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GEOLOGY OF SAMRAH AND VICINITY

KINGDOM OF SAUDI ARABIA

by

Paul K. Theobald, Jr.
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PREFACE

In 1963, in response to a request from the Ministry of Petroleum and Mineral Resources, the Saudi Arabian Government and the U. S. Geological Survey, U. S. Department of the Interior, with the approval of the U. S. Department of State, undertook a joint and cooperative effort to map and evaluate the mineral potential of central and western Saudi Arabia. The results of this program are being released in USGS open files in the United States and are also available in the Library of the Ministry of Petroleum and Mineral Resources. Also on open file in that office is a large amount of material, in the form of unpublished manuscripts, maps, field notes, drill logs, annotated aerial photographs, etc., that has resulted from other previous geologic work by Saudi Arabian government agencies. The Government of Saudi Arabia makes this information available to interested persons, and has set up a liberal mining code which is included in "Mineral Resources of Saudi Arabia, a Guide for Investment and Development," published in 1965 as Bulletin 1 of the Ministry of Petroleum and Mineral Resources, Directorate General of Mineral Resources, Jiddah, Saudi Arabia.

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The investigations reported here were initiated at the request of H. A. Quinn (1964c, p.17-18) of the Directorate General of Mineral Resources. The principal objective has been; "a geochemical survey.... of all of Ad Dawadmi area....(paying) particular attention.... to Ad Dawadmi basic intrusion, the bodies of granite pegmatite and the ancient silver mines." To accomplish this objective, another of Quinn's recommendations was followed; "The geology of the Samrah area should be mapped at scale of .... the KLM low-level air photos." Time, availability of base materials, and administrative changes in responsibility for the Ad Dawadami area have limited the area covered to Samrah and vicinity, including the mines examined in detail by Quinn at the Dyke, Umm Urgabah and Ar Rudahat. The mapping extends northeastward to include the ancient mines at Samrah East.

Presented here are an uncontrolled planimetric base compiled from the KLM areal photographs and a geologic map with accompanying descriptions. These are being presented separately from the geochemical data, to which they are the base materials. The "Ad Dawadmi basic intrusion", better termed the Harrat Jeelani basic-ring complex for the three-peaked gabbro jabal at its core, will be considered separately at a scale of 1:50,000. The largest of "the bodies of granite pegmatite" known to Quinn are within the area.

The maps tie together the detailed studies of Quinn as well as providing a base for the geochemical studies. The field work was done October 24, 1964, January 1 through January 4, May 1 through May 24, and June 21, 1965. The work has been supplemented by exchange of information with H. A. Quinn, G. F. Brown, J. W. Mytton, and R. F. Johnson. Technical support throughout has been provided by Hamad Marsuq.

Geography

Figure 1 is an uncontrolled mosaic of Samrah and vicinity showing geographic and cultural features selected to aid interpretation of the geologic and chemical data. The planimetric material was collected in the field on an overlay of seven, alternate, low-level, aerial photographs. The photographs are contact prints of the KLM mining sites series, site B19, dated 2.2.64; run 1 numbers 9181 and 9183, run 2 numbers 9117, 9119 and 9121, and run 3 numbers 9202 and 9204. The overlays of these photographs were matched to produce a "best fit" of the geographic and geologic information along the narrow margins of overlap among the photographs.

Magnetic north was established on four of the seven photographs by obtaining a Brunton bearing between two recognizeable points. The total angular discrepancy of these four measurements on the mosaic is about 3°, providing a crude measure of the accuracy of the mosaic. The north arrow shown is an average of the four measurements. Magnetic declination is about 2° east (Quinn, 1964c, p.64); about the same as the estimated angular error in the map; so it is not shown. The two longitude and latitude ticks were scaled from coordinates of conspicuous points common to the low-level photographs and 1:50,000 photo mosaics. North from the longitude differs from the measured north by about 1°. The scale of the map is given as approximately 1:12,500, the stated scale of the KLM photographs. Several checks of the 1:2,500 scale topographic sheets compiled from these photographs indicate that they are very close to the stated scale. In a single measurement Quinn (1964c, p.64) estimated the scale of the contact prints, and hence the map presented here, to be 1:11,350. The cartographic error inherent to the map, both from the scale of the photographs and the method of compilation, does not hinder its intended use; however, this base map should not be used for detailed measurements.

The drainage net will serve principally as the base for the presentation of geochemical data. All of the drainage channels shown were free of flowing water during all of the time spent in the field, though after winter showers some of them became damp. In the eastern part of the map the drainage channels are in small valleys but in the western part of the area the majority of the drainage channels are indistinct, discontinuous, and probably transient features on nearly flat pediment surfaces. The prominent granite jabals of the western part of the map are generally smooth-sided features with coherent drainage only from their lower-most slopes and on surrounding pediments. In the downstream direction, the minor drainage channels shown on the map merge into an intricate and irregular mesh of channels. The nature of the major drainage systems is indicated by the pattern shown south of Samrah and north of Umm Urgabah, but the major systems have been omitted. The location, size and general flow direction of the major systems can be estimated from the arrows placed on the minor channels where they enter the major systems.

The truck trails shown on the map are rutted trails used by the Bedouin. The road from Ad Dawadami enters the north edge of the map east of Ar Radahat, continues southward and eastward passing east of Abu Ahfore and south of Samrah. This is an established road leading, from the junction between Samrah and the Dyke, eastward to Bi'r Samrah and southeastward to Saffaqah (Mytton, 1967). Both forks of the road join the direct route from Dawadami to Saffaqah. Access in the area is excellent.

Climatic data are given by Quinn (1964a and 1964c). Summers are hot and dry; winters are cool; and precipitation is scarce. Water is available at Bi'r Samrah, about a kilometer to the east, and at Ad Dawadami, 30 minutes drive to the northeast.

Archaeology

Ruins of a series of ancient mining operations provide direct evidence of the presence of valuable metals in the vicinity of Samrah. The debris cast about by these ancient miners also contaminates the surface for considerable distances from the mining sites. Bedrock relations are obscured by extensive piles of tailings, ore or waste. This debris has been considered as a geologic unit, is shown on figure 2, and is discussed in a subsequent section. None of the other archaeological features obscure the geology so appear on figure 1.

Shallow prospect pits and trenches are clustered along some veins in the area.

A few prospect pits occur singly on veins scattered throughout the area. These are generally shallow pits two or three meters long and about a meter wide, though longer trenches are common; for example, the trench 130 meters long in the cluster of prospects at Ar Rudahat. The pits and trenches are usually floored by fine, light-colored aeolian sand and bordered by a pile of coarse, unsorted, dark-colored debris thrown from the pit. They appear as small black rings with a white core on the low-level photographs. Bedrock is rarely exposed in them as the aeolian filling merges into the surrounding waste. The nature of the waste, however, indicates that alteration in or adjacent to veins, was sought by the original prospectors.

Deeper and larger trenches merge into glory holes, shafts and open stopes where the prospects are presumed to have shown interesting mineralization. The largest and most extensive of these workings, at Samrah, are described by Bogue (1954, written communication). Deeper workings are also at Umm Urgabah, the Dyke, Samrah East and Ar Rudahat. Flanking the deeper workings are extensive piles of coarse waste rock, and the workings are usually partially filled with a mixture of aeolian sand and rubble that has caved from the working. The waste rock, outcrops in the ends of the larger trenches, and pillars left in the largest openings provide information on the material worked by the ancients. The workings are on veins, but are most extensive in the altered rock adjacent to the veins. The hard vein material was commonly left either as one wall of the opening or as a spine projecting into the opening. Bogue measured depths of openings as great as (30 meters) and apparently shared with subsequent workers the feeling that the ancient miners confined their labor to the zone of oxidation and stopped work where sulfide minerals were encountered. At Samrah their most likely objective was native silver, as wires, sheets, or nuggets, produced near the surface by oxidation of the sulfide minerals.

Evidence of ore processing works are seen at Samrah, Umm Urgabah, Ar Rudahat, and Abu Ahfore. These are extensive areas heaped with partially processed material; that is, crushed rock in several stages of reduction with a scattering of grinding stones. These piles are shown on the geologic map (figure 2) and are described by Quinn (1964a, p.2-6). The grinding stones used at Samrah are well shaped granite slabs.

Scattered heaps of slag in an arcuate zone east and south of Samrah, about half way between Samrah and Umm Urgabah, indicate that a certain amount of ore was smelted. The volume of slag is insignificant in comparison with the size of the mines and the volume of crushed rock, therefore smelting must have been an incidental operation. Bogue estimated the volume of slag as "several hundred tons" and Quinn (1964a, p.30-31) provides an adequate description of the material.

Remnants of building sites, usually a well constructed stone foundation, are common near the mining sites. The main village was apparently in the valley immediately south of Samrah, among the piles of crushed ore. Another village lay to the east of the area mapped, in the vicinity of what is now called Bi'r Samrah. Most of the outlying building sites found are shown on figure 1. The crowd of small sites in the village at Samrah are not shown.

Hills or rises are often marked by a stone monument, usually square and 1 to 3 meters on a side. They are of well laid, mortar-free stone work similar to the construction seen in the building foundations and presumably of about the same period. They were apparently hollow and are now caved leaving the outer wall as a foundation, or standing as much as a meter above the surface, surrounding either a hollow or mound of rubble. Their purpose is unknown. They are shown on figure 1 where seen since they provide excellent local land marks.

Geology

Figure 2 is a geologic map of Samrah and vicinity keyed to the planimetric base (figure 1) by the longitude and latitude ticks. It is in essence an outcrop map as the alluvial boundary usually marks the edge of the outcrop. The map was compiled as an uncontrolled mosaic simultaneously with the planimetric map.

The rocks are a series of igneous types ranging from gabbro to pegmatite and dacite. In general the more mafic, plutonic types are the older while the more felsic, dike rocks are younger. These are discussed in order from oldest to youngest. Except where the data of other workers is available, only megascopic field descriptions can be given.

Gabbro

Gabbro is largely confined to an elliptical area in the core of the amphibolite mass north of Samrah. Here the outcrops consist of large boulders bordering the alluvial fill or protruding through the alluvium. A smaller patch of gabbro boulders was mapped in the nearby, circular mass of amphibolite straddling the dacite-andesite dike swarm east of Samrah, and unmapped boulders of gabbro occur sporadically throughout the amphibolite. Northwest and north of the map, gabbro is common in the large, basic-ring complex described by Quinn in 1964.

The gabbro characteristically outcrops in the form of large nearly spherical boulders or piles of boulders mixed with curved tablets that have spalled from the boulders. The boulders are black from a thin surface varnish and are very tough. Where freely supported the boulders and particularly the tablets have a characteristic, clear, resonant ring when struck by a hammer. Fresh surfaces of the gabbro are lighter in color and are seen to be composed of dark gray, sometimes iridescent, feldspar laths and black pyroxene grains. Black opaque minerals are common and almost all pieces contain a few small, irregular, interstitial masses of a light-colored pyrite-like mineral that has been identified in the field as pyrite, pyrrhotite, or chalcopyrite. Thin sections examined in several laboratories from specimens collected in the amphibolite mass to the north of the map indicate a variety of types with olivine gabbro being the most common. Both orthorhombic and monoclinic pyroxene are usually present.

The gabbro outcrops are always within the amphibolite. Further relations are not clear from the exposures in the vicinity of Samrah; however, in the large ring complex to the north it has been tentatively concluded that the gabbro is one of the more resistant of several rock types that have subsequently been converted to amphibolite. Therefore it is assigned an age greater than the amphibolite.

Amphibolite

Amphibolite was mapped in a broad band extending southward through the area to and beyond Samrah. A subsidiary, nearly circular outcrop straddles the dacite-andesite dike swarm east of Samrah, and the south edge of the large, basic-ring complex was mapped in the vicinity of the Ar Rudahat mines. Northward from Samrah the band of amphibolite outcrops may be traced continuously to the southeast edge of the ring complex where it is interrupted by sheared granite and aplite presumably occupying a fault zone. It seems probable that the outcrops of amphibolite shown here are part of a single, larger, once continuous mass.

Bold outcrops of amphibolite are rare. The more usual physiographic expression of this rock type is as subdued, gruss-mantled hills usually flanking more prominent hills or ridges supported by later dike rocks. At a distance the hills of amphibolite are dark gray or greenish gray but on closer inspection they are littered by mottled black and white debris. Individual fragments are friable and break along grain boundaries to a fine gravel. Fresh surfaces have a more uniform gray color with dark amphiboles and gray, presumably labradorite or calcic-andesine, plagioclases rimmed by a lighter colored feldspar. Texturally the rocks are highly variable, ranging from fine-grained granular to coarse-grained pegmatoid varieties with individual crystals 3 or more centimeters long. Fine grained, granular rock masses within the amphibolite may exhibit a strong planar structure that locally imparts a schistose cleavage to the rock.

The term amphibolite has been used as a field term and is retained here for several reasons: (1) On map I-206A (Bramkamp and others, 1963) precedent was established that should not be broken without overwhelming contradictory evidence. (2) Megascopically and microscopically the rock consists essentially of plagioclase and amphibole in approximately equal amounts, thus fitting the general definition of amphibolite. The single modal analysis (Thomas Feinniger, written communication, 1964) available at present gives 60 percent plagioclase and 38 percent amphibole. (3) On the basis of textural and field evidence, largely in the basic-ring complex to the north of the area being considered here, the amphibolite appears to result from alteration of pre-existing rocks rather than being an igneous intrusive rock. The term amphibolite is more general than the terms "hornblende gabbro" or "diorite" and can be applied to metamorphic as well as igneous rocks.

Both Feinniger (written communication, 1964) and Michener (written communication, 1965) describe the amphibole-plagioclase rocks as alteration products of pre-existing pyroxene-rich and olivine-rich rocks. Relicts of pyroxene are described in the cores of amphibole aggregates in the amphibolites, and amphibole as secondary rims on pyroxene and olivine are described in the gabbros. On a macro-scale, dikes of granite, aplite, and pegmatite cutting across the layering of the gabbro and diorite of the basic-ring complex are bordered by amphibolite, regardless of the lithology being cut. The amphibolite borders merge with the broad, conformable bands of amphibolite in the complex. On this evidence the amphibolite has been assigned an age younger than the gabbro.

Dikes of all rocks younger than the foliated granodiorite cut the amphibolite. Most evidence supports the supposition that the foliated granodiorite is also younger than the amphibolite but these relations are not clear. At the extreme northwest corner of the map a dike tentatively assigned to the foliated granodiorite cuts the amphibolite. In the mass of amphibolite just northeast of Jabal Abul, between sample localities 160 and 161, the contact with foliated granodiorite appears to be gradational. Usually the contact between these two units is marked by younger intrusive rocks.

Foliated granodiorite

Foliated granodiorite is common throughout the granitic terrane occuring as angular, apparently joint-bounded, blocks included in the younger granite. These range from a few centimeters or a meter on the side to blocks of the size shown along the south side of the prominent vein system extending northeast from Samrah. Larger, reasonably coherent masses of the foliated granodiorite, as mapped in the belt south of Samrah and south of the prominent shear zone in the northwest corner of the map, are apparently giant inclusions in the granite. These are segmented by joint controlled, interconnecting dikes of the granite.

Granodiorite forms pavements underlying pediments, and bold outcrops are confined to the flanks of hills supported by more resistant younger rocks. An inclusion in the younger granite is commonly exposed as a rim separating the alluvium-covered core of the inclusion from the bordering outcrops of granite. The proportion of granodiorite to the other rock types is probably greater in the alluvial areas than in the areas of exposure.

Texturally the granodiorite ranges from foliated, almost schistose, to massive. The degree of foliation increases toward amphobolite and is best developed in the border zone of the basic-ring complex in the northwest part of the map. More massive granodiorite is exposed in the southwest part of the map, remote from amphibolite masses. The foliation is defined by allignment of biotite and quartz or by a slip cleavage, commonly with slickensided surfaces, parallel to the mineral alignment.

Grain size of the granodiorite is usually coarse with individual grains 5 millimeters or more in diameter. The coarse grain size and foliation are the most distinctive features of the unit in the field. However, as the degree of foliation decreases the grain size decreases, and texturally the granodiorite approaches the granite in appearance in the southwestern part of the area. In the vicinity of the ancient mines at Abu Ahfore a fine-grained, sugary textured rock is apparently a local variant of the granodiorite.

Megascopically, feldspar, quartz and biotite are the major constituents. Plagioclase predominates over both K-feldspar and quartz; hence the designation as granodiorite. This designation is, however, subject to petrographic verification. Biotite is the common varietal mineral though an amphibole is also present, particularly near amphibolite masses. Blebs, inclusions or autoliths, up to 10 centimeters across have a more basic composition with amphibole, plagioclase and possibly pyroxene as the predominant minerals. Like the amphibole of the surrounding granite, these are most abundant near amphibolite.

The granodiorite is older than the clean, cross-cutting dikes of granite. The granodiorite is probably younger than the amphibolite; the principal evidence to the contrary, apparent intergradation of the two units at several localities, may result from reaction of the granodiorite with the basic inclusions just described.

Equigranular granite

Equigranular granite, the most common rock type, is exposed in the western part of the area as dikes or dike-like masses. In the eastern part of the area these merge into a single mass though the general cross-cutting nature of the mass is still apparent The granite dikes typically outcrop as a low ridge standing about a meter above the surrounding pediments cut on the granodiorite. The more extensive masses of granite, like those east of the amphibolite at Samrah, form a rolling pavement. The prominent hills of the area, Umm Urgabah, Ar Rudhah, and Ar Rudahat, are also supported by the resistant granite. The granite commonly has a cavernous weathered surface and appears in the notes of earlier workers, noteably Bogue, as the "cave granite".

The rock is usually massive, equigranular and light colored. Quartz and feldspar with subordinate or minor biotite are the main mineral constituents, accompanied locally by amphibole or muscovite. The texture is fine to medium-grained hypidiomorphic granular to aplitic. Coarser varieties occur in larger masses, and aplitic varieties occur in smaller dikes.

The granite is younger than the granodiorite, which it cuts in clean dikes. This relationship has been used to distinguish the two rocks in areas where the granodiorite is more massive and finer grained than usual. The granite is older than the lamprophyre which forms clean dikes cutting the granite. The apparent reversal of this relationship north of Samrah, where dikes of lamprophyre in the amphibolite can be interpreted to be truncated by granite, results from the termination of the dikes against the more massive granite.

Lamprophyre

Lamprophyre forms north-trending dikes in and adjacent to the amphibolite mass at Samrah and extending into the granitic terrane south of the amphibolite at the northwest corner of the map. Despite the age separation of the two rocks, the spatial association of the amphibolite and lamprophyre is pronounced not only in the area mapped but where other lamprophyre dikes have been found to the north along the edge of the basic-ring complex.

The dikes are usually less than a meter wide. In granitic terrane they are irregular in thickness, sinuous in trace, and discontinuous. In the amphibolite they are more continuous, more regular, straight, and nearly vertical.

The rock is dark gray to black, massive, and aphanitic. Clear, zoned feldspar phenocrysts can be found in most exposures and provide one of the best criteria for distinguishing this rock from the dacite and andesite which it resembles. The phenocrysts are nearly equidimensional, though simple or crossed twins of laths occur, and they may be a centimeter or more in maximum dimension. Near the margins of dikes, a cleavage, locally approaching schistosity, develops parallel to the dike walls.

Lamprophyre dikes cut the granite. They are cut by the aplite and pegmatite. The lamprophyre is usually cut and offset during the period of shearing. South of Samrah, the lamprophyre dikes can be traced into the zone of shearing and recrystallization, and, though sheared, the lamprophyre is much less effected than the older rocks.

The terminalogy is based almost entirely on the position of the dikes in the intrusive sequence. They are dark colored dike rocks that follow the main granite intrusion and preceed or are equivalent to the early stages of the pegmatitic phase of intrusion. Lamprophyres commonly occur in this sequence at about this time. It remains to be demonstrated that the sequence is a single cycle of igneous activity and that the composition of these dikes fits that of lamprophyre.

Sheared granite

A network of shear zones traverses the entire area. They range from minor interlacing zones in the southeastern part of the area mapped to major fault zones like that forming the south border of the basic ring complex in the northwestern corner of the area mapped. In addition to those shown as such, the shear zones have provided channels controlling most of the later rocks and the lamprophyre.

Minor shears, relatively isolated from later events, outcrop only by accident and are usually masked in a narrow, straight, alluvium-filled trench. All of the major shears and many of the smaller ones have been hardened by addition of material during one or more of the later episodes in the geologic history of the area. These stand as brown-colored ridges traversing the area from a few to a few tens of meters above the surrounding country, and are conspicuous on the air photographs.

The rock involved in the shearing is usually the equigranular granite, suggesting that the shearing is reactivation along zones opened to permit intrusion of the granite. The zones are marked by a strong secondary cleavage crossing mineral boundaries of the host rock. The cleavage is least well developed at the margins of a zone and best developed at the core of a zone where the individual cleavage planes may be only a millimeter apart, and intricately interlaced. In the extreme, the cleavage planes merge into a black phyllonite or mylonite, as at Ar Rudahat. The outcrop is a smooth brown ridge crest strewn by angular, cleavage-bounded chips of granite. The size of the chips is determined by the spacing of the cleavage planes and the extent of subsequent hardening. The color is apparently the result of oxidation along these porous zones.

The shearing post-dates the equigranular granite and in most places the lamprophyre. South of Samrah, however, several dikes of lamprophyre appear to penetrate a recrystallized shear zone and one lamprophyre dike dies out to be replaced along strike by a shear zone. Apparently the shearing predates at least some of the lamprophyre dikes but continued well after most of the lamprophyre became brittle. Pegmatite and aplite dikes occupy the shear zones as do the younger rocks. The pegmatite and younger rocks do not appear to have been effected by the shearing, therefore they are considered to be younger. Some aplite in the shear zones is sheared and some is not, suggesting implacement during the last stages of shearing.

Aplite, pegmatite, and recrystallized granite

Aplite, pegmatite and recrystallized granite occur along the shear zones just described and are transitional phases between the unaltered shear zones and the larger unsheared pegmatites. They occur throughout the area, the most conspicuous being a north to northwest-trending zone in the middle of the map that merges into an east to east-northeast trending zone that crosses the entire mapped area north of Samrah. The prominent fault zone along the south edge of the basic-ring complex merges eastward into rocks of this type.

The outcrop pattern is essentially the same as that described for the sheared granite. The color is unusually more red than that of the sheared granite and chips are somewhat larger as the cleavage planes are often healed by recrystallization. Blocks of aplite or pegmatite may be strewn among the chips, or more persistant dikes of aplite may stand in true outcrop.

Of the three intergradational rock types, the most common is sheared granite, as described earlier, that is distinctly reddened and hardened along the cleavage planes. Megascopic examination suggests that secondary K-feldspar partially replaces the walls of the cleavage planes; but this interpretation should be confirmed. In the extreme, this process leads to a medium-grained red granite, as that exposed on the east flank of Jabal Abul. A granular aplitic rock occurs where shearing continued after recrystallization. This rock merges with typical, sugary-textured, light-colored, quartz-feldspar aplite. In almost all of the zones where aplite occurs it merges further into coarse pegmatitic pods with two feldspars and quartz. This pegmatite usually exhibits mild shearing in contrast to the more intense shearing of the earlier(? phases of this suite of rocks.

The age of these rocks spans an interval that probably began with the lamprophyre and ended with the coherent pegmatites. They are definitely younger than the equigranular granite though perhaps related to structural discontinuities that predate the granite. Usually they are younger than the lamprophyre though there are apparent local reversals of this relationship. The dacite or andesite dikes cut pegmatite, aplite, and recrystallized granite. The coherent, larger pegmatite masses are spacially related to the zones of recrystallization, may occur within them, and are themselves little sheared suggesting that they are either the last phase of this series or are separate and younger.

Pegmatite

Jabal Abul, near the middle of the map, is the most conspicuous of the pegmatite masses. Other pegmatite masses form white hills sporadically distributed throughout the mapped area and the surrounding country. Pegmatite dikes are more common in the amphibolite than in the granites. The pegmatites are resistant to erosion and stand as ridges or hills above surrounding rocks, the size of the rise being dependent on the size of the pegmatite. The quartz cores of larger masses, as at Jabal Abul, rise as spines above the outer zones of the pegmatite.

Most of the pegmatites have irregular shapes that seem to defy interpretation on the basis of pre-existing structures. The only apparent control is the position of many of the pegmatites in or near shear zones in the granitic rocks.

The pegmatites have a simple mineralogy of feldspar, quartz, and usually muscovite. Tourmaline in black needles is the most common accessory mineral. Zoning is usual and, with the discovery of float of lithian muscovite, is the reason for emphasis on these rocks in the reports by H. A. Quinn (1964a and 1964c). The zones are variations in the texture or composition from place to place in the pegmatite. They are not uniform in distribution in a given pegmatite or among the various masses. The zones most commonly distinguishable are massive quartz, quartz-muscovite rock, graphic granite, massive feldspar, and quartz-tourmaline rock.

The pegmatite dikes cut lamprophyre and are cut by dacite or andesite dikes. Their age with respect to the sheared and recrystallized granite is not clear. Pegmatites usually occur adjacent to or within zones of recrystallized granite and are themselves little sheared so are presumed to be younger than the shearing and most of the recrystallization. In many places the aplite dikes merge into pegmatites providing evidence of continuity. The pegmatites are probable the end product of the events that began with shearing and recrystallization.

Dacite or andesite dikes

Two modes of intrusive dike rocks are in this category on the map. The geographically most prominent are relatively regular, long, single dikes that underly prominent, dark colored ridges that trend slightly north of east. Most maintain their continuity for many kilometers. One crosses a part of the mapped area north of Jabal Umm Urgabah, where it protrudes as a spine-like ridge in the alluvium. Another forms a similar ridge in granite south of Jabal Ar Rudahat, terminating at the west edge of the map but continuing for many kilometers to the east. A prominent offshoot from this dike forms the extreme northeast limit of the map.

The second style of intrusion is as a swarm of smaller, interlacing, less persistent dikes in a fairly well defined and persistent zone. Where the zone is narrow and the individual dikes are close together, these outcrop at the crest of a rounded, dark-colored ridge, as in the zone extending eastward from Samrah. Where the zone is more diffuse and the dikes farther apart, outcrops are scarce and subdued, as in the extension of the zone just mentioned to the west of Samrah. There is no evidence at present that these two modes of intrusive rocks differ in composition or time, so they have been grouped.

Fresh rocks, difficult to obtain at the surface, are dark to medium gray. Weathered surfaces are brown. The texture is most commonly massive and aphanitic. In the central parts of wider dikes the holocrystalline nature of the rock is apparent but individual grains can rarely be identified. Uncommon porphyritic varieties have small elongate phenocrysts of feldspar unlike the more equidimensional and larger phenocrysts of the lamprophyre. Texturally the andesite or dacite dikes are composite with thin dikes and the margins of thicker dikes presenting a shattered, glassy texture while the cores of thick dikes are laced by a more open prismatic cleavage. It is the prismatic cleavage in the core that produces the spine-like outcrop pattern.

These rocks are given a variety of field terms in the reports of Quinn, ranging from "basalt" (1964a, p.25) to rhyolite (1964a, p.28). Petrographic descriptions by Felix Ronner (Quinn, 1964c, p.65-66) of these two extremes are listed under the general titles of "Quartz-bearing porphyrite" and "Quartz porphyrite" with notations of compositions equivalent to andesite and dacite respectively. Inasmuch as the andesite was collected in the mineralized fault zones at Samrah, it should not be considered as typical of the dike swarms though it is possible that the compositional range is as great or greater than indicated by these two samples; both names are used here.

The dacite or andesite dikes are the last coherent intrusive phase in the area studied. The dikes cut all other igneous rock types including the pegmatites. They exhibit none of the pervasive shearing common to earlier rocks, the shattering and cleavage referred to above being in all cases an intrusive phenomenon controlled by and terminating at the dike walls. The dikes are, however, cut and offset by later faults and quartz or carbonate veins.

Mylonite

Mylonite can be demonstrated along almost all of the fault zones exposed in the area, though it is usually mixed with other products of dynamic metamorphism or brittle fracture. The most prominent mapped zones of mylonite are those on the south edge of the basic-ring structure in the northwest corner of the map and the northwest-trending zone just to the northeast of Umm Urgabah. These two merge to the west of the mapped area. Where quartz or carbonate veins occupy the same structure, the vein system has been given preference in mapping since distinction of the two would be impossible at this scale. (See for example the excellent photograph in Quinn, 1964a, p.27. The fragments in the breccia in this photograph are mylonite). The most prominent mylonite zone was, therefore, not mapped as such and is the vein system extending northeast from Samrah.

The outcrop characteristics of the mylonite are similar to those of the dacite or andesite dike swarms or the larger zones of sheared granite; a dark, commonly brown, rounded, low ridge persists as a linear element for many kilometers. The ridges of the more prominent zones are only interrupted where swamped by alluvium. The ridge crests are littered by a fine debris of brown to black slivers of rock where the mylonite has not been healed by later processes.

It is an aphanitic, black granular rock where best developed, grading along and across strike into less sheared products where angular slivers to spherical blobs of minerals from the parent rock may be visible. These grade further to rocks in which the recognizable parent material is laced by a myriad of intermeshing fracture planes. The boundary to the mylonite was placed at about this point and further expressions of the fracturing were mapped as "sheared granite". Commonly the granulated rocks are re-fractured to a breccia and healed by introduction of quartz, carbonate, or hematite. Such is the case in the vein system extending northeast from Samrah and in the fault zone just northeast of Umm Urgabah. The latter might better be termed "hematite-carbonate breccia".

Several ages of mylonite are recognizable, and some zones were active during more than one time. The age span is at least from "sheared granite" or "lamprophyre" time to "post-dacite" time. There appears to be a general progression from more nearly plastic, dynamic-metamorphic mylonite in the older zones to more brittle, breccia-like mylonite in the younger zones. The age span along a single system is evident for the zone bounding the south edge of the basic-ring structures which grades from sheared and recrystallized granite in the east to a well defined mylonite-sheared granite zone in the west. Farther west this zone merges with the northwest-trending zone that passes northeast of Umm Urgabah. This latter zone offsets the dacite dike north of Umm Urgabah. The andesite dike swarm at Samrah is offset at the mylonite zone in the vein system but the offset is due not to post-andesite faulting but rather to an earlier offset of the permissive structure. Andesite was intruded along the mylonite zone as well as in the cross structure that provided the main host, as seen in the photograph by Quinn mentioned above.

Quartz or carbonate veins

The veins and vein systems have been mapped wherever seen, and have been given priority over all other rock types because they provide the only direct evidence for hydrothermal introduction of material discernable at the surface. Most of the individual veins are exaggerated to give them boundaries, and veins of systems have been combined and appear as single wide veins. For these reasons vein widths on the map only indicate in comparative terms the quantity of material introduced.

The largest vein system extends northeast from Samrah to and beyond the northeast corner of the map. The second largest is east-southeast of Samrah in the andesite dike swarm in the vicinity of the Dyke mine. These systems of veins are large enough to support topographic ridges, generally light brown in color, rounded, and strewn with chips and blocks of vein material. Offshoots from these vein systems, particularly those connecting the northeast-trending system and the recrystallized granite to the north of it, provide the next largest systems. Smaller veins are along almost all structural trends accommodating rock units younger than the equigranular granite. These are rarely of sufficient size to have distinctive topographic expression; their outcrop is controlled by the outcrop of the associated rocks.

Individual veins have fairly regular, parallel walls for considerable distances, up to a kilometer for a vein a half meter or less in width. The vein systems are, however, highly irregular. Irregularities result from branching, merging, and addition of new veins as well as local changes in the thickness of veins. Maximum vein development occurs where several structures intersect, regardless of the relative age or nature of the intersecting structures. This occurs along the system northeast of Samrah where east-trending veins cross from the recrystallized granite zone to the north. To the east of Samrah, north of the Dyke mine, a minor quartz vein replaces a minor west-northwest-trending zone of recrystallized granite only where that zone cuts and offsets a minor, northeast-trending zone of sheared granite. Samrah occupies one of the most complex intersections, involving the northeast-trending vein system, the andesite dike swarm, and a north-northwest-trending swarm of lamprophyre dikes along the amphibolite-granite contact.

Clean quartz veins are the exception. Brecciation along pre-existing structural weaknesses apparently preceded introduction of quartz, and the quartz filled interstices in the breccias (Quinn, 1964a, p.27). The breccia fragments are usually mylonite, indicating the parent structure. The quartz is vuggy and milky to white in color. Comb structures are common. Vugs are lined by clear quartz crystals, commonly red from a hard coating of hematite dust. The breccias were apparently open and the quartz grew into the openings from the walls of the breccia or the surfaces of breccia fragments. The quartz crystals are relatively perfect unless crowded during growth suggesting that this open brecciation was the last major tectonic disturbance.

Carbonate is relatively uncommon at the surface, but soft brown, rhombic-cleaving blocks are seen along the larger vein systems. At the west end of the Dyke mine system a fairly wide carbonate vein has left a residue of clear calcite rhombs on the surface. Elsewhere the iron-rich, soft blocks suggest that siderite or ankerite may be the more common carbonate mineral. Where quartz and carbonate occur together, the carbonate is younger, filling vugs in the quartz or, where quartz is scarce, filling the interstices between quartz-rimmed-breccia fragments.

No sulfides have been seen in the surface exposures, and the nature of the ancient workings and a few traverses with chemical data that cross the veins suggest that most of the valuable metals are concentrated in horses or wall rocks to the veins rather than in the veins themselves.

Most of the veins occupy a position on one wall of the structure they are following. Clean, cross-cutting relations are uncommon. All cross-cutting veins that have been found indicate that the veins are younger than all other rocks up to and including the dacite and andesite dikes. From the nature of the breccia fragments it is clear that most of the mylonite zones preceded the veins, but it is possible that some, like the northwest-trending zone northeast of Umm Urgabah, cut and offset the vein systems.

Alluvium

Alluvium includes a small amount of pure aeolian sand, wadi sand, terrace sand and gravel, pediment sand and gravel, and thick talus blankets or cones surrounding the higher hills. The thickest and most extensive cover is in the western part of the map where the west-flowing drainage system is integrating. Cover is least extensive in the eastern part of the map along the watershed between east-and west-flowing drainage.

Coarse-grained talus usually retains the general color characteristics of the weathered outcrop providing the debris, as best exemplified in the broad, white fans of talus surrounding Jabal Abul (see photograph in Quinn, 1964a, p.7A). The color is provided by larger blocks, and since these are above the general ground level they are constantly cleaned of fine debris by the usual moderate to strong winds. Beneath the surface cover of coarse debris the interstices of the coarse rubble are filled with a dull, pale-brown, fine-grained sand. Passing from the coarse blocky rubble of the talus into the drainage systems the characteristics colors of the weathered parent material are lost as the proportion of fine sand at the surface increases. The drainage pattern is marked on air photographs by the monotonous dull brown sand regardless of the characteristics of the country rock being traversed. This contrast is particularly well defined in the dark colored hills of amphibolite and gabbro, and where younger drainage patterns are superimposed on older pediment or terrace surfaces. The surface of older pediment and terrace alluvium has usually been swept clean of fine sand, leaving a veneer of pebbles coated by dark brown to black desert varnish. Beneath the veneer the color and texture of the older alluvium is again dominated by the dull-brown, fine-grained sand. Throughout the alluvial sequence the fine sand predominates and is of aeolian origin. True aeolian deposits as dunes or sand fields are, however, insignificant in size and number in the mapped area. They are confined to sand slopes on the leeward sides of minor ridges where the ridges are sufficiently irregular to break the widely divergent wind patterns of the area.

The age of the alluvium varies from modern splays overiding tailings, hence less than a thousand years old, to the older terrace deposits that may be Pleistocene or older. The alluvium is younger than any of the bedrock units.

Tailings

The main tailing accumulation is in the valley to the southeast of Samrah. Smaller accumulations are near the mines at Umm Urgabah and Ar Rudahat. These have been described and sampled in detail by Quinn (1964a, p. 2-7; 1964c, p. 23-38). Smaller piles adjoin ancient prospects at Abu Ahfore and Samrah East. These differ from those described by Quinn in that most of the debris, and at Samrah East practically all of the debris, is coarse, angular, uncrushed rock thrown directly out of the mine openings and piled immediately adjacent to the opening. An arcuate group of piles, entirely of crushed rock, lies about half way between Samrah and Um Urgabah. These can be related to no apparent mining activity or geologic structure but are commonly accompanied by slag strewn on the rock surface. The slag heaps are not sufficiently dense or large enough to obscure the bedrock geology so they are shown only on the planimetric base. The tailings associated with the slag are also described by Quinn (1964c, p. 27-28). Two radiocarbon dates on charcoal from the tailings heaps indicate a major period of activity in the early part of the eighth century. Two samples collected by Quinn (1964a, p. 14-16) have dates of 700 and 725 A.D.

Structure

The structural fabric of the small area mapped in detail is dominated by faulting. On a regional scale Quinn (1964a, p. 40-41) and Mytton (1967), present evidence for considerable folding, but the general massive nature of the rocks in the vicinity of Samrah preclude delineation of folds.

The extent of fracturing associated with the faulting is great. Practically all rocks older than the dacite or andesite dikes exhibit some form of secondary brittle cleavage even on a hand specimen scale, and the dacite and andesite dikes are offset along through-going faults. The mode of intrusion of the equigranular granite suggests that a pattern of brittle fracture was established before its intrusion, though this may have been more local, perhaps associated with stoping marginal to the main intrusion.

The lamprophyre dikes follow a set of fractures trending north to north-northwest. The fractures post-date the equigranular granite and generally predate the shearing accompanying recrystallization of the granite and introduction of the aplite and pegmatite. There is some evidence in the vicinity of and just to the west of Samrah that these fractures were re-opened to allow segmenting of the lamprophyre and afford access to pegmatitic solutions, but the time span of these fractures appears to have been relatively short and early in the structural history of the area. Minor offset can be demonstrated at several places along lamprophyre dikes but the complex post-lamprophyre history preculdes establishment of an overall displacement pattern. Although the belt of lamprophyre dikes is fairly well defined and continuous for several kilometers, individual dikes, and presumably the host fractures, are short and irregular suggesting dispersion of the dynamic force, perhaps at greater depth than the later fractures.

A period of regional shearing, locally intense, followed the lamprophyres. The principal trend of fractures in this set is eastward though there was apparently some reactivation of the older north-trending fractures. Northeast-trending fractures apparently complimented this stage of structural development. These fracture sets continued active throughout the remaining structural history of the region. The recrystallizing solutions, aplites, and pegmatites found access along the east and north-northwest trending fractures in the early stages of their development. Early fracture along the northeast-trending zones and some of the east-trending zones was of a tight, shearing nature that produced mylonite. During this early stage the fracturing was more coherent than that preceding the lamprophyre but apparently still at considerable depth where a nearly plastic deformation occured. The east-trending fractures reopened to produce regional tension fractures that allowed access to the dacite or andesite dikes. The prominent open breccias that later allowed access to the quartz-carbonate veins along the east and northeast-trending fractures probably post dated the dacite and andesite. Offset can usually be demonstrated for fractures of this set, though only apparent horizontal displacement is available from this data. Right lateral displacement is most common, as inferred from offset of the lamprophyre dike swarm and the amphibolite.

The period of open brecciation and quartz introduction along the east to northeast-trending fractures apparently followed the dacite-andesite introduction and preceded the northwest-trending breccia-carbonate-hematite zones. The northwest-trending faults are inferred to be the last structural features since they are not hosts to quartz veins but are host to carbonate, a late mineral in the quartz veins. They have apparent left lateral displacement where they offset both the dacite dike north of Umm Urgabah and the andesite dike swarm farther to the north.

Structural control of mineralization

The accumulation of economic minerals, as evidenced by the ancient mine workings and chemical data to be presented later, was controlled by the fracture patterns developed in the area. The main channels and host fractures were the east-trending set, at most of the mines, and the northeast-trending set occupied by the main quartz-vein systems, as at Samrah east. These were probably the most open, tension-type fractures at the time the metal-rich solutions moved through the area.

The mineralization is apparently not directly related to the introduction of quartz. The quartz veins preferentially occupy the same fracture sets and rare usually present in the vicinity of the ancient mines, but the great majority of the quartz veins and the largest of the vein systems are apparently barren. Most of the mining activity appears to have been concentrated in the altered rocks adjacent to rather than within the quartz-sealed zones.

The principal control for mineralization along the preferred fracture sets appears to have been "structural knots" produced at the intersection of several divergent fractures. The economic minerals were deposited in the open fractures adjacent to constrictions where these fractures pass through a congested zone hardened by repeated sealing of older fractures. A check of this hypothesis of "fracture intersections" in the area north and northeast of this area led to the location of a large number of ancient prospecting sites at the intersections recognizeable on the 1:60,000 scale aerial photographs.

A change in the nature of fracturing appears to have prompted precipitation from the ore fluids. The mines at Ar Radahat, for example, occur in the rather narrow mylonitic zone where it gives way to a broad zone of sheared granite. This is probably a varient of the control mentioned above rendered less conspicuous by the absence of the pronounced cross structures.

Hydrothermal alteration

The alteration of parent rocks in and immediately adjacent to the veins are described by Quinn (1964a, p. 37-38) based in large part on the work of Bogue in 1954. As emphasized by Quinn, the most impressive feature of the alteration is its limited extent, between the veins walls. True "wall rock alteration" is confined to areas of apparent accumulation of metal-bearing sulfides, and even here the alteration halo extends only a few meters beyond the vein walls.

A soft, waxy, pale yellow-green mineral often occurs in or near the veins as a hydrothermal alteration product. It is produced by alteration of both the amphibolite and the granites. Perhaps because of its color, this mineral is the most conspicuous of the alteration products, and almost invariably its presence coincides with recognizeable ancient prospecting activity. In a single specimen from a waste dump at the Umm Urgabah mine G. F. Brown identified the mineral as serpentine (Quinn, 1964c, p. 66). The possibility of serpentine as a major alteration product is emphasized because; (1) this is the most extensive, easily recognized alteration product, (2) it apparently bears a direct spacial relation to the introduction of valuable metals, (3) production of serpentine in the granitic rocks necessitates considerable mobility of magnesium in the hydrothermal system, and (4) an unprospected zone of this type of alteration occurs to the east of the Umm Urgabah mine.

The unprospected alteration zone is about 550 meters east of the easternmost pit of the Umm Urgabah mine, near the structurally favorable intersection of the northwest-trending mylonite zone with the north-northwest-trending zone of sheared and recrystallized granite. This intersection is in large part buried beneath alluvium at the south edge and to the south of the area mapped.

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