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RECONNAISSANCE GEOLOGY OF THE MADHA QUADRANGLE, SHEET 18/43 A, KINGDOM OF SAUDI ARABIA

by

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PREPARED FOR
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JIDDAH, SAUDI ARABIA
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This report is preliminary and has not been edited or reviewed for conformity with U. S. Geological Survey standards and nomenclature.

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RECONNAISSANCE GEOLOGY OF THE MADHA QUADRANGLE, SHEET 18/43 A, KINGDOM OF SAUDI ARABIA

by

George C. Simmons[1]

ABSTRACT

The Madha quadrangle (Sheet 18/43 A) occupies 2,891 km^2 in the geographic province of Bishah, part of the highlands of southwest Saudi Arabia, and is bounded by lats 18°30' and 19°00'N., and by longs 43°00' and 43°30'E. The area is underlain by crystalline rock and metavolcanic and metasedimentary rock of Precambrian age and basalt dikes of Tertiary age. Much of the bedrock is covered by Quaternary alluvium.

The 39 rock divisions mapped in the Madha quadrangle include 22 units and 8 facies of plutonic rocks, 4 units and 1 facies of metavolcanic and metasedimentary rocks, 3 units of dikes and veins, and 1 unit of sediments. The plutonic rock units have a great variety of composition, and include alaskite, trondhjemite, granite, granodiorite, quartz diorite, diorite, gabbro, pyroxenite, quartz diorite and granodiorite gneisses, and amphibolite schist and gneiss. The metavolcanic rock units are mostly basalt flows, but include flows, breccias, and tuffs of andesite, latite, and quartz latite; marble is the most abundant metasedimentary rock, and graywacke, conglomerate, and quartzite are less common. The volcanic and sedimentary rock units are metamorphosed to the greenschist facies of regional

[1] U.S. Geological Survey, Denver, Colorado

metamorphism. The dikes and veins are quartz, pegmatite, felsite, granite, and basalt.

Major structural features include granitic uplifts, layered synforms, a north-south fold belt, a north-south fault zone, and a northwest-trending fracture pattern. Granodiorite and quartz diorite of batholithic proportions intruded preexisting volcanic rock units and are overlain by other volcanic rock units. Younger granitic plutons are domal stocks ranging in composition from granodiorite to alaskite; the order of emplacement is indicated by the increasing potassium and decreasing sodium content. Seven layered synforms bear various degrees of resemblance to layered gabbros in the region; all may be lopoliths which have been eroded to different depths. One unit of metavolcanic and metasedimentary rock is flexed into tight north-south folds; this belt is within a wider zone of north-south faults which forms part of a major zone of structural weakness in this part of the Arabian Shield. The crystalline rock units, particularly those in the western two thirds of the quadrangle, are fractured by two intersecting sets of northwest-trending joints and faults; the fractures are the loci for many dikes, some of which are several kilometers long.

Reconnaissance geologic exploration indicates little likelihood that economic deposits of metallic minerals are present in the quadrangle.

INTRODUCTION

Geography

The Madha quadrangle (fig. 1) is in the geographic province of Bishah, part of the highlands of southwestern Saudi Arabia; the center of the quadrangle is 70 km northeast of Khamis Mushayt. Bounded by lats 18°30' and 19°00'N., and by longs 43°00' and 43°30'E., the quadrangle is slightly more than 55 km from north to south, slightly more than 52 km from east to west, and occupies about 2,891 km^2. An unpaved road from Khamis Mushayt passes through the quadrangle, and the journey from that town to the center of the quadrangle requires 2½ hours in a four-wheel-drive vehicle. Other roads and many tracks provide somewhat tedious access to much of the quadrangle. Many flat areas of hard-packed sand furnish suitable landing sites for fixed-wing aircraft.

The permanent inhabitants are concentrated in the villages of Madha (for which the quadrangle is named) and 'Areen, which are in the central and southeastern parts of the quadrangle, respectively. Shaya, Mushrufa, Far'a, Hadba, and Urfan are small communities along Wadi Tarib in the south-central part of the quadrangle; isolated homes are found along major wadis elsewhere. A nomadic Bedouin population fluctuates with the availability of water and natural feed for goats and sheep.

The desert terrane is typical of the Bishah region; bare rock hills are half buried in their own detritus, and much of the southern, central, and northwestern parts of the quadrangle consist of low hills, bosses, and myriads of small

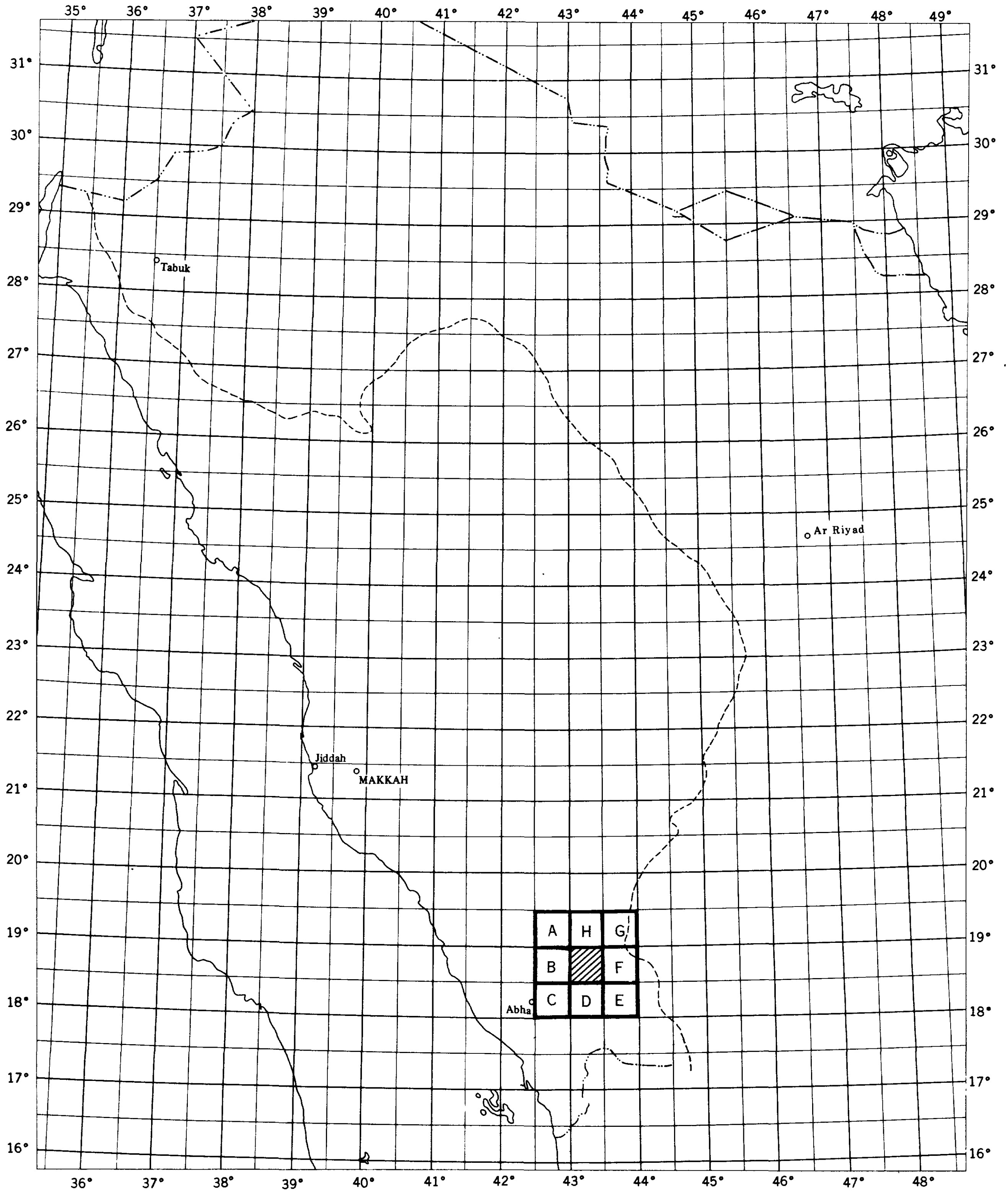

Figure 1.--Index map showing location of the Madha quadrangle (shaded) and adjacent mapped quadrangles: A, Khadrah (Mytton and Ankary, 1967; Greenwood, in press a); B, Khaybar (Coleman, 1973a); C, Khamis Mushayt (Coleman, 1973b); D, Wadi Tarib (D. B. Stoeser, written commun.); E, Malahah (Greenwood, in press b); F, Markas (A. J. Warden, written commun.); G, Hamdah (Overstreet, 1978); and H, Duther as Salam (Overstreet, 1978).

outcrops rising above a sea of alluvial sand. Much of the western part of the quadrangle is dissected by small wadis developed along intersecting fractures, forming a cyclopean maze of sandy passages through low hills. Several larger and higher rock masses have been named; the most prominent of these are Jabal Bqal and Jabal Hibr north of Madha, and Jabal Zed north of Urfan. It is doubtful that any one of these prominences rises as much as 500 m above its base. The most rugged terrane is along the eastern side of the quadrangle where the land surface ascends abruptly above the east side of the canyon of Wadi 'Areen. No altitudes have been established by surveying, but the general altitude of the sand flats near the town of Madha, as determined by altimeters on aircraft, is about 1,600 m above sea level.

No permanent streams exist in the Bishah region. In the Madha quadrangle the intermittent runoff flows in consequent stream beds draining toward the north. From east to west the principal water courses are Wadi 'Areen, Wadi Tarib, and Wadi Tabshat-Tifshah.

The climate is warm and dry. Maximum temperatures seldom rise to 45°C on the hottest summer days, and seldom drop below 0°C during the coldest winter nights; the diurnal variation is commonly 25°C. The average annual precipitation of 10 cm (Nyrop and others, 1977, p. 54) falls irregularly and is apt to be torrential, but in some years there is no rain.

The Bishah region is in the North African-Indian Floristic Zone (Nyrop and others, 1977, p. 55), which is characterized by sparse vegetation and few species. A few grasses, sedges, and woody plants provide stern and Spartan feed for livestock, and except for small areas near waterholes, the plants are either succulents or capable of carrying out a life cycle within a short period of time following a rain.

The meager vegetation supports only a small animal population, and the only large wild animal is the baboon, bands of which live in the more inaccessible highlands in the eastern part of the quadrangle. Foxes are occasionally seen crossing the sand flats, but for the most part the animals of the desert are small and nocturnal. The resident bird population is also small, but a great variety may be observed during fall and spring migrations between Africa and southwest Asia and Europe.

Previous investigations

Several published and unpublished maps pertain to the geology in and adjacent to the Madha quadrangle (fig. 1). The regional geologic setting is shown on the map of the Asir quadrangle by Brown and Jackson (1959); their map is a 4° x 3° sheet at a scale of 1:500,000. Geologic maps at 1:100,000 scale have been made of all 30' quadrangles adjacent to the Madha quadrangle. They are Khadrah to the northwest (Mytton, 1966), remapped by Greenwood (in press, a); Khaybar to the west and Khamis Mushayt to the southwest (Coleman, 1973a, b); Wadi Tarib to the south (D.B. Stoeser, written commun.); Malahah to the southeast (Greenwood, in press, b); Markas to the east (A.J. Warden, written commun.);

Hamdah to the northeast (Overstreet, 1978); and Duthur as Salam to the north (Overstreet, 1978). In addition to these maps, the unpublished field notes of Overstreet, made in 1965 during a geochemical reconnaissance that traversed through the Madha quadrangle, contain many pertinent observations which were useful during the present study.

Present investigation

The Madha quadrangle was mapped during 65 days of field work in December 1976, and January, February, May, and June 1977. Most of the work was done in 16 days with the assistance of a helicopter; the rest was accomplished by a combination of vehicle and foot traverses. Logistic support was provided by the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia, and the U.S. Geological Survey. The work was sponsored by the Ministry of Petroleum and Mineral Resources under a work agreement with the U.S. Geological Survey.

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The author expresses his gratitude to the many people who supported the investigation. At the field camp near Madha, work was facilitated by Mugith Abdullah Algahtani, translator-driver; Ahmed Osman Mohamed, cook; Bakur Mohamed Adam, camp foreman; and Ghufin Misfar Alyami, guide. Ghanum Jerri al Harbi, prospector, located most of the ancient gold prospects which were visited, and Yousef Abdullah, Field Services Officer, maintained radio communication and forwarded supplies from Jiddah.

Assistance in many geologic aspects of the work was provided by members of the U.S. Geological Survey. The author was familiarized with the geology by Douglas B. Stoeser, who mapped the Wadi Tarib quadrangle to the south of the Madha quadrangle, and by Ronald C. Worl, who studied many prospects and ancient mines in the Bishah region. Thin sections were prepared under the direction of John J. Matzko, and spectrographic and atomic absorption analyses were made under the direction of K.J. Curry.

GEOLOGY

Map units

Granodiorite gneiss (gd_1)

Granodiorite gneiss (gd_1) forms the exposed bedrock in most of the western third of the quadrangle from the southern boundary to lat 18°55'N., and includes several rock types which are interlayered, folded, and similarly metamorphosed.

The principal rock types are orthogneiss (chiefly granodiorite but grades into quartz monzonite and quartz diorite), migmatite (mostly alaskite and granite), and gneissic amphibolite. The most abundant and distinctive type is granodiorite gneiss composed of quartz, plagioclase, microcline, biotite, and traces of garnet. At many places, hornblende is present instead of biotite and may be more abundant than the latter mineral; however, the total amount of mafic minerals, as determined by grain counts, is commonly about 20 percent. The minerals are concentrated so as to form light and dark bands which are plastically folded, appearing as wavy stripes on outcrops.

Migmatite is composed of quartz, potassium feldspar, and accessory biotite, although sodic plagioclase is a major constituent in some rock, and the biotite content may be as much as 7 percent. Gneissic amphibolite forms layers as much as 20 m thick. It appears very dark in outcrop and in hand specimen, but in thin section abundant plagioclase is recognized, and in many samples the amount of plagioclase is greater than that of hornblende. Quartz is also abundant in some gneissic amphibolite, and pyroxene and epidote were identified in a few samples.

Granodiorite gneiss (gd_1) is considered by the writer to be one of the older rock units in the Madha quadrangle. The combination of the lithologies, which were undoubtedly derived from preexisting rocks, and the complex folding suggest a more complicated history than that evident in other rock units. The granodiorite gneiss (gd_1) is apparently overlain by metavolcanic rock (mv_1) and it is presumed to be intruded by quartz diorite (qd_2) although cross-cutting relations were not observed near the contact. Contiguous gneiss to the west and southwest is the Khamis Mushayt gneiss of Coleman (1973a, b).

That the complicated history of granodiorite gneiss (gd_1) indicates antiquity is a minority opinion among geologists of the U.S. Geological Survey who have recently mapped quadrangles in southern Saudi Arabia. Greenwood and others (1976, p. 524-525) consider the Khamis Mushayt gneiss to be a younger intrusive rock that has inherited the structures of older layered rocks.

Granodiorite gneiss (gd_2)

Granodiorite gneiss (gd_2) crops out in a band about 5 km wide and extending north-northwest for 13 km from the southern boundary of the quadrangle near its southeast corner. The unit includes gneisses ranging in composition from quartz diorite to granite.

The most abundant rock is granodiorite gneiss composed of plagioclase, quartz, potassium feldspar, hornblende, biotite, and minor amounts of chlorite and epidote. Hornblende and biotite are both present at most places, make up 15 percent of the rock, and are concentrated in thin, irregular streaks and layers about 1 mm thick. The granodiorite grades into quartz diorite containing little or no potassium feldspar, and less commonly into granite containing nearly equal amounts of potassium feldspar, quartz, and plagioclase with accessory muscovite, garnet, biotite, and hornblende. Migmatite occurs in thin streaks and bands that are several centimeters thick and is chiefly composed of potassium feldspar and quartz.

Granodiorite gneiss (gd_2) is also considered one of the older rock units in the quadrangle. Although not complexly folded in the manner of the granodiorite gneiss (gd_1), the presence of migmatite and well-developed foliation, features that are absent from most other rock units in the area, suggests a complicated and, hence, probably a long history. Granodiorite gneiss (gd_2) is apparently unconformably overlain by meta-volcanic and metasedimentary rock (mv_4). However, the contact was not observed, and the relation is surmised on the basis of the lack of contact effects and the discontinuity of metamorphic grade.

Metavolcanic rock (mv_1)

Metavolcanic rock (mv_1) crops out along and near the western margin of the quadrangle between north latitudes 18°38' and 18°53', and contains metabasalt flows, intrusive gabbro, and layers of what once probably were sedimentary rocks.

Most flows are fine-grained basalt, locally containing abundant breccia fragments, and at a few places having pillow structures. The flows are metamorphosed, chiefly within the greenschist facies; the common mineral assemblage is sodic plagioclase, chlorite, epidote, calcite, and actinolite. The metamorphic grade is slightly higher near the north limit of this unit in the Madha quadrangle, as indicated by the presence of biotite and fine-grained hornblende.

Some flows are separated by crudely layered rock of basaltic composition which contains rounded grains of quartz. Although the crudely layered rock resembles the other basalt, the indication of bedding, in conjunction with what appears to be clasts in thin sections, suggests that these rocks are graywacke.

The intrusive gabbro included in this unit is a coarse-grained rock that is mineralogically similar to the basalt, and may be the hypabyssal equivalent of the basalt flows.

Metavolcanic rock (mv_2)

Unit (mv_2) of metabasalt and metadiorite crops out in an area as much as 5 km wide, extending for 19 km along and near Wadi Mifleh and Wadi 'Areen in the northeastern part of the quadrangle.

Most of the unit (mv_2) is massive, fine-grained to very fine-grained basalt flows with some interlayered breccias. These rocks are intruded by small irregular bodies of fine-grained diorite, and all are metamorphosed within the greenschist facies of regional metamorphism. The mineral composition of these rocks is similar to that of metabasalt flows of metavolcanic rock (mv_1); the typical mineral assemblage consists of sodic plagioclase, chlorite, epidote, and calcite. However, the unit (mv_2) lacks the pillow structures and the rocks of probable sedimentary origin that are present in metavolcanic rock (mv_1).

In the north, metavolcanic rock (mv_2) is intruded by three rock units whose apparent sequence of intrusion, from oldest to youngest, is: diorite and quartz diorite (d_1), quartz diorite (qd_1), and granite and granodiorite (gr_2). To the west, metavolcanic rock (mv_2) is in contact with amphibolite schist and gneiss (a). The change in lithology between the two units is an abrupt transition, and the contact is a metamorphic isograd separating greenschist from amphibolite facies. To the east, metavolcanic rock (mv_2) is juxtaposed against metavolcanic and metasedimentary rock (mv_4) along a high-angle reverse fault. The two units do not occur in depositional contact, but because of its upthrown position, metavolcanic rock (mv_2) seems likely to be older.

Metavolcanic rock (mv_3)

Metavolcanic rock (mv_3) crops out in an area of about 25 km^2 in the northeast corner of the quadrangle, and consists of interbedded flows and tuffs ranging in composition from basalt to quartz latite.

Metavolcanic rock (mv_3) contains a variety of flows and tuffs in layers ranging from less than one to several tens of meters in thickness. Most flows are fine-grained to very fine grained basalt; however, some basalt is porphyritic, containing clusters of narrow plagioclase crystals. The tuffs, chiefly fine-grained crystal tuffs containing small disseminated lapilli, are andesite, latite, and quartz latite. Most tuff is massive or poorly bedded, but it is locally well laminated. The pyroclastic rocks are intruded by narrow dikes and sills of quartz latite that is a dense, dark-grayish-brown rock containing scattered anhedral phenocrysts of quartz; this type of rock is often called quartz porphyry in Saudi Arabia.

Metavolcanic rock (mv_3) is intruded by quartz diorite (qd_1), granodiorite (gd_3), granodiorite porphyry (gd_8), and alaskite and granite (ak_4). The relation of metavolcanic rock (mv_3) to the other units containing metavolcanic rocks is unknown because it is nowhere in contact with the latter. Metavolcanic rock (mv_3) is metamorphosed to the greenschist facies of regional metamorphism, and in that respect resembles the other units.

Metavolcanic and metasedimentary rock (mv_4)

Metavolcanic and metasedimentary rock (mv_4) is found in a discontinuous zone from 1 to 4 km wide in the eastern part of the quadrangle. Except for a gap of 5 km in the south, in which the metavolcanic and metasedimentary rock (mv_4) could not be recognized as a distinct unit, the zone extends for the entire length of the quadrangle. South of the gap, the unit consists of metavolcanic rock and chlorite-quartz-sericite schist that were probably derived from volcanic rock, but may be in part derived from granodiorite and quartz diorite. North of the gap, the unit includes rock of sedimentary origin in addition to volcanic rock.

The metavolcanic rocks are chiefly of intermediate composition: andesite, dacite, latite, and quartz latite. These rocks are predominantly crystal tuffs, although some contain abundant lapilli or breccia fragments and a few are undoubtedly flows. Basalt is also common in very fine-grained flows that are mostly less than 10 m thick.

The metasedimentary rock is composed of marble, conglomerate, quartzite, and graywacke. The marble is fine grained, dolomitic, and weathered to a distinctive light-rusty-brown color, by which it can readily be distinguished from associated rocks at a considerable distance. The marble layers are as much as 30 m thick and crop out for a distance of 1 km or more along strike. The graywacke and quartzite are widespread and form small lenses, commonly less than a meter thick and a few tens of meters long.

A prominent lens of conglomerate, more than 1 km long, is found along Wadi 'Areen, near its confluence with Wadi Mifleh (N. 18°53'46"; E. 43°24'26"). This conglomerate contains abundant, well-rounded pebbles and small cobbles imbedded in a matrix of greenstone. The pebbles and cobbles are mostly very fine-grained greenstone: many are silicified and contain disseminated pyrite; a few of the pebbles are gneissic granodiorite. The pebbles are not spindled by shearing, and their shingling and imbrication trend N. 25° E.

This entire unit is tightly folded and metamorphosed to the greenschist facies.

Metavolcanic and metasedimentary rock (mv_4) is bounded by faults at most places but it appears to have a nonconformable contact with granodiorite gneiss (gd_2) and is intruded by diorite (d_2), granodiorite (gd_3), quartz diorite (qd_1), alaskite (ak_1), and granite (gr_3). Contacts with granodiorite (gd_3) and quartz diorite (qd_1) are well exposed in several west-flowing tributaries to Wadi 'Areen, and the granitic rocks have stoped metavolcanic and metasedimentary rock (mv_4) along joints.

Metavolcanic and metasedimentary rock (mvm).--Metavolcanic and metasedimentary rock (mvm) is a facies of metavolcanic and metasedimentary rock (mv_4), and occupies 60 km^2 in the southeastern part of the quadrangle. This unit consists of greenstone schist, which was formed from the metavolcanic and metasedimentary rock (mv_4), but may have included plutonic rock. The original rock is sheared, silicified, and intruded by small bodies of diorite and gabbro (d_2), granodiorite (gd_3), quartz diorite (qd_1), alaskite (ak_1), and granodiorite (gd_7).

Diorite and quartz diorite (d_1)

Diorite and quartz diorite (d_1) crops out in an area of about 50 km^2 in the northeastern part of the quadrangle along the north boundary, and a small area along the north boundary near long 43°09' E. In addition to the principal components of diorite and quartz diorite, the unit contains inclusions of amphibolite and small intrusive bodies of gabbro and pyroxenite (gb), granite (gr_3), and alaskite and granite (ak_4); some of the intrusive bodies were mapped separately where they were extensive enough to record at the scale of the map.

The most abundant rock in this unit is an equigranular, medium-grained, unfoliated diorite consisting of sodic plagioclase, hornblende partly replaced by chlorite, accessory biotite, and traces of garnet(?). The other common lithologic type is quartz diorite, which is similar to the diorite but contains from 5 to 15 percent quartz.

The small intrusive bodies of granite (gr_3) and alaskite and granite (ak_4) have an annular distribution within diorite and quartz diorite (d_1); the significance of this structure is undetermined. In addition to the small bodies of granitic rock and small plugs of gabbro and pyroxenite (gb), diorite and quartz diorite (d_1) is intruded by larger bodies of granite and granodiorite (gr_2), and granite (gr_3); the temporal relation of diorite and quartz diorite (d_1) to metavolcanic and metasedimentary rock (mv_4) is unknown because the two units are everywhere in fault contact.

Diorite and gabbro (d_2)

Diorite and gabbro (d_2) crops out in an area of about 20 km^2 in the southeastern part of the quadrangle. Most of the unit is diorite and gabbro that contain numerous lenses and pods of foliated amphibolite and many small intrusive bodies and dikes of granodiorite (gd_7).

Most of the unit is a medium- and even-grained rock composed of nearly equal amounts of plagioclase and mafic minerals. The mafic minerals are mostly amphibole, but include some pyroxene, and both are partly chloritized; much of the plagioclase is saussuritized. Where weathered and not covered by desert varnish, the rock has a speckled appearance resulting from the contrast between light-colored feldspar and dark-colored mafic minerals. The lenses of foliated amphibolite appear to be the result of dynamic metamorphism along shear zones, rather than inclusions of older rock.

To the east, diorite and gabbro (d_2) intrudes metavolcanic and metasedimentary rock (mv_4), but this relation is obscured by shearing along much of the contact. To the west, diorite and gabbro (d_2) is in contact with amphibolite schist and gneiss (a); most of the contact is coincident with a major north-south fault, but some diorite and gabbro (d_2) occurs as unfoliated inclusions in the schist and gneiss.

Granodiorite (gd_3)

Granodiorite (gd_3) crops out in an area of about 160 km^2 in the eastern quarter of the quadrangle. In addition to granodiorite, the unit contains quartz diorite, which, where possible, was mapped separately as quartz diorite (qd_1).

The granodiorite is mostly coarse grained and even grained and consists of saussuritized plagioclase, quartz, sericitized potassium feldspar, and partly chloritized hornblende or less commonly biotite. The mafic minerals make up 10 to 20 percent of the rock.

The relation of granodiorite (gd_3) to quartz diorite (qd_1) is uncertain, but it seems possible that they are comagmatic. At many places, the transition from the lighter colored granodiorite to the darker colored quartz diorite is a gradual, subtle change across distances of several tens of meters or more. At other places, contacts are quite distinct, and one rock intrudes the other.

Granodiorite (gd_3) is intruded by granite (gr_3) and alaskite and granite (ak_4).

Quartz diorite (qd_1)

Quartz diorite (qd_1) crops out in an area of about 90 km^2 in the eastern quarter of the quadrangle. Quartz diorite (qd_1) includes considerable granodiorite equivalent to granodiorite (gd_3).

The quartz diorite is medium to coarse grained and consists of partly saussuritized plagioclase, slightly to nearly completely chloritized hornblende, and accessory calcite and epidote. The mafic minerals make up slightly more than one-third of the rock.

Quartz diorite (qd_1) is intruded by granite (gr_3). As previously mentioned, quartz diorite (qd_1) intrudes adjacent units containing metavolcanic rocks; however, the only contact with a large body of metavolcanic rock (mv_3) is a fault contact.

Alaskite (ak_1)

Alaskite (ak_1) crops out in a north-trending band 12.5 km long and as much as 1.5 km wide, in the east-central part of the quadrangle. The unit is composed of medium-grained alaskite containing sodic plagioclase, quartz, potassium feldspar, trace muscovite, and as much as 2 percent biotite in small clots.

Alaskite (ak_1) is completely surrounded by metavolcanic and metasedimentary rock (mv_4) and by the facies of the latter unit, metavolcanic and metasedimentary rock (mvm). The general conformity of the alaskite (ak_1) to the layered rocks indicates that it is a syntectonic intrusion.

Amphibolite schist and gneiss (a)

Gneissic and schistose amphibolite is the most ubiquitous rock in the Madha quadrangle, found as inclusions in many granitic rocks, as the only major constituent of amphibolite schist and gneiss (a), and as the principal rock type in three facies: amphibolite schist and gneiss (ao), (an), and (am).

Amphibolite schist and gneiss (a) crops out in a north-trending band 30 km long and 1 to 3 km wide, in the eastern part of the quadrangle. East, west, and south of the village of Madha, the unit (a) occurs in the keels of eroded synclines between granitic domes. Near the north boundary the unit (a) is present on the east and west sides of a granitic dome near 43°12'E. Near the south boundary of the quadrangle, near long 43°17'E., the unit (a) forms tabular bodies interlayered with intrusive rocks. Elsewhere, amphibolite schist and gneiss (a) is mapped as isolated inclusions, septa, and bands in other rocks.

The amphibolite is coarse to fine grained, well foliated except for some of the fine-grained rock, and grayish black to greenish black. The rock typically consists of about two-thirds hornblende, but it may contain as much as 50 percent quartz and plagioclase.

Much of the amphibolite may have formed from regional metamorphism of basalt. Observations made while traversing the northern contact between amphibolite schist and gneiss (a) and metavolcanic rock (mv_2) indicate an abrupt westward transition from greenstone through fine-grained amphibolite into coarse-grained amphibolite. However, not all the amphibolite is of the same origin. Near the south end of its long outcrop band, amphibolite schist and gneiss (a) contains many pebble- and cobble-sized inclusions of diorite and gabbro. Many of the inclusions are unfoliated, others are weakly or strongly foliated, and still others have unfoliated cores but grade outward into more and more strongly foliated rock which becomes indistinguishable from the enclosing amphibolite schist and gneiss. The unfoliated inclusions are petrologically identical to adjacent diorite and gabbro, and probably at least some of the amphibolite schist and gneiss (a) was derived by shearing and metamorphism of the adjacent unit, diorite and gabbro (d_2).

Amphibolite schist and gneiss (ao).--Amphibolite schist and gneiss (ao) is a facies of amphibolite schist and gneiss (a); it is distributed in an oval-shaped area covering 17 km^2 near the center of the quadrangle, where it forms a structural synform. The unit consists of amphibolite schist and gneiss that is interlayered with sills and cut by dikes of trondhjemite, alaskite, granite, and granodiorite that are similar to those lithologies in the map unit trondhjemite (tr); it is also intruded by a few sills and small plugs of gabbro.

Amphibolite schist and gneiss (an).--The amphibolite schist and gneiss (an) facies of amphibolite schist and gneiss (a), crops out in an area of about 40 km^2 in the north-central part of the quadrangle. This facies consists of amphibolite schist and gneiss that are intruded by small plugs of gabbro, pyroxenite, and diorite, and by sills and dikes of trondhjemite and granodiorite gneiss. This facies differs from the amphibolite schist and gneiss (ao) in containing more gabbro, pyroxenite, and diorite, less trondhjemite, and some granodiorite gneiss.

Amphibolite schist and gneiss (am).--The amphibolite schist and gneiss (am) facies of amphibolite schist and gneiss (a), crops out in an area of about 15 km^2 near the northwest corner of the quadrangle. This facies consists of amphibolite schist and gneiss intruded by sills and dikes of granodiorite gneiss resembling the rock in granodiorite gneiss (gd_5).

Granodiorite gneiss (gd_4)

Granodiorite gneiss (gd_4) crops out in an area of 15 km^2 in the southern part of the Madha quadrangle near long 43°18' E.; the rock in the Madha quadrangle is the northern extremity of a larger body to the south, in the Wadi Tarib quadrangle.

Most of the granodiorite gneiss is weakly foliated and medium grained, but it has coarse- and fine-grained facies. The chief minerals are orthoclase, quartz, plagioclase, and biotite, and the gneiss contains a trace of muscovite. The biotite, which is partly chloritized at some places, commonly makes up 10 percent of the rock, but ranges from 3 to 20 percent.

The age of the granodiorite gneiss (gd_4) relative to the ages of the granitic rocks with which it is in contact is uncertain because no intrusive relations were observed. Although the foliation of granodiorite gneiss (gd_4) is weak, it is more thoroughly developed than foliation in adjacent granitic rocks, and for this reason it seems possible that granodiorite gneiss (gd_4) may be older than the adjacent rocks.

Part of the difficulty in determining age relations results from the similarities in the compositions of the rocks involved. Granodiorite gneiss (gd_4) closely resembles granodiorite gneiss (gd_6), but the former commonly contains more orthoclase, less quartz, and is somewhat more foliated than the latter, although the foliation in both units is weak at most places. Granodiorite gneiss (gd_4) can be readily distinguished from alaskite (ak_2) except where the gneiss has a low biotite content that renders the foliation less obvious and the composition more similar; at these places, however, rocks can be distinguished because the granodiorite gneiss contains more orthoclase than quartz, whereas the alaskite contains more quartz than orthoclase. Granodiorite gneiss (gd_4) is distinguished from granodiorite (gd_7) by its higher orthoclase and lower plagioclase content, its slightly lower content of mafic minerals, and its more thoroughly developed foliation.

Quartz diorite (qd_2)

Quartz diorite (qd_2) crops out in an area of 360 km^2 in the southwestern part of the quadrangle. The rock is coarse grained, commonly weakly foliated, and is composed of plagioclase (60-65 percent), quartz (20-25 percent), biotite and hornblende (10-12 percent), and accessory chlorite, epidote, and opaque minerals. The biotite:hornblende ratio averages 5:1.

Quartz diorite (qd_2) is intruded by trondhjemite (tr) and alaskite (ak_3) to the north, and to the east it is intruded by granodiorite (gd_6), alaskite, granite, and trondhjemite (ak_2), granite (gr_1), and gabbro and pyroxenite (gb).

<u>Quartz diorite (qdm)</u>.--Quartz diorite (qdm) facies of quartz diorite (qd_2) crops out in an area of about 40 km^2 in the west-central part of the quadrangle. The facies is chiefly composed of quartz diorite that contains abundant inclusions of amphibolite schist and gneiss. These rocks are intruded by sills, dikes, and small irregular bodies of trondhjemite (tr), gabbro and pyroxenite (gb), and alaskite and granite (ak_4).

Granodiorite gneiss (gd_5)

Granodiorite gneiss (gd_5) crops out in an area of about 60 km^2 in the northern part of the quadrangle near long 43°10' E. The unit includes granodiorite, granite, their gneissic equivalents, locally abundant inclusions of amphibolite schist and gneiss, and small intrusive bodies of diorite and gabbro. The most abundant rock type is medium-grained, weakly foliated granodiorite gneiss composed of plagioclase, quartz, biotite, and orthoclase; the biotite content is as much as 20 percent at many places. Granodiorite gneiss (gd_5) is intruded by trondhjemite (tr) and alaskite and granite (ak_4).

Granodiorite gneiss (gdn).--Granodiorite gneiss (gdn) facies of granodiorite gneiss (gd_5) crops out in an area of 50 km^2 in the northwestern part of the quadrangle. This facies contains the same rocks as the granodiorite gneiss (gd_5), but differs in having more inclusions of amphibolite schist and gneiss, which make up 35 to 40 percent of the facies.

Granodiorite gneiss (gdm).--Granodiorite gneiss (gdm) facies of granodiorite gneiss (gd_5) forms the bedrock of about 40 km^2 in the northwestern part of the quadrangle. This facies resembles the granodiorite gneiss (gdn) facies in containing abundant inclusions of amphibolite schist and gneiss. However, granodiorite gneiss (gdm) also contains many small intrusive bodies of quartz diorite and many dikes and sills of granite and alaskite.

Trondhjemite (tr)

Trondhjemite (tr) crops out in an area of 120 km^2 in the north-central part of the quadrangle. The unit is principally composed of trondhjemite that locally grades into alaskite, granodiorite, and granite, and locally contains inclusions of foliated amphibolite. The most typical rock is a weakly foliated trondhjemite composed of plagioclase, quartz, and biotite, with or without accessory epidote and muscovite. Trondhjemite (tr) is not known to be intruded by any major plutonic rock unit.

Trondhjemite (trm).--Trondhjemite (trm) facies of trondhjemite (tr) underlies nearly 200 km^2 in the central part of the quadrangle. The facies is chiefly made up of trondhjemite that has engulfed quartz diorite (qd_2) and contains some inclusions of foliated amphibolite. The quartz diorite was stoped and occurs as inclusions ranging from pebble size to blocks tens of meters across; consequently, many of the smaller outcrops consist of quartz diorite only. However, the relation between the trondhjemite and the quartz diorite is well exposed at most large outcrops.

Granodiorite (gd_6)

Granodiorite (gd_6) crops out in several small areas totalling about 15 km^2 in the south-central part of the quadrangle. The rock is medium to fine grained, weakly foliated, and composed of quartz, plagioclase, potassium feldspar, and biotite; the biotite makes up about 12 percent of the rock. This unit contains many tabular inclusions of foliated amphibolite.

Granodiorite (gd_6) is intruded by alaskite, granite, and trondhjemite (ak_2), and by granite (gr_1). The relation of granodiorite (gd_6) to granodiorite gneiss (gd_4), discussed under the heading of the latter unit, was not determined; the age relation to granodiorite (gd_7) is also uncertain because the two units are everywhere in fault contact.

Alaskite, granite, and trondhjemite (ak_2)

Alaskite, granite, and trondhjemite (ak_2) crops out in a north-trending band about 17.5 km long, extending northward from the southern boundary of the quadrangle near long. 43°17'E.; the unit underlies about 30 km^2. The most common rock is medium grained, weakly foliated alaskite consisting of quartz, potassium feldspar, plagioclase, and accessory muscovite, biotite, and garnet. The alaskite locally grades into granite by an increase in biotite to about 7 percent, and into trondhjemite by an increase in plagioclase at the expense of the potassium feldspar. The trondhjemite is finer grained than the other lithologies. All the lithologies contain tabular inclusions of foliated amphibolite.

Granite (gr_1)

Granite (gr_1) crops out in several small areas having a total extent of about 2.5 km^2 in the south-central part of the quadrangle. The granite is medium to coarse grained, weakly to nonfoliated, and is composed of quartz (45 percent), microcline (32 percent), plagioclase (18 percent), and biotite (5 percent).

Granodiorite (gd_7)

Granodiorite (gd_7) crops out in an area of about 85 km^2 in the southeastern part of the quadrangle. The rock is coarse to medium grained, and nonfoliated to weakly foliated. It is composed of potassium feldspar, plagioclase, and quartz in nearly equal amounts and has about 12 percent biotite. Hornblende is an accessory mineral at a few places. Biotite and hornblende are slightly chloritized. Epidote is a locally abundant accessory mineral.

Gabbro and pyroxenite (gb)

Gabbro and pyroxenite (gb) is found in many plugs, dikes, sills, and small irregularly shaped intrusive bodies in the western three-quarters of the Madha quadrangle; where possible, these were mapped as a separate unit.

The rocks range in composition from medium-grained gabbro to coarse-grained pyroxenite, the coarser grain sizes being typical of the more mafic rock. Pyroxene is the most abundant mineral at most places. The only other major constituent is calcic plagioclase; biotite, chlorite, epidote, and opaque minerals are accessory minerals, which in aggregate may constitute as much as 12 percent of the rock.

Gabbro and pyroxenite (gbm).--Gabbro and pyroxenite (gbm) facies of gabbro and pyroxenite (gb) was mapped in six areas having a total areal distribution of about 64 km^2. The facies consists of gabbro and pyroxenite mixed with older amphibolite schist and dioritic gneiss. All of these rocks are intruded by dikes and sills of granite and alaskite.

Granodiorite porphyry (gd_8)

Granodiorite porphyry (gd_8) is limited to an area of 3 km^2 along the northern boundary near the northeast corner of the quadrangle; it is the southern extremity of a large body of granitic rock. The granodiorite contains phenocrysts of orthoclase and plagioclase in a coarse-grained matrix of orthoclase, quartz, and plagioclase, and has small clots of biotite that make up about 15 percent of the rock. The granodiorite porphyry (gd_8) intrudes metavolcanic rock (mv_2), the only other map unit with which it is in contact.

Granite and granodiorite (gr_2)

Granite and granodiorite (gr_2) crops out in two granitic domes in the central and northeastern parts of the quadrangle covering an area of about 20 km^2. The rocks are nonfoliated and coarse grained, and are made of of quartz, potassium feldspar, plagioclase, biotite (5 to 12 percent), and traces of epidote; the ratio of potassium feldspar to plagioclase ranges from 3:1 to 1:2. In the dome closer to the center of the quadrangle, granite and granodiorite (gr_2) is adjacent to and intruded by dikes of alaskite (ak_3).

Alaskite (ak_3)

Alaskite (ak_3) crops out in two granitic domes in the central part of the quadrangle and underlies about 20 km^2. The alaskite is coarse to very coarse grained and nonfoliated; the most common mineral assemblage is quartz-microcline-plagioclase. A less common assemblage is quartz-plagioclase-microcline; plagioclase-quartz-microcline is rare. Muscovite is a major constituent in much of the rock, but it ranges from a trace to 20 percent. The total amount of mafic minerals is everywhere less than 5 percent, and at most places is less than 2 percent. Biotite and garnet are the most common mafic minerals, but rare hornblende and opaque minerals are also present.

Granite (gr_3)

Granite (gr_3) crops out in two elongate stocks astride the boundary between the Madha quadrangle and the Markas quadrangle to the east, and in a small plug and thick sills in the northeastern part of the Madha quadrangle. The total area of outcrop is about 48 km^2.

The granite is coarse grained, nonfoliated, and is composed of potassium feldspar, quartz, plagioclase, and biotite. The biotite commonly makes up from 5 to 7 percent of the rock, sometimes as much as 15 percent, and hornblende is present at a few places.

Alaskite and granite (ak_4)

Alaskite and granite (ak_4) is found in an elongate stock along the eastern boundary of the quadrangle near lat 18°55'N., in an irregularly shaped plug near the northern boundary of the quadrangle on the east side of Wadi Tifshah, and in a few small bodies near the northern boundary on the west side of Wadi 'Areen.

The rock is coarse grained and nonfoliated. The major minerals are orthoclase and quartz, which are found in nearly equal amounts and are graphically intergrown. Plagioclase makes up from 10 to 15 percent of the rock, and biotite, hornblende, and chlorite make up from 2 to 6 percent.

Quartz veins (q)

Massive quartz forms tabular bodies and lenses as much as 10 m thick and 500 m long, but most are much smaller. Although widely distributed, the veins are most common in metavolcanic rocks, and in amphibolite schist and gneiss. Ancient prospects and mines are located on some of these veins.

Pegmatite dikes (p)

The pegmatite dike unit (p) consists mostly of pegmatite with minor granite and alaskite felsite dikes. The pegmatite dikes are concentrated in the southwestern part of the quadrangle where they were intruded along west-northwest-trending fractures;

many of the dikes are from a few to 20 m thick and several kilometers long. The pegmatite dikes are made up almost entirely of potassium feldspar and quartz and contain only rare traces of mafic minerals. Locally the dikes are composed mostly of quartz.

The granite dikes are much more numerous than the map indicates, the number shown being limited by the small scale of the map and the time spent in mapping them. Most of those that appear on the map are in mafic rocks, and their color contrast facilitates identification from a helicopter.

Basalt dikes (b)

Basalt dikes are common throughout the quadrangle. They range from less than 1 to 10 m in thickness and from a few meters to as much as 8 km in length; most of those that were mapped are several hundred meters long. The typical basalt is greenish gray, fine to very fine grained, and composed of amphibole, plagioclase, and accessory opaque minerals. A less common variety is porphyritic, containing narrow laths of plagioclase as much as 6 mm long, in a fine- to very fine-grained matrix. The basalt dikes everywhere intrude other rocks, and at no place are they themselves intruded. It is likely that they are related to the basalt flows of Miocene age in the As Sirat Mountains to the south of the Madha quadrangle (Coleman and others, 1977).

Alluvium (Q)

The alluvium unit is principally composed of alluvial sand, silt, and gravel, loess, minor deposits of poorly indurated gravel, and some colluvial deposits that were difficult to distinguish from alluvium. In the southwestern part of the quadrangle it was impossible to accurately separate alluvium from bedrock outcrops at the map scale of 1:100,000 because of the small size of alluvium-covered areas and their scattered distribution within bedrock outcrop areas.

Structural geology

Plutonism

Two distinct periods of plutonism can be distinguished in the Madha quadrangle on the basis of age, size of the plutonic bodies, and petrology: 1) an older episode of batholithic proportions involving the emplacement of granodiorite, quartz diorite, and gneisses of the same compositions, and 2) a younger episode involving the emplacement of stocks, domes, and a small batholith, chiefly composed of trondhjemite, granite, alaskite, and some granodiorite. A third episode of plutonism of intermediate age may be represented by granodiorite and quartz diorite in the eastern part of the quadrangle. These latter rocks could belong to the older period, but not to the younger, because they are intruded by stocks of younger granite and alaskite.

The northeast part of a batholith is found in much of the central, south-central, and western parts of the Madha quadrangle, and extends more than 60 km to the south where it is called the Wadi Tarib batholith in the Wadi Atf and Mayza quadrangles by R. E. Anderson (in press, 1978a, b). In the Madha quadrangle the batholith is composed principally of granodiorite gneiss (gd_1), quartz diorite (qd_2) and its facies quartz diorite (qdm), and the trondhjemite (trm) facies of trondhjemite (tr). Although the trondhjemite (trm) facies is composed dominantly of trondhjemite, the presence of included older quartz diorite indicates the original extent of the Wadi Tarib batholith. Elsewhere the margin of the batholith is also irregular or lost because of disruption by younger intrusions and faulting. Wherever large bodies of prebatholith amphibolite schist and gneiss (a) and its facies adjoin the Wadi Tarib granitic rocks, the foliated rocks dip away from the batholithic complex.

Most of the younger domes and stocks have oval or elongate oval outlines, and most of them consist of one rock unit: granodiorite gneiss (gd_5), trondhjemite (tr), granodiorite porphyry (gd_8), granite and granodiorite (gr_2), alaskite (ak_3), or alaskite and granite (ak_4). The domal structure is apparent only where these rocks are in contact with foliated amphibolite. Perhaps the best examples are 6 km southeast of Madha, where two small domes of granitic rocks are surrounded by amphibolite schist and gneiss (a) that dips away from both structures and forms the keel of an eroded syncline between the domes.

The relative ages of the younger domes and the rocks forming them can be determined somewhat from intrusive contact relations where overlying rocks have been eroded from adjacent domes or where two different rock units are within one dome. A compilation of the limited number of observed relations suggests a possible correlation between the ages of the domes and their petrologies. According to this hypothesis, the granitic rocks of the domes appear to have evolved from soda-rich to potash-rich.

Layered synforms

Seven layered synforms have been recognized in the Madha quadrangle. Five of the synforms coincide with areas mapped as the gabbro and pyroxenite (gbm) facies of gabbro and pyroxenite (gb): 1) west of Madha near lat 18°52'N., long 43°13'E.; 2) at the northeast corner of the quadrangle; 3) on the west side of Wadi Tabshat near lat 18°38'N., long 43°03'E.; 4) on the east side of Wadi Tabshat near lat 18°37'N., long 43°05'E.; and 5) near lat 18°47'N., long 43°21'E. A sixth synform is included within an area mapped as gabbro and pyroxenite (gbm) near lat 18°56'N., long 43°04'E. The seventh layered synform is largely coincident with the area mapped as the amphibolite schist and gneiss (ao) facies of amphibolite schist and gneiss (a) on the east side of the town of Madha. Six of these layered synforms resemble the layered gabbro described by Coleman, Ghent, and Fleck (1977) at Jabal Sha'i', 46 km west of the Madha quadrangle, but differ from the latter structure in containing many layers of older, nongabbroic rock, chiefly amphibolite schist and gneiss, and granitic rocks.

The synforms in the Madha quadrangle are round to oval in shape and 1 to 7 km in maximum diameter. Dips at their margins are steep, but dips near the margins and toward the centers are mostly gentle. The synform near lat 18°47'N., long 43°21'E. is typical of these structures. It has a central area that is composed chiefly of gabbro and some pyroxenite, and in which layering is poorly developed. The outer parts of the structure consist of interlayered, inward dipping amphibolite schist and gneiss and gabbro sills. The synform is intruded by dikes and some sills of granite. However, it also contains some layers of gneissic granite that may have been intruded into the amphibolite prior to the intrusion of the gabbro. The synform appears to be a lopolith from which the overlying rocks have been eroded.

The synform on the east side of Madha resembles the other synforms in shape and size, but is unique in that it contains little gabbro. The synform is developed in amphibolite schist and gneiss that is intruded by sills and dikes of granite. The amphibolite has resisted erosion more than granite and forms annular ridges, whereas the sills of granite form intervening troughs. Gabbro is present only in a few sills and plugs.

The structure of lopoliths is considered to develop from the sagging of underlying country rock, a consequence of the high specific gravity and local concentration of intruded rock. However, the synform near Madha does not contain a significant amount of intruded rock having a high specific gravity. Could the other synforms also have formed without the presence of gabbro? In other words, did the structures form because of the presence of gabbro, or did the gabbro intrude these structures after they had formed? Of course, the synform east of Madha may differ from the others only because it has been so deeply eroded that the central core has been completely removed, leaving gabbro only in a few sills near the base of the lopolith and in feeder dikes.

North-south fold belt

A belt of folded rocks, coincident with the distribution of the map unit metavolcanic and metasedimentary rock (mv_4), and part of its facies metavolcanic and metasedimentary rock (mvm) crops out as a zone 1 to 4 km wide which occupies nearly the entire length of the Madha quadrangle from north to south. The folds are tight and asymmetric; axes strike parallel to the trend of the belt and axial planes dip steeply to the west.

The fold belt is within a wider band of north-south faults, at least some of which are high-angle reverse faults; the parallelism of the axial planes of the folds and the high-angle reverse faults suggests that the two structures may have formed during the same period of compression.

North-south fault zone

North-south anastamosing faults transect the eastern part of the quadrangle in a zone ranging in width from 3.5 km in the north to 20 km in the south. The zone is part of a regional belt of crustal weakness extending far to the north and south of the Madha quadrangle. In the northern part of the quadrangle the west side of the fault zone coincides with the west side of the north-south fold belt, but elsewhere the fault zone is wider than the fold belt and offsets a variety of plutonic, metamorphic, and volcanic rocks. Many segments of faults are in the bottoms of wadis, are at changes in topographic slopes, or form contacts between different rock units, and thus are conspicuous features in the field and on aerial photographs.

The major fault segments are vertical and west-dipping high-angle faults, and at the few places where determinations were made, the high-angle faults are reverse. The rake of grooves and slickensides on fault surfaces indicates left lateral movement.

The age of the faulting is uncertain, but because of the large number of rock units affected, the last activity is presumed to be late in the sequence of major geologic events. One north-trending fault near lat 18°46'N., long 18°29'E. is apparently truncated by a stock of granite (gr_3), considered to be one of the youngest rock units in the quadrangle. However, this is believed fortuitous, and as mentioned in the following section, the latest faulting in the north-south fault zone may be younger than the young granitic plutons.

Northwest-trending fracture pattern

Many faults are present in the Madha quadrangle in addition to those in the north-south fault zone, and most of them are part of a fracture pattern consisting of two prominent, intersecting sets of joints and faults. These fractures chiefly involve granitic rocks of the western two-thirds of the quadrangle, but they also affect granitic rocks within the north-south fault zone in the southeastern part of the quadrangle. One of the sets strikes N. 45°-60° W., and the other strikes N. 80°-85° W; the fractures in both sets are vertical to nearly vertical. At many places it is difficult to distinguish faults from joints because of the homogeneity of the rocks they cut, and because alluvium and colluvium accumulate along the strike of the fractures, obscuring whatever physical evidence of faulting is present.

The northwest-trending fracture pattern is younger than the young alaskite and granitic plutons, in which it is well developed, and older than the numerous basalt dikes, some of which were intruded along the fractures. The formation of the pattern may be closely related in time to the emplacement of the young alaskite and granitic plutons; many pegmatite dikes, some more than 10 km long, were intruded into many fractures, and the composition of the pegmatite, quartz-microcline, suggests a possible magmatic relation to the young alaskite and granite plutons.

In the southeastern part of the quadrangle, where faults in the northwest-trending fracture pattern intersect faults in the north-south fault zone, neither group of faults was observed to offset the other, suggesting contemporaneity of age.

MINERAL POTENTIAL

The results of reconnaissance exploration for metallic minerals were uniformly disappointing, and the likelihood of economic deposits existing in the quadrangle is considered very remote. Areas of altered rocks observed from helicopters were investigated and most were found to contain finely disseminated pyrite. Samples from these areas, analyzed by spectroscopic and atomic absorption methods, contained such minute quantities of trace elements that no detailed sampling program was undertaken. Sands from wadis near intrusive bodies of gabbro were panned and examined with a microscope for nickel, chromium, and platinum minerals, with negative results. Several ancient prospects and small mines, where quartz veins were explored for precious metals, were investigated, and a few flakes of gold and silver were discovered during many hours of prospecting. Selected samples contained small amounts of precious metals, but none were detected in most analyses.

Areas of altered rocks, except for a few small areas near dikes, and the locations of ancient prospects and mines are indicated on the map. The locations, samples, analyses, and other data are recorded and filed in the Mineral Occurrence Documentation System (MODS) of the Directorate General of Mineral Resources.

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