DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Geology and hydrothermal alteration at the Mahd adh Dhahab epithermal precious-metal deposit, Kingdom of Saudi Arabia

by

J. L. Doebrich[1] and J. P. LeAnderson[2]

Open-File Report 84-640

Prepared for Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources, Jiddah, Kingdom of Saudi Arabia

1/ U.S. Geological Survey
Denver, CO 80225

2/ Colorado School of Mines
Golden, CO 80401

1984

CONTENTS

ILLUSTRATIONS
[Plates are in pocket]

TABLES

GEOLOGY AND HYDROTHERMAL ALTERATION AT THE MAHD ADH DHAHAB EPITHERMAL PRECIOUS METAL DEPOSIT, KINGDOM OF SAUDI ARABIA

by

J. L. Doebrich[1/] and P. J. LeAnderson[2/]

ABSTRACT

Mahd adh Dhahab is a late Precambrian epithermal gold-silver-base metal deposit located in the west-central part of the Arabian Shield. North-trending quartz veins containing base and precious metals cut an east-striking, north-dipping homoclinal sequence of volcanic, volcaniclastic, and epiclastic rocks of intermediate to felsic composition. Ore was localized where the veins cut competent, coarse-grained, fragmental units directly below incompetent and impermeable tuff units. The proximity of an epizonal rhyolite porphyry stock to these contacts also was important in localizing ore. Ore minerals include native gold and silver, gold-silver tellurides, chalcopyrite, sphalerite, and minor galena, and five stages of mineralization have been identified.

Vein-related alteration consisting of quartz-sericite-pyrite, chloritic, argillic, and silicic halos was superimposed on broad zones of pervasive silicic, potassic, and argillic alteration that surrounds the rhyolite intrusive body. Quartz-sericite-pyrite alteration associated with the earliest stage of mineralization was followed by broad, pervasive, stratigraphically controlled potassic alteration. Subsequent mineralization was accompanied by quartz-sericite-pyrite alteration and was followed by the main stage of mineralization that formed strong chloritic alteration halos. Development of broad zones and halos of argillic alteration also may have been related to the main stage of mineralization. Development of silicic halos was characteristic of the late stages of mineralization. Broad, pervasive propylitic alteration was then superimposed on all alteration types and represents cooling and inward encroachment of the hydrothermal system. All alteration, except the early silicic alteration is interpreted to have been related to circulating meteoric fluids heated by the rhyolite.

1/ U.S. Geological Survey, Denver, Colorado 80225
2/ Colorado School of Mines, Golden, Colorado 80401

INTRODUCTION

Mahd adh Dhahab ("Cradle of Gold") is a late Precambrian, gold, silver, and base-metal hydrothermal vein deposit (MODS 00003) located in the west-central part of the Arabian Shield approximately 275 km northeast of Jiddah (fig. 1. pl. 1). The deposit is in Jabal Mahd ahd Dhahab, which covers an area of 2.2 km^2 between lat 23°30'20" and 23°9'40" N., long 40°52'00" and 40°51'00" E. The summit of the jabal is the highest point in the district, being 1,238 m high or 200 m above the surrounding wadis.

Mahd adh Dhahab has been both the largest and most productive mine in Saudi Arabia in either ancient or modern times. Ancient mining of the deposit is indicated by numerous narrow workings that extend to depths of 85 m along major veins and by several tons of slag. Abundant quartz veins on the jabal, which can be easily seen from a distance, and the presence of copper oxide and carbonate minerals on cobbles in alluvial float were probably known from very early times and quite possibly encouraged early mining. The presence of older tailings below more recent ones indicates two distinct periods of ancient mining activity (Twitchell, 1958). Kufic inscriptions from the period 750 to 1100 C.E. were found on objects found within the younger of the two tailings piles. This period corresponds to the time when the Islamic Empire reached its peak under the Abbasid Caliphate. Carbon-14 age determinations on charcoal in the slag also yielded dates in this period (Worl, 1978).

The older tailings are of unknown age but may be as old as 1000 B.C. Such an age is reasonable because Mahd adh Dhahab is only 1 km from the ancient north-south caravan trade route (fig. 1) which was used for the transport of frankincense and myrrh from Yemen to Palestine and other regions during the first millenium B.C.

Although total production during ancient times is unknown, it is estimated to be between 800,000 and 1,000,000 ounces of gold and minor copper. There is no evidence of mining activity between about 1100 B.C. and the twentieth century.

Modern geologic investigations at Mahd adh Dhahab began in 1935 when K. S. Twitchell, an American mining engineer, was hired by King Abdulaziz ibn Saud to assess the Kingdom's mineral resource potential and to organize the Saudi Arabian

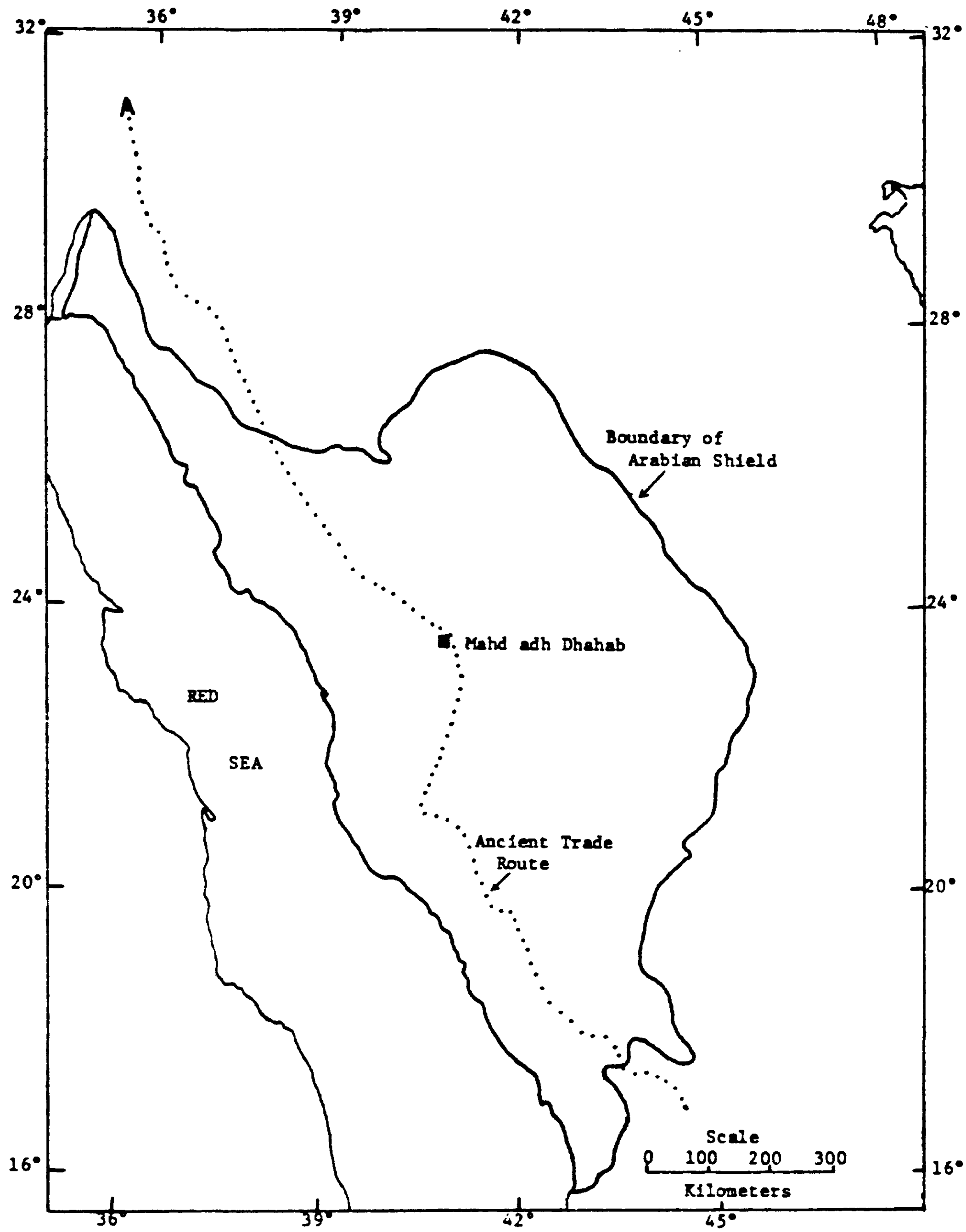

Figure 1. Index map showing the location of the Mahd adh Dhahab district.

Mining Syndicate (SAMS). His evaluation in 1936 of Mahd adh Dhahab as an economic gold-silver deposit led the King to grant SAMS a concession for development, and the first ore was produced in 1939 (Twitchell, 1958).

Between 1939 and 1954, 765,768 fine ounces of gold and 1,002,029 ounces of silver were produced from what is now known as the SAMS or Northern Ore Zone (Worl, 1979). Ancient tailings and low-grade ore dumps lying on the surface between the old stopes and high-grade ore from a quarry and four underground levels excavated to a depth of 200 m were milled on site (Twitchell, 1958). Mining ceased in 1954 because of stable gold prices and increased mining costs.

During the 1960's and early 1970's, several investigators conducted further studies at Mahd adh Dhahab that were primarily regional in nature (Theobald, 1965; Lefevre, 1969; Aguttes and Duhamel, 1971; Goldsmith and Kouther, 1971). In 1972, the U.S. Geological Survey began a program of detailed mapping and geochemical sampling because of increases in gold and silver prices (Luce and others, 1975, 1979; Roberts and others, 1978; Worl, 1977, 1979). These studies show that the area of mineralized rocks at Mahd adh Dhahab extends well beyond the SAMS workings and led to the discovery of a second zone of mineralized rocks 700 m south of the Northern Ore Zone that was named the Southern Ore Zone. Diamond drilling of this zone began in 1973, and wide veins were intercepted that averaged as much gold as 60 grams per metric ton (Worl, 1978).

In 1975, Consolidated Gold Fields Limited, London, England, was granted an exploration license for a large area including Mahd adh Dhahab. To date, Gold Fields Mahd adh Dhahab (GFMAD) has completed an exploratory decline in the Southern Ore Zone that consists of 1,100 m of adits and cross cuts and extensive surface and underground exploratory diamond drilling (fig. 2). Reserves in the Southern Ore Zone are estimated at 1.1 million metric tons of approximately 1 ounce of gold per metric ton (Worl, 1979; Malcolm Hooper, GFMAD, oral commun., 1982).

In January 1981, the U.S. Geological Survey (USGS) began a multidisciplinary study of the Mahd adh Dhahab deposit. This work was performed in accordance with an agreement between the USGS and the Saudi Arabian Ministry of Petroleum and Mineral Resources. The general goals of this study are to understand the genesis of the deposit and its regional setting and to develop exploration concepts that will be useful elsewhere in Arabia. One of the specific objectives of the study is to evaluate the alteration assemblages that formed in association with mineralization in an attempt to

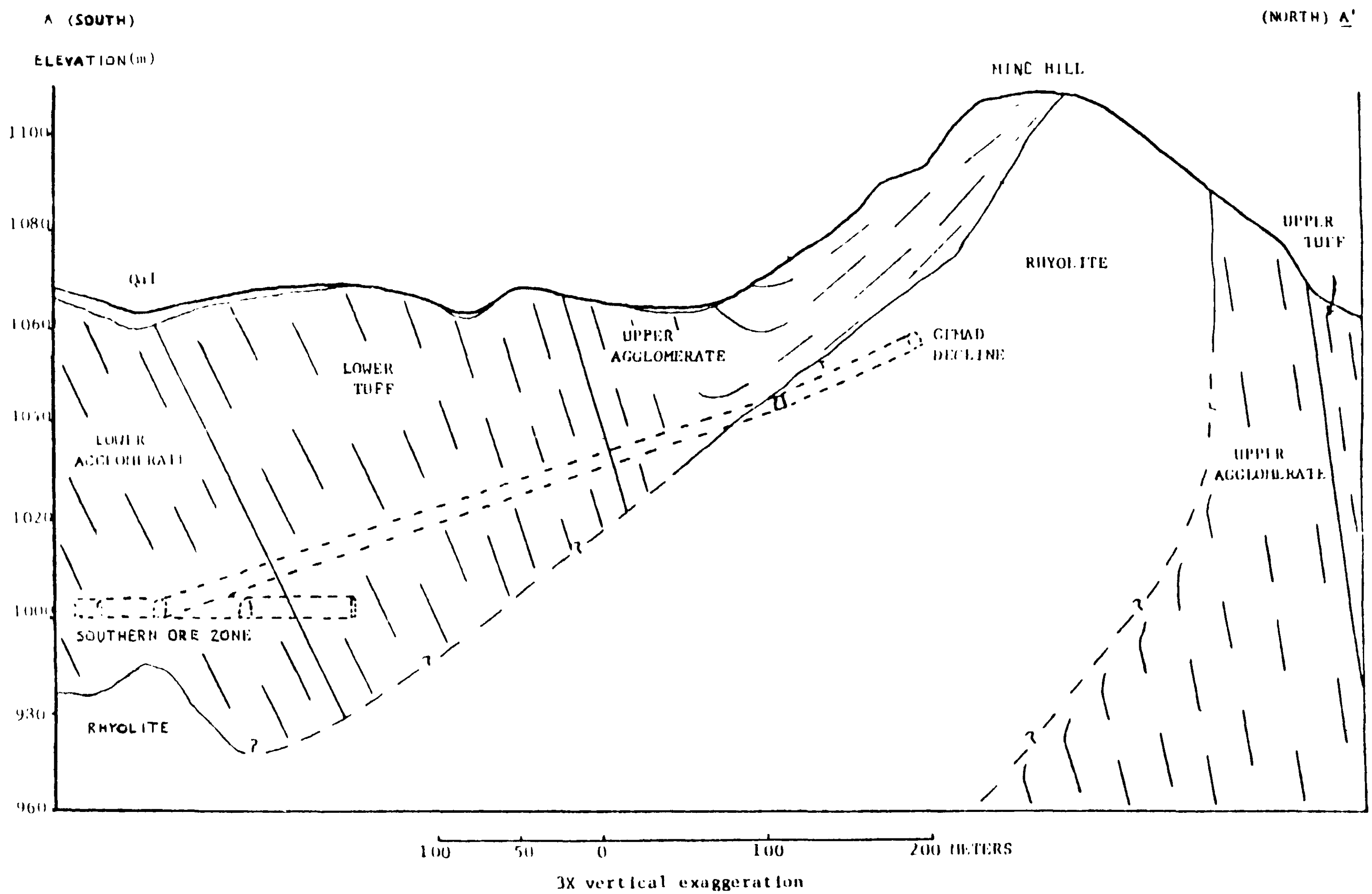

Figure 2. North-south cross section (A-A') through Mine Hill and the Southern Ore Zone in the east part of the map area. GFMAD underground workings are projected into plane of section. (See Pl. 1)

define the hydrothermal fluid flow path and to determine the changes in fluid composition and temperature in time and space. Other objectives include studies of ore mineralogy, fluid inclusions, and stable and lead isotopes (Rye and others, 1982), rock geochemistry (R. G. Worl and others, USGS, written commun., 1982), subregional geology (A. M. Afifi, USGS, written commun., 1982), and biogeochemical techniques (Ebens and others, 1983).

Mapping at a scale of 1:1,000 was conducted during the summer of 1981 and winter of 1982. The geology, structure, and distribution of quartz veins were mapped first; then the alteration assemblages were mapped and the GFMAD diamond drill cores were logged.

GENERAL GEOLOGY

Jabal Mahd adh Dhahab consists of a late Precambrian, 1-m-thick lensoid sequence of intermediate to felsic volcanic, volcaniclastic, and epiclastic rocks (pl. 1). This sequence was dated by Calvez and Kemp (1982) as being between 816 ± 3 and 748 ± 22 Ma old. The sequence forms a homoclinal belt that strikes from due west to N. 55° W. and dips 30° to 35° N. in the south and 75° to 80° N. in the north. The stratigraphic sequence (from oldest to youngest or from south to north) was originally defined by Luce and others (1975) as andesite, lower agglomerate, lower tuff, upper agglomerate, and upper tuff. Overlying these units is a sequence of fine-grained, thin-bedded clastic sedimentary rocks that was not mapped as part of the present study. The formation names assigned by Luce will be used in this report for the sake of consistency, although in the present report the rock names used are based on the classifications of Williams, Turner, and Gilbert (1954) and Moorhouse (1959). The following descriptions are based entirely on results of this study.

Rock types

Andesite

Andesite crops out south of the jabal along the entire southern margin of the map area. On the west side of the jabal it trends N. 50° to 55° W. and dips 40° to 50° NE.; on the east side it trends N. 15° to 20° W. and dips 70° to 88° NE. An angular unconformity was observed between the andesite and the overlying lower agglomerate, and the angle between the bedding in the andesite and that in the lower agglomerate is 10° on the west side of the jabal and 40° on the east side (pl. 1).

Along the contact between the lower agglomerate and the andesite, a reddish-brown oxidation zone as wide as 3 m is confined within the andesite unit. The zone is interpreted to represent submarine oxidation that may predate both folding of the andesite and deposition of the lower agglomerate. This zone is present throughout the map area, except in the southeast where the andesite is in faulted contact with the lower agglomerate; this fault has been locally mineralized by quartz veins and intruded by andesite dikes (pl. 1).

The andesite unit consists of andesite flow rocks, crystal tuffs, and crystal-lithic lapilli tuffs, all of which are intruded by andesite sills. Generally, only the fragmental units are bedded.

The andesite flow rocks contain phenocrysts of plagioclase ranging in composition from $An5$ to $An15$, some of which are zoned, and microcline phenocrysts as long as 2 mm; the phenocrysts are in an aphanitic, albite-microlite groundmass that commonly exhibits a well-developed pilotaxitic texture. No mafic phenocrysts were observed, but they may have been present initially and later altered beyond recognition. Flow tops are indicated by vesicular and brecciated horizons.

The volcaniclastic rocks contain crystal and lithic fragments of quartz, albite, microcline, and andesite as much as 1 cm in diameter in a tuffaceous matrix. Graded bedding is locally present in areas where coarse-grained fragmental constituents comprise a large proportion of the rock.

Lower agglomerate

The lower agglomerate unit is approximately 150 m thick; it lies unconformably above the andesite unit, strikes due west to N. 65° W., dips 35° to 45° N., and thins slightly to the west (pl. 1). In general, the rocks of this unit are dark greenish gray and weather red brown or tan. The rocks were very competent, and, prior to mineralization open fractures developed that were later filled with quartz-vein material. The lower agglomerate hosts the Southern Ore Zone, which underlies the southeastern part of the map area.

In the southeastern and south-central parts of the map area, the lower agglomerate is composed of a massive to poorly bedded, poorly sorted, immature, volcanic conglomerate. Crystal fragments of quartz, albite, and orthoclase, and lithic fragments of andesite, rhyolite, and locally tuff and chert are in a siliceous tuffaceous matrix. Lithic fragments may be as large as tens of centimeters in diameter, although they are usually less than 5 cm in diameter. Crystal fragments are rarely larger than 2 mm in diameter. Crystal and lithic fragments range from angular to subrounded, and, although lithic fragments are commonly more rounded, larger blocks may be very angular.

In the upper part of the lower agglomerate unit and along strike to the west, bedding is better developed, the amount of felsic fragments increases, the fragments become smaller, and the relative proportion of crystal to lithic components increases. Along strike to the west, the massive conglomeratic facies grades into a well-bedded sequence of intercalated microcline crystal tuffs and crystal-lithic lapilli tuffs containing fragments of chert, tuff, rhyolite, microcline, quartz, and relatively little andesite. This facies is well displayed in outcrops of the lower agglomerate in the southwestern corner of the map area (pl. 1). In the western part of the map area, a lens of white, calcareous chert interbedded with the crystal and lithic tuffs may indicate a moderately shallow marine environment of deposition.

Quartz veins in the lower agglomerate indicate that during deformation the lower agglomerate was more competent than overlying and underlying units (pl.2). However, an increase in vein density from west to east along the strike of the unit is thought to represent an increase in fracture density in the same direction and probably indicates that the unit was more competent in the eastern part of the map area, where it is more massive and coarse grained. The increase in vein density may indicate locally higher stress regimes and as such reflect proximity to a source of stress, which in this case could be the rhyolite intrusive body (figs. 2, 3).

Lower tuff

The lower tuff unit is a 210-m-thick sequence composed mostly of thinly laminated, siliceous tuffs and interbedded crystal-lithic lapilli tuffs, siltstones, sandstones and graywackes. Rocks of the unit are generally gray, green or brown and form cliffs that include the summit of Jabal Mahd ahd Dhahab and most of the higher ridges in the area. The contact between the lower tuff and the underlying lower agglomerate is conformable and gradational, except at its eastern end where the two units are in fault contact. This fault was observed only in the GFMAD decline because the surface trace of the fault is covered by Quaternary alluvium.

The base of the lower tuff unit is defined by a 10- to 15-m-thick, interbedded sequence of finely laminated tuffs and crystal-lithic lapilli tuffs. This sequence forms a transition between the massive to poorly bedded lapilli tuffs of the underlying lower agglomerate unit and the thinly bedded to thinly laminated tuffs of the lower tuff unit, which

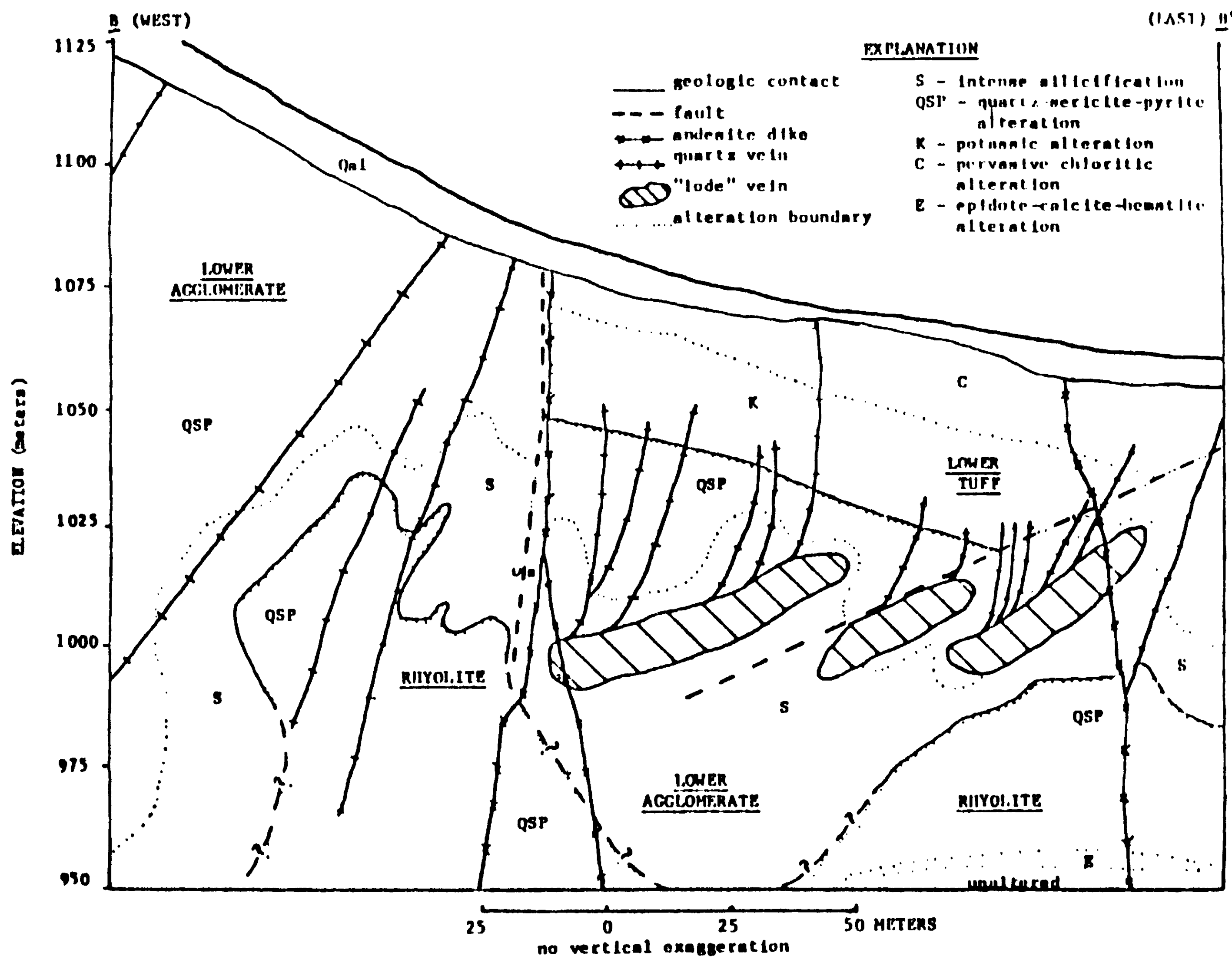

Figure 3. East-west cross section (B-B') through the Southern Ore Zone in the SE part of the map area. (See Pl. 1)

contains fewer lapilli tuffs. This transition sequence and the overlying laminated tuffs together comprise about one-fourth of the lower tuff unit.

The laminated tuffs are microcrystalline and highly siliceous and contain devitrified shards. Crystal-lithic lapilli tuffs interbedded with the laminated tuffs contain fragments of quartz, microcline, andesite, dacite, rhyolite, tuff, and unidentifiable, intensely chloritized lithic fragments in a siliceous, microcrystalline matrix. Lithic fragments may be as much as 15 mm in diameter, whereas crystal fragments are usually 1 to 2 mm in diameter.

Above the lower laminated and lapilli tuff sequence, the lower tuff unit consists of a middle section of well-bedded siltstones and sandstones with minor tuff layers and an upper section of interbedded tuffs, siltstones, graywackes, and lapilli tuffs. Epiclastic horizons are generally quartzofeldspathic and poorly sorted; the varying degrees of rounding of the grains indicates that these sediments are immature. The tuff beds are lithologically similar to those in the lower section of the lower tuff.

The lower tuff unit was less competent than the conglomeratic units, as indicated by fewer fractures and wide veins than in the lower and upper agglomerates (pl. 2). Intense veining in the unit is seen in only two areas. The first area is on the east side of the jabal and consists of a north-trending zone of abundant veins that transect all stratigraphic units; this zone of veins is related to the Northern and Southern Ore Zones. The second is in the southwestern part of the jabal and is a zone of stockwork veins. These two zones may reflect local stress regimes and proximity to a stress source, perhaps the rhyolite intrusive body.

Upper agglomerate

The upper agglomerate unit is approximately 140 m thick, forms an east-west ridge in the northern part of the map area, and lies conformably on the lower tuff (pl. 1). It has been subdivided into a tuff member overlain by a conglomerate member, similar to the subdivisions made by Worl (1979) and Hilpert and others (in press).

The tuff member consists of a basal horizon, 30 to 40 m thick, of massive, mafic agglomerate overlain by a moderately well-bedded sequence, 50 to 60 m thick, of intercalated crystal and crystal-lithic tuffs and lapilli tuffs. In the basal agglomerate spherical and elliptical fragments as large as 8 cm in diameter are in a light-gray, siliceous, microcrystalline matrix. The fragments have been completely altered to chlorite, and their original composition is unknown. The overlying crystal and crystal-lithic tuffs and lapilli tuffs are very similar to the well-bedded parts of the lower agglomerate. They consist of quartz, microcline, and albite crystals and chert, rhyolite, and laminated tuff fragments. Fragments average about 1 mm in diameter but may be as large as 6 mm in diameter.

The conglomerate member of the upper agglomerate unit is a siliceous, massive, immature conglomerate similar to the massive parts of the lower agglomerate unit. Crystal fragments range from less than 1 mm to as much as 2 mm in diameter; most lithic fragments are from 2 mm to 10 cm in diameter and angular to subangular, although well-rounded boulders as large as 25 cm in diameter are present. Crystal fragments are quartz and microcline with minor albite. Lithic constituents include laminated tuff, massive chert and jasper, porphyritic rhyolite, lapilli tuff, and chert-pebble conglomerate.

The upper agglomerate was generally a competent unit, as indicated by the abundance of fractures and quartz veins (pl. 2). Because lateral facies changes such as those in the lower agglomerate are absent in the upper agglomerate, the upper agglomerate had a more uniform competency and therefore has a more uniform vein density along strike than does the lower agglomerate.

Upper tuff

The upper tuff unit consists of well bedded, thinly laminated, extremely variable and laterally discontinuous tuffs, lapilli tuffs, cherts, jaspers, and pebble conglomerates (pl. 1).

In the northeastern corner of the map area (pl. 1), the upper tuff overlies a fault that has brought the tuff and conglomerate members of the upper agglomerate side by side (Hilpert and others, in press). This relationship indicates that the faulting was pre-upper tuff in age and that the upper agglomerate-upper tuff contact is an unconformity. In the north-central part of the map area the upper tuff overlies the conglomerate member of the upper agglomerate, whereas in the northwestern part the upper tuff overlies the tuff member of the upper agglomerate.

In the northeastern part of the area, thinly bedded argillitized tuffs intercalated with lenses of calcareous chert are present at the base of the upper tuff. Much of the upper tuff is concealed beneath wadi alluvium.

In the north-central part of the map area, well-indurated, thinly bedded to thinly laminated siliceous tuffs or possibly cherts are at the base of the upper tuff. Up-section they are interbedded with crystal-lithic lapilli tuffs containing crystals of quartz and microcline and fragments of tuff and rhyolite in a tuffaceous, siliceous matrix.

In the northwestern part of the map area, the basal part of the upper tuff consists of massive chert as thick as 5 m that grades upward into thinly bedded to laminated chert with local chert-pebble conglomerates. Between the north-central and northwestern exposures of the upper tuff and just outside the map area, a jasperoid bed and overlying thinly bedded siltstone are in contact with the upper agglomerate. The jasperoid probably represents a submarine exhalative horizon.

The upper tuff unit was incompetent, and quartz veins in the upper agglomerate commonly terminate against the upper tuff contact. Locally, however, quartz veins cut the upper agglomerate-upper tuff contact, particularly in the north-central part of the area. Nevertheless, they tend to become thinner and occasionally terminate upward within the upper tuff.

Rhyolite porphyry

An intrusive rhyolite porphyry crops out in the SAMS mine area; it trends north and plunges 25° S. (pl. 1). It is reddish on weathered surfaces because of oxidation of disseminated pyrite. The northern and eastern flanks of the intrusive body dip steeply, as shown by underground SAMS data compiled by Hilpert and others (in press). These steep flanks meet at a northeastern corner that plunges 60° SW. under the stock. The steep plunge was also observed underground below the SAMS main shaft, where the intrusive body is 300 m thick. In the SAMS mine area the upper agglomerate forms the wall rock and is domed by the intrusive body (fig. 2). The upper surface of the rhyolite is also exposed in the first few meters of the GFMAD decline (fig. 2) and dips 15° S.

A petrographically identical rhyolite porphyry was intersected in GFMAD drill core below the Southern Ore Zone. This rhyolite is probably the southern extension of the rhyolite in the SAMS mine area and may underlie the entire eastern side of the jabal (pl. 1). Under the Southern Ore Zone, the rhyolite forms two cupolas (fig. 3) in the lower agglomerate. The western contacts dip 40° to 45° W.

The rhyolite contains microcline, quartz and albite phenocrysts as long as 5 mm in a microcrystalline groundmass comprised of quartz, orthoclase, and albite. The microcline and albite phenocrysts are commonly subhedral to euhedral, whereas the quartz phenocrysts are generally subhedral to anhedral. Locally, well-developed flow layering is defined by oriented feldspar microlites in the groundmass. Euhedral, secondary pyrite as much as 3 mm in diameter is commonly present.

Two rhyolite samples from the SAMS mine area averaged 72.7 percent SiO_2 and 7.7 percent K_2O (table 1); the high potash content possibly resulted from the introduction of potassium during alteration (Hilpert and others, in press) in the form of sericite.

Three types of breccias are spatially and genetically related to the rhyolite; intrusive breccia dikes, wall-rock breccias, and cap breccias; all have an igneous matrix. The intrusive and cap breccias are best exposed in drill core from the Southern Ore Zone, but they locally crop out in the SAMS mine area. In the Southern Ore Zone, the porphyry is cut by a series of north-trending, subvertical, monolithic, rhyolite breccia dikes. In the SAMS mine area, small pebble dikes of rounded and angular rhyolite fragments as much as 2 cm in diameter cut the wall rocks surrounding the intrusive body but apparently do not cut the intrusive body itself. These dikes may represent fluid escape structures related to emplacement of the rhyolite porphyry stocks.

Marginal wall-rock breccia is exposed in the GFMAD decline. Hilpert and others (in press) suggested that the brecciation resulted from expansion of water in the pore spaces, fractures, and faults; however, it may have resulted from shear forces at the margin of the rhyolite stock related to its emplacement.

The top of the rhyolite is capped by several meters of monolithic rhyolite breccia along its upper contact with the lower agglomerate in the Southern Ore Zone. This brecciated zone may extend to the surface where a similar breccia is exposed (pl. 1). In the SAMS mine area, the rhyolite contains a breccia zone (pl. 1) identical to the one to the south. These cap breccias may represent either devolatilization of the magma or brecciation of the top of the intrusion by upward movement of magma from below.

The rhyolite porphyries are spatially related to zones of mineralization. In both ore zones, the high-grade "lode" orebodies are large, low-angle, west-dipping structures above and parallel to the 40°- to 45°-west-dipping flanks of the rhyolite.

Table 1.--Analyses of rhyolite porphyry from the SAMS mine area, Mahd adh Dhahab

[Analyses by X-ray fluorescence; adapted from Hilpert and others (in press)]

Laboratory number Field number	M-144290 111009	M-144287 111033
SiO_2	72.50	72.83
Al_2O_3	11.58	11.87
Fe_2O_3	0.63	0.77
FeO	2.17	1.74
MgO	1.66	2.02
CaO	.03	.00
Na_2O	1.29	1.25
K_2O	7.46	7.95
H_2O+	1.29	1.48
H_2O-	.24	.13
TiO_2	.17	.17
P_2O_5	.03	.04
MnO	.09	.09
CO_2	.34	.05
Total	99.51	100.01
	Normative minerals (H_2O free)	
Quartz	33.13	31.41
Corundum	1.41	1.22
Orthoclase	45.01	47.56
Albite	11.14	10.71
Anorthite	0.00	0.00
Diopside	.00	.00
Hypersthene	7.64	7.55
Magnetite	.03	1.13
Hematite	.00	.00
Ilmenite	.33	.33
Apatite	.06	.00
Calcite	.00	.00
Total	99.65	99.91

Andesite dikes

Throughout the map area, north- to northeast-trending, steeply dipping andesite dikes cut the volcanic rocks, rhyolite porphyry stocks, veins, and mineralized zones. The dark-green, aphanitic dikes are as wide as 1.5 m and several hundred meters long. They weather easily and form steep-walled trenches and drainages.

Structure

The map area lies at the nose of a north- to northeast-trending broad regional anticline that plunges 25° to 30° NE. Although the western limb of the anticline extends for several kilometers to the southwest, the eastern limb is truncated immediately east of the jabal by the regional, northeast-trending Wadi Saylah fault. Movement along the fault dropped the jabal area down to the west (A. M. Afifi, written commun., 1982). Although subsidiary folds on the flanks of the anticline are widespread, they are best developed in the northwestern corner of the map area, where a northwest-plunging syncline and anticline are present (pl. 1).

The rock units in the mine area generally strike east-west, although, as a result of regional folding, they strike more to the northwest in the eastern part of the map area. This change in strike direction may have been accentuated by drag acompanying right-lateral displacement along the Wadi Saylah fault (Goldsmith and Kouther, 1971); however, A. M. Afifi (written commun., 1983) believes that strike-slip offset along this fault is sinistral.

Luce and others (1975), and Hilpert and others (in press) identified six sets of faults in the SAMS mine area (pl. 1; table 2). North-to northeast-trending, west-dipping quartz-filled faults and fractures (table 1) are well developed in the map area and cut all rock units except the andesite dikes. Veins along faults that have a dip of more than 60° are usually less than 0.5 m wide, whereas those along faults that have dips of from 25° to 50° are commonly more than 1 m wide. High-angle imbricate structures are commonly found in the hanging wall of the shallow-dipping faults. These structures indicate a compressional event in which thrust movement was directed to the east, and, inasmuch as these structures are cut by all of the remaining faults and veins, they represent the first deformation after deposition of the units. This early deformational event was probably part of the regional compressional event that produced the large north-northeast-trending fold. The later faults and veins are parallel to the axis of the fold.

Table 2.--Principle fault sets in SAMS mine area, showing general attitudes and associated veins
[Adapted from Hilpert and others (in press)]

Set number (oldest to youngest)	Strike and dip	Vein relationships*
6	East to N. 30° W.; steeply south and west to steeply north and east	Barren; minor displacement
5	North to N. 45° E.; steeply northwest to steeply southeast	Barren; contains andesite dikes; "Persistant" fault-offsets "linked veins"
4	N. 30° W. to north; steeply southwest	Includes No. 1 vein; important ore bearer
3	N. 10° W. to N. 30° E.; steeply west, except for linked faults, which dip steeply east-west	Includes Nos. 8, 14B (14 H.W.), 16 and "linked veins" D through P. All ore bearing
2	N. 25°-30° W.; 55°-65° NE. to 70° SW.	Not significant in Mine Hill area (See Luce and others, 1975; table 2)
1	N. 45°-75° E.; 45°-60° NW. (surface) to vertical (subsurface)	No. 4 vein; important ore bearer. Offset by No. 8 fault
	N. 15° W. to N. 30° E.; 25°-45° W.	No. 14A (14 F. W.) and 14A west veins. Important ore bearers in "Glory-hole"-quarry area

*Veins are in SAMS mine area; they are not labeled on plate and figures of this study (see Hilpert, and others, in press).

One of the youngest structural features in the area is a northeast-trending set of normal faults. These normal faults were intruded by the late andesite dikes, have dips of more than 70° NW., and progressively downdrop all stratigraphic contacts to the west (pl. 1). In the Southern Ore Zone, these faults and dikes cut both the mineralized structures and the rhyolite.

MINERALIZATION

At Mahd ahd Dhahab, gold, silver, copper, zinc, and lead were deposited in north- to northeast-trending quartz veins. A rubidium-strontium age determination on potassium feldspar from a vein indicates that mineralization occurred about 675 Ma ago (Luce and others, 1979). Lead-isotope studies indicate that galena lead was derived from oceanic crustal material about 700 Ma ago (Rye and others, 1982). Ore deposition occurred in veins at two locations: in the competent lower agglomerate immediately underlying the incompetent lower tuff, forming the Southern Ore Zone, and in the competent upper agglomerate immediately underlying the incompetent upper tuff, forming the Northern Ore Zone. The Southern Ore Zone is postulated to be a north-dipping, tabular body that is 40 m thick and 400 m wide in an east-west direction and extends 250 m downdip for a total reserve of about 1.1 million metric tons of 1 ounce gold per ton of ore (Worl, 1978). The Northern Ore Zone is postulated to have been of similar dimensions and grade prior to mining.

Three major low-angle, west-dipping mineralized veins and vein systems formed at Mahd adh Dhahab. In the Northern Ore Zone, a thrust fault zone that is several meters wide and dips 45° W. contains some of the high-grade ore of the Northern Ore Zone (Hilpert and others, in press; pl. 1). This vein-fault structure has been completely stoped in the SAMS quarry and underground workings. In the hanging wall, numerous smaller, high-angle, west-dipping veins and shear zones are thought to be imbricate structures that formed as a result of movement on the fault (Hilpert and others, in press).

In the Southern Ore Zone, high-grade mineralization occurred in a system of veins that dip 40° to 45° W. and individually are as wide as 10 m (fig. 3). These veins have not been observed at the surface because of their shallow dips; their outcrop projection lies below wadi alluvium to the east. An intensely veined zone crops out directly above the low-angle subsurface structures (pl. 2); this zone consists of steeply west dipping to subvertical veins that which are less than 0.5 m wide and extend downward into the orebody.

A third vein trends north through the center of the map area and crops out primarily as a dip-slope surface covering a wide area on the western side of the jabal (pl. 2). It is as wide as 2.5 m, dips from 35° to 55° W., is commonly copper stained, and was stoped by the ancients. The northern section of the vein cuts the upper agglomerate in an area where numerous small, high-angle, west-dipping veins are in the hanging wall of the vein (fig. 4).

The large, low-angle veins in the Northern and Southern Ore Zones are from 5 to 35 m above and parallel with the west-dipping flank of the rhyolite intrusive body. The close spatial relationship between the low-angle veins and the rhyolite suggests a genetic relationship. The nearby thrust faults either predate or were contemporaneous with intrusion of the rhyolite and provided a pathway for its emplacement. They also acted as major channelways for the hydrothermal fluids.

In the Southern Ore Zone five stages of mineralization have been identified by studying of drill-core and underground samples. A proposed paragenetic sequence was constructed in collaboration with A. M. Afifi (oral commun., USGS, 1982) and is given in table 3.

Bornite, chalcocite, covellite, and malachite have been identified as supergene minerals (Rye and others, 1982). Well-developed banding of milky white quartz, gangue, and ore minerals in the veins suggests mineralization occurred during several stages of open-fracture filling. Where barren veinlets intersect pyrite-altered fragments in volcaniclastic rocks, stage III chalcopyrite has been precipitated. This relationship suggests that the previously altered wall rock locally exerted chemical control on the deposition of the chalcopyrite.

Fluid inclusions in quartz and sphalerite (Luce and others, 1979; Rye and others, 1982) homogenize between 110° and 270° C, and sulfur isotope values for coexisting sulfide pairs yield temperatures between 210° and 310° C. (Luce and others, 1979). The presence of coexisting vapor-rich and fluid-rich inclusions in mineralized veins and the general absence of vapor-rich inclusions in the barren veins (Rye and others, 1982) suggest that boiling of the hydrothermal solutions accommpanied mineralization. The presence of CO_2 in several of the high-temperature inclusions (Luce and others, 1979) suggests that effervescence of CO_2 may also have been a factor in mineral deposition (Rye and others, 1982).

Sulfur isotope values for sulfide minerals of from 0.5 to 6.3 per mil suggest that the sulfur was derived from an igneous source, and the higher values indicate that sulfur was derived from rhyolite magmas (Rye and others, 1982).

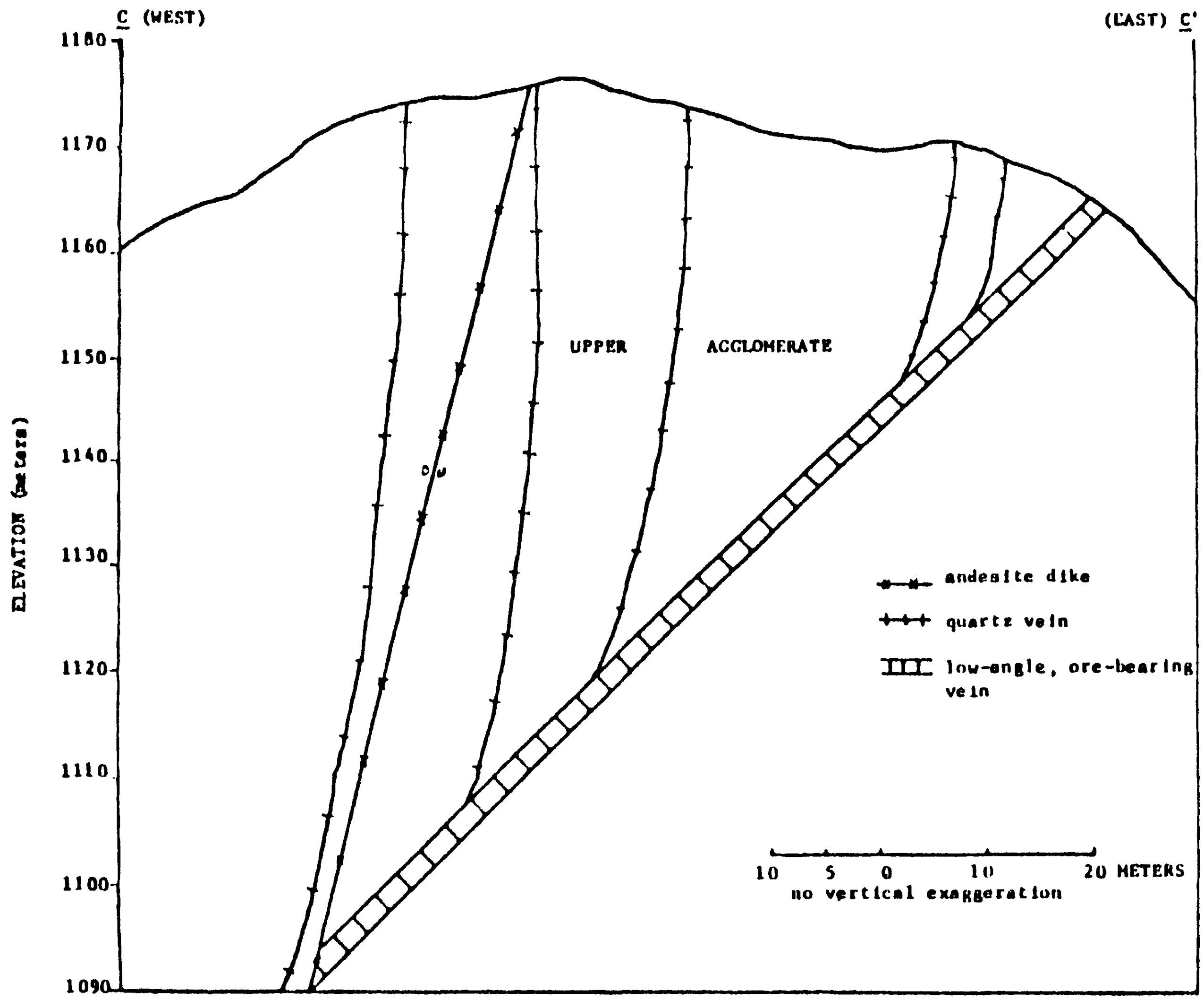

Figure 4. East-west cross section (C-C') through a large low-angle vein in the N-central part of the map area. (See Pl. 1)

Table 3.--Preliminary paragenetic vein sequence for the Southern Ore Zone

Stage	Minerals
I	Quartz + pyrite + sericite
II	Quartz + chalcopyrite + sphalerite + pyrite + calcite ± chlorite ± Au-Ag telluride ± hematite ± K-feld
IIIa	Chlorite + quartz + chalcopyrite + sphalerite + native Au + Au-Ag tellurides (sylvanite, hessite, petzite) + altaite + hematite ± galena
b	Late chalcedony, rose quartz or both
IV	Quartz + chalcopyrite + sphalerite + calcite ± barite ± chlorite
V	Quartz ± calcite

Oxygen isotope values of quartz from vein stages II to V (table 3) from both of the ore zones range from 8.5 to 11.6 per mil (Luce and others, 1979; Rye and others, 1982). This range of compositions indicates that all generations of quartz were deposited from fluids that had similar temperatures and isotopic compositions, were meteoric in origin, and were part of a single hydrothermal system (Rye and others, 1982). Furthermore, it indicates that the fluids moved through a large-scale, stable, continuous fracture system.

ALTERATION

Vein-related alteration consisting of quartz-sericite-pyrite, chloritic, argillic, and silicic halos was superimposed on broad pervasive alteration zones of silicic, potassic, and argillic alteration. Broad pervasive propylitic alteration was then superimposed on all alteration types. The structurally competent lower and upper agglomerates were host to the greatest variety of and most intense alteration. A correlation between alteration stages and vein stages is given in table 4.

Silicification

Zones of light-gray to gray, moderately to intensely silicified rocks (pl. 2) formed both in early pervasive zones related to intrusion of rhyolite and in vein halos surrounding stage IV and V veins; these silicified zones commonly are found in the lower and upper agglomerates.

Intense silicification both in the pervasive zones and in the vein halos consists of total replacement of the matrix and partial to total replacement of fragmental constituents by silica. Moderate silicification consists of partial to total replacement of the matrix only. Secondary chlorite, sericite, pyrite, and microcline are present in minor amounts in both intensely and moderately silicified rocks. Because sericite and pyrite may be contemporaneous with stages of silicic alteration, these silicified zones may actually be silica-rich quartz-sericite-pyrite zones.

Replacment of the original siliceous, tuffaceous matrix resulted in an increase in grain size. Complete replacement of lithic fragments resulted in pseudomorphs of coarse-grained, crystal aggregates of quartz and chlorite. Crystal fragments of potassium feldspar commonly have cores of secondary quartz, whereas primary quartz crystals have very irregular borders of secondary silica.

Table 4.--Correlation between alteration stages and mineralization-veining stages

Alteration stage	Mineralization-veining* stage
Silicic	None**
Quartz-sericite-pyrite	I
Potassic	I
Quartz-sericite-pyrite	II
Chloritic	IIIa,b
Argillic	III(?)
Silicic	IV
Silicic	V
Propylitic	None

*See table 3 for mineralogy.
**Related to intrusion of rhyolite.

In the SAMS mine area, an aureole of intense to moderate silicification in the upper agglomerate formed around the rhyolite (pl. 2) and is interpreted to be genetically related to it. Beneath the Southern Ore Zone, the upper part of the rhyolite and the wall rocks are also silicified; this zone of silicification includes and largely corresponds to the cap breccia (fig. 3).

In the southeastern and south-central parts of the map area, patches of silicified rocks in the lower agglomerate are generally not vein related and may have formed as part of the silicified zone above the rhyolite body intersected in GFMAD drill core.

In the southwestern part of the map area, intense silicification in the lower agglomerate commonly was associated with west-dipping, low-angle veins and their intensely veined hanging walls. In this part of the map area, moderately silicified rocks in areas of no appreciable veining may be related to a shallow intrusive body, as in the southeastern and south-central parts of the map area.

In the northwestern corner of the map area, a zone of intensely silicified rocks in the upper agglomerate is associated with a large, subvertical vein and with extensive stockwork veins. The stockwork is in the hanging wall of a west-dipping, low-angle vein. Between this area and the SAMS mine area, an extensive zone of moderately silicified rocks is contained, for the most part, in the conglomerate member of the upper agglomerate unit. Numerous vein and fault-related halos of intensely silicified rocks have been superimposed on this zone.

In areas where silicification formed vein halos, the width of the silicified zone is commonly greater in the hanging wall than in the footwall. Furthermore, the hanging-wall zone generally is widest above shallow-dipping veins. For example, in the north-central section of the map area the halos in the hanging walls of high-angle veins in the upper agglomerate are 2 to 5 m wide, whereas the halo around the northern strike extension of the low-angle, dip-slope vein is as wide as 15 m (pl. 2). This relationship suggests either upward fluid flow or greater permeability in the hanging walls of the shallow-dipping veins or both.

Quartz-sericite-pyrite alteration

Areas of intense quartz-sericite-pyrite alteration formed primarily in the lower agglomerate, upper agglomerate, and rhyolite units (pl. 2). They are characterized by the relative abundance of quartz, sericite, and pyrite and minor chlorite and calcite, and, because of the weathering of abundant, disseminated pyrite, they crop out as distinct reddish-brown zones.

Narrow halos of quartz-sericite-pyrite alteration surround stage I veins, whereas broad, pervasive vein halos of quartz-sericite-pyrite alteration surround stage I and II veins. Within any one halo, quartz, sericite, and pyrite are either as disseminated wall-rock replacement minerals or confined to numerous discontinuous quartz-sericite-pyrite veinlets or both. In the volcaniclastic rocks, lithic constituents were more favorable for replacement than the matrix, as indicated by quartz-sericite-pyrite-altered fragments in relatively unaltered matrix. As the intensity of alteration increased, quartz, sericite, and pyrite replaced the matrix as well.

Subhedral to euhedral cubes of pyrite are as wide as 3 mm and are commonly rimmed by a thin border of sericite. Sericite is generally very fine grained and may be white, yellow, or pale green in both hand specimen and thin section. Both pyrite and sericite have replaced most of the primary feldspar and much of the secondary microcline. Pyrite alteration of the feldspar commonly occurred as a skeletal replacement of both primary and secondary potassium feldspar; sericite alteration was usually confined to the cores of the potassium feldspar and the twin lamellae of plagioclase.

In rhyolite, this alteration type commonly formed quartz-sericite-pyrite stringers. However, considerable replacement of phenocrysts and groundmass by quartz, sericite, and pyrite also occurred.

In the northeastern and southeastern corners of the map area, broad pervasive zones of quartz-sericite-pyrite alteration are associated with abundant veins (pl. 2) and are believed to represent a network of overlapping vein halos related to either stage I veins or stage II veins or both. In the southeastern corner of the map area, similar alteration occurred in the lower agglomerate directly updip from the Southern Ore Zone. In the northeastern corner, quartz-sericite-pyrite alteration generally coincides with the rhyolite. A similar quartz-sericite-pyrite alteration zone is in the rhyolite below the silicified aureole of the Southern Ore Zone (fig. 3). Numerous crosscutting stage I quartz-sericite-pyrite veinlets have well-developed halos of quartz-sericite-pyrite and form polygonal patterns (fig. 5).

Although the pervasive quartz-sericite-pyrite zone in the central part of the map area is void of any veining (pl. 2), it is in the footwall of the large, west-dipping, low-angle dip-slope vein and may be related to it. The quartz-sericite-

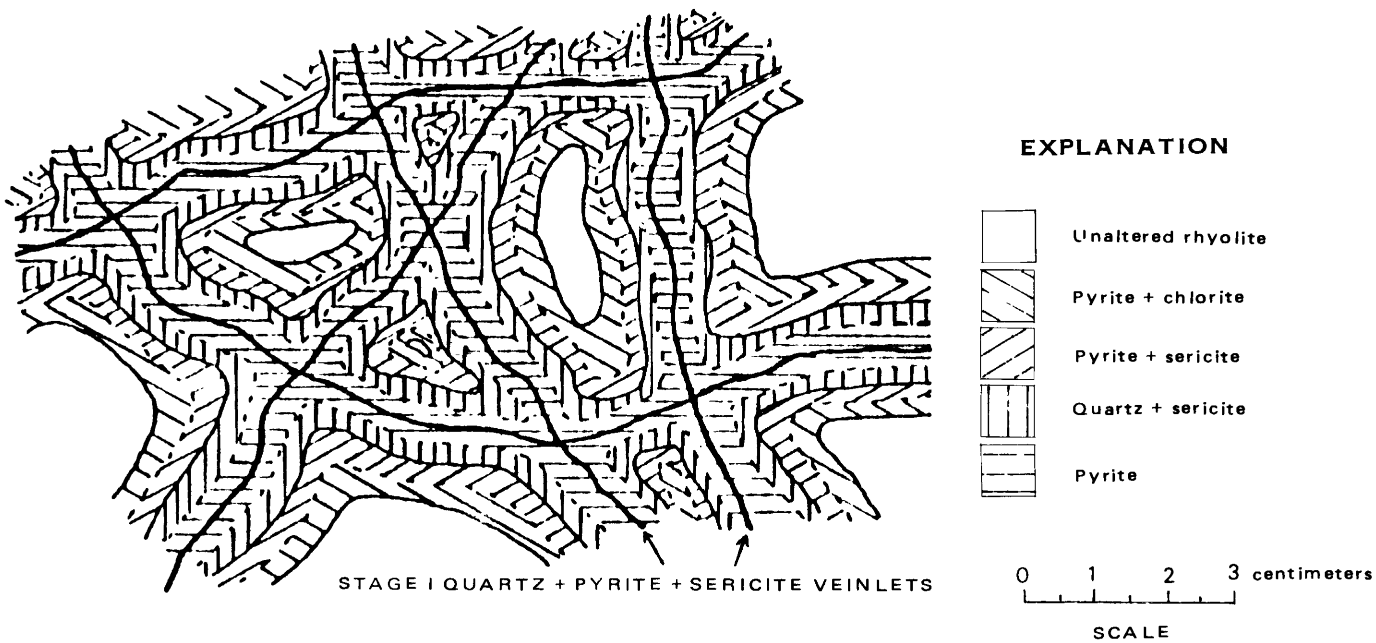

Figure 5. Stage I quartz-sericite-pyrite alteration in the southern rhyolite. Zones 1-5 are symmetric across the veins.

pyrite zone in the northwestern corner of the map area (pl. 2) is related to a west-dipping, low-angle vein and associated stockwork; this zone generally forms a halo around the low-angle vein and is almost completely surrounded by intensely silicified rocks. A similar spatial relationship between quartz-sericite-pyrite and silicic alteration zones is also found above the Northern and Southern Ore Zones.

Potassic alteration

Potassic alteration occurred primarily in broad, stratigraphically controlled, pervasive zones in competent, coarse-grained, volcaniclastic horizons, and vein-related halos have not been observed. Potassic alteration is the second stage of alteration related to stage I mineralization and veining and followed quartz-sericite-pyrite alteration.

Potassically altered rock is characterized by the presence of abundant, orange-pink, secondary microcline that occurs either as disseminated, subhedral to euhedral crystals and crystal aggregates in the wall rock or as microcline veinlets. The disseminated crystals are as large as 2 mm and have replaced both fragmental and matrix constituents in the volcaniclastic rocks. Individual crystals are often superimposed on and crosscut matrix-fragment and stage I vein-wall rock contacts. Lesser amounts of contemporaneous chlorite and both earlier and later quartz, sericite, and pyrite are also present. The chlorite is thought to be the same age as the potassium feldspar because they occur together in stage I quartz veins immediately west of the SAMS mine area. At the base of the lower tuff, potassically altered host rocks locally lack relict textures and consist of masses of chlorite and quartz and disseminated crystals and crosscutting veinlets of microcline. The microcline has often been replaced by sericite and pyrite.

Two major zones of east-trending, potassically altered rocks are present at tuff-conglomerate contacts. These zones correspond very closely to zones of anomalous concentrations of potassium-40 delineated by radiometric surveys (Gettings, 1981).

In the southern of these zones, potassic alteration occurred exclusively in the permeable and competent lapilli tuff horizons in the transition zone at the base of the lower tuff, where the lower tuff is in contact with the lower agglomerate (pl. 2). The southern zone is continuous through the southeastern and south-central parts of the map area and is also in the southwestern part of the map area; a nonpotassically altered area separates the two sections of the zone.

In the southwestern area the potassically altered zone is spatially associated with both an intensely veined and silicified zone related to stage I veining and a silicified zone that may be related to rhyolite at depth.

In the northern of these zones, potassic alteration occurred in the basal mafic agglomerate of the tuff member of the upper agglomerate, where the upper agglomerate is in direct contact with the lower tuff. Although most alteration was confined to the mafic agglomerate, it locally extended upward into the overlying tuff and lapilli tuff. Immediately west of the SAMS mine area, a small, isolated zone of potassically-altered rock is characterized by abundant quartz-chlorite-microcline veins and veinlets.

Both the presence of this potassic alteration in coarse-grained volcaniclastic units having relatively high vein densities and the general absence of potassic alteration in tuff units having low vein densities indicate that the potassic-altering fluids flowed up against the impermeable and incompetent tuff horizons and were channeled along the permeable coarse-grained rock units.

Chloritic alteration

Vein-related chloritic alteration, as opposed to pervasive propylitic chloritic alteration, occurred only in narrow halos around stage III (main stage) veins. The alteration was very intense, it destroyed primary textures and primary and secondary minerals a distance of several centimeters from the vein, and it resulted in a zone of massive chlorite accompanied by variable amounts of secondary quartz.

Argillic alteration

Argillic alteration resulted in bleached zones of illite, kaolinite, sericite, mixed-layer clays, and opaline silica along tuff-conglomerate contacts and vein halos. The clay mineralogy was determined by using X-ray diffraction, and it suggests a hypogene origin. Although the relationship between argillic alteration and veining is not clear, the alteration is interpreted to be related to formation of stage III veins.

In the southeastern and south-central parts of the map area (pl. 2), patches of argillically altered rocks are in the uppermost part of the lower agglomerate. The argillically altered rocks are often in contact with the overlying potassium feldspar-altered base of the lower tuff.

In the northeastern and west-central parts of the map area, broad pervasive zones of argillically altered rocks are along the upper agglomerate-upper tuff contact. In the northeastern part of the map area, the base of the upper tuff and part of the rhyolite have been intensely altered. On the isolated jabal in the west-central part of the map area, a less intense zone of argillic alteration formed in the upper agglomerate directly below the massive chert of the upper tuff. In the SAMS mine area, vein halos of argillic alteration formed only around stage III veins.

Propylitic alteration

Propylitic alteration has affected the greatest percentage of the map area and is found in all rock types (pl. 2). Propylitic assemblages can be subdivided into three categories: an assemblage that includes abundant chlorite; an assemblage of epidote, calcite, and hematite; and an assemblage of minor pyrite, chlorite, and sericite. All three formed after mineralization, that is, after deposition of stage V veins.

Most of the pervasive chloritic alteration occurred in zones within an east-trending belt in the lower to middle sections of the lower tuff. These zones are characterized by an abundance of chlorite pellets in the fine-grained, laminated tuffs. The pellets are spherical to oval and may be as much as 5 mm in diameter. They consist of cores of quartz-crystal aggregates rimmed by chlorite and may represent replaced potassium feldspar crystals. On dip-slope bedding surfaces, the pellets have commonly weathered out, and pits that look similar to rain-drop imprints remain. Larger clots of chlorite in the lapilli tuff horizons represent replaced lithic lapilli. Patches of chlorite-altered tuff are also in the upper section of the lower tuff immediately below the upper agglomerate.

The epidote-calcite-hematite alteration assemblage is almost exclusively in the andesite. Chlorite, zoisite, and clinozoisite are also very common in this assemblage. These propylitically altered rocks are characterized by a complete replacement of mafic minerals and a partial replacement of plagioclase. Epidote, calcite, and hematite commonly are discontinuous stringers. All of the secondary minerals fill vesicles in the andesite flow rocks.

The epidote-calcite-hematite assemblage is also along a horizon in the rhyolite below the Southern Ore Zone. This altered horizon grades upward into a zone of quartz-sericite-pyrite alteration and downward into unaltered rhyolite (fig.

3). Locally, all primary textures have been destroyed, and the altered rhyolite is very similar in appearance to the propylitically altered andesite mapped on the surface.

Areas of minor disseminated pyrite, chlorite, and sericite represent the least altered zones in the map area. These alteration minerals are very fine grained and commonly microscopic. These altered areas are characteristically found well away from zones of known ore-grade mineralization.

SUMMARY AND CONCLUSIONS

Approximately 800 million years ago, an intermediate to felsic sequence of volcanic, volcaniclastic, and epiclastic rocks were deposited in a shallow submarine environment at what is now Jabal Mahd ahd Dhahab.

Faulting and tilting occurred sporadically throughout deposition of these rocks. The sequence was later folded and tilted into a north- to northeast-trending anticline and cut by west-dipping thrust faults. Subsequently, high-angle north- to northeast-trending thrust faults developed parallel with the axis of the fold. This thrust faulting provided a pathway for the intrusion of an epizonal, rhyolite-porphyry stock. Brecciation of the rhyolite and surrounding country rock occurred contemporaneously with formation of a broad, pervasive, silicic alteration aureole above and around the intrusive body. This alteration may have resulted from magmatic fluids.

Quartz-sericite-pyrite alteration followed brecciation and silicification and was associated with stage I mineralization; it was the first stage of alteration associated with circulating meteoric fluids heated by the rhyolite. The alteration was primarily confined to the rhyolite, although it may have extended for some distance above the rhyolite.

The thrust faults acted as major fluid conduits. When the fluids encountered impermeable and incompetent horizons represented by tuffs above the transition zone of the lower tuff and basal mafic agglomerate in the upper agglomerate and the underlying lower tuff, they were channelled into competent and permeable, coarse-grained, fragmental units. This channelling resulted in the development of broad, pervasive, stratigraphically controlled, potassic alteration zones associated with stage I veining.

The initial types of alteration related to the circulating hydrothermal-fluid cell were quartz-sericite-pyrite and potassic alterations associated with Stage I veining. Although the sulfur in the system had a magmatic origin, the fluids were meteoric. Dissolved constituents in the fluids may have been either leached from wall rocks or derived from the rhyolite magma.

Open-fracture filling in the competent units continued during stage II mineralization. Quartz-sericite-pyrite alteration associated with this stage was overprinted on earlier stage I quartz-sericite-pyrite and potassic alteration.

The change from sericite to potassium feldspar during stage I veining indicates an increase in the activity of potassium, pH, or temperature or some combination of the three. A return to sericite alteration during to stage II veining represents a subsequent decrease in some or all of these variables.

Stage III (or main stage) mineralization is thought to have been related to boiling of the hydrothermal fluids. Intense chloritic vein halos characterize this stage, and argillic alteration may also be associated with this stage of mineralization. Quartz-sericite-pyrite-altered wall rock locally exerted chemical control on the deposition of stage III chalcopyrite.

The formation of chlorite during stage III mineralization indicates an increase in the activity of magnesium relative to the activities of other constituents. This increase may have resulted from leaching of the andesite. If so, perhaps ore-forming metals were also leached from the andesite. This leaching could have resulted from either an expansion of the hydrothermal cell into the andesite or a change from fracture-dominated flow in the andesite to pervasive flow along grain boundaries.

The lack of abundant ore constituents in stage IV and V veins, the silicic alteration associated with these veins, and the late propylitic alteration all suggest a cooling of the mineralizing fluids, a decrease in concentration of metals in the fluids, and a contraction of the hydrothermal cell.

After mineralization and alteration, normal faulting occurred throughout the area. These faults offset lithologic contacts, veins, and ore zones and were intruded by andesite dikes.

RECOMMENDATIONS FOR FURTHER WORK

Silicic, potassic, and quartz-sericite-pyrite surface alteration patterns above the Northern and Southern Ore Zones at the northeastern and southeastern corners of the study area are very similar. Similar alteration patterns are in the northwestern and southwestern corners of the map area, in the upper and lower agglomerates, respectively.

In both the northwestern and southwestern areas, numerous high-angle hanging wall veins are above a west-dipping, low-angle vein. These structures are similar to the low-angle veins in the ore zones.

In the southwestern area, potassic and silicic alteration zones are present in the apparent absence of quartz-sericite-pyrite alteration zones. However, a quartz-sericite-pyrite zone may be present at depth below the silicic zone. Because the southwestern area is as much as 45 m higher in elevation than the other three corners of the jabal, the possibility is enhanced that a quartz-sericite-pyrite zone is present but not exposed. In the northwestern area, a quartz-sericite-pyrite alteration zone is present, and it has the same spatial relationships to the potassic and silicic alteration zones as recognized in the two known ore zones.

We recommend that a bedrock geochemical sampling program be initiated in the northwestern and southwestern corners of the map area, both in and around the intensely altered and veined zones, and that it include analysis for gold, silver, copper, zinc, and lead. Anomalous concentrations of these metals in rocks above both the Northern and Southern Ore Zones were revealed by a similar survey (Roberts and others, 1978).

ACKNOWLEDGMENTS AND DATA STORAGE

We gratefully acknowledge the support and assistance of many members of the USGS Saudi Arabian Mission, especially A. M. Afifi for suggestions made during lengthy and stimulating discussions on the origin of the deposit. The study also benefited greatly from discussions with R. G. Worl, USGS Denver, during the progress of the study. We appreciate very much the assistance provided by Gold Fields Mahd adh Dhahab, Mr. M. J. Hooper, General Manager, for use of the GFMAD camp facilities and for access to drill cores, drill logs, and the underground workings.

The Mahd adh Dhahab mineral locality is entered in the Mineral Occurrence Documentation System (MODS) data bank and is identified by a unique five-digit number (MODS 00003). Inquiries regarding this data bank may be made to the Office of the Technical Advisor, Saudi Arabian Deputy Ministry for Mineral Resources, Jiddah. Data file USGS-DF-04-23 (Doebrich and LeAnderson, 1984) has been established for the storage of data used in this report.

REFERENCES CITED

Aguttes, J., and Duhamel, M., 1971, Geology and mineral exploration of the Jebal Sayid quadrangle: Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 71-JED-4, 49 p.

Calvez, J. Y., and Kemp, J., 1982, Geochronological investigations in the Mahd adh Dhahab quadrangle, central Arabian Shield: Saudi Arabian Deputy Ministry for Mineral Resources Technical Record BRGM-TR-02-5, 41 p.

Doebrich, J. L., and LeAnderson, P. J., 1984, Supporting data for geology and hydrothermal alteration at the Mahd adh Dhahab epithermal precious-metal deposit, Kingdom of Saudi Arabia: Implications for the genesis of the deposit: Available from Saudi Arabian Deputy Ministry for Mineral Resources Data File USGS-DF-04-23.

Ebens, R. J., Shacklette, H. T., and Worl, R. G., 1983, Biogeochemical sampling in the Mahd adh Dhahab district, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-34, 15 p.; also, U.S. Geological Survey Open-File Report 83-330.

Gettings, M. E., 1981, Geophysical investigations in the Mahd adh Dhahab district, Kingdom of Saudi Arabia, with a section on Shallow seismic refraction profiles, by H. Merghelani and M. E. Gettings: U.S. Geological Survey Saudi Arabian Mission Technical Record 10 (Interagency Report 349), 80 p.; also, 1981, U.S. Geological Survey Open-File Report 81-828.

Goldsmith, Richard, and Kouther, J. H., 1971, Geology of the Mahd adh Dhahab-Umm ad Damar area, Kingdom of Saudi Arabia: Saudi Arabian Directorate General of Mineral Resources Bulletin 6, 20 p.

Hilpert, L. S., Roberts, R. J., and Dirom, G. A., [in press], Geology of Mine Hill and the underground workings, Mahd adh Dhahab, Kingdom of Saudi Arabia.

Lefevre, J. C., 1969, Mineral resources and geology of the Sufaynah quadrangle (sheet 122): Bureau de Recherches Geologiques et Minieres (Saudi Arabian Mission) Report 69-JED-8, 51 p.

Luce, R. W., Bagdady, A. Y., and Roberts, R. J., 1975, Geology and ore deposits of the Mahd adh Dhahab district, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Project Report 195, 29 p.; also, 1976, U.S. Geological Survey Open-File Report 76-865.

Luce, R. W., O'Neil, J. R., and Rye, R. O., 1979, Mahd adh Dhahab-Precambrian epithermal gold deposit, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Project Report 256, 33 p.; also, 1979, U.S. Geological Survey Open-File Report 79-1190.

Moorhouse, W. W., 1959, The study of rocks in the thin section: New York, Harper and Row, p. 224-230.

Roberts, R. J., Bagdady, Abdulaziz, and Luce, R. W., 1978, Geochemical investigations in the Mahd adh Dhahab district, Kingdom of Saudi Arabia, with a section on Computer analysis, by L. D. North and I. H. Abuttahir: U.S. Geological Survey Saudi Arabian Project Report 231, 34 p.; also, 1979, U.S. Geological Survey Open-File Report 78-777.

Rye, R. O., Hall, W. E., Cunningham, C. G., Czamanske, G. K., Afifi, A. M., and Stacey, J. S., 1982, Preliminary mineralogic, fluid inclusion, and stable isotope study of the Mahd adh Dhahab gold mine, Kingdom of Saudi Arabia: Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-4, 26 p.; also, 1983, U.S. Geological Survey Open-File Report 83-291.

Theobald, P. K., Jr., 1965, Geologic status report, April 1965, Mahd adh Dhahab area, Saudi Arabia: U.S. Geological Survey Saudi Arabian Project Technical Letter 15, 11 p.; also, 1965, U.S. Geological Survey Open-File Report (IR)SA-15.

Twitchell, K. S., 1958, Saudi Arabia with an account of the development of its natural resources: Princeton, Princeton University Press, 268 p.

Williams, H., Turner, F. J., and Gilbert, C. M., 1954, Petrography: An introduction to the study of rocks in thin section: San Francisco, W. H. Freeman, p. 149-160, 357-364.

Worl, R. G., 1978, Mineral exploration-Mahd adh Dhahab district, Kingdom of Saudi Arabia: U.S. Geological Survey Saudi Arabian Project Report 233, 85 p.; also, 1978, U.S. Geological Survey Open-File Report 78-1073.

Worl, R. G., 1979, Ore controls at the Mahd adh Dhahab gold mine, Kingdom of Saudi Arabia, in Evolution and mineralization of the Arabian-Nubian Shield: King Abdulaziz University, Institute of Applied Geology Bulletin 3, v. 2: Oxford-New York, Pergamon Press, p. 93-106.