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Geology of the Ishmas gold district, Kingdom of Saudi Arabia

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GEOLOGY OF THE ISHMAS GOLD DISTRICT, KINGDOM OF SAUDI ARABIA

By

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ABSTRACT

The Ishmas gold district was mapped at 1:25,000 scale to place auriferous mineralization into geologic perspective, to assist in creating an ore-deposit model, and to aid in devising a strategy for subsequent exploration elsewhere in the Jabal Ishmas-Wadi Tathlith gold belt.

The precratonic evolution of the district began with the deposition of a tholeiitic mafic volcanic and volcaniclastic sequence that was intruded by diabase and gabbro. Basaltic to rhyodacitic volcanism following a calc-alkaline evolutionary trend ensued. Subsequent deposition of a thick wacke and sandstone unit represented the final phase in the volcanosedimentary accumulation. The emplacement of a large lopolithic layered-gabbro complex marked the end of the precratonic evolutionary cycle.

The district coincides with the boundary of two allochthonous terranes. The collisional Nabitah orogeny represents the suturing of the two terranes. The effects of this event are manifested by numerous north-trending, steeply dipping faults, shear zones, and mylonite belts, as well as diapiric serpentinite. During the waning stages of the orogeny, auriferous quartz pods were precipitated in dilatant structures within the north-trending shear zones by deep-seated circulating fluids.

The emplacement of a tonalite stock was closely followed by the formation of N. 20°-35° W.-trending faults. These faults influenced the emplacement of dacite porphyry stocks and associated auriferous quartz veins. The auriferous veins are massive, tabular open-fracture fillings that are spatially, temporally, and genetically related to the dacite porphyry.

The emplacement of a quartz monzodiorite stock was responsible for additional auriferous quartz vein mineralization that is almost exclusively hosted by the intrusion. A nearly random orientation of the veins indicates that no regional structure influenced their formation.

The formation of a series of N. 60°-80° W.-trending faults represents the final episode in the district's geologic history and corresponds to the cratonic reactivation that affected a large part of the Arabian Shield (that is, the Najd faulting event).

INTRODUCTION

Location

The Ishmas district covers 355 km^2 between lat 20°50'00" N. and 20°59'06" N. and long 43°12'42" E. and 43°25'06" E. at the northern end of the Jabal Ishmas-Wadi Tathlith gold belt (Worl, 1979) in the southeast Arabian Shield (fig. 1). The district lies 25 km east of Wadi Bishah and 70 km southeast of Ranyah, the regional commercial center, from which the area is accessible by 4-wheel-drive vehicle over desert track.

Geomorphology and Geography

The geomorphic character of the Ishmas district is largely a function of major structural features in the area. Two broad, northerly trending ranges or series of ridges, as much as 4 km wide, rise to elevations between 900 and 1,000 m above sea level and are flanked and separated by broad plains of subdued relief, generally not exceeding 800 m in elevation (figs 2, 3; pls. 1, 2). The ranges join in the south-eastern part of the district to form a V-shaped topographic feature with the apex directed to the south-southeast. The western range consists of a large layered-gabbro complex bounded by the Ishmas East and Ishmas West faults (pls. 1,2). To the west, covering almost a quarter of the district, is the broad plain of terrace gravels of Wadi Bishah. The eastern range represents the Nabitah Fault Zone (pls. 1,2). Many of the prominent ridges here are underlain by fault-controlled serpentinite bodies. East of this range, along the eastern margin of the district, are broad plains of subdued relief underlain by schist and amphibolite. The interior of the V-shaped geomorphic feature between ranges, in the central part of the district, is an area of subdued relief underlain by a synclinal volcanosedimentary sequence.

Prominent geographic features in the district include Jabal Umm Shat and Jabal Nabitah, serpentinite masses both located in the eastern part of the district, Jabal Al Suwaydah in the east-central part, and Jabal Al Wozariyah in the southern part of the district (pls. 1, 2). Jabal Ishmas lies immediately south of the district. Jabal Hadad, a large, steep-sided alkali-feldspar granite complex, rises above pediment gravels north of the district.

Previous Work

The first documented work in the area was that of Schaffner (undated), which entailed sampling and trenching of two of the ancient mines in the district: Ishmas (MODS 00650) and Umm Shat Gharb (MODS 01459) (pl. 2). Smith (1964) investigated and sampled the Ishmas Kabir ancient mine (MODS 01458) (pl. 2). The district lies within the southern Najd 1:500,000-scale quadrangle compiled by Jackson and others (1979) and in the northeastern part of the Jabal Ishmas 1:100,000-scale quadrangle mapped by Gonzalez (1974). In conjunction with geologic mapping by Gonzalez, V. J. Flanigan conducted aeromagnetic and airborne gamma-radiation surveys over the Jabal Ishmas quadrangle (Gonzalez, 1974; Flanigan, 1974).

Studies by Worl (1979) in the Jabal Ishmas-Wadi Tathlith gold belt included work on several of the ancient mines in the district. Detailed plane-table mapping, trenching, and sampling were carried out at the Ishmas Kabir (MODS 01458), Umm Shat Gharb (MODS 01459), and Umm Shat Sharq (MODS 01460) ancient mines (pl. 2). The same three ancient mines were investigated for placer potential by Boyle and Atkinson (1982). The district was also included in a 1:250,000-scale lithostratigraphic map compilation (Riofinex, 1980).

Objectives

The purpose of this study is to produce a 1:25,000-scale geologic map of an ancient mining district within the Jabal Ishmas-Wadi Tathlith gold belt in order to place the mines and prospects in geologic perspective. With this accomplished, a better understanding of controls on mineralization can be gained here and applied elsewhere in subsequent exploration programs.

The particular area of study was chosen because 1) it is situated along the Nabitah mobile

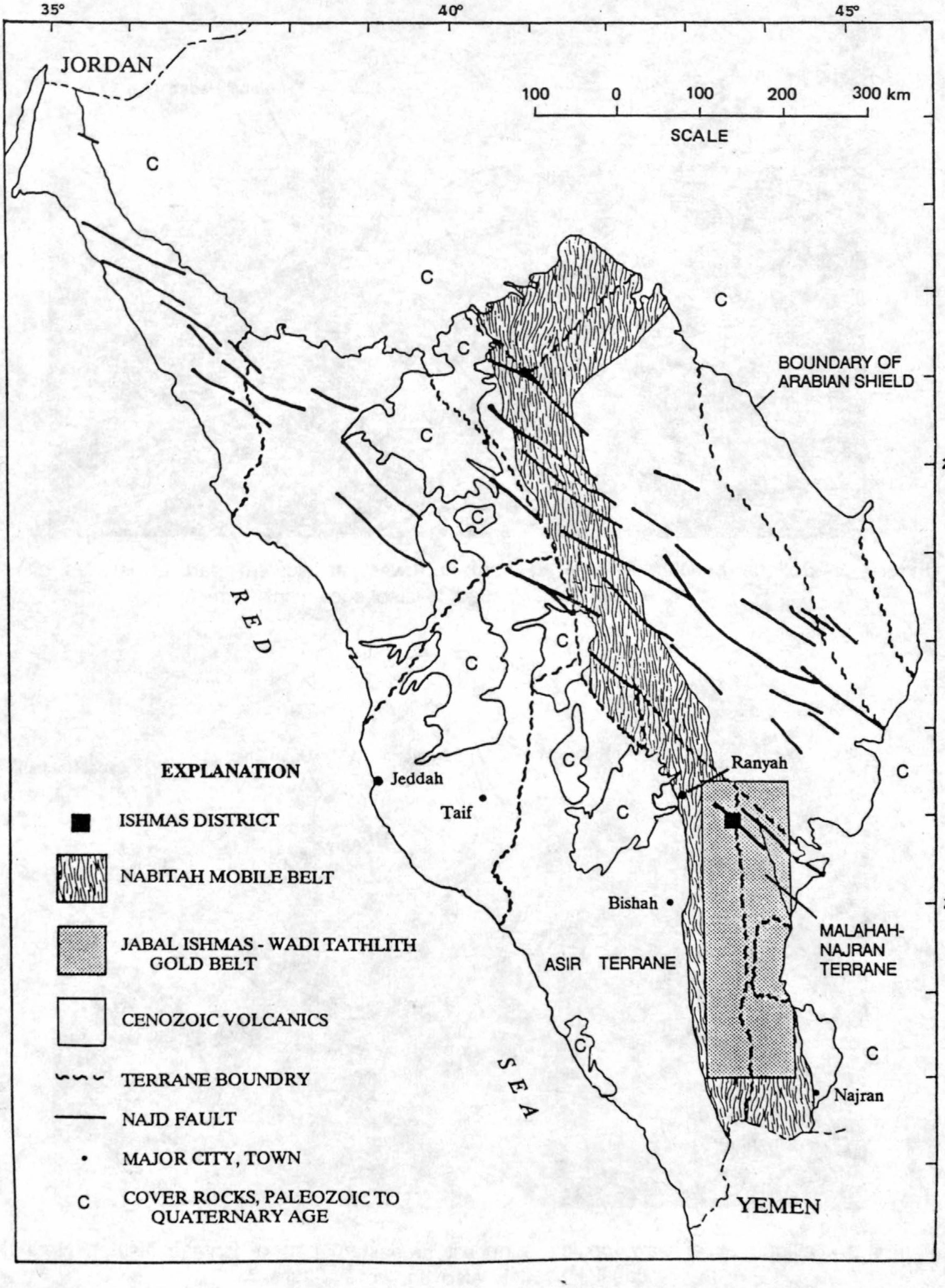


Figure 1.--Index map showing the location of the Ishmas district in relation to major tectonic and metallogenic features of the Arabian Shield [after Smith and Johnson (1986) and Stoeser and Camp (1984)].

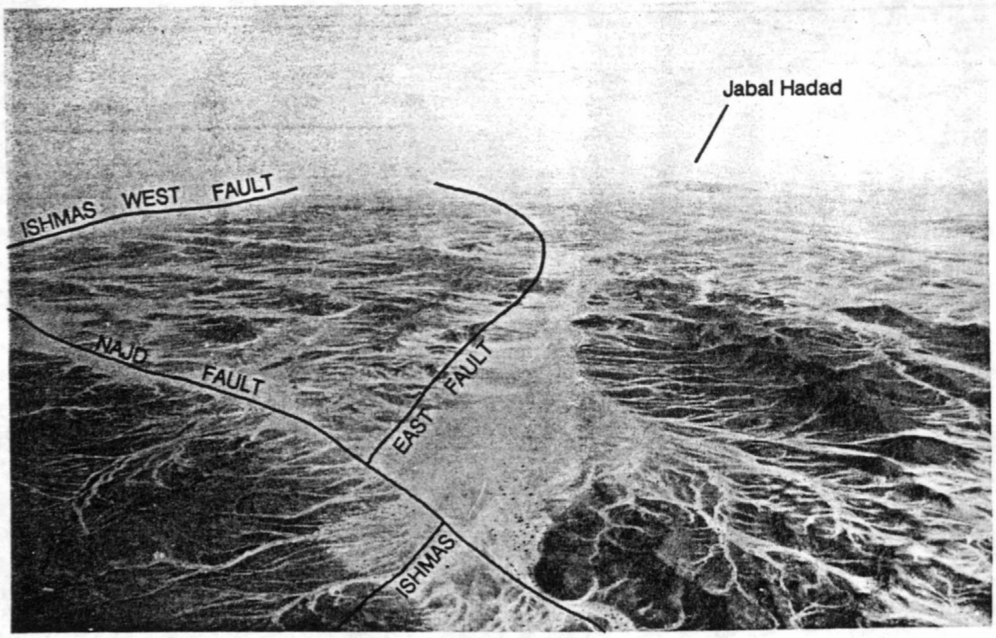


Figure 2.--Oblique aerial view looking north-northwest at western part of Ishmas district. Note that Jabal Hadad is also shown in figure 3.

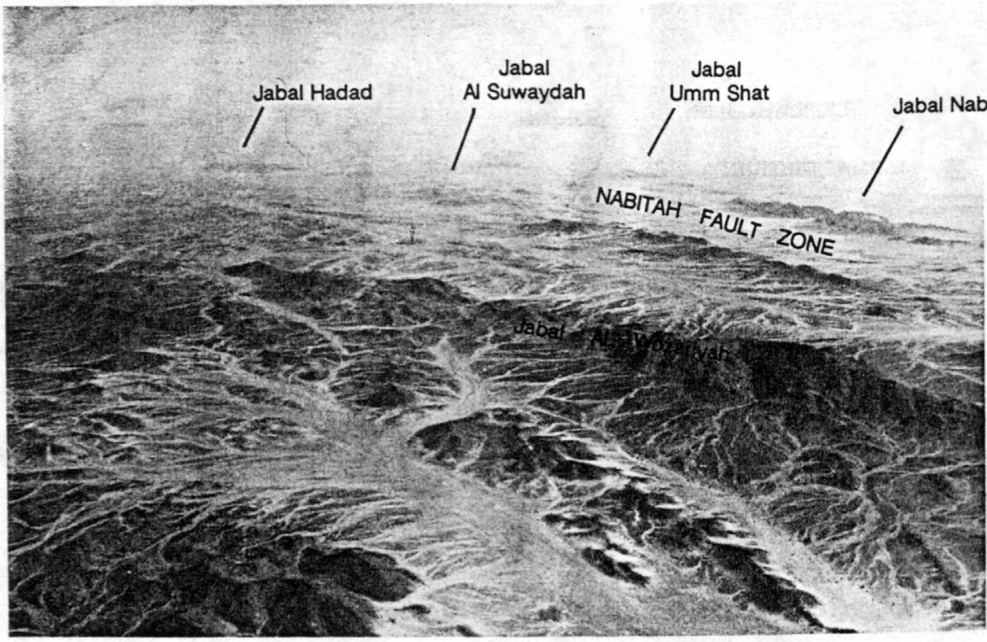


Figure 3.--Oblique aerial view looking northeast at eastern part of Ishmas district. Note that Jabal Hadad is also shown in figure 2.

belt (Stoeser and Camp, 1984), which is known to be a locus for gold mineralization throughout its extent in the Arabian Shield (Boyle and others, 1984), 2) it contains a significant number of ancient gold mines, and 3) it is not well studied, as little or no work has been done in the area in the past 10 years, during which time a better understanding of the geotectonic evolution of the Arabian Shield has been useful for compiling models for gold, base-metal, and other types of mineralization.

PRESENT INVESTIGATIONS

Field work for DMMR subproject 3.03.05 commenced in Moharram 1406 A.H. (September, 1985 A.D.) and continued through R. Awal 1406 A.H. (December, 1985 A.D.). Follow-up studies were conducted during a two-week period in Rajab 1406 A.H. (March, 1986 A.D.). Geology was mapped using enlarged aerial photographs and later compiled at 1:25,000 scale.

This study is part of a collective effort to characterize the environment, style, geologic controls, and economic potential of mineralization in the district. In conjunction with the regional geologic study presented here, a wadi-sediment geochemical survey of the district, and detailed mapping and evaluation of individual prospects were conducted by Samater (in press) and White and Doebrich (1987), respectively.

ACKNOWLEDGMENTS

Petrographic services, including the production of polished and standard thin sections, ground and stained rock slabs, and glass beads for SEM work, were provided by the USGS Mineralogy-Petrography lab under the supervision of Carl R. Thornber. Ahmad El Bazli was helpful in point-counting plutonic rock samples. Quantitative whole-rock analyses of fused rock samples were conducted by Mir Amjad Hussain using a JOEL/TRACOR SEM/EDS under the supervision of James E. Quick. Whole-rock analyses using wet chemical techniques, semiquantitative spectrographic analyses, and atomic-absorption analyses for base and precious metals were done at the USGS/DMMR laboratory under the direction of K. J. Curry and at Skyline Laboratories, Wheat Ridge, Colorado.

This study was conducted in accordance with a work agreement between the U.S. Geological Survey and the Saudi Arabian Ministry of Petroleum and Mineral Resources.

REGIONAL GEOTECTONIC SETTING

An understanding of the geotectonic history of the Arabian Shield has evolved through more than two decades of work by geoscientists. Geologic mapping at 1:500,000 scale, followed by 1:100,000-scale mapping that was compiled at 1:250,000 scale, in conjunction with geophysical, geochemical, and geochronological studies, has yielded a current geotectonic model for the Shield that was synthesized by Smith and others (1984).

The Arabian Shield has been classified and divided into tectonic domains, terranes, provinces, and tectonostratigraphic units (Smith and others, 1984). Domains represent specific stages in tectonic evolution, such as oceanic, precratonic, transitional, epicratonic, and reactivation (Smith and others, 1984). Terranes are tectonostratigraphic entities of regional extent characterized by a geologic history distinct from that of adjacent terranes. Terrane boundaries are typified by major faults and shear zones, intense deformation and metamorphism, and belts of ultramafic rocks and synkinematic granitic intrusions (Smith and others, 1984). A province is an intermediate entity (between a terrane and tectonostratigraphic unit) that informally delineates belts of rock with similar petrological and chemical affinities; whereas a tectonostratigraphic unit represents successions that accumulated in specific tectonic environments, such as island-arc complexes, volcanic-rift successions, ophiolite complexes, etc. (Smith and others, 1984). Therefore, tectonostratigraphic units make up provinces, which constitute terranes that formed during a specific domain. All these subdivisions can further be classified under a specific tectonic realm or tectonic setting, which, in the case of the Precambrian Arabian Shield, is that of a continental-margin setting, as opposed to an oceanic or continental setting (Smith and others, 1984).

The Arabian Shield is comprised of a series of precratonic island-arc terranes in the west that accreted to one another and later collided with a land mass of more continental affinity to the east. The collisional suture is defined by the Nabitah mobile belt (Stoeser and Camp, 1984), which is a north-trending feature that extends the length of the Arabian Shield (fig. 1) and is named for Jabal Nabitah in the Ishmas district. Collisional orogenesis associated with suturing (hereafter referred to as the Nabitah orogeny) occurred between 720 and 640 Ma (Smith and Johnson, 1986) and involved intense deformation and metamorphism proximal to the suture, as well as crustal reactivation and synorogenic plutonism that occurred largely east of the suture and mobile belt. Reactivation was expressed by the formation (630-540 Ma) of an extensive northwest-trending left-lateral wrench-fault system (Smith and others, 1984) known as the Najd fault system (fig. 1).

The Ishmas district is underlain by rocks of precratonic domain at the boundary of two terranes: the Asir terrane to the west (henceforth referred to as the western terrane), and the Malahah-Najran terrane (Smith and others, 1984) to the east (henceforth referred to as the eastern terrane)(fig. 1). The terrane boundary is defined by the north-trending Nabitah Fault Zone which underlies the eastern part of the district (pl. 2). The Nabitah Fault Zone is the southernmost of several fault zones that constitute the Nabitah mobile belt, and is believed to have been active between 684 and 640 Ma (Smith and Johnson, 1986). Both terranes are composed of a series of magmatic-arc and basin-margin sucessions formed during continental margin subduction between about 943 and 721 Ma (Smith and Johnson, 1986). The Ishmas district comprises the northern end of both the Ishmas volcanic arc of the Al Qa'ah gneiss-dome province in the Asir terrane and the Yafikh volcanic arc of the Yafikh province in the Malahah-Najran terrane.

The precratonic rocks of the district belong to the Shield-wide lithostratigraphic unit known as the Halaban group. The Halaban group was initially described by Brown and Jackson (1960) from its type locality, a 25-km-wide belt near the town of Halaban in the east-central part of the Arabian Shield. The Halaban group is typically a subaqueous succession of andesitic and dacitic flows, volcaniclastic rocks, volcanogenic sedimentary rocks, graywacke, minor conglomerate, and ferruginous and stromatolitic marble and chert deposited between 785 and 746 Ma (Smith and others, 1984). Rapid lateral facies changes are typical of the Halaban and indicate proximity to volcanic centers. Arc-related mafic and intermediate plutonic rocks intruded the sequence between 730 and 725 Ma (Smith and Johnson, 1986). Although the rocks in the district east of the Nabitah Fault Zone were originally believed to be considerably older (Gonzalez, 1974), it is now believed that they also belong in the Halaban group. Therefore, although the rocks on either side of the Nabitah Fault Zone were deposited and emplaced at different localities to form different terranes, they did so contemporaneously under similar geologic conditions.

STRATIFIED ROCKS

The following descriptions are based on field and petrographic observations made during the course of this study. Rock classifications are those established by Williams and others (1982) and Moorhouse (1959). The terminology and classification of cataclastic rocks is that of Higgins (1971).

Most of the stratified rocks of the district form north-trending units, many of which are fault bounded. In general, they are highly deformed and variably metamorphosed volcanosedimentary sequences of mafic to intermediate composition. The units described below are mainly lithostratigraphic and not necessarily time-stratigraphic units. This is particularly true for the basalt-andesite and silicic volcaniclastic units, as is evident from their spatial distribution (pl. 1).

EASTERN TERRANE

Amphibolite

The eastern margin of the Ishmas district is underlain by an amphibolitized volcaniclastic sequence (amh) that is expressed as hills of moderate relief among plains underlain by schist and monzogranite, all of which comprise the terrane east of the Nabitah Fault Zone (pls. 1,2). The rocks of this unit range from metasediments with relict lithic clasts to very fine-grained schistose amphibolite to massive coarse-grained amphibolite. Cleavage trends range from due north to N. 40° E. and are vertical to steeply east dipping ($>75^{\circ}$).

The metasediments are generally poorly sorted and contain rounded white siliceous clasts as much as 2 cm (but usually not greater than 3 mm) in diameter. The clasts are commonly composed of an aggregate of quartz, epidote, hornblende, clinozoisite, chlorite, and opaque minerals, and locally show relict layering. The clasts are set in a dark-green to black matrix that is comprised of a mass of tabular prismatic hornblende, usually less than 0.2 mm (but locally as much as 1 cm) across. When observed in thin section, the hornblende is characterized by pale-yellow to green pleochroic interiors and green to blue-green pleochroic margins. Mosaic patches of quartz, carbonate, and very fine-grained epidote are scattered throughout the rock.

The fine-grained schistose amphibolites are typically light green to light gray and aphanitic. Equant to tabular amphibole grains (0.2-0.6 mm across and having light-yellow to green pleochroic interiors and dark-green to blue-green pleochroic margins in thin section), are dispersed throughout a finer grained ($<$0.15mm) mass of prismatic amphibole, quartz, saussurite, clinozoisite, chlorite, and opaque minerals. The subparallel orientation of the amphibole defines the schistosity.

The massive medium- to coarse-grained amphibolites are typified by equant subhedral crystals of hornblende and tabular to equant plagioclase (An_{25}) as much as 4 mm across. Interstitial to the coarser grained hornblende and plagioclase is a very fine grained ($<$0.35 mm) aggregate of prismatic hornblende, plagioclase, quartz, and opaque minerals ($<$5 percent). In thin section, the hornblende is pleochroic yellow brown to olive green to blue green. The prismatic variety commonly exhibits variolitic texture. In general, these rocks are composed of 60-70 percent amphibole, 25 percent plagioclase, and 5 percent quartz.

The varied intensity of metamorphism in this unit is inconsistent with a regional derivation. In general, intensity increases toward the monzogranite pluton that underlies a large region east of the district as well as a small area in the southeastern part of the district. Consequently, the amphibolite-grade metamorphism of this unit is believed to be contact metamorphism associated with the intrusion of the monzogranite mass.

Schist

Immediately east of the Nabitah fault zone in the eastern part of the map area is a north-trending belt (as much as 2 km wide) consisting of schistose cataclastic rocks (sch) with well-developed subvertical foliation. This unit is characteristically expressed as plains of subdued relief with sporadic "islands" of relatively unsheared protolith. Foliation trends range from N. 20° W. to N. 10° E. and are steeply west dipping ($>70^{\circ}$), although in the northern part of the belt (pl. 1) foliation is steeply east dipping ($>75^{\circ}$).

In general, these rocks have been dynamically metamorphosed to a cataclastic sequence of micro- and megascopic breccias, mylonites, ultramylonites, and mylonite gneisses and schists as defined by Higgins (1971). Intrusive rocks ranging from microdiorite to medium-grained granodiorite commonly form microbreccias with local megascopic foliation. Clasts as much as 2 mm across are comprised of tabular, subhedral to euhedral plagioclase (An_{30-35}), potassium feldspar, and anhedral equant quartz, with individual crystals ranging from 0.35 to 0.75 mm in diameter. The interclast material is largely composed of chlorite, biotite, and muscovite, with lesser amounts of quartz and feldspar mortar, opaque minerals, and leucoxene. Slip planes are defined by the aggregation of platy micaceous minerals along undulating surfaces.

The mylonitic rocks are typified by megascopic fluxion structure and local compositional layering. The schistose rock types are characterized by an aphanitic ($<$20 m) mass of quartz, light-brown pleochroic chlorite, and sericite, all of which are either uniformly dispersed throughout the rock fabric or form monomineralic layers as much as 2 cm thick, giving the rock a gneissic appearance. Layering is also defined by horizons of different grain size, particularly with regard to quartz. Opaque to deep-red iron oxide occurs as streaks outlining the fluxion structure. Locally, irregularly shaped masses (as much as 3 mm in the longest dimension, comprised of an aggregate of quartz, carbonate, plagioclase, and potassium felspar, all between 0.05 and 0.1 mm) display no cataclastic textures and probably represent recrystallized porphyroclasts.

Lenses of gray to black ferruginous chert and blue dolomitic marble occur throughout the unit, but are most common in the western part of the unit. The chert is largely converted to ultramylonite with megascopic fluxion structure and compositional layering defined by bands of different grain size and separation of quartz and iron oxide. The finer grained bands tend to exhibit well-developed fluxion structure and may represent planes or bands that absorbed a large amount of the slippage. The marble lenses acted much more competently under cataclasis, resulting in megascopic monolithic breccias. Subangular breccia fragments, as much as 4 cm across, with irregularly shaped opaque-rich patches, are set in a carbonate mortar (<0.35 mm). Sericite clusters and quartz-carbonate stringers are common.

By observing the relatively unsheared "islands" of the unit, a crude reconstruction of the protolith can be made. The section immediately east of the Nabitah Fault Zone in the western part of the unit contains relatively abundant ferruginous chert and dolomitic marble lenses. Inselbergs of unsheared material in the eastern part of the unit are comprised of interbedded laminated tuff, volcaniclastic greenstone, and basalt. Therefore, the protolith was probably a submarine volcanic-arc sequence of intermediate to mafic composition similar to others in the terrane west of the Nabitah Fault Zone.

WESTERN TERRANE

The stratified rocks of the western terrane are divided into two formations of the Halaban group, henceforth known as the Suwaydah and Wozariyah formations. The Suwaydah formation, which underlies Jabal Al Suwaydah and the Nabitah Fault Zone, is a mafic volcanosedimentary sequence. The Wozariyah formation, which underlies Jabal Al Wozariyah and the central part of the district, is a silicic volcanosedimentary sequence. The individual units comprising each formation are described as lithostratigraphic and not lithologic units.

Suwaydah formation

VOLCANOGENIC SEDIMENTARY UNIT

In the eastern part of the map area, a belt of volcanogenic sedimentary rocks (hsn) crop out in the central part of the Nabitah Fault Zone along its entire length. Most of the unit is fault-bounded, yielding a minimum thickness of 1.2 km. Bedding attitudes range from N. 15^{o} W. to N. 15^{o} E. Dips are steep to the west (>70^{o}) in the northern part of the unit and moderately to steeply east (>50^{o}) in the southern part. Cleavage trends tend to parallel adjacent major structures and range from N. 25^{o} W. with vertical dips in the south, to N. 20^{o} E. with steep easterly dips (>75^{o}) in the north.

In general, wacke, laminated tuff, and ash-flow tuff with interbedded chert and marble and subordinate andesite flow rock comprise the sequence. In hand specimens, the wacke appears as a porphyritic volcanic rock with white rounded patches in a grayish-green groundmass. The white patches represent saussurite-rich areas in the matrix and are not pseudomorphic. The wacke is poorly sorted with subrounded to subangular clasts (between 0.1 and 0.6 mm) of plagioclase, quartz, and potassium feldspar in a matrix of subangular grains (less than 0.1 mm) of the same material, which also contains clinozoisite, epidote, and saussurite.

The laminated ash-fall tuff consists of alternating white, gray, and dark-gray bands as much as 1 cm thick. Each band is comprised of numerous laminations about 0.2 mm thick. Grain size is generally less than 0.5 mm. The whiter layers contain more saussurite and the grayer layers more quartz. The saussurite appears to have replaced plagioclase, as zoned extinction of saussurite clusters resembles zoning in plagioclase. All quartz is highly strained, which is consistent with the fact that the banding is commonly contorted, and that a microscopic foliation, locally perpendicular to the banding, exists.

The ash-flow tuff is laminated to thinly bedded. Flow laminations are conspicuous. Devitrified shards are completely saussuritized and thus are semiopaque and easily discernable. Mineralogy consists of quartz, epidote, clinizoisite, and chlorite, grains of which are all less than 0.05 mm in diameter. Elongated (as long as 1.5 mm) patches of carbonate are oriented parallel to the flow laminations. Saussurite is common.

The predominance of wacke and laminated tuff in this sequence, and the presence of interbedded chert and marble suggest that the rocks were deposited in a submarine environment distal to a volcanic source and proximal to an eroding terrane.

BASALT AND DIABASE

In the northeast part of the district, highly altered and broken mafic rock (hd) crops out in a north-trending fault-bounded block. Although the block as a whole trends N. 15° E., cleavage trends range from N. 35° E. to N. 20° W. (pl. 1). In outcrop, the rock is a patchy light and dark grayish green and consists of fine-grained equigranular diabase and porphyritic basalt that contains white feldspar crystals.

The basalt is typified by intensely saussuritized euhedral phenocrysts (as much as 5 mm across) of plagioclase in a saussuritized groundmass of fibrous tremolite, and subhedral clinozoisite, epidote, quartz, and carbonate grains, all less than 0.15 mm in diameter. Locally, equant secondary crystals with ragged margins, and as much as 0.5 mm across, are scattered throughout. Zoned euhedral crystals (as much as 0.6 mm in length) of clinozoisite fill voids and commonly form radiating crystal clusters. Chlorite commonly replaces hornblende and secondary plagioclase. Sericite and quartz after secondary plagioclase are also common and indicate a more sodic plagioclase than the primary saussuritized phenocrysts.

The equigranular grains of diabase are green pleochroic uralitic hornblende after subhedral to euhedral orthopyroxene, clinopyroxene, and intensely saussuritized plagioclase, all between 0.5 and 1.0 mm. However, the plagioclase may locally occur as phenocrysts as much as 6 mm across. Fibrous tremolite, clinozoisite, epidote, quartz, and carbonate are disseminated throughout the rock.

VESICULAR BASALT AND ANDESITE

The western margin of the Nabitah Fault Zone is underlain by a fault-bounded block of amygdaloidal andesite and basalt (hbv) that has a minimum thickness of 1.4 km. The rock is typically dusky to dark yellowish green and aphanitic with variable amounts of quartz-filled amygdules, which are resistant to weathering and protrude from the rock, causing it to appear as a pebbly mudstone. Both flow foliation (the attitude of vesicle trains) and cleavage trends range between N. 40° E. and N. 5° W. though are mostly about N. 15° E. and subvertical (pl. 1).

These rocks are characterized by a well-developed pilotaxitic texture defined by oriented tabular plagioclase and acicular actinolite grains (generally less than 0.3 mm long), which constitute the groundmass. Variable amounts of epidote, clinozoisite, and carbonate are intergranular to the plagioclase and actinolite. Where actinolite dominates, the texture is more felty and less pilotaxitic. Ovoid quartz-filled amygdules (as much as 8 mm long and 4 mm wide), which locally constitute as much as 20 percent of the rock, are elongate parallel to the orientation of the groundmass microlites. In addition to quartz, which is commonly highly strained, the amygdules contain variable amounts of sericite and epidote.

Subhedral to euhedral pseudomorphic phenocrysts (between 1.0 and 7.5 mm long) of quartz and chlorite after tabular plagioclase, and quartz and uralitic hornblende after equant pyroxene, commonly constitute less than 10 percent of the rock. Clinozoisite and epidote crystal aggregates, as much as 1 mm across and exhibiting radial crystal growth, also appear to be pseudomorphic after plagioclase.

The characteristic vesicular nature of this unit and the lack of pillow structures or other evidence of submarine conditions indicates that eruption took place under subaerial conditions. The vesicles indicate a gas-rich magma, which is consistent with explosive conditions necessary to produce the coeval volcaniclastic unit described below.

MAFIC VOLCANICLASTIC UNIT

In the northeastern and east-central parts of the Ishmas district, a mafic volcaniclastic unit (hc) occurs as a large lens (as much as 700 m thick) within the vesicular andesite and basalt unit described above. The northern part of this lens underlies a large part (including the higher elevations) of Jabal Al Suwaydah (pl. 1). Bedding and cleavage trends range from N. 20° W. to N. 25° E., and dips vary from 70° W. to 62° E. The northern end of the unit pinches out, and the southern end projects under wadi alluvium.

The unit is comprised of mafic ash-fall tuff, ash-flow lapilli tuff, tuff breccia, and subordinate basalt. The lapilli tuff and tuff breccia are composed of subrounded to angular lithic fragments as much as 7 mm across. The lithic constituents include vesicular andesite and basalt of the unit described above, and nonvesicular plagioclase-phyric andesite with well-developed pilotaxitic texture. Both varieties contain considerable secondary actinolite, quartz, sodic plagioclase, chlorite, and epidote. Crystal fragments are as much as 3 mm in length and include chlorite after hornblende after pyroxene, sericitized plagioclase, and minor quartz. Matrix material commonly exhibits conspicuous flow foliation defined by wispy, near-opaque streaks of epidote-clinozoisite and saussuritized material in a mosaic of quartz grains (<10 microns).

Ash-fall tuff is typically laminated to thinly bedded and ranges from pale olive green to grayish yellow green to dusky green. Layering is between 1.5 mm to 2 cm thick. Anhedral quartz and plagioclase grains 0.05 to 0.2 mm across occur in a microcrystalline saussuritized matrix of quartz, sericite, chlorite, and carbonate, all generally less than 20 microns across. Devitrified shards are defined by cuspate quartz aggregates. Layering is commonly defined by the relative abundance of saussuritized material, which gives the layer a light-colored appearance in hand specimen and a semiopaque appearance in thin section.

Intercalated grayish-green basalt containing dark-green to black phenocrysts is subordinate in this unit. It is characteristically pyroxene phyric with tabular to equant, euhedral clinopyroxene grains (1.5 to 9 mm across) in a groundmass of fibrous actinolite, plagioclase, and quartz grains that are generally less than 0.15 mm across. Epidote-clinozoisite and minor sericite is disseminated throughout the groundmass.

The position of this unit as a lens occurring within the vesicular andesite and basalt unit indicates that the two are coeval. The presence of vesicular volcanic fragments in the coarser grained varieties of this unit also suggests a similar eruptive source for both units.

Wozariyah formation

BASALT AND ANDESITE

The basalt and andesite unit (hb) occurs at three localities in the district. The unit crops out west of the Ishmas mine as a 375-m-wide, N. 30° E.-trending belt, contains lenses of interbedded ferruginous chert, and is in contact with silicic volcanic rocks (pl. 1). In the south-central part of the Ishmas district, the unit occurs as a N. 10° W.-trending belt with subordinate interbedded laminated tuff. Here the unit is in contact with laminated tuff and silicic volcanics to the east and lies under wadi alluvium to the west (pl. 1). In the central part of the district, the basalt and andesite unit crops out along both the western and eastern limbs of the central syncline. Along the western limb, the unit is as much as 1.3 km thick and is in contact and intercalated with the exhalative, sedimentary, and silicic volcaniclastic units. Along the eastern limb and near the hinge, the unit thins and eventually pinches out, trending N. 25°-55° W. and dipping moderately to steeply northeast (>65°) (pl. 1). Here the unit is intercalated with the laminated tuff and the exhalative and silicic volcaniclastic units, and is truncated by the westernmost of the north-trending faults of the Nabitah Fault Zone (pl. 1).

The basalts are typically dark gray to grayish black and contain phenocrysts of subhedral to euhedral orthopyroxene commonly altered to pseudomorphs (as much as 2.5 mm across) of uralitic hornblende and plagioclase (An_{60-65}) (between 0.5 and 2 mm across). Phenocrysts constitute between 40 and 60 percent of the rock fabric. The groundmass is typically altered to a mass of grains (all less than 0.1 mm) of fibrous actinolite, quartz, clinozoisite, and carbonate. In thin section, the plagioclase exhibits both normal and oscillatory zoning and is altered to carbonate, epidote, and chlorite. Locally, clinopyroxene forms rims on euhedral orthopyroxene phenocrysts.

The andesites are actually quartz andesites. They are characterized by tabular to equant, suhedral to euhedral zoned andesine (An_{35-40}) and orthopyroxene phenocrysts (0.75 to 4 mm across). The groundmass is comprised of a granular (all grains less than 0.6 mm) aggregate of plagioclase, hornblende, quartz, biotite after hornblende, clinozoisite after plagioclase, fibrous actinolite, and minor sphene and apatite. Although some quartz may be secondary, most is believed to be primary, as it exhibits an ophitic to poikilitic texture with hornblende and plagioclase. Minor carbonate is scattered throughout the groundmass. Approximate mineral modes are about 50 percent plagioclase, 25 percent quartz, and 25 percent mafic minerals.

Several occurrences of oligomictic andesitic conglomerate were observed interbedded with the volcanics. The clasts are subangular to rounded and 1 mm to 5 cm across. The andesite is aphyric and displays good pilotaxitc texture of plagioclase microlites (<0.1 mm) and intergranular chlorite, carbonate, and epidote. The interclast material is composed of a matrix of quartz and saussuritized material. In general, clasts constitute 60 to 70 percent of the rock. The presence of conglomerate indicates periods of subaqueous erosion during episodes of volcanic quiescence.

Though compositionally distinct, this unit is commonly intercalated with the laminated tuff, the silicic volcanic, and the silicic volcaniclastic units, as well as with the exhalative and epiclastic units. This is consistent with a coeval origin and suggests that bimodal volcanism was occurring during the deposition of this unit.

LAMINATED TUFF

Laminated-tuff sequences (ht) crop out along the eastern limb of the central syncline in the central part of the district and at two localities in the south-central and southeastern parts of the district (pl. 1). Along the east limb of the central syncline the unit is highly disrupted and exhibits soft-sediment deformation. The presence of flame structures indicate that the younging direction is to the west. Evidence for subaqueous reworking, such as cross-bedding, was also observed. In the south-central locality, the sequence is as much as 1.3 km thick and cut by a northwest-trending fault of the Najd system. Well-developed drag is displayed by north-trending attitudes swinging to N. 50° W. as the fault is approached from the north (pl. 1). No drag was observed south of the fault.

The rocks are characteristically fine grained; layering ranges from 0.2 mm to 9 mm thick. Massive rock units were also observed. While some layers are cryptocrystalline and isotropic, others are composed of crystal and lithic fragments, mostly between 0.05 and 0.6 mm across, although some may be as large as 6 mm. The more coarse-grained layers are commonly grain supported and contain between 15 and 25 percent matrix material composed of grains smaller than 20 microns. Subangular quartz grains, sericitized plagioclase, rounded chlorite masses and grains of andesite-basalt, felsic tuff, and gabbro comprise the variety of crystal and lithic constituents. Quartz and plagioclase are the primary matrix constituents. Locally, grains of light-brown to pale blue-green pleochroic hornblende and epidote are scattered throughout the rock.

South of the northwest-trending fault at the south-central locality, crystal tuffs dominate and are typified by subangular, anhedral crystal fragments of quartz, plagioclase, and minor alkalic feldspar that constitute 20 to 30 percent of the rock. The crystal fragments tend not to be more than 0.25 mm across and reside in a matrix of quartz, plagioclase, and locally abundant brown biotite. Biotite makes up as much as 25 percent of the groundmass and imparts a dark-gray, almost black color to the rock in hand specimen. Patches of carbonate occur locally.

The laminated-tuff unit is compositionally similar to the silicic volcaniclastic unit but probably represents a more distal facies. However, their relative age is not certain. It is possible that they are approximately coeval and derived from different eruptive centers.

SILICIC VOLCANIC ROCKS

Silicic volcanic rocks (hv) crop out in the southwestern and south-central parts of the district. In the southwest, the unit comprises a belt west of the Ishmas mine and grades northward into mylonite along its eastern contact, and eventually projects under alluvium (pl. 1). The area east of the Ishmas mine is underlain by a fault-bounded sequence of silicic volcanic rock with interbedded ferruginous chert lenses. In the south-central locality, silicic flows are discontinuously intercalated with silicic volcaniclastic rock, laminated tuff, and basalt. The section has been repeated by faulting and is at least 800 m thick. Attitudes shown on the map (pl. 1) were obtained from interbedded tuff layers.

The silicic volcanic rock unit is comprised largely of dacite flows and sills, subordinate andesite flows, and interbedded crystal-lithic tuff similar to that of the silicic volcaniclastic unit described below. The dacite flows are typically medium gray to medium dark gray and contain 10 to 20 percent quartz and plagioclase in the form of phenocrysts. The phenocrysts range from 0.3 to 3.5 mm across, are subhedral to euhedral, and equant to tabular. Plagioclase is andesine (An_{30-40}) and constitutes about 40 percent of the phenocryst population. The groundmass is characterized by a felty- to pilotaxitic-textured aggregate of plagioclase microlites, quartz, subordinate potassium feldspar, olive-green to brown biotite, and minor apatite; all grains are smaller than 0.1 mm. Locally, symplectite (myrmekitic ?) texture is abundant in the groundmass feldspar. Patches of brown biotite (partially altered to chlorite) and variolitic aggregates of acicular pyrophyllite, chlorite, and rutile (as much as 0.5 mm across) are present at some localities.

Andesite flows are characterized by subhedral to euhedral, tabular to equant plagioclase phenocrysts as much as 2.5 mm across in a highly altered groundmass of quartz, plagioclase, biotite, chlorite, carbonate, and opaque minerals. Numerous patches of secondary quartz, 0.2 to 2.0 mm across, are common. Ovoid patches may represent amygdules. Plagioclase is altered to epidote. Quartz-carbonate and quartz-sericite-biotite veinlets are also present.

This unit is compositionally similar to the silicic volcaniclastic and laminated-tuff units and probably originated from the same or a similar source. The presence of biotite as a primary constituent in all three of these units is a diagnostic characteristic. The presence of interbedded chert indicates a submarine depositional environment.

SILICIC VOLCANICLASTIC UNIT

The silicic volcaniclastic rocks (hvc) form one of the most extensive map units in the district. The unit crops out 1) as a belt along the central part of the Ishmas East fault and forms the western limb of the central syncline (pl. 1; also see structure section), 2) as an isolated lens in the center of the district within the core of the central syncline, 3) as a remnant section along the truncated eastern limb of the central syncline in the northeast part of the district, and 4) as an area of high relief comprising Jabal Wozariyah in the south-central part of the district (pl. 1).

This unit consists of a sequence of intercalated tuff-breccia, crystal-lithic lapilli tuff, ash-fall and ash-flow tuff, subordinate dacite flows, and minor marble. Tuff breccia and lapilli tuff are commonly dark gray with reddish-orange and gray subrounded lithic clasts (as much as 7 mm across) in an aphanitic matrix. Lithic constituents include mostly siliceous aphanitic tuff and lesser amounts of andesitic flow rock, some of which is vesicular and looks very similar to the rock of the vesicular andesite and basalt unit described above. Matrix material is composed of grains of quartz, plagioclase, sericite, biotite, chlorite, epidote, carbonate, and opaque minerals, all generally less than 20 microns, though locally quartz and plagioclase grains approach 1 mm in size.

Intercalated with the tuff breccia and lapilli tuff are medium light-gray crystal tuffs. Subhedral to euhedral crystals (between 0.25 and 1.5 mm across) of quartz, plagioclase, and alkalic feldspar constitute as much as 40 percent of the rock. The remainder is matrix material composed of quartz crystals less than 30 microns in size. Biotite, chlorite, iron oxide, and carbonate grains are scattered throughout the matrix. Relict shard outlines are visible in thin section under transmitted light. Plagioclase crystals are commonly sericitized. Many crystal fragments exhibit overgrowth or corona textures while some display embayed margins.

Ash-flow tuffs are most abundant along the western limb of the central syncline and grade into mylonites toward the northwest. Overall, the sequence becomes coarser grained and thicker toward the southeast, suggesting proximity to a volcanic center. Lithic and crystal lapilli constitute between 25 to 70 percent of the rock. Lithic grains are commonly well rounded, 1.5 to 2 mm across, and the lithologies present include ash-fall and ash-flow tuff, andesite and basalt, dacite, granophyre, and diabase. Crystal fragments (0.5 to 1.5 mm across) include subangular quartz, plagioclase, and minor potassium feldspar. Fiammi altered to a mass of chlorite and sericite, and devitrified shards, are abundant locally. The matrix is composed of grains of quartz with variable amounts of chlorite, sericite, epidote, and clinozoisite, all less than 20 microns in size. Flow laminations are emphasized by the elongation of fiammi and by the orientation of wispy streaks of chlorite-biotite aggregates. Sericite after plagioclase and patchy carbonate are common.

Subordinate dacite flows occur throughout the unit. The dacite is typically olive gray to grayish green and pyritic with euhedral, equant to tabular plagioclase phenocrysts (0.3 to 1.5 mm long) in a flow-laminated groundmass of plagioclase and quartz grains that are less than 60 microns in size. Flow laminations are macroscopic and defined by wispy streaks of epidote-biotite-sericite aggregates. Euhedral epidote grains as much as 0.2 mm long are abundant as a replacement of the plagioclase phenocrysts. Pyrite cubes as large as 0.25 mm are common.

In contrast to the older basaltic and andesitic volcanic and distal volcaniclastic rocks of the Suwaydah Formation, the character of this unit is consistent with a less primitive and more proximal derivation. The age relationship is based on the presence of vesicular andesite and basalt as fragments in the tuff breccia and lapilli tuff of this unit. The presence of intercalated marble indicates a submarine depositional environment.

FINE-GRAINED AMPHIBOLITE

The western part of the district is underlain by poorly exposed massive fine-grained amphibolite (ham) (pls. 1,2). The unit is characteristically dusky green and aphanitic, though sporadic pebbles were observed suspended in the aphanitic matrix. Locally the metamorphism is less intense and the rock types are chiefly metasedimentary or metavolcanic.

The amphibolite is comprised of very fine grained (< 0.15 mm) yellow-green to grass-green amphibole, quartz, and minor sodic plagioclase. The amphibole displays both an equant and prismatic habit. The prismatic form locally exhibits variolitic texture and gives the rock a felty-textured appearance. Quartz is generally anhedral, has serrated grain boundaries, and is commonly in contact with plagioclase, forming a mosaic texture interstitial to the amphibole. In general, amphibole comprises 35-70 percent of the rock, quartz 15-40 percent, and plagioclase less than 25 percent. Disseminated opaque minerals locally constitute 10 percent of the rock. Saussurite patches are common, as are euhedral wedges of sphene.

Locally, the presence of amygdaloidal cavities filled with coarse-grained quartz amphibole, clinozoisite, and epidote suggest that the protolith was a mafic volcanic rock. The presence of sphene is also consistent with such a protolith. However, the relative abundance of quartz and the felty-textured amphibole in other areas indicate a sedimentary origin. Therefore, this unit represents a volcanosedimentary sequence that recrystallized probably under, at most, amphibolite-facies conditions.

FERRUGINOUS CHERT AND CARBONATE UNIT

Ferruginous chert and carbonate (hx) crop out within the central syncline in the central and north-central parts of the district. In the central locality its outcrop pattern displays the configuration of the gently plunging hinge of the central syncline (pl. 1). Here the unit trends N. 20° W.-N. 15° E., dips steeply (>75°) to the east and is intercalated with the basalt and andesite (hb), silicic volcaniclastic (hvc), and laminated tuff (lt) units. Although the unit pinches out at both ends here, it is as much as 1 km thick along the western limb and thins as it wraps around the synclinal hinge and continues along the eastern limb. The unit becomes intensely sheared proximal to the northwest-trending fault transecting the area (pls. 1,2).

At the north-central locality, the ferruginous chert and carbonate unit form isolated outcrops along the western limb of the central syncline. Here, bedding trends range from N. 35° W. to N. 50° E. and dips are vertical. Along strike to the north, the lithology of the unit changes abruptly to wacke and sandstone with interbedded basalt, whereas to the south the unit pinches out into the basalt and andesite unit with which it is also in contact along its eastern margin. The unit at the north-central locality, is faulted along its western boundary and highly sheared and broken up where proximal to this fault. At both localities, the exhalative-chert and carbonate unit is characterized by subdued relief and poor exposure. The lenses and discontinuous layers of chert and carbonate that constitute most exposures of the unit are resistant and rise above the general level of erosion. At one locality the chert and carbonate was observed to be intercalated with basalt. The chert and carbonate are boudinaged in the areas of intense shearing.

The chert and carbonate are ferruginous, containing both dark yellowish-brown limonite and dark reddish-brown hematite as coatings and powdery void fillings. Malachite staining was observed locally. Generally, the chert tends to be dark gray to grayish black, whereas the carbonate is typically reddish black to black. Banding is common and ranges from 0.5 mm to tens of centimeters thick. The chert is cryptocrystalline quartz containing variable amounts of iron oxide segregated to impart the banding. The carbonate consists of alternating discontinuous bands of semiopaque iron oxide, carbonate with iron-oxide staining, and quartz. All mineral grains are subhedral to anhedral and 0.5 to 0.75 mm across. Some of the chert lenses display evidence of brecciation and thus may be siliceous caps on gossans.

The intercalated sequence of ferruginous chert, ferruginous carbonate, and basalt indicates submarine exhalative conditions. Consequently, the areas underlain by this unit were sites of fumarolic activity where iron and iron-copper sulfides were probably deposited on the seafloor and later converted to oxides and carbonates.

WACKE AND SANDSTONE

Volcanic wacke and sandstone, interbedded dolomitic marble, minor basalt, and chert (hs) crop out in the core of the central syncline in the north-central part of the district. This unit is exposed in low-lying hills and isolated outcrops within broad plains of pediment gravel and is generally poorly exposed. In the Umm Shat Gharb area (pl. 1), bedding trends range from N. 10° W. to due north and dip steeply to the west (>80°). Here the unit is intruded by dacite-porphyry plugs and dikes and contains numerous ancient mines of the Umm Shat Gharb group. In the area east of Umm Shat Sharq, bedding trends are extremely variable (N. 30° W.-N. 50° E.) due to disruption by multiple intrusions. Black dolomitic marble lenses that weather to a pale blue to medium bluish gray are present here and commonly form screens between intrusive rock and wacke sandstone, as well as between individual intrusions. They are as much as 450 m thick and 1.3 km long, but commonly are less than 100 m thick and 500 m long.

Wacke is generally dark gray to black and poorly sorted with subrounded to subangular clasts of plagioclase, quartz, potassium feldspar crystal fragments, and dacitic and andesitic lithic fragments between 0.1 and 0.5 mm across. Disseminated pyrite cubes as much as 1 mm across are ubiquitous. Matrix material consists of subangular grains of quartz and plagioclase with minor sericite, chlorite, and saussurite aggregates, all less than 0.1 mm in diameter.

Sandstone is commonly grayish green, moderately well sorted, and tuffaceous. Subangular grains of sericitized and chloritized plagioclase and alkalic feldspar, basalt and andesite, and aphanitic tuff are in a cryptocrystalline, semiopaque matrix that constitutes 5 to 10 percent of the rock.

Marble is dolomitic and extremely pure. Carbonate grains are commonly between 30 microns and 0.1 mm across, although in places patches contain grains as much as 1.5 mm across. Locally, banding is defined by streaks of opaque minerals.

The ferruginous chert is commonly cryptocrystalline and contains alternating quartz-rich and iron-oxide rich bands ranging from 0.5 mm to 1 cm in thickness. Locally, the chert displays mylonitic features and is very finely recrystallized.

CHEMISTRY OF STRATIFIED ROCKS

Chemical data for selected volcanic rocks of the Ishmas district are plotted in figures 4 and 5. A chemical distinction is evident both spatially and temporally. The older volcanic rocks in the eastern part of the district (the Suwaydah formation) are considerably more mafic and of tholeiitic affinity (fig. 4). The higher than normal SiO_2 content of many of these rocks is a secondary phenomenon, particularly in the vesicular varieties where the amygdules are filled with quartz. When plotted on an AFM diagram (fig. 5), the older mafic volcanic rocks show considerable scatter. This may be attributable to disruption during fractional crystallization and crystal settling within a parent tholeiitic basalt magma.

The younger volcanic rocks in the central and western parts of the district (the Wozariyah formation) are clearly more dacitic in composition than the Suwaydah formation and display a distinct bimodality (fig. 4). They partly fall within the high-alumina basalt field. When plotted on an AFM diagram (fig. 5), they clearly follow a calc-alkaline trend, suggesting that they evolved from the same parent magma. It may be that the parent magma for both volcanic formations was the same, but evidence is not conclusive.

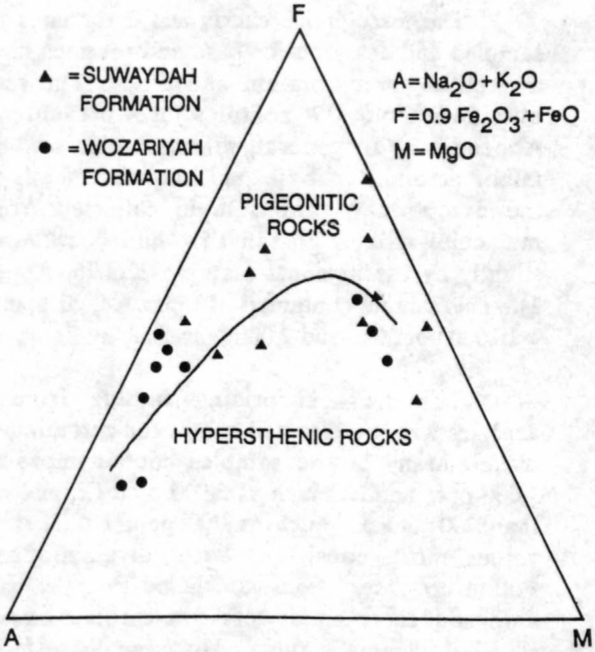


Figure 5.–AFM diagram for selected volcanic rocks of the Ishmas district. Field boundary from Kuno (1968).

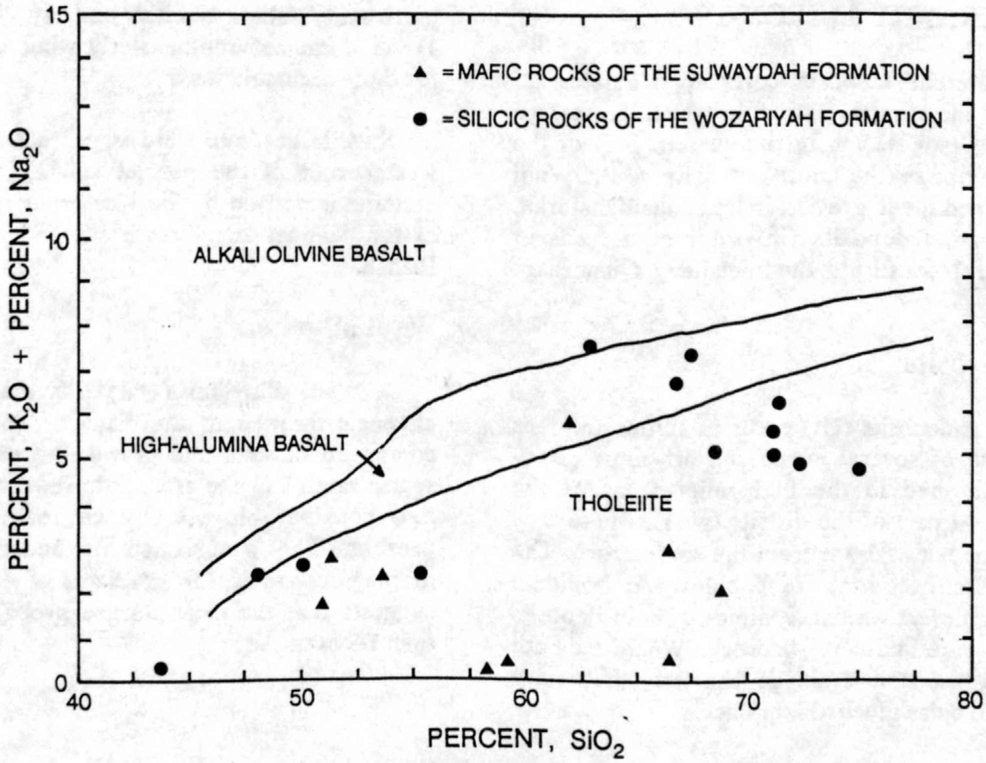


Figure 4.–SiO_2 vs Na_2O+K_2O variation diagram for selected volcanic rocks of the Ishmas district. Basalt series field boundaries from Kuno (1968).

The ferruginous cherts and carbonates were sampled and analyzed for base and precious metals, as well as for chromium and nickel. The results obtained from 37 samples are presented in Appendix 1. In general, most samples contained minor amounts of base and precious metals with the exception of one sample collected from a malachite-stained gossan that had been worked slightly by the ancients (sample 226076, Appendix 1). This sample contained 510 ppb Au, 20 ppm Ag, >10,000 ppm Cu, and 2,000 ppm Zn.

The most surprising finding from the analyses was the elevated values for chromium and nickel. Many of the samples contain more than 1,000 ppm and as much as 5,000 ppm Cr, and more than 300 and as much as 700 ppm Ni. These are values more consistent with ultramafic rocks. Follow-up observations concluded that the carbonate and chert units were not carbonatized and silicified ultramafic rocks. However, these ferruginous cherts and carbonates are within shear zones and thus intensely sheared and boudinaged, though primary banding is preserved. Consequently, the high chromium and nickel values are an enigma.

QUATERNARY DEPOSITS

Quaternary deposits cover approximately 25 percent of the Ishmas district, of which the terrace gravels of Wadi Bishah in the western part of the district comprise the most extensive unit. Wadi alluvium, pediment gravels, talus, eolian material, and quartz-lag deposits (in order of decreasing areal extent) constitute the remaining Quaternary cover.

Talus deposits

Talus deposits (Qt) occur as aprons and fans at the base of several jabals and are most extensively developed in the high-relief areas of the south-central part of the district (pl. 1), where they extend as much as 1 km from the source rock. The talus generally consists of cobbles and boulders with black desert-varnish coatings. These deposits usually obscure and cover bedrock. Where they are incised by modern drainage channels they were observed to be as much as 3 m thick.

Terrace and pediment-gravel deposits

Terrace and pediment gravels (Qg) are not differentiated on plate 1; however, they are geographically distinct. The terrace gravels of Wadi Bishah underlie the broad plain in the western part of the district. The pediment gravels occur among outcrops in the southwestern part of the district but are most extensive in the extreme north-central part (pl. 1). The terrace-gravel deposits consist of pebbles of quartz, gabbro, and metavolcanic material mixed with variable amounts of silt and sand. Much of the terrace-gravel plain is covered by a thin veneer of sandy windblown material. The pediment gravels tend to contain less silt and sand and more angular pebbles. Quartz-lag deposits (Qlg) are interspersed with the north-central gravel deposits. These deposits are proximal to areas of quartz veins and ancient mines in the Umm Shat Gharb and Umm Shat Sharq areas.

Eolian deposits

Accumulations of windblown sand (Qe) occur on the southern and eastern flanks of some of the more prominent jabals in the district, particularly Jabals Nabitah and Al Wozariyah (pl. 1). A dominant southeasterly wind is responsible for these accumulations.

A large dune field is present in the northwest corner of the district (pl. 1). Here, eolian material is derived by the winnowing and reworking of the channel and terrace silt and sand of Wadi Bishah.

Wadi alluvium

Wadi alluvium (Qal) fills major drainage channels throughout the district. The alluvium is comprised of sand and gravel, but because of the sparse rainfall in the area, little reworking is evident and considerable windblown material may be present. The occurrence of bedrock in some drainage channels, the gradients of which are low, suggests that the deposits are probably not more than 1-2 m thick.

PLUTONIC ROCKS

Approximately 30 percent of rocks exposed in the Ishmas district are plutonic. Gabbro and diabase were emplaced during the early and intermediate stages of the district's plutonic history, whereas stocks of more granodioritic affinity were emplaced during the later stages. All plutonic-rock names introduced below are based on the classification scheme of Streckeisen (1976).

EASTERN TERRANE

Monzogranite

Two small outcrops of monzogranite (mg) are located within the eastern terrane in the southeast part of the district (pls. 1,2). The monzogranite intruded amphibolitized flow and volcaniclastic rocks and appears to have caused the amphibolitization. This intrusive body is poorly exposed and because it is characterized by a low weathering profile, it is expressed at the surface as broad plains covered by a white, coarse-grained grus, particularly east of the district.

The monzogranite is typically light colored and has a color index of about 5. Gneissic foliation is common. The texture of the rock is holocrystalline and hypidiomorphic-granular with grains 1.0 to 3.8 mm across. Cataclasis of perthitic alkali feldspar, quartz, and sodic plagioclase is manifested by mortar material and recrystallization along grain boundaries. Deep red-brown biotite altered to chlorite constitutes less than 5 percent of the rock. Granophyric-micrographic intergrowth of potassium feldspar and quartz is common. Modal abundances are plotted in figure 6A.

The placement of the monzogranite in the overall plutonic history of the district is somewhat arbitrary because it occurs in a terrane exotic to the district. All that can be concluded is that it post-dated the rocks it intrudes and metamorphosed, and predated the Nabitah orogeny (collision of east and west terranes), during which it aquired a tectonic foliation.

WESTERN TERRANE

Nabitah mafic complex

The Nabitah mafic complex is comprised of intercalated diabase and gabbro. It is divided into diabase and gabbro units based on the major constituent.

DIABASE

In the eastern part of the district, diabase (db) crops out in two north-trending bands separated by mylonite within the Nabitah Fault Zone (pls. 1,2). This unit extends to the border of the western terrane on the eastern flanks of Jabal Nabitah. Sills of the diabase complex intrude the Nabitah metasedimentary unit (hsn) and are transected and locally bounded by north-trending faults of the Nabitah Fault Zone. At Jabal Nabitah, diapiric serpentinite was emplaced along a Nabitah structure that cut the diabase complex. Cleavage trends in the diabase typically dip steeply and strike parallel to nearby north-trending faults. Rhythmic layering was observed locally in coarse-grained gabbroic parts of the complex with northerly trends dipping steeply ($>70^{\circ}$) east and west.

The diabase is characteristically fine grained and grayish green to dusky yellow green in hand specimen, with a color index greater than 50. In thin section it is characterized by diabasic texture and locally by the presence of very fine grained granophyric intergrowths of quartz and feldspar emanating (in spherulitic fashion) from plagioclase grain boundaries. Primary plagioclase has altered to equant to tabular pseudomorphs (as much as 2.5 mm across) comprised of albite, epidote, clinozoisite, saussurite, carbonate, and chlorite. Few primary mafic minerals have survived, although the diabasic texture has. Locally, pyroxene is altered to uralitic amphibole, which in turn is altered to chlorite.

There is ubiquitous evidence for cataclasis, which resulted in the formation of microbreccia and (locally) mylonite. The microbreccias are characterized by "islands" of unbroken material (commonly plagioclase) in a broken and altered matrix that may exhibit minor flow structures (whose undulations follow planes of failure) defined by the orientation of chlorite, biotite, and sericite crystals. Minor recrystallization may be present along these fracture planes. Carbonate, quartz, epidote, and clinozoisite are also present in the matrix. Mylonite typically contains oval porphyroclasts whose long axes are as much as 3.4 mm long, consisting of crystal aggregates of strained quartz or albite with bent twin lamellae. The porphyroclasts are set in a mortar (<0.05 mm) of quartz, plagioclase, white mica, and chlorite with semiopaque patches of saussuritized material. Fluxion structure is common in the mortar.

Small gabbroic bodies are included within the diabase unit. At one locality in the northeast corner of the district, a small mafic intrusion that contains layers 2-5 cm thick crops out as an island in the mylonite belt (pls. 1,2). Leucocratic layers are medium grained and consist of at least 50 percent primary anhedral quartz with highly altered plagioclase. Plagioclase grains are almost completely replaced by epidote, clinozoisite, actinolite, and chlorite. Myrmekitic textures are present locally. Although only the leucocratic layer was observed in thin section, the mafic-rich layers appear to be largely amphibole-after-pyroxene cumulates. Given the above description, this gabbroic body is best classified as a layered plagiogranite.

The combined granophyric and diabasic texture, rhythmic layering, the outcrop pattern, and its intrusion into the volcanogenic sedimentary unit of the Suwaydah formation all indicate that this unit is a diabase-sill complex.

GABBRO

In the southeastern part of the district, a northwest-trending gabbro body (gbn) is fault bounded and dissected by structures associated with the Nabitah Fault Zone (pls. 1,2). Elongated diapiric serpentinite bodies delineate these structures locally. The unit extends to the border of the western terrane along its southeast margin (pls. 1,2). The gabbro intrudes the metasedimentary unit along its northern border, is in fault contact with the same unit to the east, and is in fault contact with younger basalt and tuff along its western margin (pls. 1,2). This unit contains subordinate diabase similar to that of the diabase unit described above.

The gabbro is equigranular, with grain sizes ranging from 0.5 to 3 mm. Plagioclase has largely altered to albite, which in turn has altered to sericite and quartz. No primary mafic minerals are preserved. Euhedral to subhedral triclinic and monoclinic pseudomorphs containing cores of clinozoisite + epidote and rims of chlorite, or cores of carbonate with rims of chlorite, probably represent altered plagioclase and pyroxene, respectively.

In general, the primary difference between this unit and the diabase unit described above is the relative abundance of gabbro and diabase. This, in conjunction with the fact that they both intrude only the volcanogenic sedimentary unit of the Suwaydah formation, suggests that they most likely are coeval.

Ishmas gabbro

The Ishmas gabbro (gbi) crops out in the western part of the district as a large layered lopolithic body turned on end by large-scale folding, and so the shape of the outcrop is lenticular in plan view. It has major and minor axis dimensions of at least 17 km and 4 km, respectively (pls. 1,2). It is the largest plutonic unit in the district and represents approximately 20 percent of all the rock exposures in the map area. The layered complex has an overall trend of about N. 20^{o} W. and is completely fault bounded. The eastern margin of the complex is formed by the Ishmas East fault along which diapiric serpentinite bodies occur. The western margin of the complex is formed by a part of the Ishmas West fault and a N. 30^{o} W.-trending fault (pl. 2).

The southern part of the complex is located in an area of high relief, typical elevations of which exceed 1,000 m, the highest in the district. The central and northern parts of the complex form low hills of subdued relief with several higher areas forming isolated jabals (pls. 1,2).

Layering is generally subparallel to the overall trend of the complex, although local variations are common. Dips are mostly steep and to the west, although locally they may be as gentle as 35^{o}, particularly near the center of the intrusion (pl. 1). Although layering was observed throughout the complex, no single layer was traceable over a great distance. Differential weathering of mafic- and plagioclase-rich layers resulted in alternating resistant and weathered out layers on all scales. In areas where layering is 0.5 to 1 m thick, this phenomenon can give an outcrop the appearance of a series of parallel dikes represented by the resistant plagioclase-rich layers.

In the southwest part of the district, west of the Ishmas West fault, the intrusion contains three ancient mines: Ishmas (MODS 00650), Abu Tal (MODS 01433), and an unnamed mine (pls. 1,2). Layering was observed only in the northern half of the exposures, north of a northwest-trending fault (pl. 1). Gabbro exposed south of this fault contains no layering and appears less altered than the Ishmas gabbro. At one locality, bodies of well-developed wollastonite-grossularite vesuvianite-clinozoisite skarn are in contact with the gabbro (pl. 1).

Rhythmic layering in the Ishmas gabbro ranges from 0.5 cm to 1 m thick and is characterized by the relative abundance of pyroxene and plagioclase. Mafic-rich layers (color index >50) consist of mostly altered clinopyroxene and lesser orthopyroxene with intergranular plagioclase, whereas leucocratic layers (color index 5-20) are composed of white or turbid gray plagioclase with intercumulate pyroxene. Poikilitic textures are present in all phases. Ophitic to subophitic textures are common and typified by plagioclase grains enclosed by optically continuous pyroxene.

Mineral grains resulting from primary cumulate phases are generally subhedral to euhedral and range from 0.2 to 3 mm in their longest dimension, the orientation of which tends to be parallel to the layering. Plagioclase is labradorite (An_{65}) where measureable. More commonly, the plagioclase has altered to an aggregate of clinozoisite, carbonate, and quartz forming tabular pseudomorphs after the feldspar mineral. Pyroxene is commonly rimmed by colorless, olive-green, brown, or blue-green pleochroic hornblende. Locally, total replacement of the pyroxene is exhibited by uralitic (actinolite) pseudomorphs that occur with minor quartz.

Highly serpentinized pods of olivine pyroxenite (lherzolite-wehrlite) (um) occur sporadically throughout the layered-gabbro body. In outcrop the pods and lenses are conspicuously much blacker than the surrounding gabbro/norite.

In the pyroxenites, the pyroxene is mainly clinopyroxene, although minor orthopyroxene was observed locally. This indicates that the rock is a wehrlite comprised of 50 to 80 percent serpentine (antigorite) after olivine. Cumulate-grain sizes are 0.5-3 mm across. Locally, ophitic texture is preserved, exhibited by clinopyroxene oikocrysts (as much as 7.5 mm across) filling interstices between what is now an aggregate of serpentine, carbonate, and opaque minerals. Pyroxene forms margins around serpentine pseudomorphs after olivine. Actinolite and serpentine commonly replace pyroxene along fractures and twin planes. Minor chlorite is also present. Stringers of magnetite with or without hematite are ubiquitous, probably the result of serpentinitization of olivine. However, disseminated anhedral to euhedral opaque minerals represent cumulate chromite rimmed by secondary magnetite, which in turn are altered to hematite.

SKARN

The skarn associated with the Ishmas gabbro is fine to medium grained, possesses relict layering, and displays a variety of colors depending upon the dominant mineral or mineral assemblage. Constituent minerals include wollastonite, grossularite garnet, vesuvianite, clinopyroxene, and clinozoisite. In outcrop, the wollastonite is white, the garnet is greenish brown, the vesuvianite is pale green, and the clinopyroxene is dark green. In thin section, the grossularite is colorless to brown, contains replaced calcite, and has embayed wollastonite grain boundaries. Vesuvianite is colorless, has a brownish olive-green to deep berlin blue birefringence, and is locally zoned. The clinopyroxene includes both diopside and salite. The diopside is a characteristic grass green, whereas the salite is colorless to beige. Locally, zoning of clinopyroxene is exhibited by salitic cores grading outward to diopsidic rims. Clinopyroxene is commonly replaced by wollastonite and garnet. Brown diamond-shaped wedges of sphene are also present. No minerals of economic importance were observed.

The overall mineral assemblage indicates that the protolith was an impure limestone or calcareous sediment. This is in contrast to the pure blue marble derived from pure limestone found largely in the wacke and sandstone unit (pl. 1).

Quartz diorite

In the southwest part of the district, quartz diorite (qd) intrudes the Ishmas gabbro. In outcrop the rock is dull gray and weathers to smooth, rounded surfaces, in contrast to the adjacent boulder-covered outcrops of the gabbro. In thin section the rock is hypidiomorphic to xenomorphic granular. Primary minerals include zoned plagioclase (An_{20-40}), quartz, green hornblende, brown biotite, and minor alkalic feldspar, the grains of which are all between 0.5 and 3 mm across. The rock is relatively unaltered, although calcic plagioclase cores are altered to epidote and sodic rims are altered to sericite. Minor chlorite after biotite is also present. Modal abundances (figs. 6A and 6B) are 46 percent plagioclase, 36 percent mafic minerals, 15 percent quartz, and 3 percent alkalic feldspar.

Tonalite

Tonalite (ton) is exposed over a large area of subdued relief and grus-covered plain in the north-central part of the district (pls. 1,2). Xenoliths of marble and volcanogenic wacke and sandstone occur within the intrusion. Marble also occurs as screens between the stock and the adjacent country rock.

In outcrop, the tonalite unit is reddish to moderate red and consists of white, medium- to coarse euhedral feldspar grains in a gray aphanitic groundmass. A seriate texture is diagnostic of this unit. In thin section, the rock is holocrystalline, hypidiomorphic seriate, although locally it displays equigranular textures. Subhedral, equant to tabular plagioclase phenocrysts (An_{30-40}) as much as 6 mm across coexist with a groundmass of anhedral quartz and plagioclase grains as much as 0.75 mm across. The plagioclase exhibits both normal and oscillatory zoning, which is emphasized by selective sericitization of growth zones. Brown biotite altered to chlorite is common and locally abundant, causing the color index to increase from a normal of 10-15 percent to as much as 50 percent. A poikilitic texture is exhibited by oikocrysts of quartz (as much as 2 mm across) enclosing chadacrysts of plagioclase (< 0.2 mm across). Euhedral wedges of sphene as much as 0.75 mm are common. Modal abundances range from 55-65 percent plagioclase, 15-35 percent quartz, and less than 5-30 percent mafic and opaque minerals combined (fig. 6A). Modes based on normative data derived from whole-rock analyses suggest that this unit is granodioritic (fig. 6B).

Dacite porphyry

Dacite porphyry stocks (dp) are exposed at two localities in the north-central part of the district and at several localities in the central part. In the Umm Shat Gharb area (pl. 2), the intrusion was emplaced in pyritic wacke and is exposed intermittently as cupolas and dikes elongated parallel to the dominant N. 25^{o}-35^{o} W.-trending structures of the area. Here the porphyry stock exhibits variations in crystallinity. In the Umm Shat Sharq area (pl. 2), dacite porphyry crops out as an elongated stock with a northwest orientation and intrudes tonalite and volcanogenic wacke and sandstone. Screens of marble between the stock and country rock, as well as marble xenoliths, are locally present (pl. 1). In the central part of the district, in the vicinity of the Al Wozariyah mines (pls. 1,2), dacite porphyry crops out intermittently as cupolas similar to those found at Umm Shat Gharb. An elongated plug of dacite porphyry is emplaced into a N. 25^{o} W.-trending fault that transects the district and passes through both the Umm Shat Gharb and Al Wozariyah areas (pls. 1,2).

Dacite porphyry is typically pale red to pale reddish brown in outcrop. In hand specimen, the rock is porphyrtic with white feldspar and gray quartz phenocrysts 3 to 5 mm across making up 50 to 75 percent of the sample. In thin section, this unit is characteristically holocrystalline hypidiomorphic porphyritic; normally zoned subhedral plagioclase, quartz, and columnar biotite pseudomorphs after hornblende comprise phenocrysts 1.0 to 5.0 mm across. The groundmass consists of a very fine grained (<0.1 mm) aggregate of anhedral quartz, plagioclase, sericite, biotite, and minor euhedral brownish-gray apatite. Locally, plagioclase phenocrysts are intensely sericitized, whereas minor carbonate is scattered throughout the groundmass. Of the phenocryst population, 25 to 30 percent is quartz, 65 to 70 percent is plagioclase, and the remainder is mafic minerals (fig. 6A). Modal proportions obtained from normative data place the unit mostly within the granodiorite field (fig. 6B), as is the case with the tonalite.

Although the dacite porphyry stock is exposed over a relatively large area in the Umm

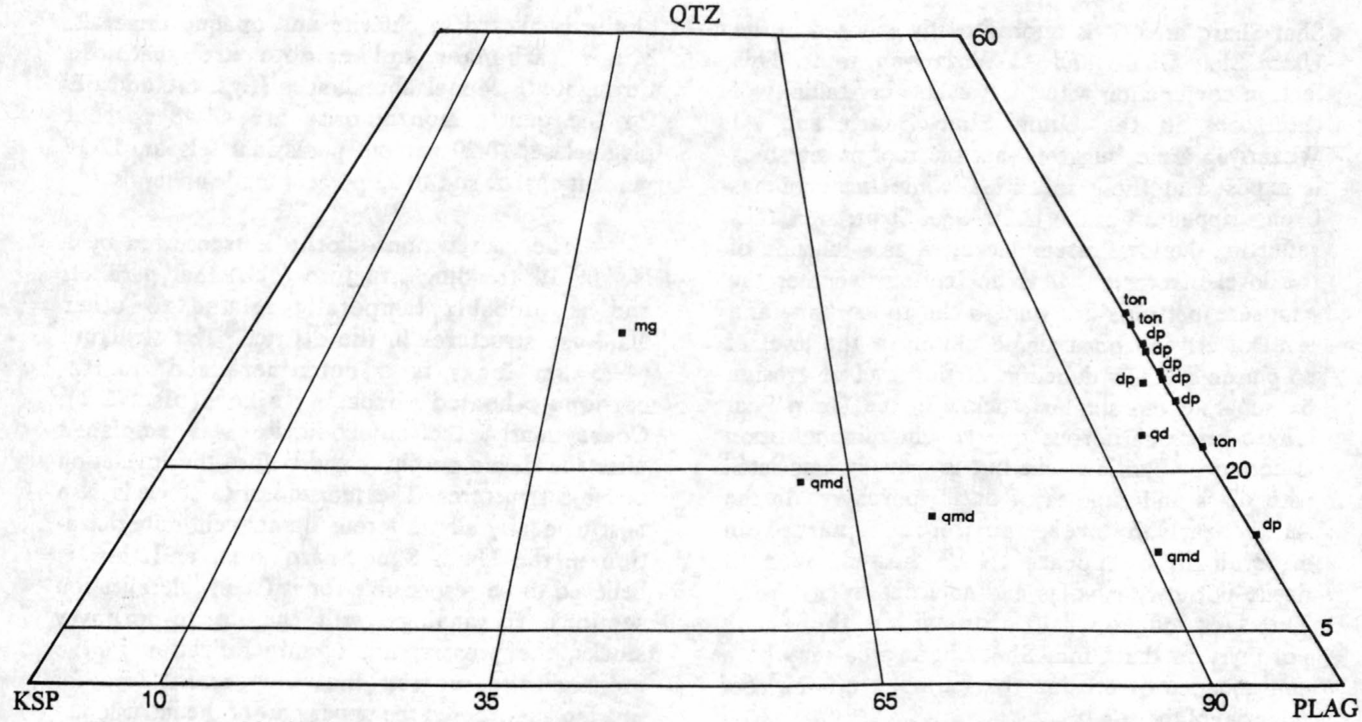


Figure 6A--Modal plot for selected plutonic rocks of the Ishmas district based on point-count data; mg = monzogranite, qd = quartz diorite, ton = tonalite, dp = dacite porphyry, and qmd = quartz monzodiorite. Field boundaries are those of Streckeisen (1976).

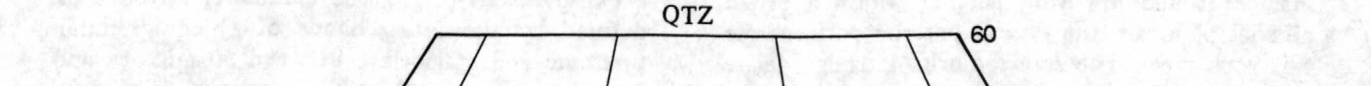


Figure 6B--Modal plot for selected plutonic rocks of the Ishmas district based on normative data; mg = monzogranite, qd = quartz diorite, ton = tonalite, dp = dacite porphyry, and qmd = quartz monzodiorite. Field boundaries are those of Streckeisen (1976).

Shat Sharq area, it is intermittently exposed in the Umm Shat Gharb and Al Wozariyah areas. This fact, in conjunction with the variable crystallinity of the stock in the Umm Shat Gharb and Al Wozariyah areas, suggests that the roof of the stock is exposed at these localities, while the roof has been stripped off in the Umm Shat Sharq area, thus reflecting the level of emplacement as a function of the level of erosion. It is not certain whether the exposure patterns are due to the topography and level of erosion on a single pluton or the level of emplacement as a function of the level of erosion on separate but similar stocks. In the Umm Shat Gharb area, auriferous quartz-vein mineralization is hosted by pyritic wacke but is spatially associated with dikes and cupolas of dacite porphyry. In the Al Wozariyah area, auriferous quartz-vein mineralization appears to be hosted by both dacite-porphyry cupolas and adjacent country rock. The lack of mineralization within the dacite porphyry in the Umm Shat Sharq area may be a consequence of erosion that stripped off the roof material of the stock.

Quartz monzodiorite

Quartz monzodiorite (qmd) is exposed in the north-central part of the district as a circular stock in the Umm Shat Sharq area (pls. 1,2). Small inselbergs and low-lying patches within a broad alluvial plain are the typical outcrop patterns for this rock type. The monzodiorite intrudes dacite porphyry and volcanogenic wacke and sandstone. Screens of marble occur locally along the western contact with the dacite-porphyry stocks (pl. 1).

In outcrop, the quartz monzodiorite weathers to smooth, rounded surfaces, is light to moderate gray, and finc grained with a color index of about 25. In thin section, the rock is holocrystalline and hypidiomorphic granular, although locally it has a distinctly bimodal grain-size distribution. Tabular, subhedral to euhedral plagioclase (An_{30-50}) grains 0.65 to 3.0 mm across coexist with an aggregate of anhedral intergranular quartz, plagioclase, and perthitic alkalic feldspar grains that show tartan twinning and are all between 0.15 and 0.5 mm across. The plagioclase displays both normal and oscillatory zoning, which is emphasized by selective sericitization of growth zones. Granophyric textures exist locally. Orange-brown biotite and green hornblende comprise the mafic constituents. Apatite and zircon are common accessory minerals. Plagioclase is sericitized and biotite is altered to chlorite and opaque minerals. Minor carbonate and epidote are scattered throughout. Modal abundances (figs. 6A and 6B) for the quartz monzodiorite are 44-48 percent plagioclase, 18-29 percent potassium felspar, 12-17 percent quartz, and 10-22 percent mafic minerals.

The quartz monzodiorite is transected by a N. 70° W.-trending structure (qhb) that parallels and is probably temporally related to other Najd-age structures in the district. The structure (4.25 km long) is a nonmineralized quartz-carbonate-healed breccia dike (pls. 1,2). Consequently, the monzodiorite was emplaced after the dacite porphyry and before the formation of Najd structures. The monzodiorite stock is also host to nearly all auriferous quartz-vein mineralization in the Umm Shat Sharq area, and thus is believed to be responsible for it (see Mineralization section). By analogy with the dacite-porphyry stocks, the preservation of mineralization in the monzodiorite suggests that the present level of erosion has exposed the upper part of the intrusion.

Young gabbro

An isolated outcrop of unaltered microgabbro (gbj) occurs just north of Umm Shat Sharq in the northeast part of the district (pl. 1). The rock is a two-pyroxene-plagioclase cumulate. Layering is defined by alternating bands of 1) equigranular pyroxene and plagioclase between 60 microns and 0.2 mm across, and 2) poikilitic pyroxene oikocrysts as much as 2 mm across with rounded plagioclase chadacrysts less than 0.1 mm in diameter. All the constituent-mineral grains are anhedral. Irregularly shaped patches (as much as 1.15 mm across) of opaque minerals constitute as much as 5 percent of the rock. Plagioclase is slightly altered to clinozoisite and is saussuritized.

In the south-central part of the district, three small individual gabbro plugs were emplaced in laminated tuff and tuff breccia (pl. 1). The gabbro is a medium-grained two-pyroxene norite and is nearly as unaltered as that described above. Poikiolitic textures are also present.

The absence of alteration compared to other gabbros in the district, in conjunction with the occurrence of these plugs along a northwest-trending Najd structure (pl. 1), suggests that the young gabbro represents the latest plutonic episode in the district.

Unassigned gabbro and diorite

Several isolated plugs of highly altered gabbro and diorite scattered throughout the district cannot be assigned to major units and hence remain unclassified with regard to the plutonic history of the district. However, a post-mylonitization age for emplacement is inferred by the presence of an unsheared body within mylonite schist directly east of Jabal Nabitah (pls. 1,2). These rocks are generally medium to coarse grained and highly altered. Remnant ophitic and myrmekitic textures were observed locally. All mafic minerals have been totally altered to a mass of carbonate, chlorite, clinozoisite and quartz. Plagioclase is intensely saussuritized and sericitized. Iron oxides are also abundant locally.

Dikes

Mafic (basaltic to andesitic) and felsic dikes are found throughout the district, although most are in the central and western parts (pl. 1). Dikes are generally absent within the Nabitah Fault Zone and in rocks of the eastern terrane. Most dikes are generally less than a meter wide and are traceable for several tens of meters, (locally, for as much as 450 m).

Mafic dikes are generally dark gray to dark green, very fine grained to porphyritic-phaneritic, and basaltic to andesitic. Saussuritized plagioclase is accompanied by variable amounts of secondary epidote, chlorite, carbonate, quartz, and iron oxides. Felsic dikes are typically leucocratic, aphanitic to porphyritic phaneritic, and rhyolitic. Pink sericitized alkalic feldspar, quartz, hornblende, and minor saussuritized plagioclase comprise the rock.

Both mafic and felsic dikes are emplaced into structures of all ages and probably represent several epidodes of dike emplacement. For the most part, however, felsic dikes are relatively unaltered and are probably related to post-tectonic felsic plutonism that occurred throughout the Arabian Shield.

STRUCTURAL GEOLOGY

TECTONICALLY DERIVED ROCKS

Mylonite

Several north-trending mylonite belts (myl) are present within the Ishmas district, all associated with major north-trending faults or fault zones. These include a major belt in the Nabitah Fault Zone in the eastern part of the map area, and less extensive zones associated with both the Ishmas East and West faults in the western part of the district (pls. 1,2).

MYLONITES OF THE NABITAH FAULT ZONE

In the mylonite of the Nabitah Fault Zone, foliation is generally north trending, although it locally varies as much as 20° from north and dips steeply east ($>70^{\circ}$) (pl. 1). At the southern end of the belt, foliation changes to cleavage and the unit pinches out just west of Jabal Nabitah (pl. 1). The mylonite belt has a maximum width of 1.5 km.

The mylonite is a gray, flinty, and highly cleaved rock in the southern and central parts of the belt, and is interlayered with a soft bluish-gray schistose rock in the northern part. The flinty-gray variety commonly contains ovoid white spots that give the rock a porphyritic appearance. The white clusters represent saussurite-rich patches in porphyroclasts. The porphyroclasts constitute between 20 and 40 percent of the rock, are commonly oval shaped, as much as 9 mm in the longest dimension, and are elongated parallel to the fluxion structure. In addition to saussurite, the porphyroclasts consist of a foliated aggregate of quartz, epidote, clinozoisite, sericite, and carbonate, the grains of which are less than 0.5 mm across. Megascopic fluxion structure is defined by streaks of iron oxide, whereas microscopic fluxion structure is exhibited by streaks of saussuritized material and the orientation of sericite in the matrix. The matrix is comprised of as much as 80 percent mosaic quartz with variable amounts of disseminated and patchy sericite, saussurite, chlorite, carbonate, and opaque minerals, the grains of which are all less than 0.5 mm.

The bluish-gray schistose variety is comprised of variable amounts of quartz, pale-green chlorite, and sericite with minor carbonate. In general, it is similar to the mylonite schists of the eastern terrane.

The spatial distribution of the mylonite, and the composition of observed porphyroclasts indicate that the likely protolith was diabase. The blue-gray schistose variety may represent more mafic to ultramafic units within the diabase/gabbro complex.

MYLONITES ASSOCIATED WITH THE ISHMAS FAULTS

The mylonites associated with the Ishmas faults occur as belts as much as 600 m wide along the northern half of the Ishmas East fault, and as much as 300 m wide along the central section of the Ishmas West fault (pl. 1). In both cases, foliation is subparallel to the fault (N. 15°-30° W.) and dips steeply west (>60°). Mylonite located along the Ishmas West fault projects under alluvium to the north and pinches out to the south in the vicinity of the Ishmas mine (pl. 1). The mylonite along the Ishmas East fault projects under alluvium both to the north and south (pl. 1).

Rocks of both belts are typically gray, flinty, and highly cleaved. They consist of porphyroclasts of quartz, plagioclase, and saussurite-quartz masses as much as 6 mm across in a matrix of the same material though less than 40 microns in size and possessing well-developed fluxion structure. Carbonate, chlorite, and quartz occur as crush trails emanating from porphyroclasts. Epidote replaces plagioclase throughout the rock. In the case of both mylonite belts associated with the Ishmas faults, the mylonites are gradational into protolith, which is dacitic volcanic and volcaniclastic rocks. Gabbro adjacent to both faults is locally fragmented and sheared.

Serpentinite

Lenticular serpentinite bodies (sp) occur along several north-trending Nabitah structures within the Nabitah Fault Zone as well as along the Ishmas East fault (pls. 1,2). They commonly form prominent jabals (Jabal Nabitah and Jabal Umm Shat, for example) and north-trending ridges. The rock is typically dark green to black and characteristically weathers into brown to tan caves and cavities. Veins and veinlets of white cryptocrystalline quartz are common. Altered serpentinite (asp) is typically rusty red-brown to pink, silicified and carbonatized, and occurs as isolated patches within the serpentinite bodies (most commonly along fault-bounded contacts). Locally, alteration of the serpentinite is extensive, resulting in an entire jabal of the altered rock. Such an occurrence exists east of Jabal Al Suwaydah (pl. 1)

In thin section, the serpentinite is characterized by a mass of fibrous, very fine grained (0.10 mm) mesh-textured serpentine (antigorite) and chlorite with variable amounts of dusty and stringer magnetite. Generally, no primary silicates are preserved. Locally, relict cumulate layering is best displayed by opaque minerals (chromite altered to magnetite altered to hematite). Poikilitic textures are present within the opaque layers and are characterized by chadacrysts (0.1-0.2 mm) of serpentine pseudomorphs after olivine in anhedral opaque oikocrysts (0.4-1.2 mm). Layering is 5-7 mm thick. Disseminated grains of carbonate less than 0.5 mm, as well as patches as much as 6 mm across, are common. Areas of local shearing contain chlorite schist with euhedral wedges of sphene, and magnetite with ilmenite exsolution lamellae.

Altered serpentinite is characterized by a relative abundance of medium-grained carbonate, quartz, and iron oxide. Clinopyroxene and albitic plagioclase are observed and may reflect metamorphic grade. Serated crystal boundaries and patches of finer grained material are indicative of recrystallization. Discontinuous and disrupted bands and lenses of magnetite (as much as 1 cm thick) in a matrix of carbonate and quartz certainly represent remnants of cumulate chromite bands in an ultramafic protolith. Where they occur as thin units along major faults (for example, along the northern section of the Ishmas East fault), altered serpentinites exhibit evidence of intense cataclasis, ranging from mylonites to ultramylonites. The mylonites are characterized by the presence of well-developed contorted fluxion structure and 10-15 percent porphyroclasts of carbonate-quartz-iron-oxide aggregates. Coarser grained carbonate commonly fills veinlets discordant to the fluxion structure. Ultramylonites are typified by the formation of compositional layering, 1.5-7 mm thick, and contain less than 5 percent porphyroclasts. The layering is generally manifested by the relative abundance of carbonate, quartz, and iron oxide.

The occurrence of serpentinite bodies along what are believed to be deep-seated Nabitah faults is consistent with a diapiric origin for the serpentinite. The timing of mylonitization in relation to serpentinitization is uncertain, but the two events are thought to be coeval. Mylonitization of altered serpentinite was observed at one locality, but unsheared altered serpentinite in contact with mylonite is observed elsewhere.

Structural Events

The structural history of the Ishmas district encompasses two Shield-wide tectonic episodes: the Nabitah orogeny and the Najd faulting event (see section on Geotectonic Setting). An intermediate episode forming transitional structural features is also evident.

Nabitah orogeny

The Nabitah orogeny is defined as collisional orogenesis in response to suturing of accreted island-arc terranes in the west to a landmass of more continental affinity to the east (Stoeser and Camp, 1984). As elsewhere in the Arabian Shield, the Nabitah orogeny imparted a strong north-trending structural grain to the rocks of the district.

Within the Ishmas district itself, the Nabitah orogeny can be divided into three phases. These are 1) folding, 2) faulting, shearing, and mylonitization, and 3) emplacement of diapiric serpentinite.

Folding occurred about north-northwest-trending subvertical axes throughout the district. The folding produced the near-vertical orientation of all layered rocks in the district and is manifested by a large, tightly folded syncline underlying the plain of subdued relief in the central and north-central part of the district (pl. 1). Load structures in laminated tuff show younging directions that would indicate the presence of a syncline. The accompanying anticlinal structures are less evident because their hinges failed, resulting in major north-trending faults. The general westerly dip of layering in the Ishmas gabbro suggests that it represents the western limb of a tightly folded anticline, the failed hinge of which is now the Ishmas East fault. The Ishmas West fault corresponds to the failed hinge of an accompanying syncline. The highly faulted eastern part of the district represents a series of failed fold hinges proximal to the collisional boundary. Therefore, the initial phase of deformation during the Nabitah orogeny was folding in response to the imminent collision of the eastern and western terranes (Malahah-Najran and Asir terranes, fig. 1) (Smith and others, 1984).

Slight tilting of the district toward the north is expressed by a moderate northward plunge of the syncline in the center of the district (pl. 1). Tilting may have been contemporaneous with or postdated folding.

Faulting, shearing, and mylonitization followed folding and correspond to the collision and suturing of the eastern and western terranes. The failing of fold hinges initiated this phase of deformation. The most intense deformation occurred within the Nabitah Fault Zone in the eastern part of the district and immediately east of it, in the mylonite schist of the eastern terrane (pls. 1,2). Deformation in the Ishmas district was characteristically penetrative and plastic during the Nabitah orogeny. Extensive subvertical cleavage is almost ubiquitous in the rocks of the district and tends to strike parallel to the nearest north-trending Nabitah structure (pl. 1). The plastic deformation is manifested by extensive belts of mylonite adjacent to the Ishmas faults and in and directly east of the Nabitah Fault Zone, as well as by numerous highly foliated shear zones associated with Nabitah structures. The plasticity of the deformation indicates that the rocks were ductile and therefore under the influence of high temperature and confining pressure. This is consistent with such thermotectonic events as collision and suturing of terranes.

A distinction is made between collision and suturing because of a divergence in the orientation of fold axes and failed hinges between the western part of the district and the Nabitah fault zone (pls. 1,2). The Ishmas faults and the hinge line of the central syncline all swing from due north to N. 20°-30° W. The orientations of structures in the Nabitah Fault Zone vary from due north (±10°) in the north to N. 20°-30° W. in the south. Although a variety of directions of plate movements and orientations of plate boundaries is possible, oblique collision of terranes can satisfactorily explain the variations in structural orientation (fig. 7). Initial principle compressive stress oriented in a NE-SW direction resulted in N. 20°-30° W.-trending folds that ultimately failed along their hinges. As collision ensued, suturing occurred along a north-trending line and resulted in the formation of the Nabitah Fault Zone, which clearly truncates the central syncline as seen along the trace of the fault that bounds the western margin of Jabal al Suwaydah. Evidence for post-mylonitization sinistral strike-slip displacement along the suture line is displayed by drag folding of shear foliation in the mylonitic schists of the eastern terrane (pl. 1).

Emplacement of diapiric serpentinite bodies constituted the final phase of the Nabitah orogeny. Serpentinite emplacement must have postdated faulting and shearing because the faults were conduits for the ascending diapirs. The very presence of the serpentinites suggests that the structures are deep seated. The trace of these deep-seated serpentinite-bearing Nabitah structures are well delineated in aeromagnetic surveys (Andreasen and Petty, 1973; Gonzalez, 1974). The absence of serpentinite along the Ishmas West fault (pl. 2) and the corresponding absence of a magnetic signature along its trace (Gonzalez, 1974) indicates that it is not as deep seated as other Nabitah structures in the district, which may be a consequence of its distance from the zone of suturing (that is, the Nabitah Fault Zone).

Intermediate event

A temporally intermediate structural episode resulted in the formation of N. 20°-N. 35° W.-trending faults, henceforth known as transitional faults. These structures are transitional between Nabitah and Najd structures in both orientation and deformational style. Although shearing and cleavage formation in adjacent rock exists at one locality along a transitional fault, evidence for more elastic deformation may be present elsewhere along the same structure. The lack of both mylonitization and serpentinite emplacement distinguishes these structures from Nabitah structures of similar orientation.

Transitional structures are located primarily in the central, north-central, and southwestern parts of the district. Their orientation is subparallel to the Nabitah fold axes in the central part of the district and may have been influenced by the fold axes. The transitional faults sinistrally offset Nabitah structures in the Nabitah fault zone and cut the tonalite intrusion (pls. 1,2), an indication that they postdate them. In the Umm Shat Gharb area, a transitional fault offsets an east-west trending dike that was probably emplaced in a conjugate Nabitah structure (White and Doebrich, 1987).

Evidence for variable deformational style is best displayed by the transitional fault that transects the center of the district and passes through both the Umm Shat Gharb and Al Wozariyah ancient mines (pls. 1,2). South of Umm Shat Gharb, where the fault places basalt (hb) in contact with the ferruginous chert and carbonate unit (hx), the ground east of the fault is intensely sheared with boudinaged chert and carbonate pods. Along the same structure in the Umm Shat Gharb group of mines, continuous auriferous quartz veins occupy tensional open-space fractures indicative of elastic deformation in brittle rock (Billings, 1972). It is also evident that the same transitional fault influenced the distribution and orientation of dacite porphyry cupolas and dikes in the Umm Shat Gharb and Al Wozariyah areas and thus preceded their emplacement (pls. 1,2).

Najd faulting event

Throughout the Arabian Shield the Najd faulting event was characterized by elastic deformation of a brittle craton resulting in an extensive left-lateral wrench-fault system (Moore, 1979), located primarily east of the Nabitah mobile belt (fig. 1). In the Ishmas district, this event is manifested by a series of steeply dipping N. 60°-80° W.-trending faults that offset both Nabitah- and intermediate-age structures (pls. 1,2).

The style of deformation is elastic, as no shearing and minor localized cleavage development is evident. The sense of displacement is largely left-lateral with some coupled right-lateral movement, as displayed by offset sections of the

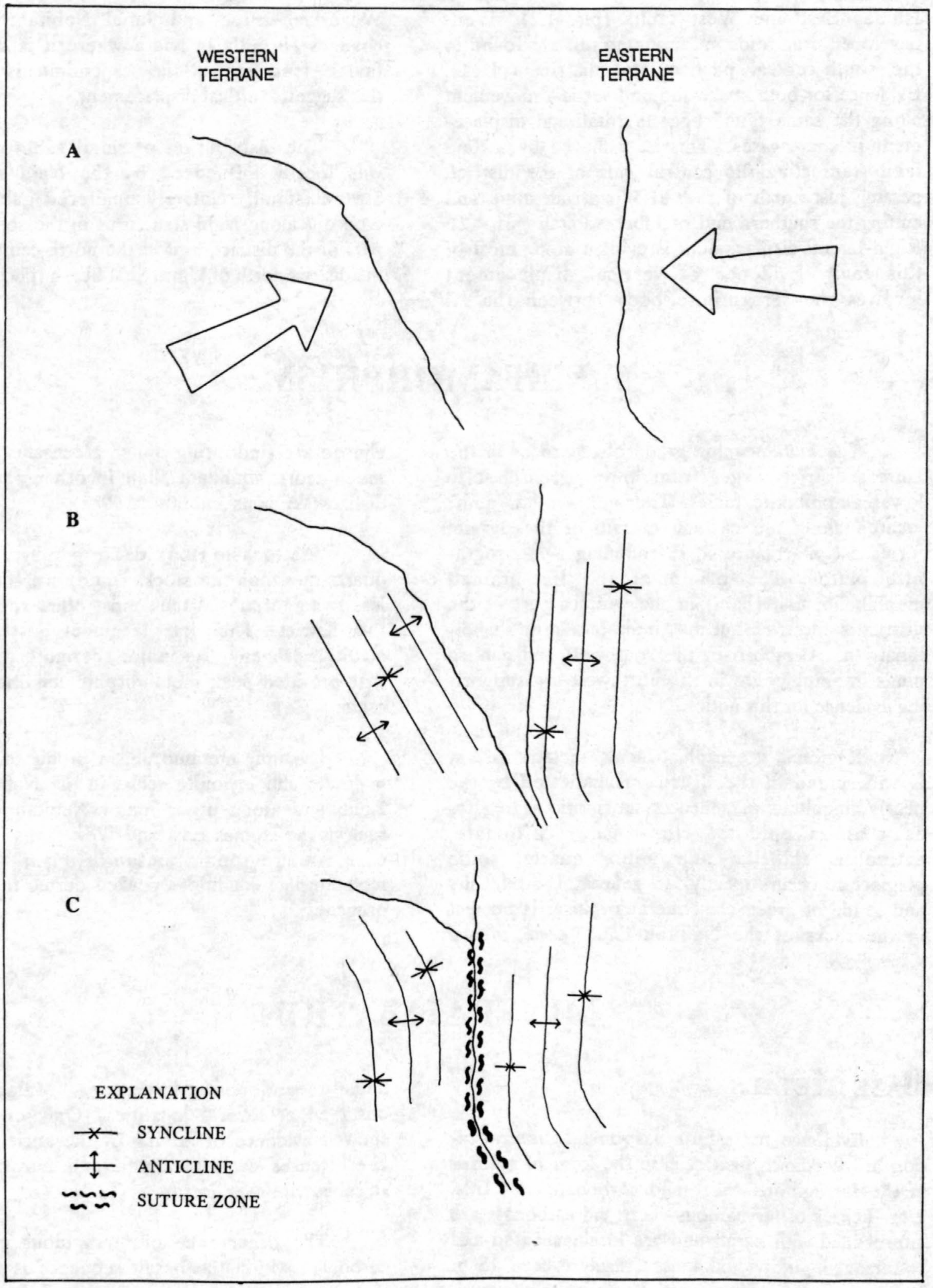


Figure 7–Schematic diagram illustrating the change in structural orientation in time due to obliqeness in plate movement and terrane boundaries; A) converging terranes, B) imminent collision and folding, C) suturing and bending of fold axes.

Ishmas East and West faults (pls. 1,2). Well-developed drag folds in laminated tuff are found in the south-central part of the district (pl. 1). Evidence for both strike-slip and vertical movement along the same fault suggests rotational displacement in some cases. This is displayed by a Najd fault transecting the central part of the district, passing just north of the Al Wozariyah mine and cutting the southern end of Jabal Nabitah (pls. 1,2). Right-lateral displacement is evident along most of this fault. Evidence of vertical displacement involves the serpentinite body between the Al Wozariyah mine and Jabal Nabitah; the body changes abruptly in width where it is cut by this fault. Assuming that the serpentinite is lenticular, this suggests vertical displacement.

The distribution of small gabbroic plutons was locally influenced by the Najd structures. Several small, relatively unaltered gabbro plugs crop out along Najd structures in the south-central part of the district, and in the north-central part of the district north of Umm Shat Sharq (pl. 1).

METAMORPHISM

The metamorphic grade of the rocks in the Ishmas district ranges from lower greenschist to lower amphibolite facies. The amphibolite (amh) located along the eastern margin of the district forms a contact aureole surrounding a monzogranite pluton. The origin of the fine-grained amphibolite unit (ham) in the western part of the district is uncertain but may indicate a large shallow intrusion. A gabbro in the southwest and gabbro plugs in amphibolite in the northwest are supporting evidence for this notion.

Regional greenschist-facies metamorphism is widespread in the district as indicated by the nearly ubiquitous presence of saussuritic aggregates as well as epidote, clinozoisite, carbonate, actinolite, chlorite, and minor quartz; sodic plagioclase occurs locally. In general, the intensity and grade of greenschist metamorphism is highest in the rocks of the Nabitah Fault Zone, where clinozoisite (indicating upper greenschist facies) is much more abundant than in other parts of the district (Williams and others, 1982).

The tonalite (ton), dacite porphyry (dp), and quartz monzodiorite stocks (qmd) are considerably less metamorphosed than most other rock units in the district. Their emplacement post-dated the Nabitah orogeny, the major thermotectonic event that provided peak metamorphic conditions in the region.

Dynamic metamorphism produced extensive mylonite and mylonite schist in the Nabitah Fault Zone and along other major Nabitah structures such as the Ishmas East and West faults. As in the case of regional metamorphism, dynamic metamorphic conditions peaked during the Nabitah orogeny.

MINERALIZATION

Base Metals

Evidence for minor base-metal mineralization in the Ishmas district is in the form of gossans in the ferruginous chert and carbonate unit (pls. 1,2). Lenses of ferruginous chert and carbonate are interbedded with basalt and are locally sheared and boudinaged. Individual lenses rarely exceed 15 m in length and 5 m in width. Some of the ferruginous lenses are true gossan, containing yellow-brown to deep red-brown powdery limonite and hematite and boxwork textures. Malachite was observed at several localities. Only one locality showed evidence of mining by the ancients. Some chert lenses are brecciated and may represent siliceous caps over gossan.

The occurrence of ferruginous chert and carbonate within the basalt sequence is consistent with an exhalative origin. Fumarolic activity in a seafloor setting occurred during a period of precratonic evolution.

The limited extent of the gossanous bodies and the low metal contents (Appendix) indicate a low potential for base-metal mineral resources in the district.

GOLD

Gold deposits in the Ishmas district are grouped chronologically, based on their structural and plutonic associations. All occurrences are fault-controlled auriferous quartz veins and pods that were worked in ancient times. The older deposits are within north-trending Nabitah-age fault zones that are spatially defined by schist and mylonite. The presence of slickensided pods of quartz suggests that the quartz bodies were formed during the late stages of movement on the enclosing faults. None of the older occurrences are spatially associated with a potential source intrusion.

The younger, post-Nabitah-age deposits are located either in transitional faults or within and near intrusions that postdate transitional faults. All occur in faults characterized by fault breccia and gouge, and most are spatially associated with intrusive masses of dacite porphyry, quartz monzodiorite, and rarely, quartz diorite.

Nabitah-age deposits

Nabitah-age deposits are exemplified by auriferous quartz pods exposed at the Ishmas, Al Suwaydah, and Nabitah ancient mines (White and Doebrich, 1987), as well as by numerous unnamed mines and workings occupying faults and shear zones that originated during the Nabitah orogeny (pl. 2). Although not discussed here, the rocks of the Nabitah Sharq, Nabitah Shamal, and Nabitah Janub ancient mines (pl. 2) have similar characteristics and occur within the Nabitah fault zone. They are all located up-drainage from and are believed to be responsible for gold anomalies identified in the wadi-sediment geochemical survey of the district (Samater, in press).

ISHMAS

The Ishmas ancient mine is the largest of several similar occurrences in the western part of the district that are hosted by the layered Ishmas gabbro complex and proximal to the Ishmas West and Ishmas East faults (pl. 2). The Ishmas West and East faults are north-trending Nabitah-age structures that represent failed fold hinges somewhat removed from the Nabitah fault zone. Both faults are characterized by mylonite belts; the Ishmas East fault is also characterized by the presence of serpentinite diapirs. Numerous discontinuous carbonate-altered fault zones within the Ishmas gabbro complex tend to parallel the Ishmas West and East faults (pl. 2).

At Ishmas, the discontinuous north-trending zone of shearing and carbonate alteration is bounded on the north and south by gabbro, on the west by mixed gabbro and hornblendite, and on the east by hornblendite, which was probably a layer of mafic cumulate. The most intensely altered rock contains irregular clots of ankerite and iron-magnesium-rich calcite, surrounded by matrix aggregates of chlorite and quartz. Iron-oxide pseudomorphs of pyrite are common.

Gold is concentrated at the contact between the quartz pods and adjacent unsheared gabbro. Iron-oxide pseudomorphs of pyrite, native gold, and chalcopyrite rimmed by chalcocite occur in quartz from the mine dumps, and a composite grab sample of quartz from the dump contains 4,600 ppb gold and 100 ppm lead (White and Doebrich, 1987). The limited extent of the potential contact area between quartz pods and gabbro suggests that even if high gold concentrations were within the contact area, the tonnage would not be adequate. However, gold values indicate that quartz pods in carbonate-altered shear zones carry sufficient amounts of gold to warrant prospecting.

AL SUWAYDAH

The Al Suwaydah ancient mine is located at Jabal Al Suwaydah in the east-central part of the district along the western edge of the main Nabitah Fault Zone (pls. 1,2). This mine and two other unnamed workings occupy small subsidiary north-trending fault zones within a block that is bounded by two major mylonite-defined north-trending Nabitah structures (pls. 1,2). At Al Suwaydah, the structure cuts a north-trending, steeply east-dipping sequence of mafic lapilli tuff and tuff breccia with interbedded tuff and feldspar-porphyry flow rock.

At Al Suwaydah, quartz veins and pods

occupy dilatant structures within a quartz-sericite-pyrite altered fault zone. Gold is concentrated in the altered rock adjacent to the most extensive quartz veins and pods, as indicated by the localization of ancient workings, but gold is also distributed throughout the 20-m-wide zone of alteration, as indicated by rock-chip samples that average 290 ppb gold (White and Doebrich, 1987). Although this value is not sufficient to be of economic interest, the wide areal distribution of pyrite and gold is suggestive of a potential for large tonnage. Other similar fault zones might contain the higher gold concentrations necessary to justify prospecting.

NABITAH

The Nabitah ancient mine consists of a single small working in mylonite adjacent to a north-trending Nabitah-age fault in the east-central part of the district (pls. 1,2). The fault separates the serpentinite of Jabal Nabitah on the east from diabase on the west. The serpentinite directly adjacent to the fault is locally altered to red-brown listwaenite, composed of ferroan dolomite, brucite, and talc, with numerous irregular pods and discontinuous veins of quartz (White and Doebrich, 1987). Listwaenite is common to all fault-bounded serpentinite in the district.

The ancient working is located within a quartz pod at the contact between serpentinite and mylonite. Although gold values from dump samples of 7,000 ppb gold are significant, the small size of the Nabitah ancient mine gives little promise of adequate tonnage.

Post-Nabitah-age deposits

Post-Nabitah-age deposits are exposed at Ishmas Kabir, Umm Shat Gharb, Al Wozariyah Shamal, Al Wozariyah, Umm Shat Sharq, Al Suwaydah Janub and Al Suwaydah Sharq ancient mines (pl. 2). Ishmas Kabir is located in quartz diorite; Umm Shat Gharb, Al Wozariyah Shamal, and Al Wozariyah are located within or near masses of dacite porphyry; and the Umm Shat Sharq mines are located in quartz monzodiorite. The rocks at Al Suwaydah Janub are the only post-Nabitah-age deposits that do not have an apparent associated intrusion.

ISHMAS KABIR

The Ishmas Kabir ancient mine is marked by a row of mine dumps that is about 530 m long and rises approximately 8 m above the surrounding gravel-covered plain (pl. 2). It is the largest individual working in the district. The ore structure strikes N. 59° E., an orientation that does not compare with typical regional trends, but is characteristic of the variable strikes of veins within and near intrusions. Country rock exposed in trenches is foliated quartz diorite, but Gonzalez (1974) and Worl (1979) found biotite schist on the main dumps, suggesting that the principal workings might be on or near the contact between a quartz-diorite intrusion and an adjacent body of schist. The schist may also be sheared quartz diorite.

Gonzalez (1974) and Worl (1979) noted that quartz veins exposed in the principal working are as much as 1 m wide, contain carbonate, and are locally brecciated and cemented by younger quartz. Worl (1979) indicated the presence of multiple parallel veining. Chalcopyrite, pyrite, and native gold are present in quartz collected from the main dumps (Worl, 1979). An average of grab samples collected from dumps over a traverse of 518 m by Smith (1964) yielded 6.86 g/t gold. Gonzalez (1974) obtained a 3 g/t gold average from dump samples and Worl (1979) collected two samples that averaged 6.2 g/t gold.

The deposits at the Ishmas Kabir mine should be tested by drilling. A comparatively large ore body is indicated by the extent of ancient mine dumps, the widths of veins, the thicknesses of possible faulted gold-bearing rock, and the potential for parallel structures and veins. Multiple fluid injection, indicated by brecciation of quartz veins, suggests the possibility for enhancement of grades by overlap of more than one episode of gold precipitation. Moderate ore grades were obtained by testing the dump samples; locally high ore concentrations in the quartz vein support these results. In short, moderate grade and high potential tonnage warrants drilling at Ishmas Kabir.

UMM SHAT GHARB

The Umm Shat Gharb group of ancient mines consists of 24 individual workings along auriferous quartz veins that trend N. 20° W. to N. 35° W. (pl. 2) located in the north-central part of the district. The country rock is a weakly metamorphosed sequence of interbedded lithic wacke and carbonaceous shale cut by several dikes and irregular masses of dacite porphyry, which suggests the proximity of a larger intrusion in the surface. Sericitization extends about 300 cm outward from the veins in volcanogenic sedimentary country rock, and extends at least 500 cm into dacite porphyry dike rocks. Iron-oxide pseudomorphs of pyrite, common throughout these zones, produce a distinctive red-brown halo in the weathered country rock.

In the single mine examined, thought to be typical of the group, the structure that hosts the quartz vein averages 70 cm wide, including a footwall zone of argillized gouge. The highest gold concentrations obtained are 5,200 ppb and 1,100 ppb both over 5-m intervals from trench samples (White and Doebrich, 1987). Average gold concentrations are 1,050 ppb in the main structure and 54 ppb in samples collected from outside it. Gold values compare favorably with those of channel samples (averaging 3,000 ppb) collected by Gonzalez (1974) from the other veins in the Umm Shat Gharb Group. In addition, arsenic is concentrated in the vein and adjacent argillized gouge; molybdenum concentrations as high as 15 ppm occur in the quartz vein.

Gold values in the quartz veins of the main structure, though high, do not show the consistency over sufficient lengths and widths to justify further exploration. The pronounced concentration of gold in the main ore structure, and its general absence in adjacent wall rock, suggest that gold is not likely to be dispersed between veins of the Umm Shat Gharb Group in sufficient quantity for bulk mining.

AL WOZARIYAH SHAMAL AND AL WOZARIYAH

The Al Wozariyah Shamal and Al Wozariyah ancient mines are located in the central part of the district (pl. 2). At Al Wozariyah Shamal, ancient pits and dumps are oriented N. 35-40° W. parallel to an adjacent northwest-trending transitional fault that may have localized both the gold-bearing quartz veins and the dacite porphyry intrusion in which they occur. This transitional fault may be the same feature that locallized the Umm Shat Gharb deposits. The highest gold values in trench samples are 1,900 ppb over a 5-m interval, 150 ppb over a 5-m interval, and 115 ppb over a 10-m interval (White and Doebrich, 1987). Gold is apparently locallized along structures and does not extend into adjacent country rock for any distances that are significant enough to provide large tonnage.

At Al Wozariyah, most quartz veins occur in dacite porphyry on the flanks of a small knoll, but some are located in finely crystalline basalt that caps the knoll. The same northwest-trending transitional fault that borders Al Wozariyah Shamal may have localized the emplacement of the dacite-porphyry intrusion at Al Wozariyah. The highest gold concentrations are 1,300 ppb over a 5-m interval in one trench, 500 ppb over a 5-m interval in another, and 500 ppb over a 10-m interval in a third. The localization of gold along narrow structures does not permit the intervein volumes necessary for large tonnage.

UMM SHAT SHARQ

The Umm Shat Sharq group of ancient mines is a cluster of workings almost exclusively located within a quartz-monzodiorite stock in the north-central part of the district (pl. 2). At this locality, three individual deposits were examined. Mine A, which exposes deposits typical of the interior of the stock, is a series of ancient pits aligned N. 18° E. along strike for a distance of 215 m. The deposit is located within a 1-m-wide fault composed of fault breccia, gouge, and a 55-cm wide quartz vein. The breccia is composed of quartz and red iron-oxide-stained quartz monzodiorite cemented by calcite; a sericite zone of undetermined width occurs in the adjacent monzodiorite. The highest gold concentration obtained from the quartz vein is 10,000 ppb, and the average over the entire structure is 4,726 ppb. The relatively high gold values over a minimum width of one m, and the gentle westward dip, (which makes more of the vein accessible to surface mining) indicates a need for further testing. Drilling vertical holes on the projected westward dip face of the ore structure is recommended.

Mines B and C are located along clusters of older gently dipping, variably oriented quartz veins in the vicinity of a younger steeply dipping, northwest-trending breccia vein near the southwest margin of the quartz monzodiorite stock. The gently dipping (from 13° to 34° W) veins occur in faults (as much as 26 cm wide) that are composed of ferruginous fault breccia and argillized gouge.

The breccia vein, of probable Najd age, contains angular clasts of monzodiorite, reddish-brown cataclasite, and greenish-gray breccia in a matrix of quartz, which forms crustified corona-like rims around clasts. Masses of calcite transect and isolate fragments of the quartz-matrix breccia and in some areas compose 80 percent of the breccia vein. Clasts compose 20 percent.

The concentration of gold in gently dipping structures is as high as 2,800 ppb, but averages 1,046 ppb. Three samples collected from the breccia vein yielded an average of 82 ppb gold. Locallization of ancient workings and the concentration of higher gold values in the area leaves little doubt that the gently dipping structures controlled emplacement of most of the gold, but the limited strike lengths do not provide sufficient mineral resource potential to justify drilling.

AL SUWAYDAH JANUB

The Al Suwaydah Janub ancient mine, located in the central part of the district, consists of five small ancient pits, each of which is oriented differently, but as a group are aligned about N. 40° E. along strike for a distance of about 120 m. Country rock is fine-grained, foliated green metatuff. No potential source intrusions are exposed in the area.

The deposit consists of a 30-cm-wide quartz vein bounded on its footwall by gouge and broken rock, and on both walls by a zone of quartz-sericite-pyrite alteration as wide as 80 cm. The highest gold value obtained from the quartz vein is 650 ppb. The low grade and short strike length of individual gold-bearing fault segments limits their economic potential.

AL SUWAYDAH SHARQ

The Al Suwaydah Sharq ancient mine is in the east-central part of the district southeast of Jabal Al Suwaydah (pl. 2). The country rock is a sequence of interbeded gray-green wacke and light-gray schistose siltstone. The deposit is within a north-trending Nabitah-age fault that contains a 260-cm-wide quartz vein bounded on its footwall by either ferruginous fault breccia or argillized wacke, and on its hanging wall by either ferruginous wacke or mica schist. Gold concentrations as high as 190 ppb are found in the fault breccia. Although the ore body is one of the widest in the Ishmas area, low and erratic gold values indicate that further exploration is not warranted.

Even though the deposit is located within a Nabitah-age fault, the quartz-bearing structure possesses the open fault breccia characteristic of the younger features. Perhaps the Nabitah-age fault was reopened during a later tensional tectonic event. No potential source intrusions are exposed in the area.

DISCUSSION

The mica schist and mylonite of the Nabitah-age structures suggest plastic flow and recrystallization occurred in shear zones, typical of deformation by compressional forces at depth. The fault breccia and argillized fault gouge of the post-Nabitah-age faults indicate deformation by brittle fracturing, typical of tensional features formed in shallower environments. The slicken-sided surfaces of the quartz pods in Nabitah-age faults suggest that gold-quartz precipitation occurred during the late stages of schist formation and is part of the same tectonic event that produced the faults, (that is, the Nabitah orogeny). The dramatic change in tectonic environment through time, however, suggests that the post-Nabitah faults and enclosed deposits are much younger than Nabitah-age structures, and may be more closely related in time to the emplacement of the intrusions with which most are spatially associated.

The fluids tapped by deep-seated structures formed during the Nabitah orogeny may have had their source at deep levels of the crust, whereas the fluids that precipitated quartz and gold in the younger open structures may have had a shallow source. Perhaps the spatially associated intrusions reopened pre-existing faults, preparing them for fluid injection, and provided the heat necessary to mobilize pre-existing formation water, or even the metal-bearing fluids necessary for mineralization.

SUMMARY AND CONCLUSIONS

In this report, the geologic, structural, and metallogenic evolution of the Ishmas district is divided into eight stages. Each stage is characterized by a unique combination of depositional, plutonic, or structural events. In several cases these events are associated with minor base-metal and considerable gold mineralization. A chronologic illustration of evolutionary stages is schematically portrayed in figure 8.

STAGE I

Western terrane

During the initial phases of precratonic evolution of the Ishmas district (about 785 Ma [Smith and Johnson, 1986]), a mafic volcanic and volcaniclastic sequence of tholeiitic affinity, the Suwaydah formation, was deposited in a submarine, (probably fore-arc basin) environment. The sequence was initially derived from a distal volcanic source, although during the later phases of volcanic accumulation, subareal conditions and proximal volcanism prevailed. Deposition of the Suwaydah formation was directly followed by emplacement of the Nabitah mafic complex.

STAGE II

Western terrane

Chemical evolution of volcanism along a calc-alkaline trend resulted in the accumulation of a thick sequence of basaltic to rhyodacitic volcanic and volcaniclastic rocks, the Wozariyah formation. Submarine fumarolic activity resulted in the formation of a basaltic unit containing considerable ferruginous chert and carbonate. The chert and carbonate locally are true gossans derived from submarine exhalative accumulations of base-metal sulfides, and represent the only precratonic mineralization in the district. The deposition of a thick sequence of fine- to medium-grained sandstone and wacke with interbedded carbonate (now marble) represents the final volcanosedimentary phase in the district and probably corresponds to near-shore sedimentation during a regressive cycle.

A large lopolithic layered-gabbro complex, the Ishmas gabbro, was emplaced into the volcanosedimentary sequence. Within the complex, pods of peridotite and pyroxenite formed locally. In the southwestern part of the district, skarn developed in response to intrusion of the gabbro.

Eastern terrane

Although the timing of the precratonic evolution of the eastern terrane is somewhat uncertain, it is believed to have evolved contemporaneously with the western terrane, between 785 and 746 Ma (Smith and Johnson, 1986). In the Ishmas district, the layered rocks of the eastern terrane comprise a volcanic and volcaniclastic sequence similar to that of the western terrane. Although the rocks of the eastern and western terranes are allochtonous, they appear to have formed contemporaneously in a similar geologic environment.

A large monzogranite pluton intruded the eastern terrane in the southeastern corner of the district and produced an extensive contact aureole. Amphibolite-facies metamorphism formed the amphibolite unit adjacent to the intrusion.

STAGE III

Following the precratonic evolution of both terranes, isoclinal folding about N. 25°-30° W.-trending, steeply dipping axes occurred in response to the imminent collision of the eastern and western terranes. This folding event is responsible for the near-vertical dip of all layered rocks in the district and may be considered to be the initial phase of the Nabitah orogeny.

As convergence and folding progressed, fold hinges failed, producing major north-trending, steeply dipping faults in the western and central parts of the district. The Ishmas East and West faults (pls. 1,2) are believed to represent failed anticlinal and synclinal hinges, respectively (fig. 8).

STAGE IV

The ultimate collision of terranes produced a series of tight, north-trending folds whose hinges failed, resulting in the formation of the Nabitah Fault Zone (pl. 2), believed to have been active between 684 and 640 Ma (Smith and Johnson, 1986). The difference in structural orientation between the Nabitah Fault Zone (or suture) and the Ishmas faults is thought to be a consequence of oblique convergence of nonparallel terrane margins upon collision (fig. 7).

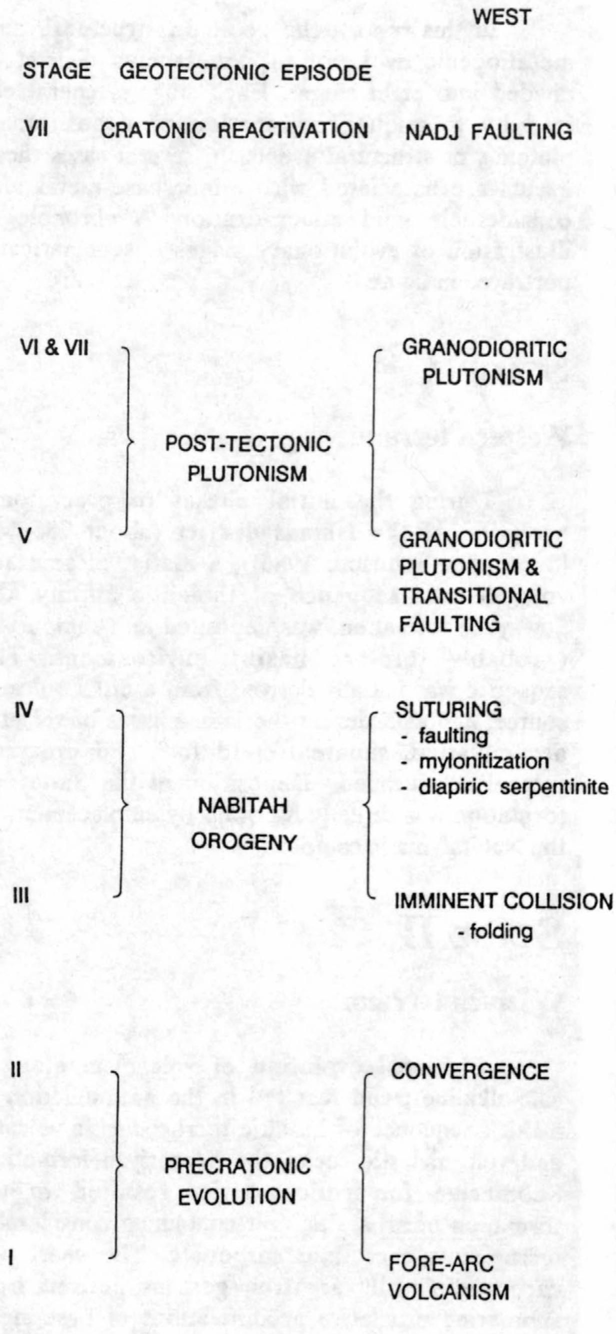
As suturing progressed, plastic deformation resulted in the formation of extensive belts of mylonite along the major Nabitah structures. Deformation was penetrative throughout the district, resulting in steeply dipping, north-trending cleavage in areas distal to major faults and shear zones. However, the most extensive deformation is clearly proximal to the suture line (that is, within the Nabitah Fault Zone) and along the margin of the eastern terrane.

Following shearing and mylonitization, serpentinite diapirs intruded along the Ishmas East fault and throughout the Nabitah Fault Zone. The presence of the serpentinite indicates that the structures are deep seated.

Auriferous quartz-vein mineralization constituted the final phase of the Nabitah orogeny. Pod-shaped quartz veins occupied dilatant structures in carbonate-altered and sericitized schist and mylonite associated with north-trending Nabitah structures and subsidiary faults. The highest concentrations of gold are commonly found in altered rock adjacent to the quartz veins, typified by the Ishmas, Al Suwaydah, and Nabitah ancient mines (pl. 2). Their occurrence along deep-seated structures and the absence of genetically related intrusions suggest that the ore-bearing fluids were derived from a deep source and consequently classifies them as part of the Nabitah orogeny.

STAGE V

Subsequent to the emplacement of quartz diorite in the southwestern part of the district, a large tonalite stock was emplaced in the central and north-central parts of the district. This plutonic event was the first of three that affected the central part of the district.



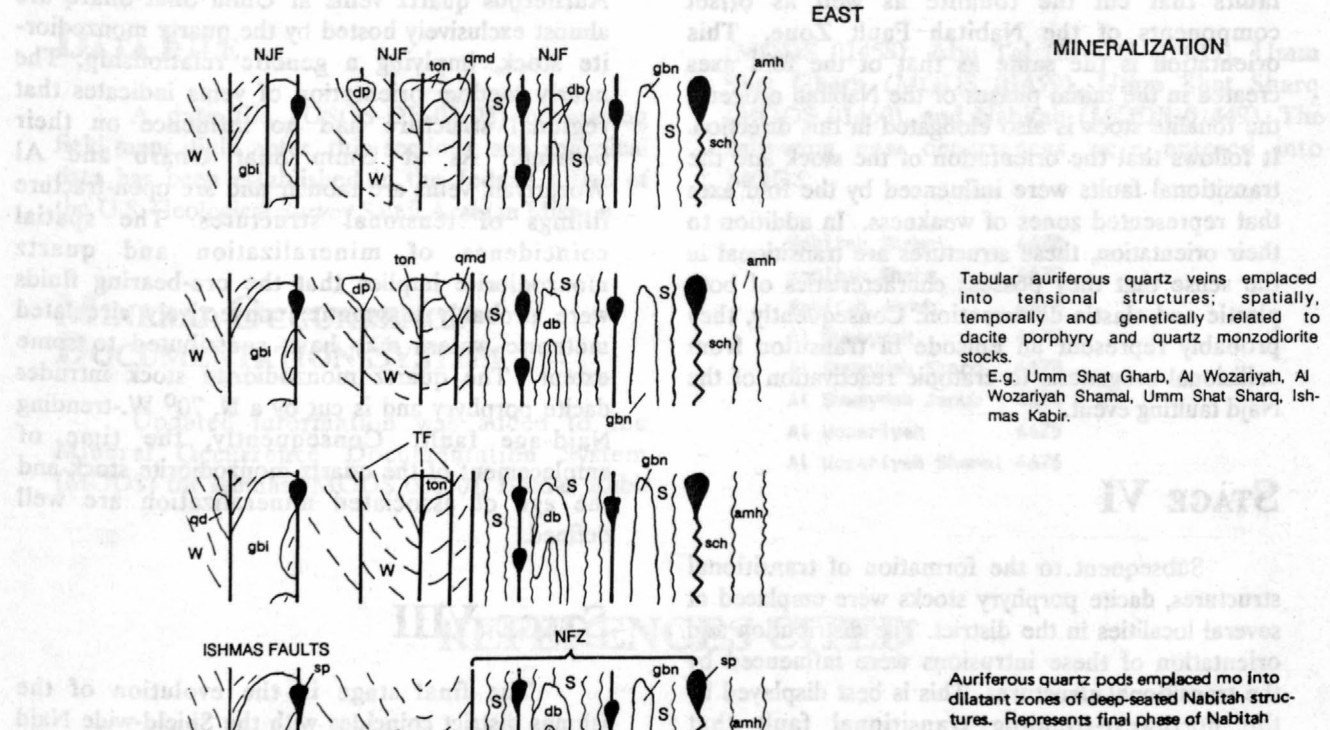


Figure 8–A chronologic series of schematic east-west cross-sections through the Ishmas district showing geologic and structural evolution. Stages correspond to those described in Summary and Conclusions section. Labels are the same as used on Plates 1 and 2; NFZ-Nabitah Fault Zone, TF-transitional fault, NJF-Najd fault.

Soon after the emplacement of the tonalite stock, an intermediate-age structural event created a series of N. 25°-35° W.-trending, steeply dipping faults that cut the tonalite as well as offset components of the Nabitah Fault Zone. This orientation is the same as that of the fold axes created in the initial phases of the Nabitah orogeny; the tonalite stock is also elongated in this direction. It follows that the orientation of the stock and the transitional faults were influenced by the fold axes that represented zones of weakness. In addition to their orientation, these structures are transitional in the sense that they possess characteristics of both plastic and elastic deformation. Consequently, they probably represent an episode of transition from collisional orogenesis to cratonic reactivation of the Najd faulting event.

Stage VI

Subsequent to the formation of transitional structures, dacite porphyry stocks were emplaced at several localities in the district. The distribution and orientation of these intrusions were influenced by the transitional structures. This is best displayed by the northwest-trending transitional fault that transects the center of the district and passes through the Al Wozariyah and Umm Shat Gharb ancient mines.

In the Umm Shat Gharb and Al Wozariyah areas (pl. 2), gold mineralization in the quartz veins is genetically related to the emplacement of the dacite-porphyry intrusions. Variability in crystallinity of the intrusion and intermittent exposure as cupolas suggest that mineralization occurred in the roof zone of the intrusion and in contiguous country rock. Veins are tabular open-fracture fillings and contrast with the pod-shaped Nabitah-age occurrences. In the Umm Shat Gharb area, auriferous veins are parallel to the transitional fault and are believed to have been influenced by it. The genetic association between dacite porphyry and mineralization suggests that ore-bearing fluids were either magmatic or convectively circulated meteoric waters or both. Mineralization at Umm Shat Gharb was coeval with mineralization at Al Wozariyah.

Stage VII

The emplacement of a quartz monzodiorite stock in the Umm Shat Sharq area was the third and final granodioritic plutonic event to affect the central and north-central parts of the district. Auriferous quartz veins at Umm Shat Sharq are almost exclusively hosted by the quartz monzodiorite stock, implying a genetic relationship. The nearly random orientation of veins indicates that regional structure had no influence on their bearing. As at Umm Shat Gharb and Al Wozariyah, veins are tabular and are open-fracture fillings of tensional structures. The spatial coincidence of mineralization and quartz monzodiorite implies that the ore-bearing fluids were probably magmatic; convectively circulated meteoric waters may have contributed to some extent. The quartz monzodiorite stock intrudes dacite porphyry and is cut by a N. 70° W.-trending Najd-age fault. Consequently, the time of emplacement of the quartz-monzodiorite stock and the age of associated mineralization are well defined.

Stage VIII

The final stage in the evolution of the Ishmas district coincides with the Shield-wide Najd faulting event, which occurred between 630 and 540 Ma (Smith and others, 1984). The district lies at the extreme southern end of the Najd fault system. A series of N. 60°-80° W.-trending Najd faults offset both transitional and Nabitah structures. Small gabbro plugs emplaced locally along these Najd structures represent the final plutonic event in the district.

DATA STORAGE

DATA FILE

A data file (USGS-DF-07-05) containing field maps, field notes, thin sections, and analytical data has been established in the Jeddah office of the U.S. Geological Survey Saudi Arabian Mission.

MINERAL OCCURRENCE DOCUMENTATION SYSTEM

Updated information was added to the Mineral Occurrence Documentation System (MODS) for Ishmas (MODS 00650), Ishmas Kabir (MODS 01458), Abu Tal (MODS 01433), Umm Shat Gharb (MODS 01459), Umm Shat Sharq (MODS 01460), and Nabitah (MODS 01449). The following new occurrences were entered into MODS:

Nabitah Shamal	4678
Nabitah Sharq	4679
Nabitah Janub	4677
Al Suwaydah	4672
Al Suwaydah Sharq	4673
Al Suwaydah Janub	4674
Al Wozariyah	4675
Al Wozariyah Shamal	4676

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APPENDIX 1.--Chemical data for ferruginous chert and carbonate units in the Ishmas district. For sample localities see Data-File USGS-DF-07-05.

Entry	1	2	3	4	5	6	7	8
Sample	226673	226674	226675	226679	226680	226681	226682	226683
PPM								
AG	0	0	0	0	0	0	0	0
CU	10	30	14	10	45	95	7	26
PB	7	5	4	1	3	14	3	6
ZN	4	4	24	5	20	31	22	20
CR	150	150	2000	150	2000	5000	1000	1000
NI	10	15	300	15	700	1000	300	700
PBB								
AU	0	16	0	0	0	52	0	39

Entry	9	10	11	12	13	14	15	16
Sample	226684	226685	226686	226687	226688	226689	226690	226691A
PPM								
AG	0	0	0	0	0	0	0	0
CU	25	10	60	15	15	3	50	10
PB	1	2	1	1	2	1	2	4
ZN	5	27	130	8	13	92	62	15
CR	500	2000	100	200	500	100	150	200
NI	20	700	20	20	50	30	100	50
PPB								
AU	0	0	36	0	25	0	46	8

Entry	17	18	19	20	21	22	23	24
Sample	226691B	226692	226693	226694	226695	226697	226699	226700
PPM								
AG	0	0	0	0	0	0	0	0
CU	11	14	30	22	10	55	16	10
PB	3	2	5	3	4	13	2	2
ZN	60	16	60	23	6	85	33	4
CR	2000	1000	1000	2000	300	2000	1000	200
NI	700	700	500	500	30	300	500	10
PPB								
AU	0	8	0	0	7	4	0	5

APPENDIX 1.--Chemical data for ferruginous chert and carbonate units in the Ishmas district--continued.

Entry	25	26	27	28	29	30	31	32
Sample	226701	226702	226703	226704	226705	226706	226707	226708
PPM								
AG	0	0	0	0	0	0	0	0
CU	20	15	72	7	10	46	4	1560
PB	6	6	4	2	1	5	1	1
ZN	100	17	15	16	2	6	4	20
CR	2000	200	500	150	100	100	200	200
NI	700	20	20	100	10	20	10	10
PPB								
AU	0	11	101	14	0	62	0	10

Entry	33	34	35	36	37
Sample	226709	226710	226711	226712	226076
PPM					
AG	0	0	0	0	20
CU	9	5	6	6	10000
PB	0	10	2	1	70
ZN	5	12	8	4	2000
CR	200	200	200	300	50
NI	10	10	10	10	20
PPB					
AU	112	160	88	45	510