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MAHD ADH DHAHAB: PRECAMBRIAN EPITHERMAL GOLD DEPOSIT, KINGDOM OF SAUDI ARABIA

By

R. W. Luce, J. R. O'Neil, and R. O. Rye

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by

R.W. Luce[1], J.R. O'Neil[2], and R.O. Rye[3]

ABSTRACT

The largest and most productive mine in Saudi Arabia in ancient and modern times has been Mahd adh Dhahab. Country rocks in the district are pyroclastic and clastic rocks that belong to the Halaban group of late Precambrian age. From oldest to youngest, the units are: andesite, lower agglomerate, lower tuff, upper agglomerate, and upper tuff. These units have been tilted northerly forming a homocline and are complexly broken by six sets of faults; three of these sets, which strike N.25°-30°W., N.10°W. to N.20°E., and N.30°-60°E., contain productive quartz veins.

The principal ore minerals are native gold and silver, pyrite, chalcopyrite, sphalerite, and galena, plus minor tetrahedrite and argentite. The gold and silver are finely disseminated in the veins and in the altered selvages of the veins. Widespread potassic and propylitic alteration accompanied ore formation.

Early widespread propylitic and potassic alteration and sulfide and quartz precipitation are believed to have taken place at temperatures below 350°C, based on K-feldspar stability

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and sulfur isotope data. Most of the quartz and precious metals precipitated in the range 200°-150°C, based on studies of fluid inclusions. The isotopic data indicate that sulfur and carbon came from a deep-seated source, but that the water, especially in the later stages, was meteoric.

INTRODUCTION

Mahd adh Dhahab, literally "cradle of gold", was the most productive mine in Saudi Arabia in both modern and ancient times. It is located roughly midway between Makkah and Medina, 275 km northeast of Jiddah on the western edge of the Arabian Shield (fig. 1). Modern investigation of the mine began in 1935 by K.S. Twitchell, an American mining engineer, whose evaluation led to the formation of the Saudi Arabian Mining Syndicate (SAMS). Production by SAMS during the years 1939 to 1954 was large, totaling 765,768 fine ounces of gold and 1,002,029 ounces of silver (Goldsmith and Kouther, 1971). A quarry level and four underground levels to a depth of 200 m were worked.

It was estimated by Dolph (1942) that nearly one million tonnes of tailings were piled in dumps around the ancient workings. Ancient production must have been great in this largest ancient mine of Saudi Arabia. Tens of thousands of stone implements used for ore dressing and mining still litter parts of the mining area. In his book on Saudi Arabia, Twitchell (1958) noted two distinct layers of ancient tailings; the younger tailings were dated by Kufic inscriptions as belonging to the Abbasid Caliphate (750-1258 A.D.).

Figure 1. Index map showing location of Mahd adh Dhahab deposit.

The geology of Jabal Mahd adh Dhahab and the immediate vicinity was mapped at a scale of 1:2400 in 1972-73 (Luce, Bagdady, and Roberts, 1976). Figure 2 is a simplified version of that map of the 3 km^2 area, which includes the SAMS quarry in the northeast corner. Data mapped on plane table and aerial photographic bases were compiled by means of a stereoplotter and incorporated a 1:480 scale map made by Dirom (1947) of the SAMS mine area in the northeast corner. Coordinated with the geologic investigation was an extensive surface geochemical sampling program (Roberts, Bagdady, and Luce, 1978a). A subsequent drilling program and more detailed surface mapping in the eastern third of the area were done under the direction of Ronald G. Worl of the U.S. Geological Survey (Worl, 1978). Partly as a result of interest generated by these studies, Consolidated Gold Fields, Ltd. obtained a license to the district in 1975.

ACKNOWLEDGMENTS

We gratefully acknowledge the contributions of the many members of the USGS Saudi Arabian Mission who assisted at Mahd adh Dhahab, especially R.J. Roberts and Abdulaziz Bagdady who collaborated in field mapping and R.G. Worl and Roberts who collected many specimens for some of the later laboratory work. Dr. A.M.S. Al-Shanti, then of the Saudi Arabian Directorate General of Mineral Resources, helped identify fine-grained minerals under the ore microscope. We also thank L.A. Adami and L.D. White for O, C, H isotope

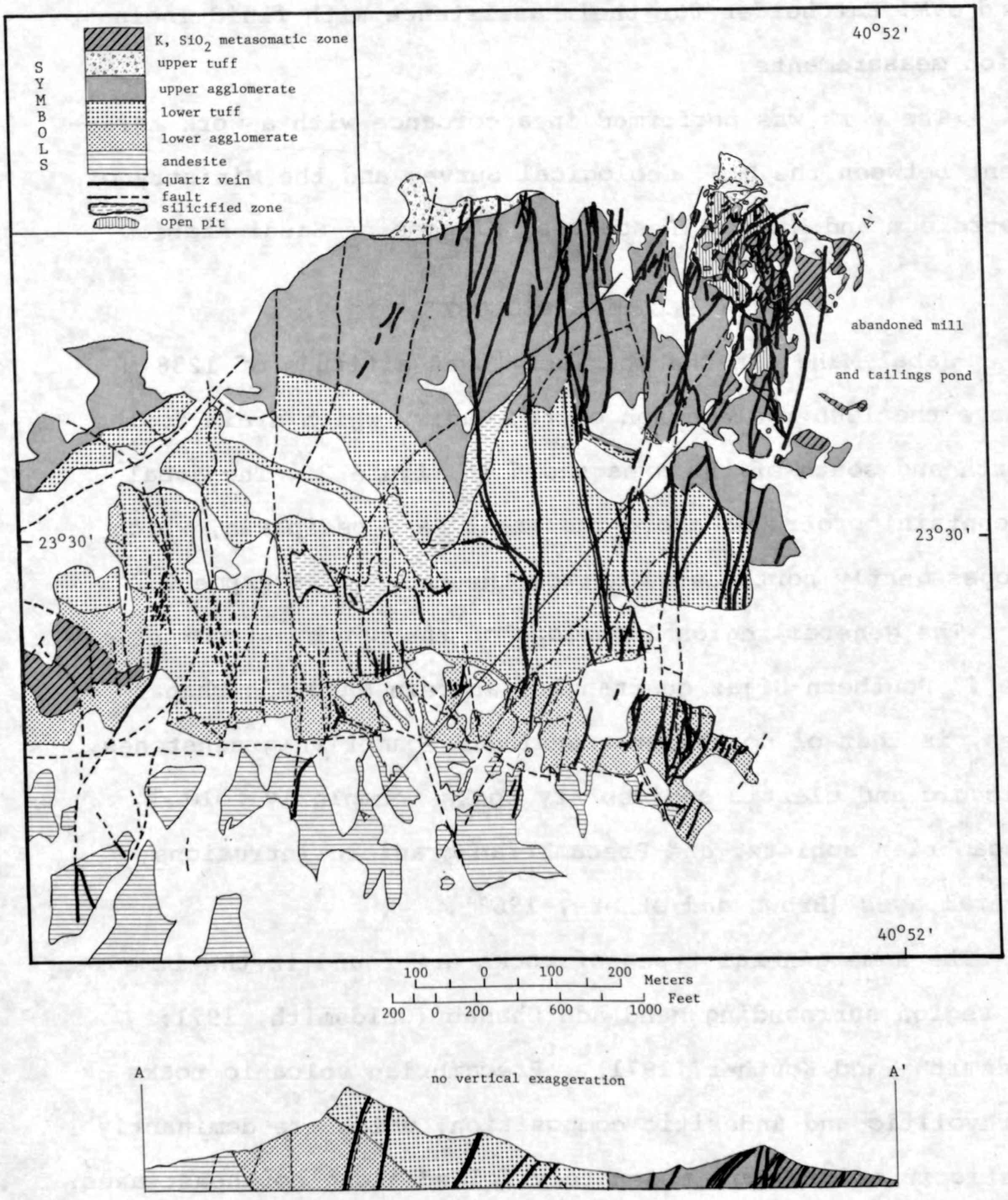


Figure 2. Geologic map of Mahd adh Dhahab deposit (after Luce, Bagdady, and Roberts (1975)[1976]).

measurements in O'Neil's laboratory, J.F. Whelan for S isotope measurements in Rye's laboratory, and H.E. Belkin and J.M. Batchelder for their assistance with fluid inclusion measurements.

The work was performed in accordance with a work agreement between the U.S. Geological Survey and the Ministry of Petroleum and Mineral Resources, Kingdom of Saudi Arabia.

REGIONAL GEOLOGY

Jabal Mahd adh Dhahab rises to an altitude of 1238 m above the 1000 m elevation of the wadis, which drain to the north and south of the area shown in figure 2. The jabal (mountain) protrudes above the great Najd pediplain, which slopes gently northeastward from the Red Sea Escarpment.

The general regional geology of the northwest corner of the 4° Southern Hijaz quadrangle, wherein Mahd adh Dhahab lies, is that of northeast-trending Precambrian greenstones, volcanic and clastic sedimentary rocks, complexly folded Precambrian schists, and Precambrian granitic intrusions of several ages (Brown and others, 1963).

The same general types of rocks are found in the immediate region surrounding Mahd adh Dhahab (Goldsmith, 1971; Goldsmith and Kouther, 1971). Precambrian volcanic rocks of rhyolitic and andesitic composition, which are dominantly clastic in origin, are moderately folded along northeast axes. A large northeast-trending right-lateral fault system passes east of Mahd adh Dhahab. Subsidiary block faulting has affected Jabal Mahd adh Dhahab. Basaltic dike swarms that trend north to northwest south of the mine area have apparently been shifted to a northeast trend in the vicinity of the fault system.

SEDIMENTARY AND VOLCANIC ROCKS

Taken as a whole, the predominantly pyroclastic rocks in the Mahd adh Dhahab area appear to have been deposited on the flanks of a caldera, although no direct evidence of such a structure remains today. By lithologic correlation with other areas, we believe them to belong to the Halaban group (Greenwood and others, 1976).

The sequence of rocks of late Precambrian age in the Mahd adh Dhahab area from oldest to youngest is andesite, lower agglomerate, lower tuff, upper agglomerate, and upper tuff. During a study of the regional geology in 1966, Goldsmith and Kouther used Maclean's (1961) terminology, Mahd adh Dhahab series, and correlated the series with the Murdama and Fatima formations. More recently Aguttes and Duhamel (1971) have assigned the Mahd adh Dhahab series to the next older Halaban group.

Andesite

The oldest rock unit in the area is andesite, which crops out in an east-west belt in the southern part of Jabal Mahd adh Dhahab and on pediments south of the jabal. Goldsmith and Kouther (1971) suggested that the andesite is unconformably underlain by the younger units in the jabal, but this relationship cannot be seen in the map area because of faulting along the boundary. The thickness of the andesite was not measured, but is estimated to be more than 300 m.

The andesite is generally fine grained, although coarser porphyritic layers are locally present. Some units are crystalline and resemble diabase or diorite. A few layers are fragmental and suggest a pyroclastic origin. The combination of these diverse lithologic units suggests that the andesite is partly volcanic, partly intrusive, and partly pyroclastic in origin.

Microscopically, the andesite shows a pilotaxitic texture of fine plagioclase laths in a matrix of chlorite and clay minerals. The rock is so propylitized that the composition of the plagioclase could not be determined and no original mafic minerals remain because of strong alteration to chlorite, epidote, and magnetite.

Lower agglomerate

The lower agglomerate unit crops out on the south flank of Jabal Mahd adh Dhahab. The contact with the underlying andesite is a normal fault that cuts east-west diagonally across the agglomerate, causing a gradual narrowing of the belt of outcrop.

The lower agglomerate is a lapillistone and pyroclastic breccia with a tuffaceous matrix. Lithic fragments in basal units are mostly subangular andesite; fragments of rhyolitic composition are locally abundant in the upper part. Bedding and sorting are poor for the most part and attitudes can be taken only on thin tuffaceous interbeds. The lower agglomerate, like the upper agglomerate, is a lahar deposit. Epidote and chlorite are common alteration products of the matrix.

The lower agglomerate is extensively mineralized along faults in the southeastern and south-central parts of the jabal. The agglomerate was apparently competent and maintained open fractures during metallization, permitting the formation of mineralized quartz veins and silicification of adjacent rock.

Lower tuff

The lower agglomerate grades upward into the lower tuff through an interbedded zone about 10 m thick. The lower tuff is a cliff-forming, resistant unit that makes up the backbone of Jabal Mahd adh Dhahab and forms the highest point.

The lower tuff is mostly a fine-grained, laminated, indurated, siliceous ashfall tuff with some sandy units. A stratigraphic section was measured in the central part of the jabal where the unit is about 207 m thick. This section may be conveniently divided into three parts: a lower laminated ashfall tuff; a middle sandstone and graywacke; and an upper interlayered tuff, shale, and lapilli crystal tuff.

The lower part, 55 m thick, is characterized by thin-bedded, fine-grained, felsic ashfall tuff that is interbedded with lithic lapillistone. The tuff contains andesitic fragments, sanidine shards and devitrified spherulites, now partly chloritized, and potassium feldspar crystal tuff layers. Near the top of this lower part, the lapilli tuff component becomes less prominent and the tuff becomes thicker bedded.

The middle part of the lower tuff unit, 72 m thick, is characteristically medium- to fine-grained sandstone and subgraywacke with lapillistone layers in places. Beds near the upper boundary of this part are commonly stained by iron oxides, which form prominent liesegang rings.

The top part, 80 m thick, is made up of alternating tuff, sandstone, rare shale beds, and local lapilli crystal tuffs. The uppermost 28 m is strikingly hornfelsic.

The lower tuff locally contains small veins along faults, but in general the lower tuff was not extensively mineralized. The largest mineralized areas in this unit are in the southeastern and western parts of the district.

Upper agglomerate

The upper agglomerate rests conformably on the lower tuff. Measurements on cross sections give an average thickness of about 140 m.

The upper agglomerate unit is similar in general appearance to the lower agglomerate; it is a crystal lithic lapillistone with subangular tuff, jasper, and andesitic lithic fragments.

The upper agglomerate, like the lower agglomerate, was competent, fractured well, and maintained open fractures. These characteristics made it a favorable host for metallization and the fractures are now filled with quartz.

Upper tuff

The youngest stratigraphic unit in the district is the upper tuff that crops out in a narrow east-west zone on the northern edge of the jabal; it dips north 45°-55° and underlies the wadi, where it is largely covered by a thin layer of alluvium and mine dumps.

The upper tuff is a thin-bedded, fissile, ashfall tuff. In places, it contains lapillistone layers 10 to 20 cm thick. Microscopically, it is seen to consist of ashfall tuff with some introduced potassium- and plagioclase feldspars, quartz, and calcite.

The upper tuff rests unconformably on the upper agglomerate unit. Many quartz veins appear to terminate against the upper tuff, but this may be because the tuff was a relatively impermeable barrier to hydrothermal solution movement.

IGNEOUS ROCKS

Andesite dikes

A series of andesite dikes up to 2 m wide were emplaced along northeasterly-trending fault zones in many parts of the jabal. The dikes are composed mostly of saussuritic aggregates of altered micaceous minerals and chlorite that were largely derived from plagioclase and mafic minerals.

Some dikes contain amygdules, mostly composed of chlorite, calcite, and quartz. The dikes are believed to have been emplaced late in the ore-forming process because they cut and displace veins in many areas. Metallization continued on a small scale after dike emplacement as some gold- and silver-bearing quartz-calcite veins cut the dikes locally. Analyses show that some of these late veins contain small amounts of gold and silver.

SURFICIAL DEPOSITS

Three surficial units--talus, older alluvium, and younger alluvium--were mapped (Luce and others, 1976). These are omitted from figure 2 for clarity. Talus consists of coarse debris that mantles the lower slopes of the jabal. It includes material of a wide age span from Late Tertiary or Early Quaternary to Holocene and also includes dumps discarded by ancient and modern miners.

Older alluvium includes fan or terrace gravels that are commonly covered by a coating of desert varnish. The finer fractions generally have been removed by wind and water, and a lag pebble pavement remains.

The younger alluvium is found in the present wadis. It is commonly lighter in color than the older alluvium because it has been reworked during the torrential floods that occur several times a year in this area. Some areas underlain by younger alluvium contain placer gold deposits, but the richer ores are commonly in the lower gravel layers, which probably are part of the older alluvium. Placer and eluvial gold deposits were mined by ancient miners on the flanks of Jabal Mahd adh Dhahab and in valleys that drain the jabal.

STRUCTURE

The principal structural feature at Madh adh Dhahab is an east-trending homocline that dips northerly (fig. 2). The homocline in the southern part of Jabal Mahd Dhahab dips northerly 30°-40°. The dip gradually steepens in the central part to 50°-60°N. and in the northern part to 70°-75°N. The homocline is complexly broken by six sets of faults, which are listed below, numbered in order of formation:

Fault set	Trend	Mineralization
6.	N.45°W.; vertical to steeply SW.	None
5.	N.30°-45°E.; steep to vertical	Contains andesite dikes
4.	N.30°-60°W.; steeply SW. to vertical	Locally significant
3.	N.10°W. to N.20°E.; steeply W.	Major
2.	N.30°-60°E., 35°-65°NW., steepening	Major
1.	N.25°-30°W.; 55°-65°NE. to 70°SW.	Minor

The oldest fault set (1) trends N.25°-30°W., has been broken and displaced by other sets, and is so fragmented that only short segments are now seen. Ancient mine workings along faults of this set indicate small-scale mineral production.

The second fault set strikes N.30°-60°E. and commonly dips 35°-65°NW.; many mineralized veins and silicified zones are along faults of this set. Quartz veins on this set tend to be lenticular and show shearing along their margins as well as internally. Their generally low dips suggest that they may be thrust faults. The west silicified zone forms a series of sheared flatirons up to 4 m thick that cap large areas of the slope on the western side of the jabal. These flatirons have been cut by north-south faults of the third set and cut and displaced by the fourth set of faults, which strike N.30°-60°W. and dip steeply.

The third fault set strikes north (N.20°E. to N.10°W.) and dips steeply west. Normal faults of this set offset the contact of the lower agglomerate and lower tuff in a series of steps; the downthrown block is generally on the west. This set also contains major mineralized quartz veins that strike north to N.10°E. Veins in this set of faults have been extensively mineralized, especially in the lower and upper agglomerates at the northeastern end of the jabal. Two veins of this set have been productive in underground workings. There has been repeated movement along faults of this set, and quartz fillings are commonly brecciated.

Long, continuous faults that strike N.30°-45°E. form the fifth set. Many of these show considerable left-lateral displacement. Two faults at the eastern edge of the jabal strike north-northeast but have right-lateral displacement and may be part of this set. Andesite dikes in this northeast fault zone attest to later reactivation. These are not zones of major quartz veining; however, young brecciated quartz veins follow the attitude of the dikes that they cut.

The sixth and youngest fault set strikes northwest and dips vertically to steeply southwest. These are small transverse faults that cut the third fault-vein set and generally show left-lateral offsets of as much as a meter or two. They are probably related to regional Najd faults, which are discussed later.

The faults at Mahd adh Dhahab formed in response to regional stresses during several periods. Shearing along northwest and northeast directions, with a probable north-south principal stress, is inferred during the formation of faults of the first and second sets. A continuation of the same general stress field is thought to have produced the fourth set. The north-south faults of the third set are uncommon in the region outside Jabal Mahd adh Dhahab and most likely originate from vertical uplift. Faults of the fifth set show progressive downthrow on the west and may be related to uplift of the jabal during and following regional emplacement of intrusive bodies as well as a continuation of the general stress field. Faults of the sixth set seem to be related to northwesterly movements during Najd wrench faulting late in Precambrian time; one strand of the Najd fault system passes a few kilometers north of the district.

METASOMATISM AND QUARTZ VEINS

Intense silicic and potassic metasomatism is evident in the area of SAMS mining on the northeastern edge of the map area in the upper agglomerate and also on the western tip of the jabal in the lower agglomerate. Both of these units in the two areas are generally silicified and the rock matrix recrystallized. Primary quartz and K-feldspar phenocrysts have been embayed and generally fractured. The K-feldspars have been remade to a more potassium-rich composition not only in these two large areas but also in many coarse and therefore relatively permeable layers within the lower tuff and in both agglomerate units. There has also been an introduction of K-feldspar in early bands of some quartz veins, especially in the SAMS mining area. Sericitic alteration is found in the same places as the potassic alteration but occurs to a minor degree. Argillic alteration is slight and it is not yet known to what extent feldspar alteration to clays is caused by weathering.

Two feldspar separates, one of a banded ore vein and one of metasomatized phenocrysts from a thin sill in the lower tuff, have been analyzed by the X-ray diffraction method of Wright (1968) and Wright and Stewart (1968). They are nearly identical maximum microclines with a composition of Or_{100}. The upper stability limit of maximum microcline at P_{H_2O} less than 0.4 kb, a reasonable estimate for Mahd adh Dhahab, is 375° (Tomisaka, 1962; Wright, 1967) so it is likely that the vein feldspars and the chemically altered phenocrysts formed below this temperature. The age of the vein feldspar has been determined by Zell Peterman (written commun. from R.J. Fleck, 1973). Assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.704, the data yield an age of about 675 m.y., making the hydrothermal alteration and metallization of late Precambrian age in rocks that correlate with late Precambrian rocks.

The intensely metasomatized areas were originally mapped as rhyolite porphyry by Dirom (1947) and Luce and others (1976).

Worl (1978) considered the rhyolite to be intensely metasomatized lower tuff. Upon further examination it is believed that most rock textures are pyroclastic. There are units within these areas that have flow banding and sanidine phenocrysts, but many of these can be shown to be lithic fragments. However, certain features such as doming of strata underground in the SAMS mine area (Dirom, 1947) and recrystallization may be related to a near-surface intrusive, as yet not found.

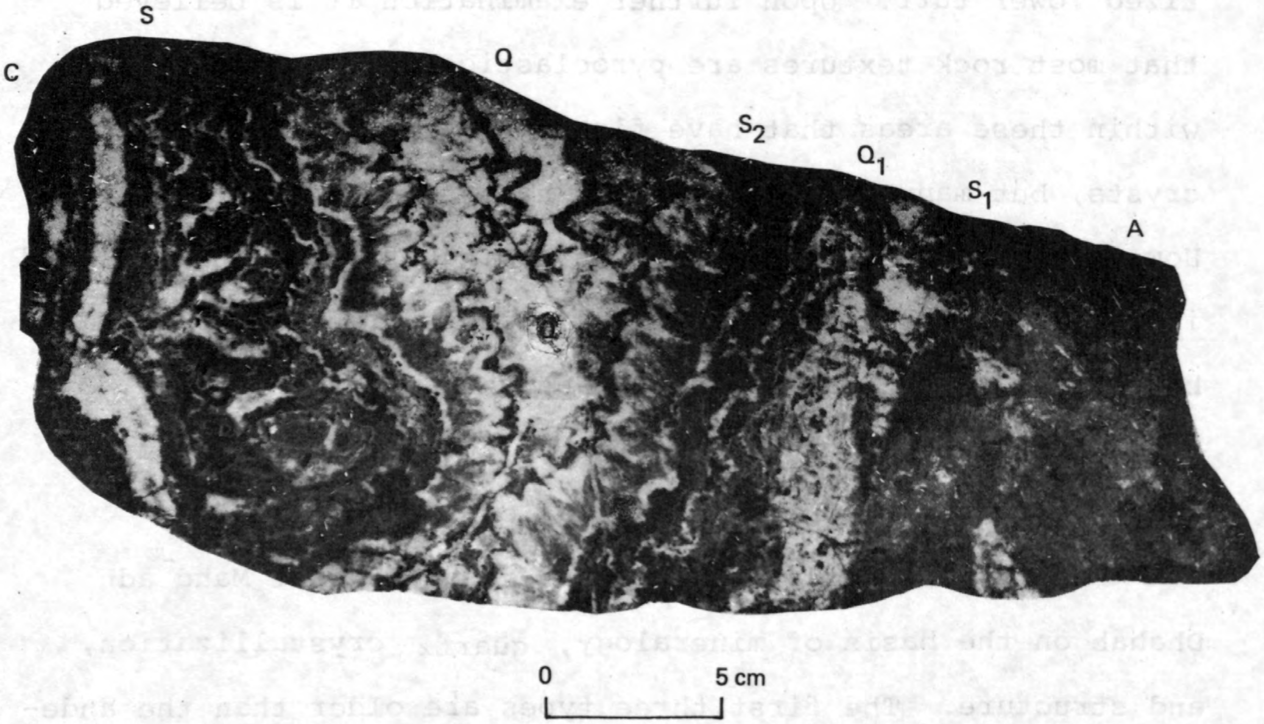
The great preponderance of introduced material is in quartz veins, with which metallization is associated.

Four types of quartz veins are recognized at Mahd adh Dhahab on the basis of mineralogy, quartz crystallization, and structure. The first three types are older than the andesite dikes, and the fourth type is younger than the dikes.

Type 1 veins are mainly massive milky white quartz that formed early in the metallogenic cycle. These veins contain sparse pyrite and commonly have a low gold content.

Type 2 veins are composed of banded and crustified milky to clear quartz, generally with comb or cockade structure. Red to pink potassium feldspar (maximum microcline) is commonly an early mineral in this type of vein, and was followed by banded base metal sulfides--chalcopyrite, galena, and sphalerite. Fe-rich chlorite is commonly interlayered with the sulfides and quartz.

Chemical analyses were made of some type 2 veins to determine the distribution of gold and silver in them. Figure 3 shows one of these veins. Silver is distributed throughout



	Au (ppm)	Ag (ppm)
Chloritic selvage - C	3.80	14.4
Altered tan selvage - S	46.0	50.0
Late quartz vein - Q	0.51	16.0
Altered tan selvage - S_2	96.0	77.0
Early quartz veinlet - Q_1	3.70	77.0
Border selvage - S_1	0.45	17.4
Agglomerate host rock - A	0.92	7.30

Figure 3. Type 2 quartz vein from lower agglomerate showing crustification structure. Chemical analyses are of the different banded units and were performed by atomic absorption following digestion in hydrochloric and nitric acid, at the chemical laboratory of the Saudi Arabian Directorate General of Mineral Resources, Jiddah, under the supervision of W.L. Campbell, A.Z. Khan, and Ibrahim Baraja.

the specimens in galena and tetrahedrite, but gold is mainly in the selvage zones. The two generations of quartz in the specimen shown contain comparatively little gold. According to Goldsmith (1971) much of the gold mined by SAMS was in the selvages of quartz veins; microscopic study of ore specimens supports his statement.

Type 2 veins show well developed banding, cockade, and crustified textures that testify to formation of the vein at shallow depths in open fractures (fig. 3). In some type 2 veins, base metal sulfides are especially abundant and may constitute a base metal ore.

Type 3 veins are characterized by comb quartz, sphalerite and chalcopyrite, and a late-stage carbonate such as ankerite, manganiferous calcite, or calcite. Banded veins showing repeated reopening and filling textures are common (fig. 4).

Quartz veins of type 4, which cut the andesite dikes, are commonly calcareous and contain only sparse sulfides, mostly pyrite plus minor chalcopyrite.

ORE MINERALS

The primary sulfide minerals in order of abundance are pyrite, chalcopyrite, sphalerite, galena, tetrahedrite, and argentite. Native gold and silver accompany the major sulfides. The sulfide minerals mostly crystallized in open spaces and are commonly euhedral. The early pyrite is generally in the form of cubes as much as 0.5 cm on a side. Chalcopyrite commonly replaces pyrite along fracture zones and is mostly fine grained, although some late-stage

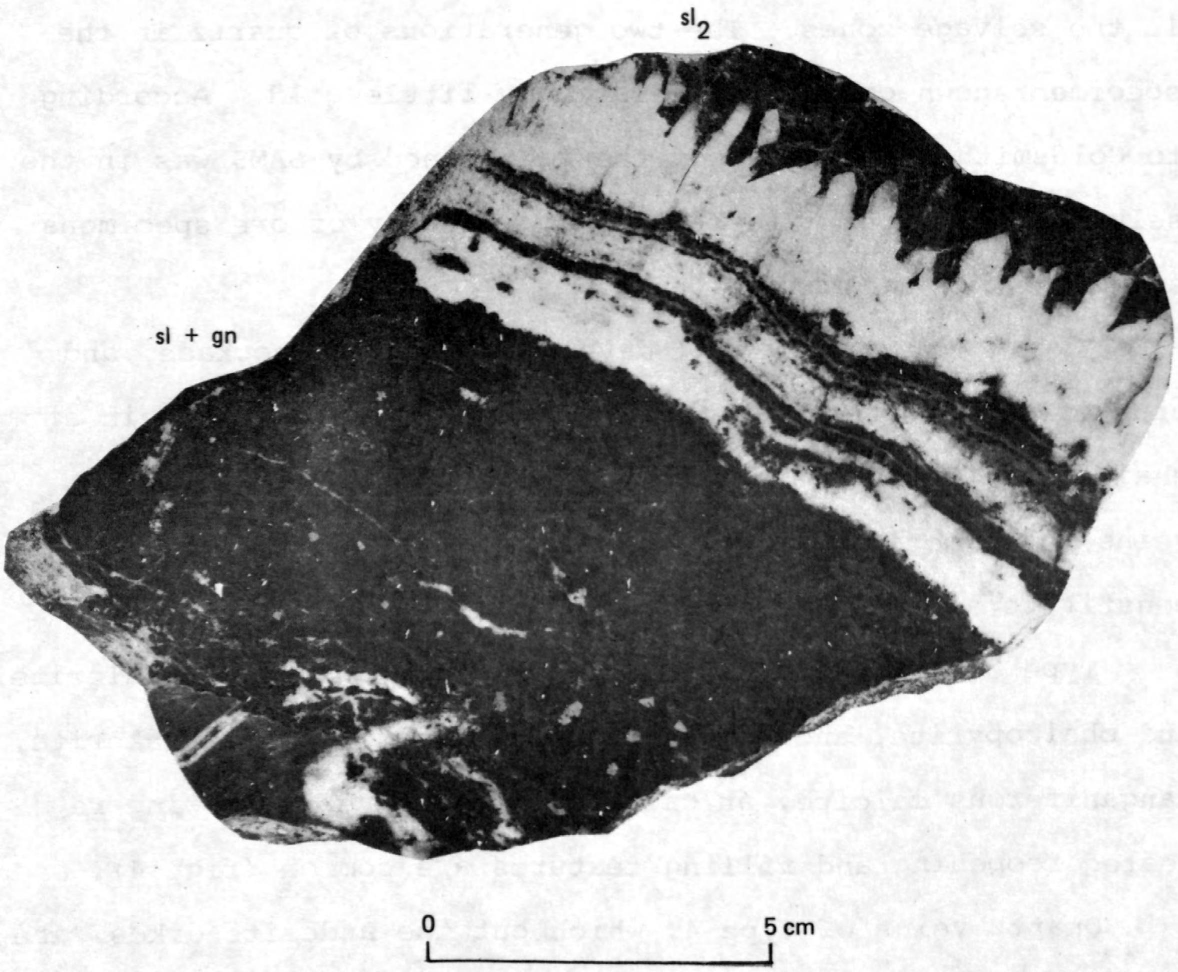


Figure 4. Disseminated sphalerite (sl) and galena (gn) in chloritic gangue bordered by quartz veins, chlorite layers, and late-stage massive sphalerite (sl_2).

chalcopyrite is coarsely crystalline. Sphalerite ranges from finely to coarsely crystalline and dark gray to black. It commonly contains exsolved chalcopyrite in an emulsion texture. Galena is generally fine grained and is closely associated with chalcopyrite and sphalerite. Tetrahedrite and chalcopyrite are frequently found altered in part to covellite and malachite. Native silver is very fine grained and is mainly associated with galena, sphalerite, and tetrahedrite. Minor argentite and a mineral suspected to be pyrargyrite or polybasite have also been found. Gold is most commonly fine grained and occurs as the free metal in quartz or chlorite. A few small crystals and some gold wires were seen in hand specimens, but generally the grains are too small to be recognized except under the microscope. The native gold sometimes has tiny inclusions of a weakly anisotropic mineral, which is probably a telluride such as calaverite.

The sulfide minerals are commonly weathered in the oxidized zone to a depth of 10 m or more. Pyrite alters to limonite and hematite; chalcopyrite and tetrahedrite to covellite, chalcocite, malachite, and chrysocolla; sphalerite to hydrozincite, hemimorphite, and smithsonite; galena to anglesite and cerussite; and the manganiferous carbonates to wad and pyrolusite.

PARAGENESIS

Study of polished slabs, ore mounts, and specimens collected from open stopes and dumps has established the general paragenesis of ore and gangue minerals; the sequence of these minerals is shown in table 1.

NATURE OF THE MINERALIZING SOLUTIONS

Standard techniques for fluid inclusion and isotopic study were employed on specimens from drill core, outcrop, and from the SAMS mine dump mainly taken from the higher mineralized eastern third of the jabal. Variations in the isotopic compositions and fluid inclusion temperatures are slight within the small area and depths (<200 m) sampled, indicating that the conditions of hydrothermal alteration and mineralization were fairly uniform with an expected general but slight increase in temperature with depth.

Fluid inclusions

The vein quartz contains a great abundance of tiny secondary fluid inclusions as a result of entrapment of liquid following the intense fracturing in the district. More scarce large (<20μm) primary and pseudosecondary fluid inclusions in diverse veins gave homogenization temperatures that spanned the range 142° to 278°C. Salinity was quite low in all samples measured, and ranged from 0 to 0.1 percent equivalent NaCl by weight. Several of the higher temperature inclusions (254°-278°C) contained liquid CO_2 with a maximum volume proportion estimated at 40 percent.

Sulfur isotopes

The $\delta^{34}S$ values of sulfides are typical of post-magmatic vein-type hydrothermal deposits (table 2). For individual

Table 1.--*Paragenetic sequence of primary ore and gangue minerals, Mahd adh Dhahab*

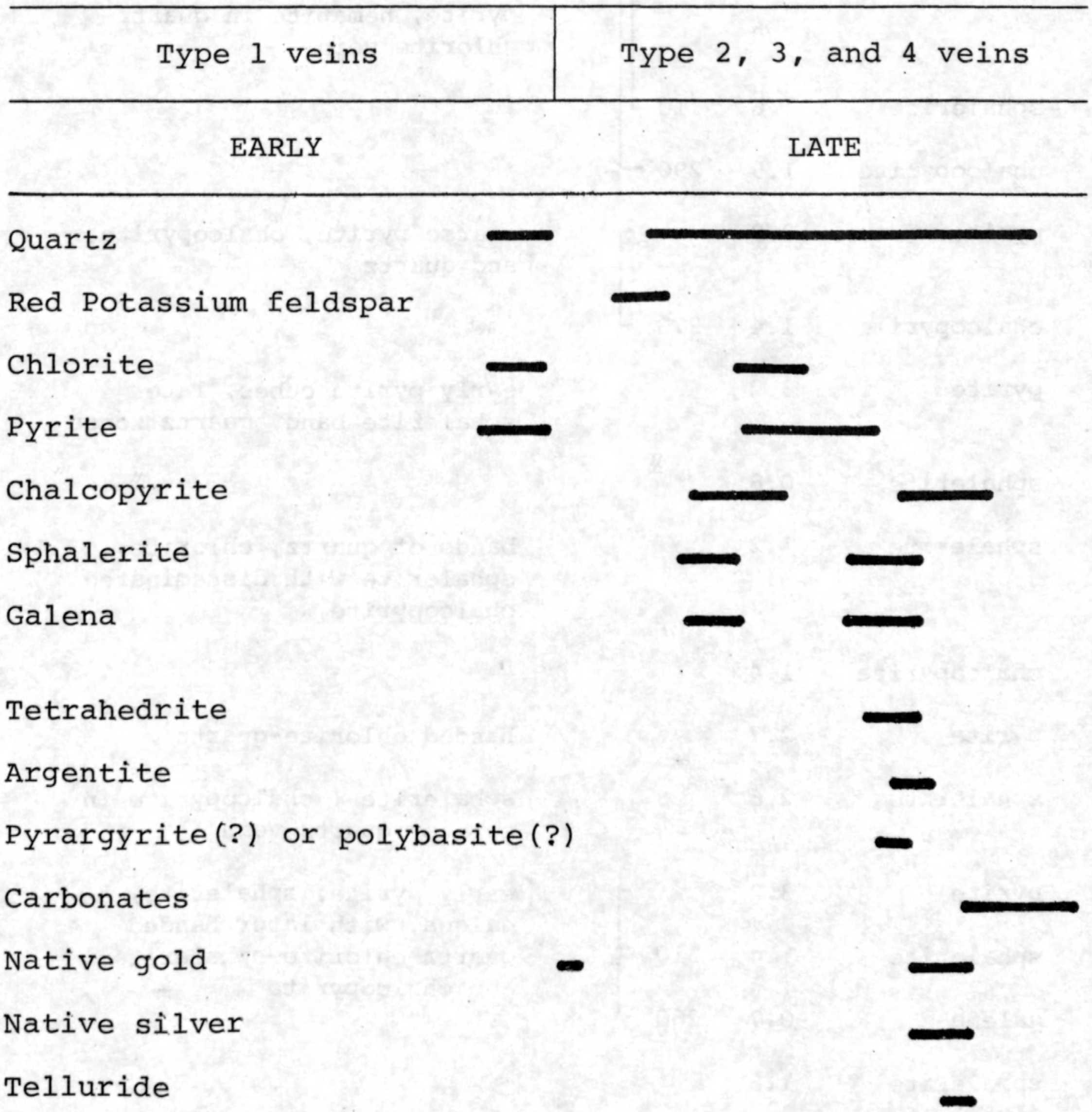


Table 2.--*Sulfur isotope values of coexisting sulfides*

Sample	Mineral	$\delta^{34}S$	T,°C	Description
107930	pyrite	2.9		pyrite, sphalerite, chalcopyrite, hematite in quartz-chlorite vein
	sphalerite	1.6	210	
	chalcopyrite	1.5	290	
107933	pyrite	2.9		coarse pyrite, chalcopyrite, and quartz
	chalcopyrite	1.4	270	
87376A	pyrite	3.2		early pyrite cubes, late sphalerite band, quartz zones
	sphalerite	0.8		
87375	sphalerite	1.2		bands of quartz, chlorite, sphalerite with disseminated chalcopyrite
	chalcopyrite	1.4		
69116	pyrite	2.7		banded chlorite-quartz
87281	sphalerite	2.6		sphalerite + chalcopyrite in earlier quartz vein
69115	pyrite	3.2		early pyrite, sphalerite, galena, with later banded quartz-chlorite-sphalerite and chalcopyrite
	sphalerite	1.4	310	
	galena	-0.7	260	
	sphalerite (late)	1.6		
87281	sphalerite	2.7		brecciated pyroclastics surrounded by quartz, chalcopyrite, and sphalerite
87283	chalcopyrite	1.6		quartz with chlorite stringers chalcopyrite

minerals, values have a narrow range: from 2.7 to 3.2 permil in pyrite and from 0.8 to 2.6 permil in sphalerite, but probably cover a wider range in the paragenesis. $\delta^{34}S$ values in coexisting mineral pairs (galena-sphalerite, pyrite-sphalerite, and pyrite-chalcopyrite) indicate temperatures of 210°-290°C. All of these minerals probably precipitated prior to the deposition of late vein quartz and thus the indicated temperatures are reasonable for depositional temperatures. The fact that the mineral pairs always give reasonable temperatures even though they are not contemporaneous suggests that the chemistry of the hydrothermal solutions was very tightly controlled during the deposition of the various sulfides by equilibration with the volcanic host rocks in the ore zone or at depth. It is this tendency toward equilibration, along with the lower $\delta^{34}S$ values, that separates the Mahd adh Dhahab sulfur isotope data from those for Jabal Sayid (50 km northwest) and other massive sulfides in Arabia (Roberts and others, 1978b).

The sulfur at Mahd adh Dhahab may have been derived from igneous sources; however, it possibly may have come from a massive sulfide deposit, inasmuch as its $\delta^{34}S$ value is close to average $\delta^{34}S$ value of many of the Arabian massive sulfides.

Oxygen, carbon, and hydrogen isotopes

Field and petrographic observations that carbonate formed later than most of the quartz are substantiated by the ^{18}O disequilibrium between coexisting quartz and carbonate (table 3). $\delta^{18}O$ of calcite is higher than that of quartz

Table 3.--*Oxygen, carbon, and hydrogen isotopic values of quartz-carbonate pairs, microclines, chlorites, carbonates, and quartz*

[q = quartz, c = carbonate]

Sample	$\delta^{18}O_q$	$\delta^{18}O_c$	$\delta^{13}C_c$	δD	Description
97896	9.96	8.26	-6.67	-	coexisting vein quartz and carbonate
105177	11.66	-	-	-	Do.
105426	11.15	11.83	-7.08	-	Do.
110286	8.91	9.36	-6.56	-	Do.
110356	8.85	19.60	-5.66	-	Do.
69079	10.19	15.24	-6.99	-	Do.
64026	10.31	-	-	-	microcline bordering quartz vein; Rb/Sr dated
69070	9.36	-	-	-	microcline; metasomatized lower agglomerate
69026	2.59	-	-	-65	chlorite; propylitized andesite
97668	7.22	-	-	-66	chlorite; vein selvage
69169	-	11.95	-6.46		carbonates
69122	-	14.45	-6.27		Do.
64033	-	15.74	-7.43		Do.
69122	-	16.42	-6.48		Do.
64032	-	14.34	-6.41		Do.
64105	15.66	-	-7.58	-75	quartz; 171-278°C homogenization method
64120	-	-	-	-39	quartz; 151°C homogenization method

in all samples except 97896, for which $\Delta_{Q-C} = +1.7$ permil[1]. This latter case corresponds to a temperature of 450°C (Bottinga and Javoy, 1973) that is not in agreement with all other temperature determinations. A more reasonable explanation is that carbonate formed later and at a lower temperature than quartz. This is the obvious explanation where $\delta^{18}O$ for calcite is +15 or +19 permil.

The $\delta^{18}O$ values of the water involved with quartz ranges from -0.3 to 3.1 permil if we take T = 200°C for the formation of all quartz analyzed ($\Delta^{200}_{Q-W} = 12.0$ permil, Clayton and others, 1972). The exception is 64105 quartz with a $\delta^{18}O$ value of 15.66 permil. If 64105 quartz formed at 200°C, $\delta^{18}O_W = +3.56$ permil and might indicate a magmatic component. More likely it could have formed in water of $\delta^{18}O \simeq 0$ permil, but at a temperature $\simeq$ 150°C.

Likewise, both microcline types, which have similar $\delta^{18}O$ values, thus suggesting a similar origin, yield a range of $\delta^{18}O_W = -0.1$ to 1.0 permil using the equation of Bottinga and Javoy (1973). A similar value for the water causing the chloritization can be obtained by a circuitous route. Primary Sierra Nevadan chlorites have an average $\delta^{18}O$ value of +4.0 permil (O'Neil and Dodge, unpub. data) and with $\delta^{18}O_W$ assumed to be +8.0 permil, a typical magmatic value, we reason to a Δ_{Chl-W} value of -4.0 permil at 700°C. Now, $\Delta_{M-W} = -1.0$ permil at the same temperature and $\Delta_{M-W} = 3.0$ permil

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[1] Subscripts are Q, quartz; C, carbonate; W, water; Chl, chlorite; M, muscovite. $\Delta_{Q-C} = \delta^{18}O_{quartz} - \delta^{18}O_{calcite}$.

at 200°C (Bottinga and Javoy, 1973). If we assume the change in the isotopic fractionation factor with temperature, $\frac{\partial\alpha}{\partial T}$, to be approximately the same for chlorite-water and muscovite-water, we conclude that $\Delta_{Chl-W} = +3.0$ permil at 200°C. Therefore, water in equilibrium with 69026 chlorite would have had $\delta^{18}O \simeq -0.4$ permil. The assumptions involved in this calculation are not so gross as to affect the value more than 1-2 permil.

Thus, all indications are that the hydrothermal waters had $\delta^{18}O$ values near zero and probably up to 3 permil lighter. Despite the fact that the Mahd adh Dhahab hydrothermal solutions were Precambrian, they were isotopically similar to the only modern ground waters measured in the region (Oman), for which $\delta^{18}O$ ranges from +0.4 to -1.7 permil (Barnes and others, 1978). This similarity, coupled with the low salinity in fluid inclusions, leads us to the conclusion that the waters were preponderantly meteoric. The mineralizing waters of Mahd adh Dhahab closely resemble in isotopic composition and low salinity those of epithermal Tertiary Au-Ag deposits in the Great Basin of Nevada (O'Neil and Silberman, 1974).

The carbon isotope data is all in the narrow range of -7.58 to -5.66 permil, which is typical for mantle-derived carbon (Taylor and others, 1967; Pineau and others, 1976). Again, the data resemble those for younger epithermal deposits in the western U.S. where carbon and sulfur had a deep-seated source and water, at least in the late stages, had come from above.

Deuterium isotope data are more ambiguous. Based on minerals such as serpentine and muscovite Δ_{Chl-W} at 200°C is about -70 permil. The exact fractionation depends on the chemical composition of the octahedral site (Suzuoki and Epstein, 1976; Kuroda and others, 1976). Therefore, it appears that if $\delta D_{Chl} = -65$ permil, then the water had a δD_W value close to zero, compatible with the oxygen isotope calculations. Quartz samples 64105 and 64120 gave δD values of -75 and -39 permil, respectively, for water in inclusions. Chlorite of $\delta D = -65$ permil could have formed in water of $\delta D = -39$ permil if the temperature had been about 400°C. δD_Q for sample 64105 remains anomalous for being so low, but perhaps its fluid had a magmatic component.

SUMMARY

The Precambrian pyroclastic rocks that make up Jabal Mahd adh Dhahab range from andesitic to rhyolitic in composition and were probably deposted in a caldera environment. They were tilted but only gently folded into a homoclinal structure, which was then repeatedly sheared, fractured, and block faulted. Silicic and potassic metasomatism took place in the northeastern and western parts of the jabal and also formed northeast-, northwest-, and north-trending quartz veins throughout. An epithermal mineral assemblage consisting mainly of pyrite, chalcopyrite, sphalerite, galena, tetrahedrite, argentite, tellurides, and native gold and silver was introduced into the quartz veins and their chloritic selvages. Isotopic age dating of vein feldspar shows that mineralization took place in late Precambrian time.

The early hydrothermal solutions that propylitically altered the country rock and precipitated K-feldspar, sulfides, and some quartz had temperatures in the range 200°-310°C. Later solutions that precipitated quartz and precious metals had temperatures in the range 150°-200°C and had low salinities. Introduced sulfur and carbon came from a deep-seated source, whereas most of the water, particularly in the later stages, had a meteoric origin. The Precambrian hydrothermal solutions had an isotopic composition similar to that of present day ground water in the region, an interesting but perhaps fortuitous fact.

The preservation in the Arabian Shield of a mineral deposit that formed at a high crustal level probably is due to downward block faulting of the jabal.

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