibolite"), and mafic layered rocks of the Nuf formation that crop out in and near the northwest corner of the Rak quadrangle. Chevremont interpreted these rocks to be a part of a dismembered ophiolite complex. Kellogg (1983) defined the term "Samra intrusive suite" to include only the intrusive rocks of Chevremont's Ha'il mafic and ultramafic complex. The Samra intrusive suite includes the oldest known intrusive rocks of the region.

### Metapyroxenite

Several small hills of metapyroxenite (px), surrounded by metagabbro and metavolcanic rocks of the Nuf formation, are mapped in the northwest corner of the quadrangle. In hand specimen, the rock is black, medium to coarse grained, equigranular, with a slight resinous luster. Microscopic examination reveals that the rock is composed of a fibrous intergrowth of fine-grained, pale-green to non-colored actinolitic amphibole pseudomorphous after pyroxene, and a few percent clots of rod-like opaques (ilmenite?) and epidote. Sparse hematite-actinolite-epidote intergrowths are probably pseudomorphous after olivine. No quartz or plagioclase is noted in the rock. This unit outcrops as a highly fractured black rock with grayish-white regolith.

The metapyroxenite intrudes both the metabasalt and meta-andesite member and the metadacite and metarhyodacite member of the Nuf formation, and is suspected to be genetically related to metagabbro.

## Metagabbro

Metagabbro (gb) occurs in numerous outcrops in the Rak quadrangle, but is most abundant in the northwest corner in association with the basalt and andesite member of the Nuf formation. The rock is variable in texture and composition, but it is typically black with a greenish cast, massive to moderately foliated, medium grained, and hypidiomorphic, equigranular. It contains about 30 to 70 percent plagioclase (An45 to An70), 30 to 60 percent green hornblende that locally forms large poikiolitic phenocrysts, sparse augite cores within some hornblende crystals, a trace to two percent opaques, and zero to trace-amounts of biotite, quartz, apatite, and secondary epidote and calcite. Secondary quartz pods and veinlets are common. Locally, the rock grades into hornblende diorite, so at least some of the rocks mapped as hornblende diorite may be coeval with the metagabbro. In outcrop, the metagabbro is generally very fractured, but commonly forms well-indurated, black, rounded boulders with a characteristic "iron ring" when struck by a hammer. The regolith is typically light gray to greenish gray.

Metagabbro defines large blocks, up to several km across, that have been incorporated into the Ha'il and Dhiyyab granites. Metagabbro clearly intrudes the rocks of the Nuf formation, although petrologic and geochemical similarities (K. S. Kellogg, unpublished data), and spacial proximity suggest that both the metagabbro and the more mafic extrusive rocks of the Nuf formation are cogenetic.

## Hornblende diorite and quartz diorite

Hornblende diorite (di) and quartz diorite (qd) are similar rock types that are gradational in composition and texture to one another. In some cases, hornblende diorite is also gradational to the metagabbro, although neither hornblende diorite nor quartz diorite have the same intimate association to the Nuf formation as does the metagabbro.

Quartz diorite is massive to slightly foliated, light-to dark-gray and greenish-gray, medium-grained, hypidiomorphic-equigranular, and contains 50 to 60 percent saussuritized plagioclase (An20 to An45), 20 to 30 percent green hornblende, 5 to 20 percent biotite, and 5 to 15 percent quartz. Trace minerals are sphene, apatite, zircon, opaques, and in one thin-section, monazite. Alteration is slight to moderate, and is manifested by the chloritization of biotite, the presence of small epidote and hematite grains, and the localized growth of calcite and secondary quartz.

Hornblende diorite is similar in texture and alteration to quartz diorite, but contains greater amounts of hornblende (up to 50 percent) and lesser amounts of biotite (0 to 5 percent) and quartz (0 to 5 percent). Clinopyroxene is a local varietal constituent. A notable and distinct diorite body underlies approximately 0.5 km2 at the village of Al Idwah. Here, the rock is a greenish-black, coarse grained, idiomorphic inequigranular, hornblende-clinopyroxene porphyry, containing about 2 percent fine-grained potassium feldspar.

Hornblende diorite and quartz diorite are both generally highly fractured, and weather to a gray regolith with low to moderate relief.

## Granodiorite and monzogranite suite

The granodiorite and monzogranite suite comprises granitoid intrusive rocks that underlie large portions of the northeastern Arabian Shield. Preliminary zircon-Pb ages from some of the less deformed of these rocks from outside the Rak quadrangle indicate that they were emplaced approximately 620 Ma ago (C. E. Hedge, oral commun.). Modal compositions for various members of the granodiorite and monzogranite suite are shown in figure 2.

### Cataclastic granite gneiss

Cataclastic granite gneiss (ggn) crops out in the southeastern corner of the quadrangle and consists of light-gray to slightly pinkish-gray, fine- to medium-grained biotite ±hornblende granodiorite to monzogranite gneiss. Five thin sections from this unit contain between 43 to 47 percent slightly sausseritized plagioclase (An25), 30 to 40 percent undulatory quartz, 23 to 36 percent microcline, 1 to 4 percent biotite, 0 to 8 percent hornblende, and trace amounts of zircon, opaques, and sphene. The foliation is due to both cataclasis and recrystallization, and augen texture is locally well-developed. Grain boundaries are granulated, although at least some of the hornblende and biotite is secondary and oriented parallel to foliation. Most of the gneiss is strongly lineated in a nearly horizontal direction. This rock is well exposed in the wall of the tuff-ring crater at Jabal Umm Harruj.

Contact relationships of the cataclastic granite gneiss to other units were not observed, although dioritic

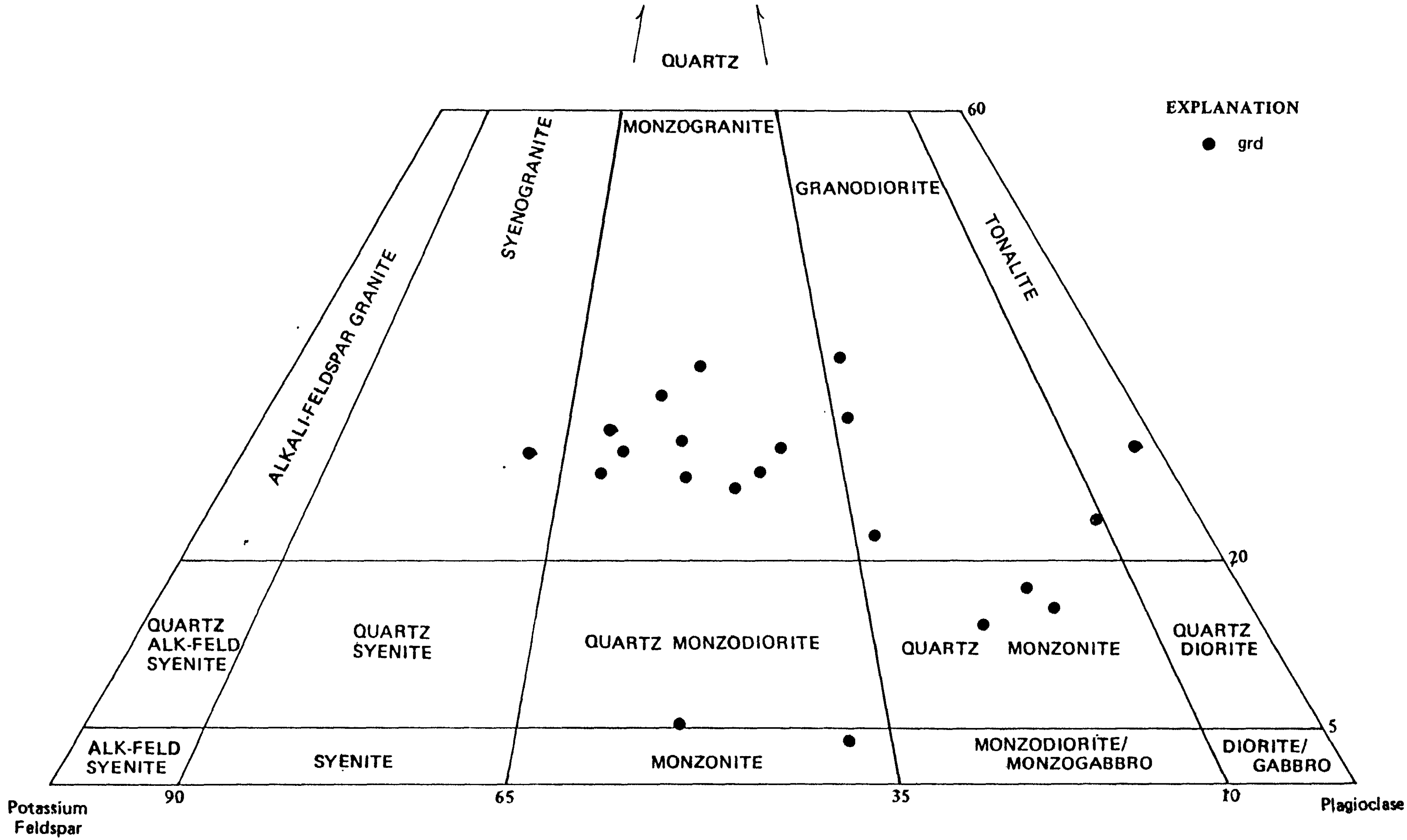


Figure 2.--Modal compositions of the Dhiyyab granite (grd). Classification scheme is that of Streckeisen (1976).

inclusions in the gneiss suggest that the gneiss postdates the hornblende diorite and quartz diorite.

## Ha'il granite

Only small areas of Ha'il granite (grh), a very heterogeneous unit that crops out extensively in the adjacent Qufar quadrangle (Kellogg, 1983), are mapped in the Rak quadrangle, in the northwest corner, and along the western boundary. The Ha'il granite is generally a pink to pinkish-gray, medium-grained, xenomorphic equigranular, biotite-hornblende monzogranite, although quartz monzonite and syenogranite also occur. The rock commonly has well-developed granulated grain boundaries, and a cataclastic foliation. The rock contains sausseritized plagioclase ($An_{10}$ to $An_{15}$), perthitic potassium-feldspar, 1 to 6 percent biotite (variably altered to chlorite), 0 to 10 percent green hornblende, trace to 2 percent opaques, and trace amounts of zircon, sphene, allanite, and secondary epidote and sericite. The mafic minerals are commonly clumped. The Ha'il granite crops out in low reddish-brown, blocky hills, and strongly fractured pediment surfaces.

Numerous dikes of Ha'il granite intrude the Nuf formation and the metagabbro in the northwest corner of the quadrangle. Relationships in the Qufar quadrangle to the west also reveal that the Ha'il granite postdates the hornblende diorite and quartz diorite. The cataclastic and commonly foliated nature of the Ha'il granite, as well as compositional similarities, suggest that this unit may correlate with the cataclastic granite gniess.

## Granophyre

Granophyre (gyd) occurs as irregular-shaped masses in the Dhiyyab granite north of Jabal Salma. The outcrops are up to 3 km across in map view, and consist of gray to pinkish-gray, very fine-grained to fine-grained, generally leucocratic, inequigranular to slightly quartz- and plagioclase-phyric, massive to slightly foliated granophyre of approximate granodiorite to monzogranite composition. The granophyre is typically highly fractured, with a moderate to well-developed fracture cleavage.

The granophyre unit probably represents the stoped upper regions of the Dhiyyab granite magma chamber. On the west side of Jabal al 'Abt, dikes and small intrusive bodies of Dhiyyab granite intrude both the Dhiyyab granophyre and metagabbro, although are not indicated on plate 1.

## Dhiyyab granite

The Dhiyyab granite (grd), named after a small hill (Jabal adh Dhiyyab) in the west-central part of the quadrangle, comprises a batholith-sized pluton in the north-central part of the quadrangle, much of which is apparently concealed beneath the Saq Sandstone. The Dhiyyab granite is also mapped south of Jabal Salma, and crops out extensively south of the quadrangle.

The Dhiyyab granite is a medium-gray to slightly pinkish-gray, medium- to coarse-grained, hypidiomorphic inequigranular biotite monzogranite, biotite granodiorite and biotite quartz monzodiorite (figure 2). The rock contains partially sericitized plagioclase (An10 to An17), microcline, undulatory quartz, 2 to 10 percent biotite (generally partially altered to chlorite, hematite and epidote), 0 to 3 percent green hornblende (though the rock typically contains none), trace to 1 percent opaques, and trace amounts of sphene, zircon, apatite, allanite, ±clinozoisite, and ±primary muscovite. Quartz veins and pods, and dikes of variable composition and orientation, are common in the Dhiyyab granite. The rock has been eroded to a flat pediment, and underlies a flat sandy plain containing abundant lag quartz.

A 2 km wide western margin of the Dhiyyab granite is foliated parallel to the contact with the Nuf formation, into which it intrudes. The age of the Dhiyyab granite relative to the Ha'il granite is unknown, although the generally less altered nature of the Dhiyyab granite suggests that it may be the younger of the two units. The Dhiyyab granite is clearly intruded by the rocks of the Salma complex.

Dikes and quartz veins intruding the Dhiyyab granite

Numerous dikes of various composition, but predominantly either red rhyolite porphyry or diabase, intrude the Dhiyyab granite and surrounding rocks of the Nuf formation, and are probably related to closing stages of Dhiyyab granite magmatism. Felsic dikes are predominantly red rhyolite porphyry, and crop out along prominent east-west trends in the northwest part of the quadrangle. Mafic dikes, predominantly diabase, are far more numerous than shown in plate 1. Dikes of unknown composition, where prominent, are also shown in plate 1. Numerous quartz veins and plugs are associated with closing stages of emplacement of the Dhiyyab granbite.

## Akash granite

The Akash granite (gra), named after a prominent hill, Jabal Akash, which occurs along the northwest boundary of the pluton in the Ha'il quadrangle (Kellogg and Stoeser, unpubl. data), occupies the extreme northwest corner of the quadrangle. The pluton is oval shaped, and partially concealed by Saq Sandstone. In the Qufar quadrangle (Kellogg, 1983), this unit is named biotite monzogranite. The rock is light gray to pinkish-gray, medium-grained, xenomorphic inequigranular to potassium-feldspar phyric, and contains 38 to 43 percent coarsely perthitic potassium-feldspar, 23 to 28 percent plagioclase (An10 to An12), 29 to 33 percent undulatory quartz, 1 to 2 percent biotite, trace to 1 percent muscovite, and trace amounts of zircon, magnetite, fluorite, allanite, and apatite. Radioactivity is about twice that of the Ha'il and Dhiyyab granites. The rock crops out in tan rounded domes containing widely-spaced joints, and in smooth slabs defining a flat pediment surface.

The Akash granite clearly intrudes the Ha'il granite and the metagabbro. In contrast to the Ha'il and Dhiyyab granites, the Akash granite has been cut by very few dikes.

A tin- tungsten- and zinc-bearing greisen has been discovered along the northwest contact of the Akash granite, on and near Jabal Akash. Highly evolved tin- and tungsten-bearing granites in the Arabian Shield are generally thought to be about 580 Ma old (D. B. Stoeser, oral commun.), about the same age as the core granite of the Salma granite complex.

## Salma granite complex

The Salma granite complex crops out in a wide, concave-southward arc of rugged mountains, extending from the quadrangle's southwestern corner to the east-central region, where it widens and disappears under a Tertiary and Quaternary volcanic field. This granite arc extends about 15 km south of the quadrangle boundary. The Salma granite complex is crudely zoned, and demonstrates a chemical evolution in time. An early, peralkaline rim, associated at least in part with comenditic (peralkaline) rhyolites of the Qarfa formation, envelops a metaluminous core of biotite syenogranite and granophyre. It is suggested here that the Salma granite complex represents a collapsed caldera with a resurgent granite core.

A monzogranite stock and a diabase dike swarm mark the last stages of magma injection, and indicate a possible late period of bimodal magma separation ("basalt-rhyolite association"). Modal compositions for various members of the Salma granite complex are shown in figure 3.

### Quartz syenite porphyry

Quartz syenite porphyry (syp) is a massive, nonlayered, nonfoliated unit that occupies extensive hilly areas along the northeast side of the complex. The rock is very distinctive in hand specimen, being composed of up to 30 percent gray albite phenocrysts up to 1 cm across, rimmed with pink potassium feldspar, and up to 2 percent angular, aphanitic,

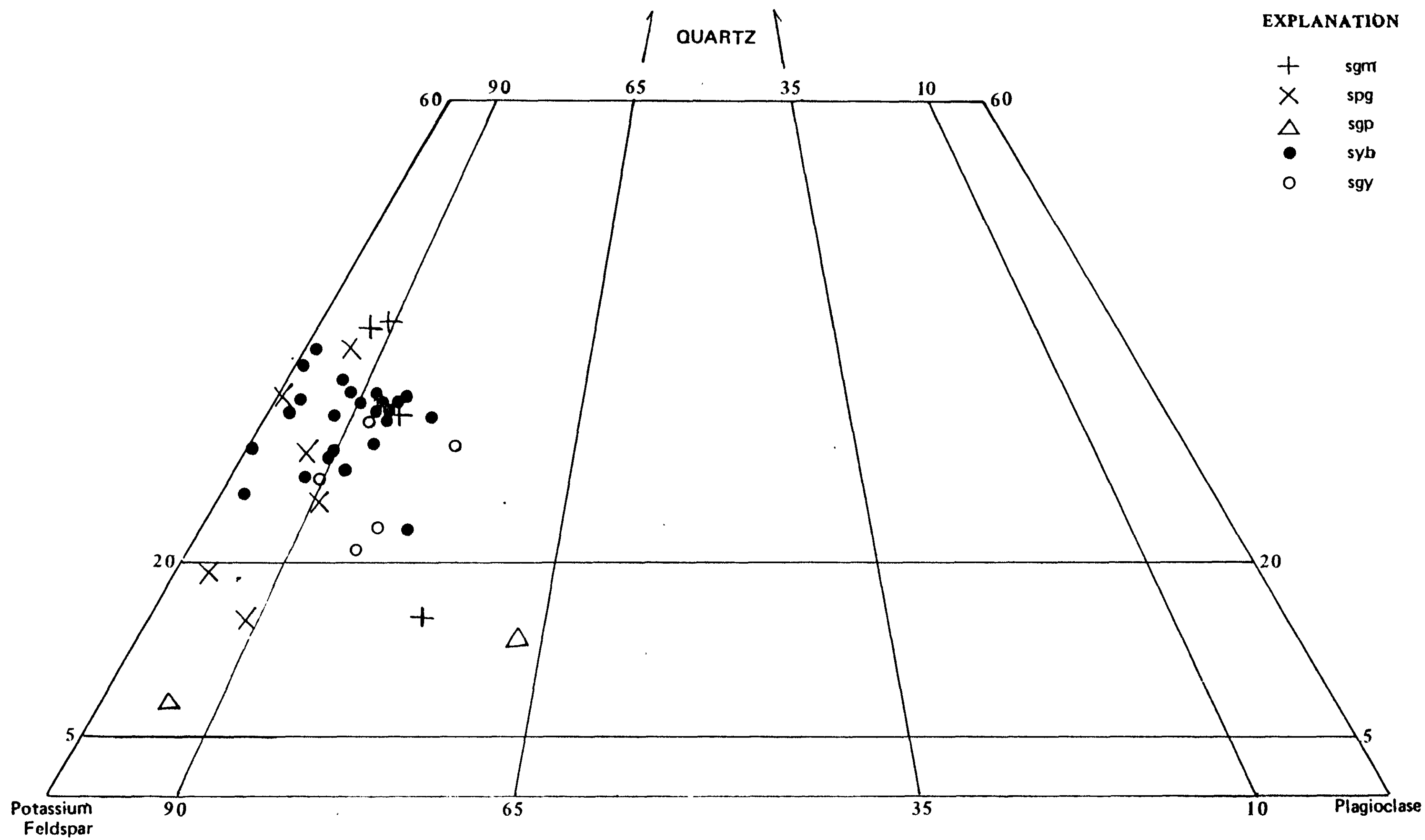


Figure 3.--Modal compositions of rocks from the Salma granite complex: open triangle, quartz syenite porphyry; x, peralkaline granite; cross, iron-oxide granite; solid circle, biotite syenogranite; and open circle, medium-grained samples from the Salma granophyre. Rock names for each field are the same as for figure 2.

gray volcanic clasts up to 2 cm across. The matrix is idiomorphic to hypidiomorphic, very inequigranular, and contains 5 to 10 percent amphibole. Slab and thin section examinations also reveal that the rock is commonly granophyric, and is a quartz syenite to quartz alkali-feldspar granite porphyry. Potassium-feldspar (50 to 80 percent) is very cloudy brown and plagioclase (10 to 30 percent) is albite (An0). Quartz (5 to 25 percent) occurs as both granophyric intergrowths with potassium-feldspar, and as euhedral, equant crystals. Mafics consist of up to 8 percent green hornblende or blue-green amphibole (kataphorite or arfvedsonite), trace to 5 percent pyroxene (augite, pigeonite, or aegerine-augite), up to 2 percent opaques, and trace amounts of zircon, apatite, and allanite. Secondary hematite, and a bright orange fibrous mineral (hematite-stained chlorite?) are ubiquitous. No biotite has been observed. The rock occurs in chocolate-colored fractured outcrops that resemble some outcrops of the Qarfa formation volcanics.

The quartz syenite porphyry is the oldest rock of the Salma granite complex. Just east of Jabal al Hamra, this unit is clearly intruded by the peralkaline granite, and elsewhere within the quartz syenite porphyry dikes of Salma granophyre are common.

### Iron oxide granite

Iron oxide granite (sgm) crops out in widely separated hills in the southern part of the quadrangle. The rock is medium to coarse grained, pinkish gray, hypidiomorphic inequigranular syenogranite or alkali-feldspar granite. The potassium feldspar is cloudy and perthitic, the plagioclase (An11) occurs as numerous microlites in potassium-feldspar. Up to 8 percent skeletal opaques are associated with abundant secondary red hematite and a micaceous orange mineral. Trace amounts of zircon are also present. The rock crops out in tan to orange-brown slabs and domes.

The iron-oxide granite intrudes hornblende diorite, and is intruded by a rock tentatively assigned to the peralkaline granite unit. It is suggested, however, that the iron-oxide granite may have resulted from the high temperature alteration of a peralkaline granite itself, during which the sodium- and .iron-rich mafic minerals broke down into iron oxides and iron- (and sodium-?) rich micas.

### Peralkaline granite

The peralkaline granite (spg) occurs as a border phase of unknown width along parts of the north side of Jabal Salma, and as isolated intrusions to the east of the quartz syenite porphyry, among the easternmost outcrops of the Salma intrusive complex. The rock is a pinkish-brown, medium-grained, hypidiomorphic to xenomorphic equigranular alkali-feldspar granite and quartz alkali-feldspar syenite containing finely perthitic potassium-feldspar, uniform quartz (15 to 30 percent) and up to 12 percent mafic minerals. Granophyric texture occurs locally. The mafics are dark greenish brown to dark-blue arfvedsonite or kataphorite, aegerine-augite, and up to 2 percent opaques. Rocks containing only amphibole or pyroxene both occur. Trace minerals are zircon, allanite, apatite and fluorite. At least some alteration is present in all samples, with the development of epidote, hematite, a fine-grained orange micaceous mineral and sparse calcite. The rock crops out in distinctive brown slabs and rounded knobs. A fine-grained amphibole-bearing granite, tentatively assigned to the peralkaline granite unit, intrudes the iron-oxide granite 3 km northeast of Jabal umm Idin. Elsewhere, the peralkaline granite clearly intrudes the quartz syenite porphyry and is cut by dikes of Salma granophyre. The peralkaline granite defines a rim at least 1 km wide adjacent to the biotite syenogranite along the north side of the Jabal Salma. The peralkaline granite clearly intrudes the quartz syenite porphyry, and is considered to be only slightly older than the biotite syenogranite.

## Biotite syenogranite

Biotite syenogranite (sgb) comprises the core region of Jabal Salma, and is the dominant rock type in the south-western part of the quadrangle. The rock is generally pink to pinkish tan, medium grained, hypidiomorphic equigranular to inequigranular biotite syenogranite, although biotite alkali-feldspar granite is also common (figure 3). The rock is locally granophyric. The potassium-feldspar is cloudy and coarsely perthitic; the plagioclase is partially sericitized, and varies from $An_7$ to $An_{20}$, the more calcic varieties occurring near the border of the complex. Trace minerals are zircon, opaques, fluorite, apatite, and $\pm$allanite. Sphene was not found, indicating the low calcium and titanium content of the rock. The biotite syenogranite crops out in characteristic large tan domes and rounded slabs cut by widely-spaced joints.

Green amphibole, in amounts up to 2 percent, is present along the southwestern part of the biotite syenogranite, within about 2 km of the western border. A 3 km long biotite-hornblende syenogranite body, about 3 km south of the villiage of An Na'i, contains up to 6 percent green hornblende, and equal amounts of fine-grained biotite. This rock also contains sparse albite phenocrysts. Despite the slightly more mafic nature of this rock, it is considered to be a phase of the biotite syenogranite.

Although the biotite syenogranite is locally granophyric, a feature which is more pronounced toward the northeast, it is clearly intruded by sheets of Salma granophyre, as well as by a diabase dike swarm in the southwestern part of the quadrangle. One stock of fine-grained monzogranite (verging on syenogranite) intrudes the biotite syenogranite in the extreme southwestern corner of the quadrangle.

### Salma granophyre

The Salma granophyre (sgy) is the major rock unit in the central part of the quadrangle, and it marks the last major period of plutonic activity in the Salma granite complex. The rock is pink to brick-red, leucocratic, fine to medium grained, granophyric, and generally miarolitic. Potassium-feldspar and quartz occur as both early subhedral crystals (typically 30 percent of the rock), and as a granophyric intergrowth. As discreet crystals, the potassium-feldspar is cloudy and perthitic, and the quartz equant and uniform. The color index of the rock is generally less than 3. All original mafic minerals, probably predominantly biotite, have been completely altered to intergrowths of chlorite, hematite, epidote and a fine-grained, bright-orange, micaceous mineral. Trace amounts of zircon are present. The occurrence of miarolitic cavities generally increases towards the eastern border. Many cavities are lined with fibrous zeolites (natrolite?) and calcite. The Salma granophyre weathers to characteristic pink domes and blocky outcrops.

The Salma granophyre grades from the biotite syenogranite, and in some cases the distinction between the two is somewhat arbitrary. Furthermore, the Salma granophyre was not emplaced during a single magmatic event. Early, massive granophyre is injected by numerous, commonly conformable, sheet-like bodies of similar but younger granophyre. Weathering emphasizes the layered character of the younger granophyre, such as 4 km west of An Na'i, where undulatory sheet-like intrusions resemble folded layers of volcanic rock. In many other localities, large, shallow-dipping granophyric sheets, up to 200 m thick, form prominent cliffs. Numerous sheets of the Salma granophyre intrude the biotite syenogranite, as well as the peralkaline granite, iron oxide granite, quartz syenite porphyry, and the rocks of the Qarfa formation. The contact between the main body of Salma granophyre and the older rocks to the east dips steeply to the east and defines a convex-westward surface.

### Hornblende-biotite monzogranite

A small stock of light-gray, fine-grained, hypidiomorphic equigranular to slightly quartz and potassium-feldspar phyric hornblende-biotite monzogranite (smg) intrudes the biotite syenogranite in the southwest corner of the quadrangle. The rock contains about 25 percent quartz, 25 percent slightly perthitic potassium feldspar, 40 percent normally-zoned plagioclase (An20 to An30), 4 percent hornblende, 2 percent biotite and trace amounts of opaques, zircon, apatite, and secondary epidote and chlorite. The outcrops are blocky, and the rock weathers to a light-tan color.

### Diabase dikes

A swarm of deuterically-altered diabase dikes intrudes biotite syenogranite and sills of Salma granophyre in the southwestern part of the quadrangle. The rock has a subophitic texture, is generally non-porphyritic, and is composed of about 60 percent plagioclase (An54), 10 percent original pyroxene, about 5 percent original magnetite and about 1 to 2 percent fine apatite needles. Clinopyroxene is mostly altered to fine-grained chlorite and hematite, and only a few grains contain relict cores of the original mineral. Individual dikes range in thickness up to 5 m, and have a uniform trend of about N. 70° W.

## PALEOZOIC ROCKS

### Saq Sandstone

According to Powers and others (1966), the Saq Sandstone was named by H. L. Burchfiel and J. W. Hoover in 1935 (no reference cited) for Jabal Saq, about 100 km southeast of the Rak quadrangle. Only the basal portion of the Saq Sandstone crops out in the northern third of the Rak quadrangle, and consists of reddish-brown, buff and yellowish-tan, commonly cross-bedded, poorly indurated, friable, well-sorted, locally ferruginous quartzite. A desert-varnished, case-hardened crust is commonly developed. Shaley layers and partings occur locally in the lower part of the sequence. Well-rounded pebbles, cobbles, and boulders, predominantly of brick-red rhyolite and subordinantly of a variety of Precambrian rock types, fill shallow channels at the base of the section. Detailed petrography of the Saq Sandstone was not performed for this report.

Most of the outcrop surface of the Saq Sandstone is a rough, hummocky plain of low relief, containing sand pockets and low, slabby sandstone bluffs.

## TERTIARY AND QUATERNARY VOLCANIC ROCKS

Well-exposed basaltic flows, cinder cones and tuff rings erupted along several linear trends in the quadrangle (figure 4). The most prominent of these trends defines a north-south line of craters in the southeastern and east-central part of the quadrangle. These volcanic rocks are part of the Harrat

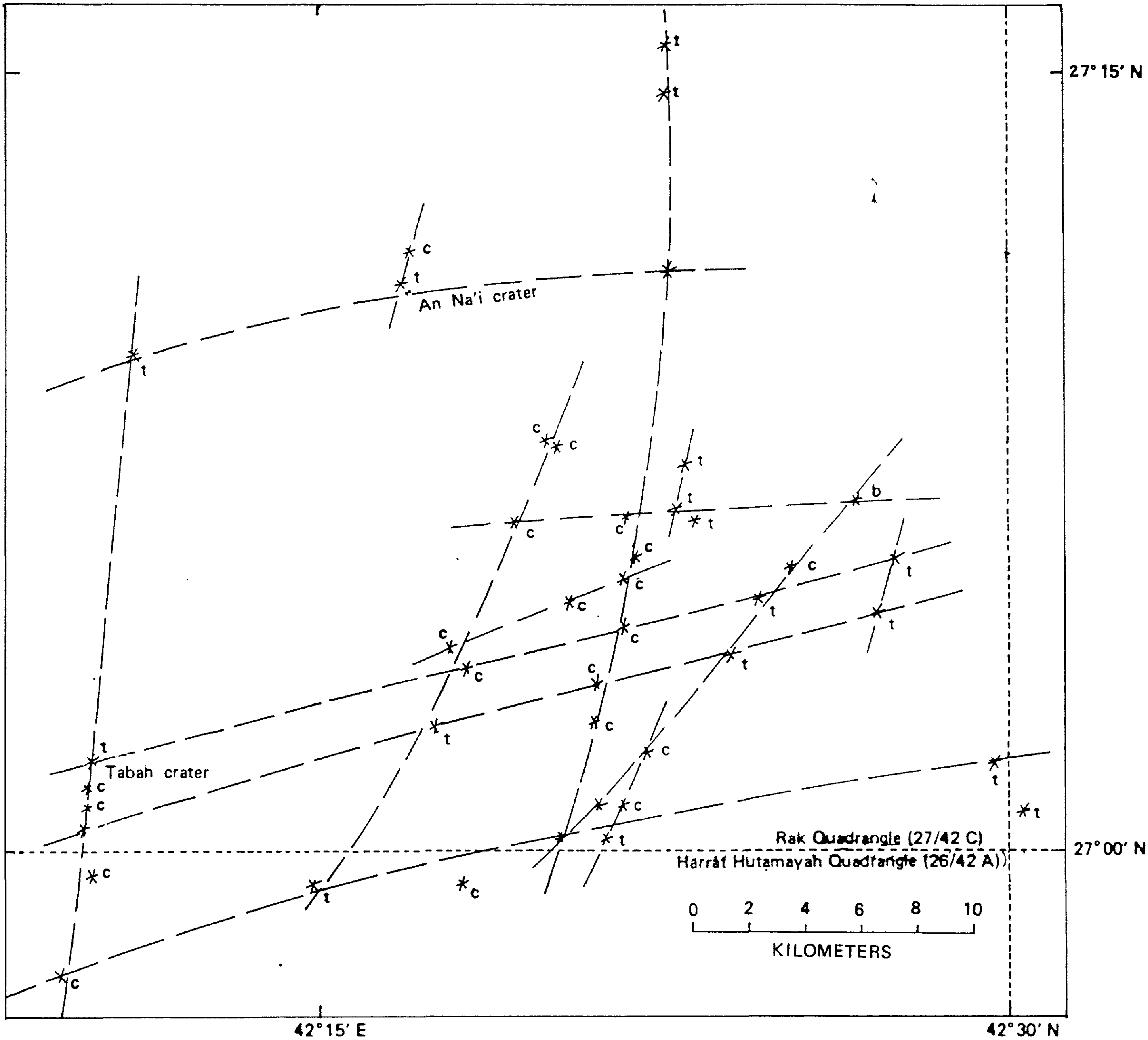


Figure 4.--Distribution of volcanic vents of the northern Harrat Hutaymah volcanic field, including areas immediately adjacent to the Rak quadrangle. Stars (*) represent the position of tuff rings (t), cinder cones (c) and one identified basalt vent (b). Basalt flows are associated with many of the cinder cones. Dashed lines represent inferred linear trends.

Hutaymah volcanic field, a prominent basalt flow in the southern part of the field. Erosion has dissected many of the craters, although their original morphology is generally still recognizable. All the rocks of this volcanic field are probably alkali-olivine basalts (Coleman and others, 1983). A potassium-argon whole rock are of 1.8 Ma has been determined from the basal flow in the crater wall of a relatively uneroded tuff ring 2 km south of the quadrangle's southern boundary (J. S. Pallister, oral commun.). This age is on the Tertiary-Quaternary boundary (Berggren, 1972), so it seems reasonable that rocks of both Tertiary and Quaternary age may be represented elsewhere in the field.

### Alkali-olivine basalt

All observed alkali-olivine basalt (QTb) flows in the Harrat Hutaymah volcanic field have rubbly, vesicular surfaces and range in thickness from about 2 to about 20 m. The thinner flows are composed of about 40 to 50 percent basaltic glass containing numerous microlites of calcic plagioclase and typically 20 percent euhedral phenocrysts of olivine, 10 to 15 percent clinopyroxene, and 0 to 10 percent hypersthene. Fine-grained titanomagnetite comprises up to 3 percent of the rock. Thicker flows have a subophitic texture composed typically of 65 percent calcic plagioclase (An55), 15 percent olivine, 15 percent clinopyroxene, and 3 percent opaques. Iddingsite commonly rims some of the olivine, and calcite lines many of the vesicles. A sparse potassium-staining mineral (leucite?) was observed at one locality. Peridotite nodules up to 10 cm in diameter occur in most if not all flows.

Lobate flow morphology is well-preserved in some of the younger flows. Exposed elsewhere, as in some of the crater walls, are numerous older flows interbedded with pyroclastic base-surge deposits.

### Basaltic pipe breccia

Basaltic pipe breccia (QTp) is shown on the cross-section only; it is not exposed in the area of plate 1, and is inferred to exist by analogy with diatreme-like bodies elsewhere in the world (for example, Wohletz and Sheridan, 1983).

### Basaltic tuff deposits

Basaltic tuff deposits (QTt) form brown to grayish-brown, bedded sheets of fragmental basaltic material adjacent to large craters ("tuff rings"), interpreted to be the result of explosive volcanic activity. Wohletz and Sheridan (1983) believe that tuff rings result from the hydromagmatic interaction of rising basaltic magma and ground water, and that the deposits are caused by settling of material from the ensuing gas-rich clouds (pyroclastic base surges). The deposits are composed of poorly sorted, poorly consolidated, angular fragments of red, brown and black basalt, up to 20 cm in diameter, though ranging to fine-grained sand sized particles. Peridotite nodules, including harzburgite, websterite and mela-gabbro norite, are commonly found among the volcanic fragments. The tuff deposits are well-laminated, and beds are typically 5 cm and up to 20 cm thick. Dune-forms, truncated beds and inverse graded bedding, all typical of pyroclastic base-surge deposits (Wohletz and Sheridan, 1983), are characteristic in these deposits. Beds dips away from the crater rim at between 8° and 12°. Several wells dug into wadi alluvium on the east side of Jabal Salma have encountered tuff deposits up to 40 m below the surface, so the extent of these deposits below surficial cover is considerably larger than shown on plate 1.

## Basaltic cinder deposits

Basaltic cinder deposits (QTc) consist of black to reddish-brown, poorly-sorted, poorly-consolidated basaltic cinders, ranging up from sand-sized particles to large (up to 4 m in diameter) angular blocks, resulting from basaltic lava fountains that erupted from the central crater of cinder cones. The blocks include "bread-crust" and tear-shaped bombs, as well as abundant broken fragments. Agglutinization of cinders has generally occurred. The deposits are more massively bedded than for tuff rings, and bedding dips generally 30° or more away from the crater rim. Palagonitazation has affected the deposits much less than for those of tuff rings. J. S. Pallister (oral commun.) has observed that cinder deposits in the Harrat Hutaymah quadrangle immediately to the south are notably devoid of peridotite nodules, an observation supported by mapping in the Rak quadrangle.

Cinder cones, in contrast to tuff rings, erupted during emplacement of basaltic magma into a relatively dry environment (Wohletz and Sheridan, 1983). In the Rak quadrangle, cinder cones occupy a considerably smaller area than do tuff rings, though they define more prominent, steeper-sided conical hills with cinder-filled craters that are generally less than 0.5 km in diameter.

## Mixed cinder and lava flow deposits

Mixed cinder and lava flow deposits (QTcb) consist of chaotic lava blocks and finer-grained cinders, adjacent to a cinder cone, that generally have the morphology of a lava flow. These deposits probably resulted from the simultaneous eruption of a cinder cone and a lava flow, so their origin cannot be clearly established.

## QUATERNARY DEPOSITS

### Alluvial deposits

Alluvial deposits (Qal) are composed predominantly of silt and sand in currently active wadi channels and on alluvial terraces. Gravel, cobble, and boulder deposits occur adjacent to some areas of higher relief. The color of the alluvial deposits is highly variable, reflecting the wide variety of source rock types. For example, the large alluvial apron adjacent to the north side of Jabal Salma is a distinct reddish-brown color, and in the areas of basaltic volcanism, the deposits are gray to grayish-tan. In the northern part of the quadrangle, underlain by Saq Sandstone, alluvial deposits include large areas of sheet sand which may be in part eolian.

The thickness of these alluvial deposits is unknown, although along some of the larger wadis it is probably in excess of several tens of meters.

### Reworked volcanic ash deposits

Alluvial deposits composed predominantly of gray, reworked volcanic ash (Qa), adjacent to and inside some tuff rings and cinder cones, are designated separately on plate 1. These deposits contain clasts that range in size from fine-grained sand up to pebbles.

### Dune deposits

Well-stabilized dune deposits (Qd) are present in a few areas in the northeastern part of the quadrangle. These are small seif dunes, and are composed of light-tan, fine-grained, well-sorted predominantly quartzose sand.

### Playa deposits

The crater floors of most tuff rings, dammed areas behind some basalt flows (such as in the south-central part of the quadrangle), and several other closed depressions are underlain by playa deposits (Qp). These deposits are composed of light-tan silt that accumulates in the shallow depressions during periods of heavy rainfall. The thickness of these deposits is unknown.

## STRUCTURE AND METAMORPHISM

A number of structural trends are apparent in the Rak quadrangle, although a dominant, approximately north trend is noted for many units of diverse age.

The rocks of the Nuf formation and the Samra intrusive suite, are metamorphosed to upper greenschist facies, and are foliated along northerly trends oriented between about N. 30° W. and N. 30° E. Foliation is steep, and is generally parallel to a well-developed fracture cleavage. Metamorphic mineral assemblages in the more mafic rocks typically include fibrous green actinolitic amphibole, epidote, ±biotite, ±quartz, and ±chlorite. The more felsic rocks contain abundant secondary biotite, quartz, ±actinolite, and ±epidote. Chlorite is not common in any rocks of the Nuf formation, indicating that metamorphic grade is upper greenschist facies. Secondary quartz is locally abundant as groundmass crystals and as small veins and pods. Biotite is commonly clumped, and is oriented parallel to foliation. Plagioclase is very sausseritized, and is generally oligoclase. Primary igneous features, such as subophitic and porphyritic textures, are usually preserved.

Localized zones of intensely sheared rock are common in these older rocks, with cataclastic foliation also oriented approximately north. In a prominent road-cut about 3 km east of Al Idwah, gneissic metabasalts, and diorites intrusive into the metabasalts, are highly injected by thin ptygmatically-folded granitoid dikes. The metabasalts contain abundant biotite clots, as well as stretched, quartz-filled vesicles.

The Dhiyyab granite is strongly foliated to the north-northwest, within 1 km of its western contact with the Nuf formation. Foliation is steep, and locally compositionally layered. Mafic inclusions are stretched parallel to foliation. Away from the contact, the Dhiyyab granite is massive and nonfoliated.

In the southeastern corner of the quadrangle, granitic gneiss is foliated and lineated in a northwesterly (about N. 45° W. to N. 60° W.) direction and dips steeply (65° to 80°) to the southwest. Foliation is largely cataclastic, as demonstrated by strongly granulated grain boundaries and augen textures, although secondary, partially chloritized, clotted biotite is parallel to foliation. The lineation direction is nearly horizontal and is parallel to sheared mineral grains and long axes of the augens.

The rocks of the Qarfa formation and the Salma intrusive complex are essentially unmetamorphosed, although mafic minerals are generally strongly altered to opaque intergrowths. The Qarfa volcanics are gently folded and dip generally toward the center of the intrusive complex. Contacts near outlying plutons of peralkaline granite are, however, commonly steep.

The peralkaline (and iron-oxide) granite defines an arcuate outcrop pattern concentric with and outside the rocks of the Qarfa formation. The Qarfa formation and the partially cogenetic hypabyssal quartz syenite porphyry form an inner partial ring surrounding the younger Salma granopohyre. The contact between the ring and the granophyre dips between 30° and 50° outward. These relationships strongly suggest that the Salma granite complex is a collapsed caldera with a resurgent core. The Qarfa formation represents the remnants of a pre-collapse volcanic pile, and the peralkaline granite intruded along the ring fracture resulting from collapse.

Several fault trends are noted in the quadrangle. North- to northwest-trending faults, parallel to trends in foliation, are mapped cutting the rocks of the Nuf formation and the Samra intrusive suite. These faults may have been active during or slightly after the metamorphic event which affected the older rocks in the quadrangle, although late (Cambrian or later) reactivation is indicated by continuations of these faults into the Saq Sandstone. Up to 10 meters of apparent vertical movement is noted along several 2 to 3 m wide north-trending fault zones which displace both Precambrian rocks and Saq Sandstone, 6 km east of the village of Urayja. These faults (only 2 of which are shown on plate 1) coalesce into a single fault which continues north out of the quadrangle area.

A set of faults trending about N. 70° W., with apparent right-lateral offset, intersects the rocks of the Salma granite complex. Largest apparent offset is about 1.5 km, 4 km west of Tabah. Similar trends and offsets have been noted elsewhere in the northeastern shield (Quick, 1983; Kellogg, 1983). In the Ghazalah quadrangle, Quick (1983) refers to these faults as the Saqf fault system, and the name will be retained for this report.

The vents of the Harrat Hutaymah volcanic field are arrayed along two sets of intersecting linear trends, one oriented approximately N. 10° E. to N. 20° E., and the other about N. 70° E. (fig. 4). The more northerly trend is predominant, and it has been noted that this trend may mark a zone of extension related to flexure along the axis of the Ha'il Arch (Greenwood, 1974). The N. 70° E. trend is approximately parallel to the east-northeast-trending Saqf faults system. The points of intersection of these two trends are apparently the loci for vent emplacement.

## GEOCHRONOLOGY

The only dated unit in the Rak quadrangle is the biotite syenogranite of the Salma intrusive complex. Aldrich (1978) reports a model Rb-Sr model biotite age of 575 Ma and a biotite K-Ar age of 590 Ma from a biotite syenogranite collected from the southwestern corner of the quadrangle.

Ages of older rocks in the quadrangle can only be inferred by comparison with dated rocks from elsewhere in the northeastern Shield. For example, the rocks of the Nuf formation resemble an assemblage of basalts, andesites and marble mapped as the Afna formation of the Hulayfah group in the Nuqrah quadrangle (Delfour, 1977), about 200 km to the southwest. Delfour (1977) estimates the age of the Afna formation at about 740 Ma, based on the oldest potassium-argon age from three different determinations.

Quartz diorites and tonalites from the northestern Shield give preliminary zircon-Pb ages that cluster around 680 Ma, although a quartz diorite which underlies the layered rocks on Jabal Hibshi, 50 km to the south of the quadrangle, gives an age of 643 Ma (C. E. Hedge, oral commun.). This suggests that the quartz diorite of the Rak quadrangle may be between about 640 and 680 Ma old.

Calc-alkaline granites of the northern Shield yield Pb-zircon ages that cluster around 620 Ma (C. E. Hedge, oral commun.), which suggest that the Dhiyyab and possibly Ha'il granites may also be about this age.

During mapping for the Ha'il quadrangle (27/41 B), the Akash granite has been established as a tin-bearing granite (Kellogg and Stoeser, unpub. data). Zircon-Pb dating of similar granites in the northeastern Shield suggests that these highly evolved rocks were emplaced about 580 Ma ago (D. B. Stoeser, oral commun.).

A K-Ar age for a basalt at the base of a flow sequence in the wall of the tuff ring crater 2 km south of the quadrangle boundary is 1.8 Ma (J. S. Pallister, oral commun.), and may mark the approximate age of the earliest alkali-olivine basaltic volcanism in the Harrat Hutaymah volcanic field.

Basaltic rocks of Tertiary age older than 1.8 Ma do exist nearby, however. A remnant of an olivine basalt flow in the Qufar quadrangle immediately to the west has given a K-Ar whole rock age of 23.4±0.2 Ma (Kellogg, 1983).

## GEOLOGIC HISTORY

The Precambrian geologic events of the Rak quadrangle can be divided into 3 major episodes: 1) an early period of largely marine basaltic to dacitic volcanism, and emplacement of cogenetic gabbro and dioritic rock, 2) continued dioritic plutonism evolving into an episode of voluminous granodiorite and monzogranite plutonism, and 3) a late period of metaluminous and peralkalic magmatism and associated volcanism associated with the emplacement of a large resurgent caldera under the present east end of Jabal Salma. A chemical evolution in time is thus documented.

The rocks of the Nuf formation are the oldest in the quadrangle, and represent a period of dominantly marine volcanism during which extensive basalts, commonly pillowed, and subordinate andesites, dacites and rhyodacites, were deposited. The Nuf metabasalts are strongly tholeiitic (K. S. Kellogg, unpublished data), and it is suggested that this early episode of mafic to intermediate volcanism occurred in a maturing island arc. Metagabbro and subsequent hornblende diorite and quartz diorite may represent the gradually maturing root of this island arc system.

This older mafic to intermediate assemblage was subseqeuntly deformed and metamorphosed along northerly trends by west-oriented compression. A major metamorphic event, possibly related to an arc-continent collision about 650 Ma ago (Schmidt and others, 1979; Kellogg, 1983; Stoeser and others, 1983) has been recognized in the southeastern Arabian Shield, and has been named the Nabitah orogeny by Stoeser and others unpub data). This same event may have also affected the rocks of the northeastern Shield. The Nabitah orogeny has been held responsible for the formation of numerous north-oriented mafic and ultramafic ophiolite belts. The north-trending zone of mafic (and ultramafic) rocks in the Rak quadrngle may also represent a telescoped sequence of oceanic crust and (or) island arc rocks that formed in a closing ocean basin before a major collisional event approximately 650 Ma ago.

A period of extensive calc-alkaline magmatism about 620 Ma ago partially dismembered the older, deformed mafic assemblage, and formed batholith-sized plutons. The Ha'il and Dhiyyab granites belong to this suite of granites. Dikes of wide-ranging composition were emplaced shortly after the cessation of calc-alkaline plutonism.

Alkalic magmatic activity began some time after about 590 Ma ago with the eruption of the highly evolved rhyolitic volcanics of the Qarfa formation. Some of these volcanics are comemditic, and are chemically and petrographically similar to the quartz syenite porphyry which intrudes the Qarfa formation. It has been suggested (P. W. Lipman, oral commun.) that the quartz syenite porphyry may represent a thick intracaldera tuff that erupted during or shortly after caldera collapse. If so, then this unit is not part of the intrusive complex at all, but should be included as part of the Qarfa formation.

The Qarfa formation probably represents part of the eastern portion of a collapsed cauldera block (Smith and Bailey, 1968). Folding of the Qarfa rhyolites probably occurred during caldera collapse when compression near the base of the caldera block deformed the hot plastic rock (figure 5).

The Salma granite complex is zoned in concentric rings and has evolved chemically in time. The early peralkaline rocks are peripheral to later metaluminous core granites, and probably represent ring intrusions into the ring fractures surrounding the roughly circular caldera collapse. The core granites of the complex were emplaced about 580 Ma ago (Aldrich, 1978), beginning with the emplacement of biotite syenogranite, and mark a period of resurgent magmatism and probable doming of the collapsed volcanic pile. Numerous sheet-like bodies of granophyre in the upper regions of the resurgent magma chamber solidified during the closing stages of granite emplacement when the rising and partially crystallized magma chamber vented. The sudden pressure release quenched the residual liquid, resulting in the eutectic crystallization of quartz and potassium feldspar, and a granophyric texture (Carstens, 1983). The numerous granophyric sheets, both within and external to the granophyre unit, may represent different pulses of pressure release.

A small stock of fine-grained monzogranite and a diabase dike swarm are the last Precambrian intrusive events in the quadrangle, and are related, at least spatially, with the last stages of magmatism associated with the Salma granite complex.

Apparent right-lateral faulting along east-northeast trends (Saqf fault system) displaces rocks of the Salma granite complex. These faults may form a conjugate set with the northwest-trending left lateral Najd faults that are prominantly developed to the south of the quadrangle. The Saqf fault system was in fact predicted by Schmidt and others (1979) in their analysis of upper Proterozoic east-west compression of the southeastern Shield.

Following a period of extensive erosion, the area was planed to an almost flat surface in the Cambrian Period, and platform sedimentation began with the deposition of the quartz sandstone, shales and minor basal conglomerates of the Saq Sandstone. A thick sedimentary sequence probably developed, although uplift and tilting towards the northeast, related to the development of the Red Sea rift in middle Tertiary time, resulted in the erosion of most Phanerozoic rocks from the quadrangle area.

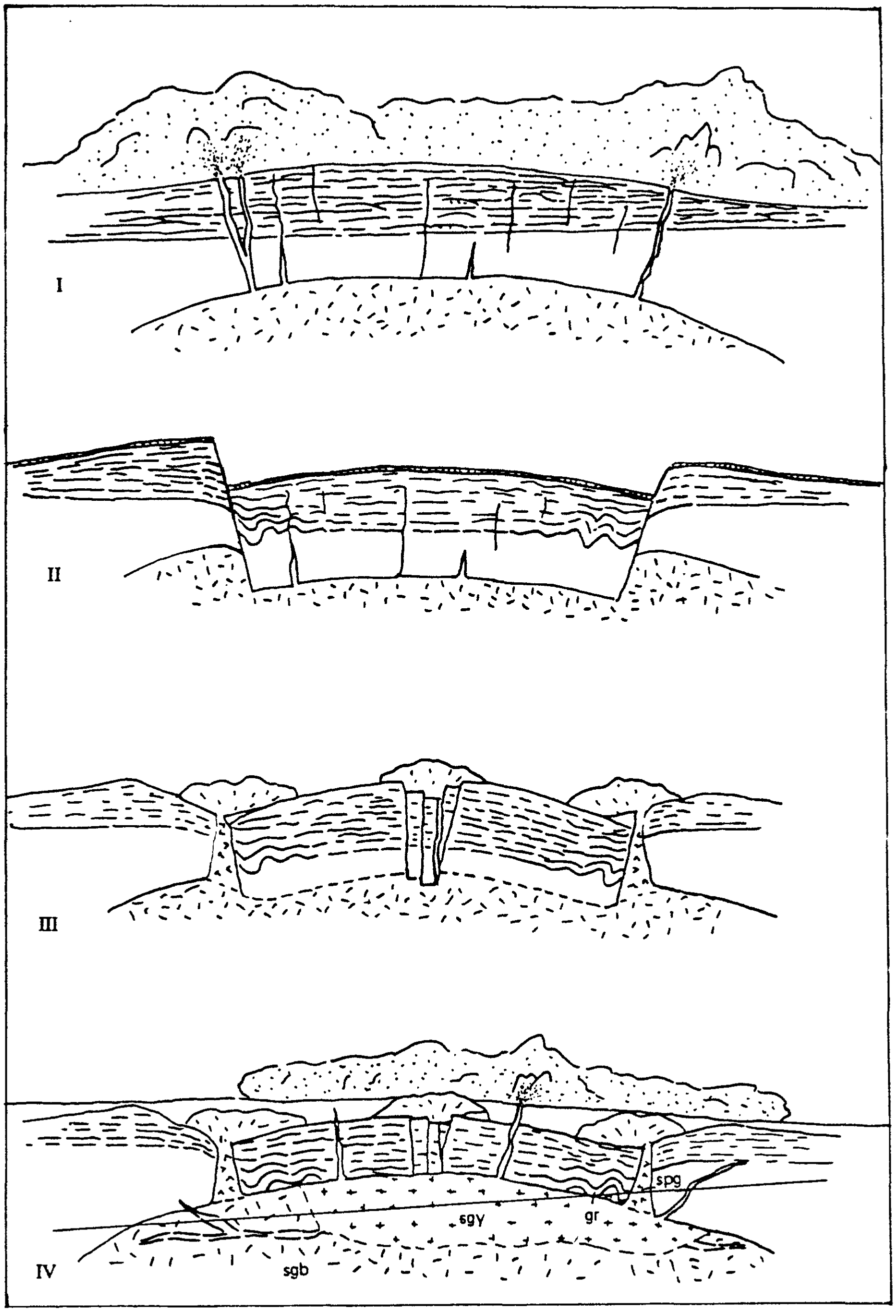


Figure 5.--Four hypothetical stages in the formation of the Salma granite complex, adapted in part from Smith and Baily (1968). Stage I - regional tumescence of the Qarfa volcanic pile·by magma pressure culminates in the eruption of voluminous rhyolitic ash. Stage II - Caldera collapse resulting from the removal of magma during the major eruption. Deformation of the lower, outer margin of the caldera block results from compression of the hot, plastic rock during collapse. Stage III -Renewed magma pressure causes doming (resurgence) of the caldera block and emplacement of peralkaline ring granites along the fracture zone. Axial graben formation probably accompanies this stage. Stage IV - Sudden pressure release caused by venting of the residual fluid at the top of the cooling magma chamber quenches the magma, forming granophyre (sgy). Sheets of granophyre intrude biotite syenogranite (sgb), Qarfa rhyolite (qr) and the peralkaline granite (spg) of the ring fracture zone. The straight line indicates the approximate present erosion surface. Tertiary uplift associated with rifting of the Red Sea restores this line to horizontal.

In late Oligocene or early Miocene time, alkali-olivine basalts began erupting in the northeastern shield in response to uplift associated with opening of the Red Sea. A north-trending zone of extension in the present northeastern Shield (the "Ha'il arch") was one manifestation of this uplift. A few small olivine basalt plugs just west of the Rak quadrangle are all that remain of this earlier period of Tertiary volcanism. In the Rak quadrangle, basaltic tuff rings, cinder cones and lava flows of the Harrat Hutaymah volcanic field began erupting about 2 Ma ago. The position of the vents was governed by the intersection of the Saqf fault system and fractures that are parallel to the axis of the Ha'il arch (figure 4). This model implies that the lines of intersection of these two fracture systems marked a path of least resistence for rising magma, but perhaps more importantly it implies that faults of the Saqf fault system and the fractures underlying the Ha'il arch are approximately vertical, and extend all the way to the basaltic source region, presumably the upper mantle.

Rejuvenation of faulting along preexisting north trends in the rocks of the Nuf formation and the Samra intrusive suite may also be related to the development of the Ha'il Arch. The traces of some of these faults extend into the Saq Sandstone, although relative movement in the cover rocks was no more than a few meters.

The present topography of the region reflects the extreme aridity of the climate during Holocene time. Wide, sandy wadis, playa lake deposits, and sand-covered pediment surfaces cover large areas of the quadrangle, and minor eolian deposits occur near the northern border.

## ECONOMIC GEOLOGY

No ancient mines have been observed in the Rak quadrangle, and no outcrops of economically favorable mineralization have been recognized. However, tungsten and molybdenum anomalies have been identified in the Salma intrusive complex by Mytton (1970). In addition, Stuckless and others (1982) have also noted the anomalously high uranium content of the rocks of the Salma granite complex, although they believe that the liklihood of there being economic concentrations of uranium is low. Recent wadi sediment sampling adjacent to Jabal Salma, just south of the quadrangle's southern boundary, has also identified anomalous values for niobium, thorium and rare earth elements (R. M. Samater, oral commun.).

The Akash granite was found to contain anomalous values of tin, tungsten, molybdenum, and zinc in extensive zones of greisen along the northwest contact of the granite (Kellogg and Stoeser, unpub data), about 5 km from the Rak quadrangle's northwest corner. In 1983, investigations are currently underway to evaluate the extent of this mineralization.

## DATA STORAGE

A data base file of compilation material and other data was established for the Rak quadrangle and archived as USGS-DF-04-14 (Kellogg, 1984). No Mineral Occurrence Documentation System (MODS) localities were established.

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