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GEOLOGY AND ORE DEPOSITS OF THE MAHD ADH DHAHAB DISTRICT, KINGDOM OF SAUDI ARABIA

by

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ABSTRACT

Mahd adh Dhahab is the principal gold-silver mine in Saudi Arabia; it was productive during three principal periods, two during ancient times (about 950 B.C. and 750-1258 A.D.) and one in modern times (1939-54). The early production is not known, but the recorded production in 1939-54 is 765,768 fine ounces gold and 1,002,029 ounces silver.

The district is underlain by a sequence of pyroclastic and clastic rocks which probably belong to the Murdama Group. 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 they 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 pyrite, chalcopyrite, sphalerite, galena, and minor tetrahedrite, argentite, and native gold and silver. The gold and silver occurs finely disseminated in the veins and in the altered selvages of the veins. Widespread potassic and propylitic alteration accompanied the ore-forming processes. Potassium feldspar was introduced during an early stage of vein formation. Isotopic analyses of lead in vein potassium feldspar and galena yield a modèl age of about 900-1050 million years with the possibility of the original lead source having been remobilized about 600 million years ago. Chlorite and carbonate are also prominent vein minerals.

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INTRODUCTION

The Mahd adh Dhahab gold-silver mine is the most productive mine in Saudi Arabia. It was worked extensively during the reign of Solomon (961-922 B.C.) and during the Abbasid Caliphate (750-1258 A.D.) and again in the years 1939 to 1954 by the Saudi Arabian Mining Syndicate (SAMS). Production during 1939-54 totals 765,768 fine ounces gold and 1,002,029 ounces silver. Recent substantial increases in the price of gold and possibilities for modern lower cost methods of mining and ore processing have given impetus to further investigations in this well-mineralized district to determine its future potential.

This report on the geology and ore deposits of Jabal Mahd adh Dhahab is one of a series of reports that will summarize a reinvestigation of the Mahd adh Dhahab district. A geochemical sampling program is being undertaken in the district and previous mining data and underground geology are being investigated. Geophysical studies in the district are also being undertaken (Al Akil, written commun. 1976), as is the placer potential. An exploratory diamond drilling program is in process. The work is being done as part of a program of mineral deposit investigation being conducted cooperatively by the Saudi Arabian Directorate General of Mineral Resources and the U. S. Geological Survey.

The aim of the present report is to provide a geologic and structural framework for Jabal Mahd adh Dhahab and to discuss pertinent details of alteration and ore-forming processes.

The highest point near the center of Jabal Mahd adh Dhahab is at an elevation of 1238 m, at lat. 23°29'59.3"N. and long. 40°51'38.2"E. The town of Mahd adh Dhahab lies 2 km north and is situated on the main north-south inland route in the southern Hijaz, roughly midway between Makkah and Medina (fig. 1). The drive from Jiddah to Mahd adh Dhahab requires about 7 hours.

Jabal Mahd adh Dhahab was mapped on a scale of 1:2500 using a topographic map prepared by KLM. One and a half months were spent in the field in 1972-73. The southeast one-third of the mountain was mapped by plane table directly at 1:2500-scale. The geology of the northeastern part of the area (Mine Hill) was modified from a 1:480-scale map of Dirom (1947). The geology of the western and northwestern parts were mapped on aerial photographs and compiled on the 1:2500 base map using a Kern PG2L stereoplotter (plate 1).

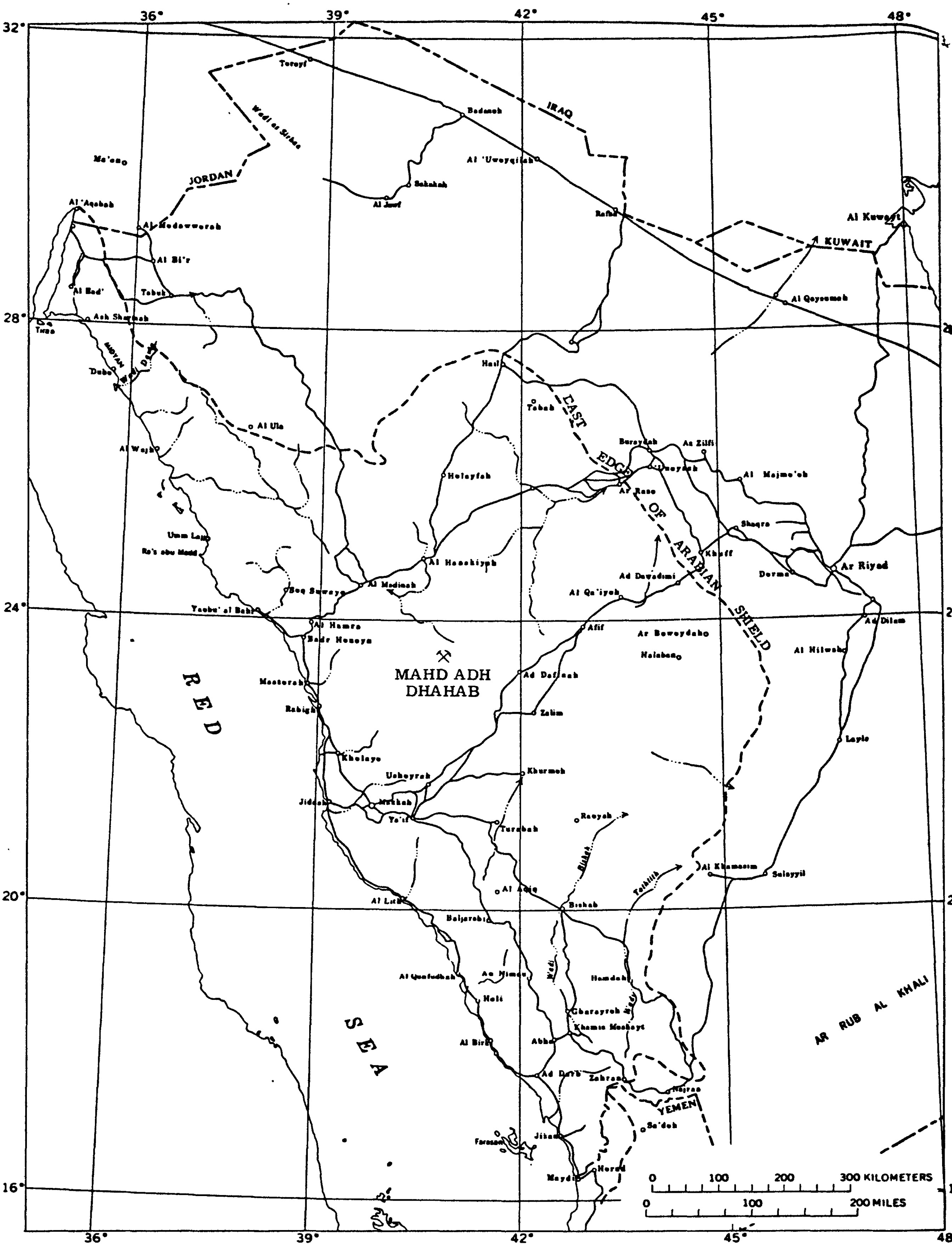


Figure 1.- Index map of western Saudi Arabia showing the location of Mahd adh Dhahab.

Geologists of the Saudi Arabian Mining Syndicate first visited the Mahd adh Dhahab area in the early 1930's and wrote short reports on the area (Dirom, 1946, 1947; Playter, 1953); copies of some of these reports are now in the files of the Directorate General of Mineral Resources in Jiddah. In 1943, Dirom completed a map at a scale of 1:3600 of the area in and surrounding the SAMS concession. This map was later incorporated in reports by Theobald (1965) and Goldsmith (1968, 1971). The regional geology of the Northwestern Hijaz quadrangle (1:500,000) was compiled by Brown and others (1963). Davis and others (1972) reported on shallow geophysical exploration of the western side of Jabal Mahd adh Dhahab as a prelude to physical exploration carried on by Theobald (1965).

SEDIMENTARY AND VOLCANIC ROCKS

The sequence of rocks of Precambrian age in the Jabal Mahd adh Dhahab area from oldest to youngest is andesite, lower agglomerate, lower tuff, upper agglomerate, and upper tuff (table 1). Maclean (1961) named these rocks the Mahd adh Dhahab Series. Brown and others (1963) later mapped this series as Halaban Andesite and Fatima Formation. During study of the regional geology in 1966, Goldsmith pointed out that the units at Mahd adh Dhahab greatly resemble units in a section of Fatima Formation he measured in Wadi Fatima, but Goldsmith and Kouther used Maclean's (1961) name, Mahd adh Dhahab Series, and correlated the sequence with the Murdama and Fatima Formations. More recently, Aguttes and Duhamel (1971) have assigned the sequence to the Halaban Group. W. R. Greenwood (oral commun., 1973) disagreed with this assignment, and suggested that the rocks at Mahd adh Dhahab more properly belong to the Murdama Group because they rest on granitic rocks of the kind that intrude the Halaban Group elsewhere in the region.

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 unconformably underlies the younger units in the jabal, but this relationship cannot be seen in the map area (plate 1) due to 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 dense, and is commonly uniformly fine grained, although porphyritic layers are locally present.

Table 1. - Stratigraphic section at Mahd adh Dhahab

Lithologic unit	Thickness (meters)	Lithology and stratigraphic relations	Favorability for mineralization
Surficial deposits	0-10	Talus, coarse debris on slopes and fans; includes dumps in mined areas. Younger alluvium, coarse, unsorted silt to gravel-size debris. Older alluvium, in part well washed material of sand to gravel size	Contains placer deposits, especially in older alluvium
Upper tuff	200	Tuff, thin-bedded, fissile, white to cream ashfall; weathers light brown to purplish red. Locally contains lapilli tuff layers.	Unfavorable: forms impermeable capping on ore deposits in upper agglomerate
Upper agglomerate	±140	Agglomerate, crystal lapilli tuff with subangular rhyolite, andesite, and jasper fragments. Light olive gray where fresh; weathers reddish brown	Favorable: well mineralized
Lower tuff	207 — 80	Upper part, mostly alternating tuff and sandstone; local lapilli tuff and shaly layers.	Unfavorable: contains weakly mineralized quartz veins
	72	Middle part, sandstone, gray to green; subgraywacke; and lapilli tuff layers.	
	55	Lower part, siliceous ashfall tuff, cliff-forming, fine-grained, laminated; some sandy units; local lapilli tuff layers.	
Lower agglomerate	±120	Agglomerate, dark greenish-gray, weathers tan to reddish gray. Lithic fragments mostly andesite in lower part, rhyolite and jasper in upper part. Mostly poorly bedded; some tuff interbeds	Favorable: well mineralized along quartz veins and faults
		UNCONFORMITY	
Andesite	300	Andesite, mostly dense to fine-grained; some crystalline units may be dioritic sills; few intercalated pyroclastic layers. Generally propylitically altered; in fault contact with lower agglomerate	Unfavorable: poorly mineralized

Some units are crystalline and resemble diabase or diorite. The color of the fresh rock is generally dark olive green and it weathers tan. A few layers also are fragmental, suggesting 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. No original mafic minerals remain because of strong alteration to chlorite, epidote, and magnetite, although outlines suggestive of the former presence of clinopyroxenes were noted. Pyrite cubes are present in many specimens.

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 actual thickness of the agglomerate was not measured, but scaled on a cross section it was as much as 120 m.

The lower agglomerate is dark greenish gray; where deeply weathered it is tan, medium brown, or grayish red. The lithic fragments in basal units are mostly subangular andesite; rhyolite fragments are locally abundant in the upper part. The matrix is tuffaceous, and contains abundant potassium feldspar crystals. These may be, in part, of metasomatic replacement origin. The unit is poorly bedded for the most part, and attitudes can be taken only on thin tuffaceous interbeds. Epidote and chlorite are common alteration products of the matrix. Iron staining is marked along fault zones.

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 the silicification of adjacent rock.

Lower tuff

The lower agglomerate grades upward into the lower tuff through an interbedded zone about 10 m thick (fig. 2).

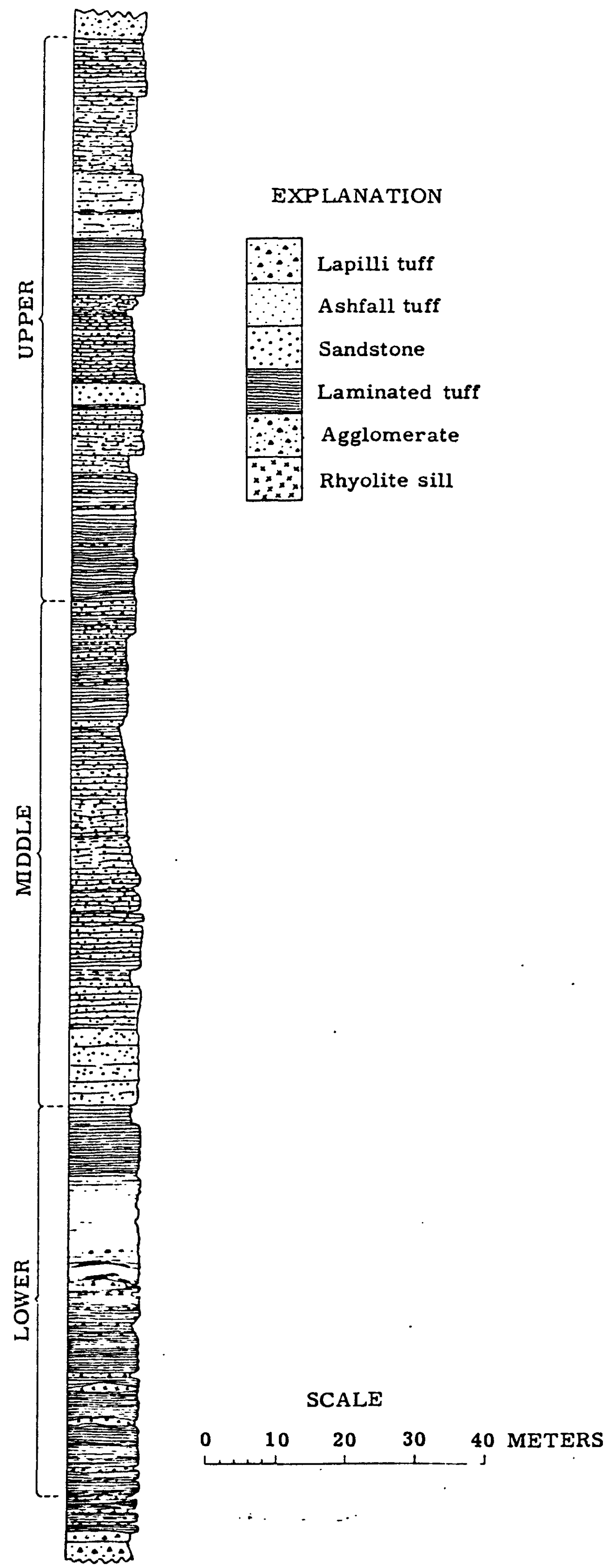


Figure 2. - Stratigraphic section of the lower tuff unit.

The base is taken at the lowest fine-grained unit in the gradational zone. The lower tuff is a resistant unit that makes up the backbone of Jabal Mahd adh Dhahab and forms the highest point.

The lower tuff is a cliff-forming, mostly fine-grained and 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 gray to tan thin-bedded, fine-grained, felsic ashfall tuff which is interbedded with variegated pink, gray, and green lithic lapilli tuff which contains andesitic fragments and sanidine crystals. The fine-grained tuff in places contains glass shards and devitrified spherulites, now partly chloritized, and pink potassium feldspar crystal tuff layers in places. Near the top of this 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 gray to green, medium- to fine-grained sandstone and subgraywacke with lapilli tuff layers in places. Beds near the upper boundary of this part are commonly stained with iron oxides which form prominent liesegang rings.

The top part, 80 m thick, is made up of alternating tuff, sandstone, rare shale beds, and locally lapilli crystal tuffs. The uppermost 28 m is strikingly hornfelsed, probably due to metamorphism by an underlying intrusive body.

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

Upper agglomerate

The upper agglomerate rests conformably on the lower tuff; the basal part of the upper agglomerate is readily eroded, and forms a valley in the northwestern part of the area. The section was not measured, but 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 lapilli tuff with subangular tuff, jasper, and andesitic lithic fragments. It is light olive gray where relatively fresh. It weathers to reddish shades due to weathering of disseminated iron-bearing minerals, especially pyrite.

The upper agglomerate, like the lower agglomerate, was competent, fractured well, and maintained open fractures which are filled with quartz. It is therefore a favorable rock for metallization.

Upper tuff

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

The upper tuff is a thin-bedded, fissile, white to cream ashfall tuff. It weathers light brown to pale violet to purple-red. In places it contains lapilli tuff layers 10 to 20 cm thick. Under the microscope it is seen to consist of ashfall tuff along with some introduced potassium and plagioclase feldspar, quartz, and calcite.

The upper tuff rests with angular unconformity on the upper agglomerate unit. Its relationship to the rhyolite porphyry of Mine Hill is obscured by faulting. The upper tuff is probably older than the rhyolite porphyry as quartz veins believed to be genetically related to the porphyry cut the upper tuff. Many quartz veins appear to terminate against the upper tuff, but this may be because the tuff was an impermeable barrier which deflected the rising hydrothermal solutions.

PLUTONIC ROCKS

The sedimentary and volcanic rocks of the Mahd adh Dhahab area were cut by plutonic rocks at two different periods. The earlier rock is an intrusive plug or dome of rhyolite porphyry and the later are andesite dikes.

Rhyolite porphyry

A rhyolite porphyry body of elliptical shape is exposed on Mine Hill and in the underground workings. The body is about 350 m long and as much as 260 m wide. This rhyolite porphyry was considered by Dirom (1947) to be a volcanic flow and to be overlain unconformably by the upper agglomerate. We were unable to find evidence on the surface for this unconformity and suggest instead that the rhyolite porphyry is a plug or dome.

The rhyolite porphyry is a light olive-gray porphyritic rock with an aphanitic groundmass that weathers light brown. Under the microscope the groundmass consists of microlites of potassium feldspar alined in subparallel flow lines among patches of feldspar and quartz which formed by recrystallization of an original glassy matrix. Subhedral quartz and feldspar microphenocrysts up to 1 mm long are scattered throughout the groundmass. The mafic minerals are now altered to chlorite, hematite, and leucoxene.

Rhyolite porphyry also forms extensive sills in the andesite, lower agglomerate, and lower tuff in the southern part of Jabal Mahd adh Dhahab, in the southwestern part of the area, and on Mine Hill. This facies of rhyolite porphyry weathers to variegated pink, gray, and tan. It contains abundant microperthitic potassium feldspar phenocrysts and lithic fragments; locally on Mine Hill the fragments are abundant, forming pebble dikes. A mosaic texture in the groundmass indicates devitrification. The few contained mafic minerals are now altered to hematite, chlorite, and leucoxene. Clay minerals and white mica have replaced feldspars.

The textures of the two rhyolite porphyry facies are slightly different but the mineralogy is the same. They appear to be parts of an intrusive complex which may underlie most of the jabal. The rhyolite porphyry and its related deeper bodies are the most likely source for hydrothermal solutions which produced the extensive system of quartz and quartz-feldspar veins, propylitic alteration and accompanying ore minerals.

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. These dikes weather readily and locally form trenches with steep walls along their courses.

The dikes are gray to greenish gray and are composed mostly of plagioclase which has been altered to saussuritic aggregates and chlorite which was largely derived from plagioclase and mafic minerals.

Some dikes contain amygdules, mostly composed of chlorite, calcite, and quartz. The dikes were emplaced late in the ore-forming process as they cut and displace veins in many areas (fig. 3). Metallization continued on a small scale into post-dike time as 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 (pl. 1). Talus consists of coarse debris that mantles the lower slopes of the jabal, and also includes dumps discarded by ancient and modern miners. It includes material of a wide age span from Late Tertiary or early Quaternary to Holocene.

Older alluvium includes fan or terrace gravels which are commonly covered by a coating of desert varnish. The finer fractions have been generally washed out, leaving a pebble pavement.

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 are likely to occur several times a year in this area. Some areas underlain by younger alluvium contain placer gold deposits, but the richer sections are commonly in the lower gravel layers, which probably are part of the older alluvium.

STRUCTURE

The principal structural feature at Mahd adh Dhahab is an east-trending homocline that dips northerly. The homocline has been complexly broken by fault sets of six different trends, and has been deformed locally by emplacement of the rhyolite porphyry plug or dome.

The homocline in the southern part of Jabal Mahd adh 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. According to Dirom (1947) the dips underground are locally vertical to overturned on the north flank of the jabal. This steepening and overturning may be related in some way to the forcible emplacement of the rhyolite porphyry.

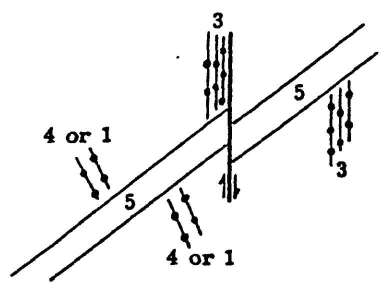
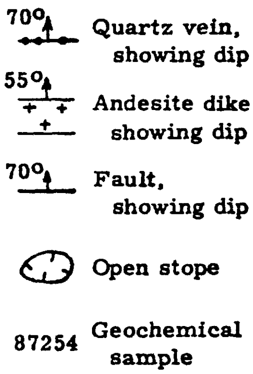


Diagram showing sequence of events in accordance with table 2.



GEOCHEMICAL ANALYSIS (ppm)

Sample number	Au	Ag	Cu	Pb	Zn	Mo
87252	13.4	7.60	600	1 100	1 400	10
87253	4.00	7.30	5 225	3 000	2 100	10
87254	6.60	13.40	435	6 000	5 000	10
87255	24.80	15.60	28 000	5 500	12 000	10
87256	26.80	13.40	4 500	5 000	2 425	10
87257	5.80	5.60	1 050	2 550	950	10
87258	7.40	6.40	17 000	23 000	12 500	10
87259	49.60	11.00	800	6 000	450	10

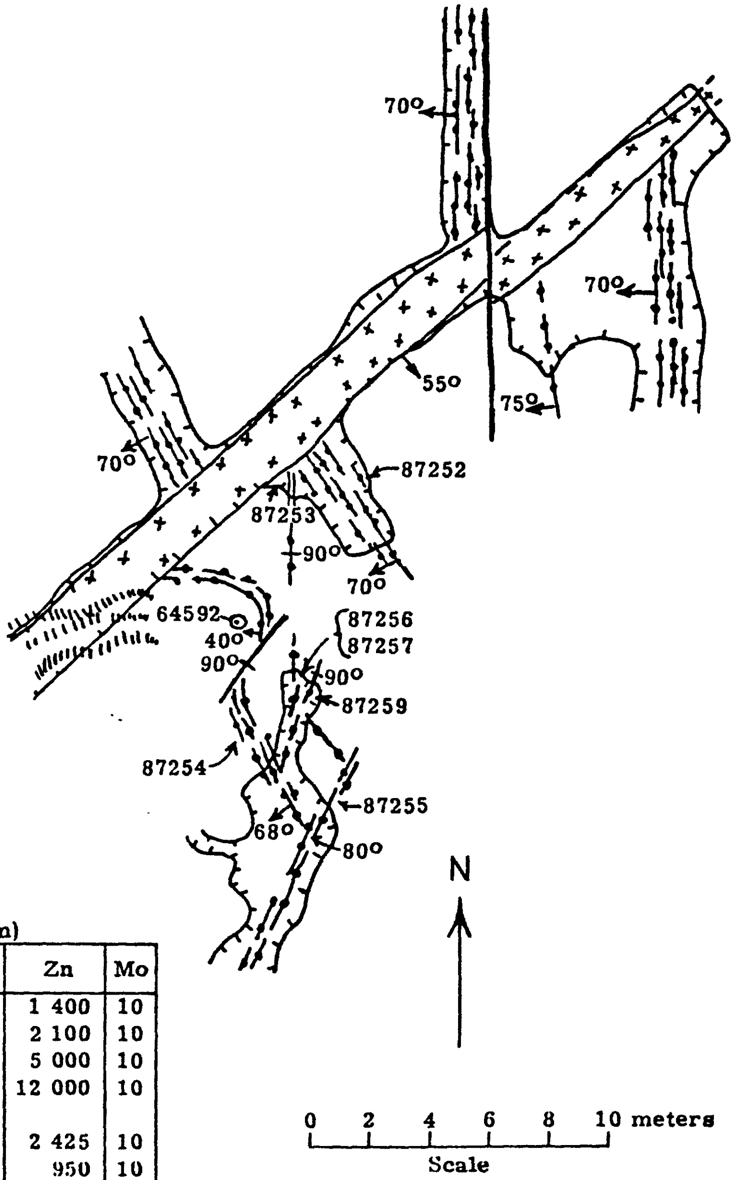


Figure 3. - Geologic map of veins in open stopes near geochemical station no. 64592, Mine Hill.

The homocline is cut by six sets of faults which are listed below, in order of formation:

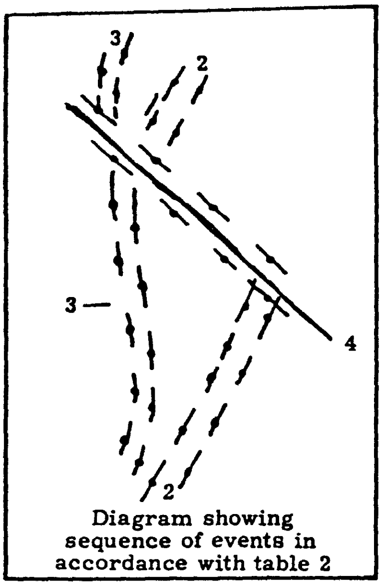
Table 2. Fault trends at Mahd adh Dhahab

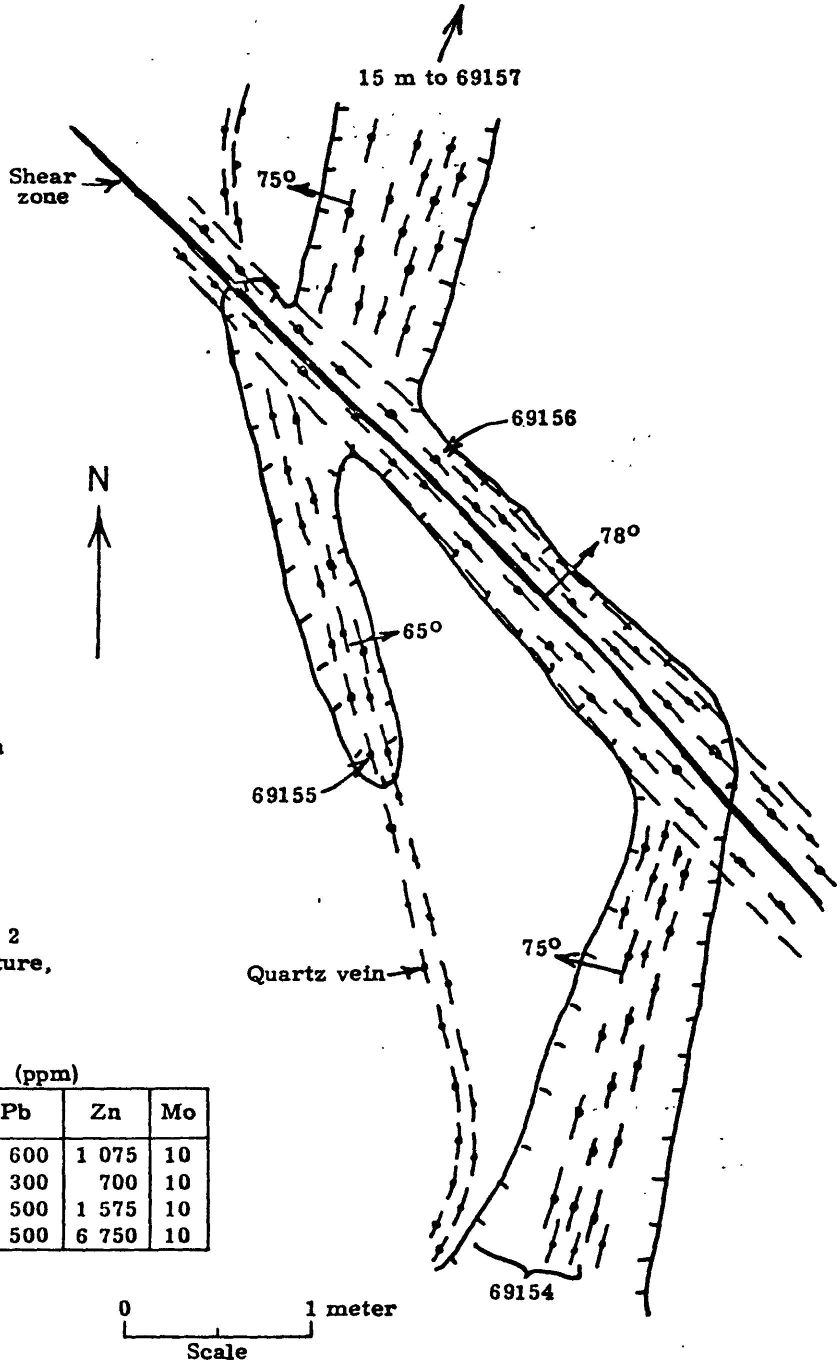
	Trend and dip	Metallization
6.	N.45°W.; vertical to steeply SW.	None
5.	N.30°-45°E.; steep to vertical.	Contains andesite dikes (fig. 3).
4.	N.30°-60°W.; steeply SW to vertical.	Locally significant (fig. 4).
3.	N.10°W. to N.20°E.; steeply W.	Major; veins nos. 8, 15, 18, 20 (figs. 3, 4).
2.	N.30°-60°E.; 35°-65°NW., steepening downward.	Major; veins nos. 4, 14 FW, 16.
1.	N.25°-30°W.; 55°-65°NE. to 70°SW.	Minor.

The oldest fault set 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. The no. 14 vein dips 45°-55° in surface workings and steepens to nearly vertical on lower mine levels. 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 and displaced by the fourth set of faults which strike N.30°-60°W. and dip steeply.

The third fault set strikes north-south (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





Quartz vein

Open stope

All three veins are type 2 (crustified, comb structure, much chlorite)

GEOCHEMICAL ANALYSIS (ppm)

Sample number	Au	Ag	Cu	Pb	Zn	Mo
69154	8.20	12.60	1 400	2 600	1 075	10
69155	16.66	14.20	1 300	2 300	700	10
69156	8.00	7.30	19 250	9 500	1 575	10
69157	15.20	21.80	14 000	41 500	6 750	10

Figure 4.- Geologic map of veins in open stopes near geochemical station no. 87059, Mine Hill

veins which strike north to N.10°E. Veins in this set of faults have been extensively mineralized especially in the lower and upper agglomerates and in rhyolite porphyry at the northeastern end of the jabal. Two veins, nos. 8 and 15, of this set have been productive in underground workings. No. 15 extends nearly a kilometer south but apparently was low in grade south of Mine Hill. There has been repeated movement along faults of this set, and quartz fillings are commonly brecciated.

Long, continuous faults which 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 which they cut.

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

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 accompanying emplacement of the rhyolite porphyry. 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.

ORE DEPOSITS

The Mahd adh Dhahab district is the most productive district in the Kingdom of Saudi Arabia. Radiocarbon dates on slag at the mine indicate that it was mined during two distinct periods in ancient time. Carbon from the older slag gave a date of about 3000 years ago, whereas carbon from other slag gave a date of about 1000 years ago (W. C. Overstreet, written commun., 1973). The older date coincides with the reign of King Solomon (961-922 B.C.) and the younger one with the great expansion of Islamic culture in Syria and Iraq during the Abbasid Caliphate (750-1258 A.D.).

No records of production are available for these early operations, but when Saudi Arabian Mining Syndicate operations began in 1939 it was estimated by Dolph (1942) that nearly 1,000,000 short tons of tailings and dumps were piled around the workings. About 293,848 tons of these were later treated by SAMS and yielded about 0.62 ounce of gold per ton (Twitchell, 1958a, b), so it is inferred that higher grade material was treated in the earlier operations.

During the SAMS operation from 1939 to 1954 nearly 900,000 short tons of ore were milled in a cyanide-flotation plant that had a daily capacity of about 225-300 short tons. About one third of this total tonnage came from old tailings and the remainder came from underground and surface workings. According to Goldsmith and Kouther (1971), 765,768 fine ounces of gold and 1,002,029 ounces of silver were produced between 1939 and 1954; the total value of these metals was about $27,600,000[1].

Table 3 shows available SAMS records of ore milled, production of gold and silver, and gold:silver ratios at Mahd adh Dhahab. During the early operations the Au:Ag ratios ranged from .749 to .928; they increased to 1.091 to 1.500 during 1944 to 1948, then decreased markedly to .530 to .822 during 1949 to 1954. The reasons for the moderate early ratios and high middle ratios are not clear; presumably they are related to the proportions of dump and underground ore milled. The later decrease in gold:silver ratios is probably due to relative increase in underground ore which is inferred to have contained on the average less gold than the near-surface ores.

1/ Twitchell (1958a) reports that 591,200 short tons of underground ore averaged 1.089 ounces gold to the ton and that 1,003,130.92 ounces silver were produced. The gold averaged $40 per ounce and silver $0.80, giving a total production of $31,587,780.

Table 3. SAMS records of ore milled, production, and gold:silver ratios, 1939-1954, Mahd adh Dhahab mine.

YEAR	TONS MILLED					PRODUCTION (Oz.)		RATIO
	ANCIENT TAILING	MINE ORE	MILL TAILING	DUMP ORE	TOTAL	Au	Ag	Au:Ag
1939						15,864	17,866	0.888
1940					76,620	31,964.67	37,625.12	0.850
1941						36,520	45,304	0.806
1942					60,661 1/	32,697	43,677	0.749
1943						44,330	47,768	0.928
1944						4,569	3,514	1.300
1945						36,215	24,145	1.500
1946						49,227	30,556	1.611
1947						52,838	43,104	1.266
1948						73,976	67,818	1.091
1949						66,835	81,295	0.822
1950					63,780	66,251.02	124,286.68	0.533
1951	1,781	59,933	24,832	11,483	98,029	73,103.78	109,912.50	0.665
1952	13,382	70,734	38,041	--	122,157	69,394.39	111,945.69	0.620
1953	8,488	73,844	28,947	--	111,279	81,565.79	150,625.83	0.542
1954 2/	3,963	21,181	1,213	712	27,359	30,592.94	57,680.12	0.530

1/ Excludes total tons milled for November 1942

2/ Figures for Jan-Apr and June, 1954

The ancient workings occur principally on Mine Hill and in the southeastern and western parts of the district. The ancient workings on Mine Hill were stoped to a depth of 85 m; the modern workings are developed on five levels, the quarry level and 50-(SAMS 150'-level), 100-(SAMS 300'-level), 150-(SAMS 450'-level), and 200-meter (SAMS 600'-level) levels. Most of the ore mined came from the nos. 1, 4, 8, 14, and 16 veins which ranged from a meter or less to more than 10 m wide. According to Goldsmith (1971) much of the gold was in the selvages of the quartz veins; studies of ore specimens by the present authors under the microscope support his statement.

Quartz veins

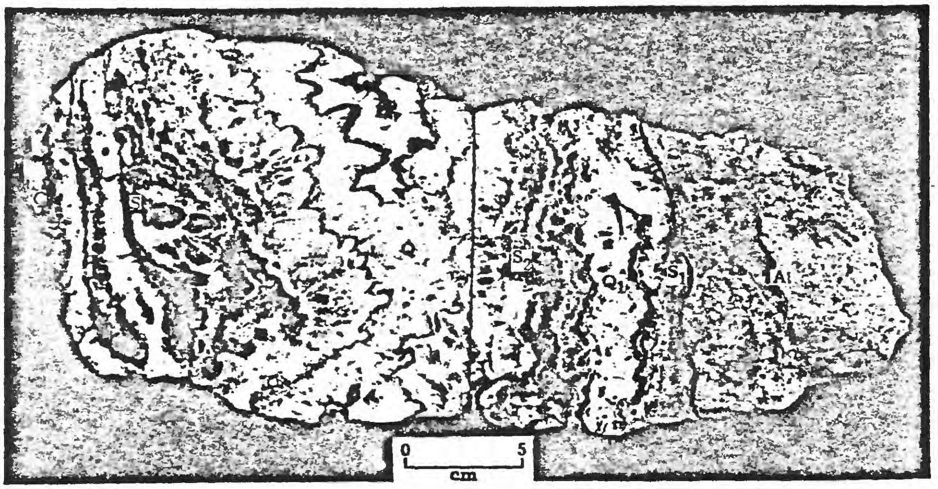
Four types of quartz veins are recognized at Mahd adh Dhahab on the basis of mineralogy, quartz crystallization, and structure. The first three types are older than the andesite dikes, and the fourth type is younger than the dikes.

Type 1 veins are mainly massive, milky white quartz which 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 is commonly an early mineral in this type of vein, and was followed by banded base metal sulfides--chalcopyrite, galena, and sphalerite. 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 5 shows one of these veins. Silver is distributed throughout the specimen in galena and tetrahedrite, but gold is mainly in the selvage zones (S_1 and S_2). The two generations of quartz in the specimen contain comparatively little gold.

Type 2 veins (fig. 6) show well developed banding, cockade, and crustified texture which testify to formation of the vein at shallow depths in open fractures. In some type 2 veins, base metal sulfides are especially abundant and may constitute a base metal ore. Two generations of sphalerite are found in figure 7. The early sphalerite is intergrown with galena in a chlorite matrix. The late sphalerite is intergrown with chalcopyrite in late quartz.



	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 5.- Quartz vein from lower agglomerate showing crustification structure.

Figure 6.- Quartz vein in chloritic breccia showing cockade structure. Chalcopyrite (cp) and pyrite (py) are disseminated throughout the breccia and in shear zones (sz).

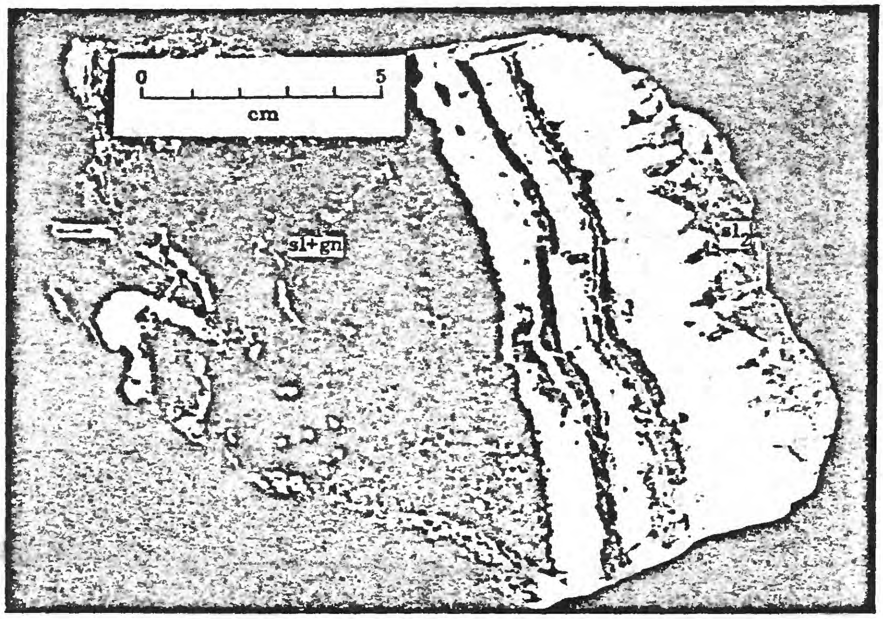


Figure 7. - Disseminated sphalerite (sl) and galena (gn) in chloritic gangue bordered by crustified quartz veins, chlorite layers, and late-stage massive sphalerite (sl_2).

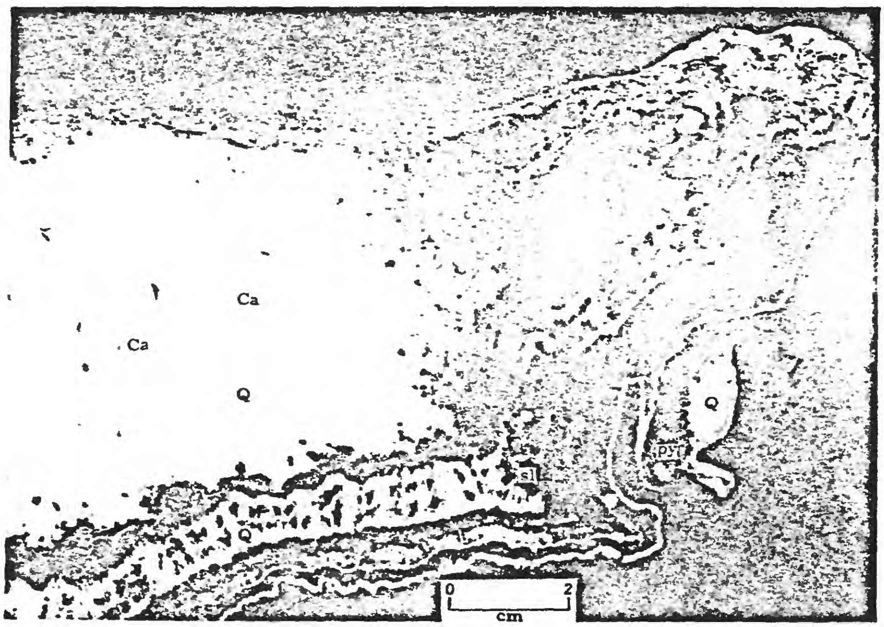


Figure 8. - Crustified quartz veins (Q) locally containing sphalerite (sl). Dark chlorite gangue has scattered pyrite (py) and chalcopyrite veinlets. Quartz in lower right contains calcite (Ca).

Type 3 veins are characterized by comb quartz, sphalerite and chalcopyrite, and a late stage carbonate such as ankerite, manganiferous calcite, or calcite. Figure 8 shows a representative type 3 vein which is well banded with layers of sphalerite, chlorite, and quartz. Banded veins showing repeated reopening and filling textures are common (fig. 9); the carbonate is earlier than that in figure 8.

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

Fluid inclusions from a variety of quartz veins show very low salinity (approximately 0.1 percent by wt. NaCl equivalent) for all samples examined but proportions of liquid CO_2 mixed with liquid water and vapor vary from zero to about 40 percent. Temperatures determined by the homogenization method ranged from 170° to 278°C in one group of specimens and from 150° to 155°C in another group (J. N. Batchelder, written commun., 1974). All fluid inclusions studied were pseudosecondary or secondary but because of the multiple quartz veining in the district the temperatures measured are believed to be meaningful and to indicate epithermal to low mesothermal vein-forming conditions.

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 were 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 (figs. 6, 8, 10); chalcopyrite commonly replaces pyrite along fracture zones and is mostly fine grained, although some late-stage chalcopyrite is coarsely crystalline (fig. 10). 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 (fig. 7) 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 most commonly is fine grained and occurs as the free metal in quartz or chlorite. A few small crystals and some gold wires

Figure 9. - Multiple quartz veinlets formed by reopening during formation. Thin layers of pyrite (py), galena (gn), and sphalerite (sl) in chlorite (c) border quartz veins. Early milky quartz (Qe) and carbonate (Ca) are brecciated and cut by late quartz veins (Q).

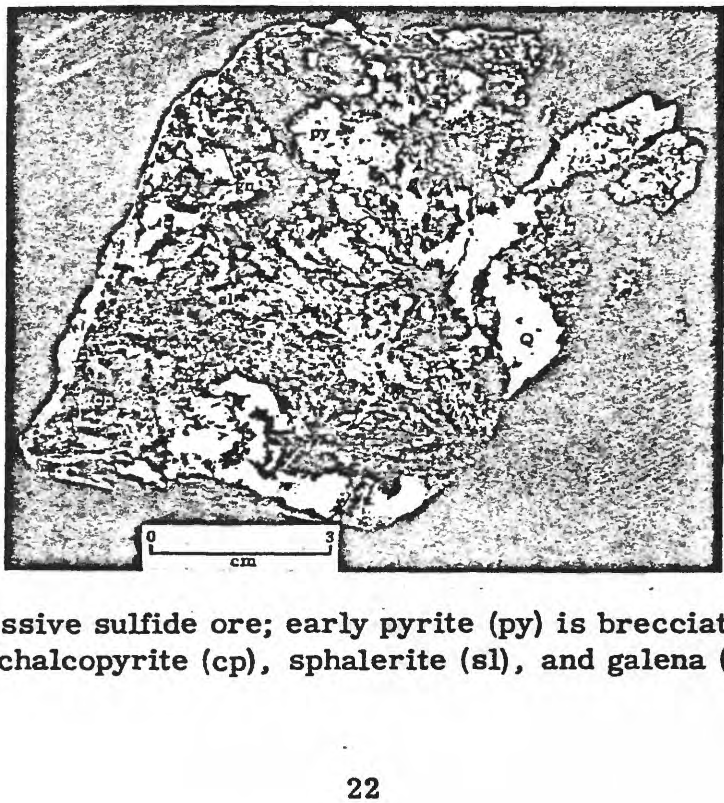


Figure 10. - Massive sulfide ore; early pyrite (py) is brecciated and replaced by chalcopyrite (cp), sphalerite (sl), and galena (gn).

were seen in hand specimens, but generally the grains are too small to be recognized except under the microscope (fig. 11). The native gold sometimes has tiny inclusions of a weakly anisotropic mineral which is probably a telluride such as calaverite.

Gangue minerals

The gangue minerals in order of abundance in the ore include quartz, chlorite, carbonates, and potassium feldspar. The quartz ranges from massive to drusy to comb quartz; most crystals are less than 3 cm thick and 10 cm long.

Chlorite occurs disseminated throughout altered rock and in crustified zones in veins, interlayered with quartz and ore minerals. The carbonates include ankerite, manganiferous calcite, and calcite which fill late stage cavities in the veins.

Potassium feldspar is present as an early-stage alteration mineral in the upper agglomerate (fig. 12) and as an early vein mineral (fig. 13). The crystals range from a fraction of a millimeter to 2 cm long. Two feldspar separates, one from a Mine Hill ore vein and one 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 an Or weight percent of 100.

Isotopic analyses of leads in vein potassium feldspar and in galena at Mahd adh Dhahab by Bruce Doe and Maryse Delevaux (written commun., 1973) indicate a model age of about 900 m.y. but could be as old as 1,500 m.y. The possibility exists that the lead could have been remobilized about 600 m.y. ago (B. R. Doe, written commun., June 1973). The age of the feldspar has been determined by Zell Peterman (written commun. from R. J. Fleck, Feb. 1973). Assuming as a best guess an initial $^{87}Sr/^{86}Sr$ ratio of 0.704, the data yield an age of about 690 m.y.

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 4.

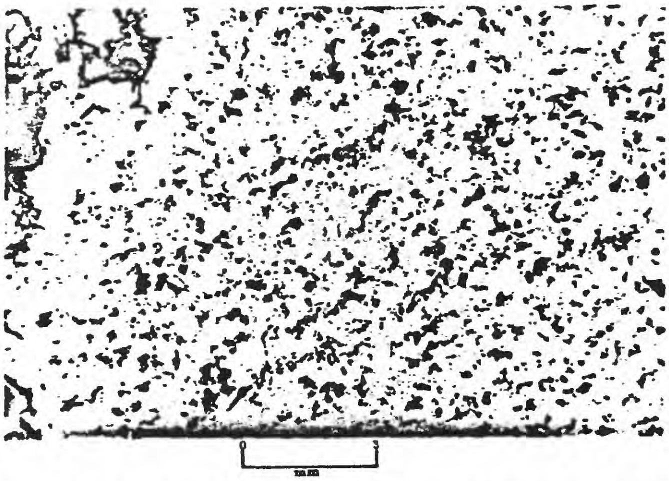


Figure 11. - Disseminated gold (bright) in quartz (light gray).

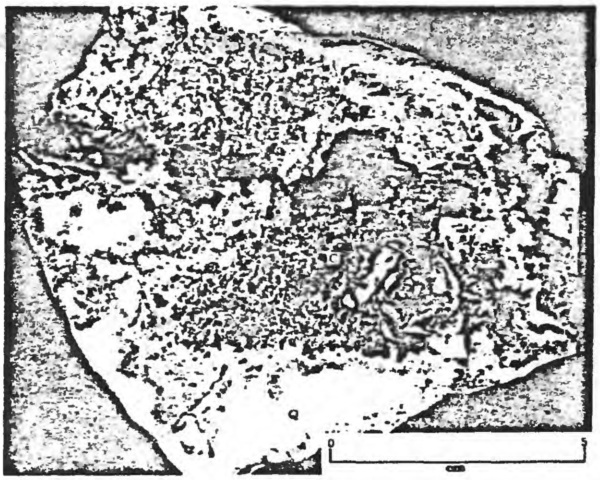


Figure 12. - Breccia of upper agglomerate fragments (a) and chloritized rock (C) cut by potassium feldspar (F) and later quartz (Q).

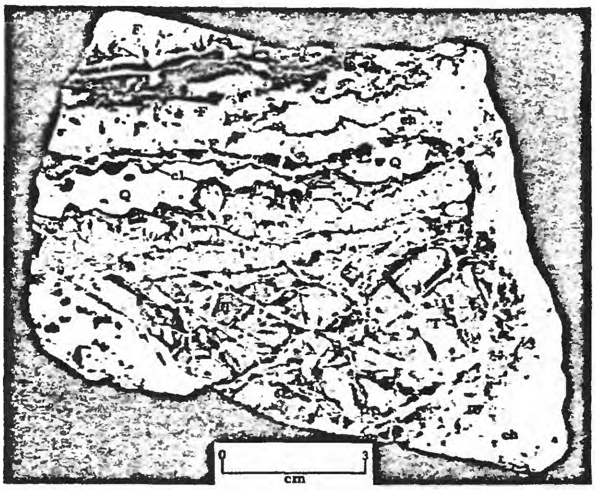


Figure 13. - Tuff unit (T) in upper agglomerate cut by multiple veins of potassium feldspar (F), quartz (Q), and chlorite (cl). Chalcopyrite (ch) and pyrite (py) occur in veins that cut the tuff.

Table 4. Paragenetic sequence of primary ore and gangue minerals, Mahd adh Dhahab.

	Type 1 veins	Type 2, 3, and 4 veins
	EARLY	LATE
Quartz	—	—
Red potassium feldspar		—
Chlorite	—	—
Pyrite	—	—
Chalcopyrite		— —
Sphalerite		— —
Galena		— —
Tetrahedrite		—
Argentite		—
Pyrargyrite(?) or polybasite(?)		—
Carbonates		—
Native gold	—	—
Native silver		—
Telluride		—

Oxide minerals

The sulfide minerals are commonly altered in the oxidized zone to a depth of 10 meters 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; the manganiferous carbonates to wad and pyrolusite.

PLACER DEPOSITS

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. A trenching program carried on in several areas in 1973 showed that the richest ground remaining lies southeast of Mine Hill in several ancient channels. The reserves total about 300,000 cu m of gravel averaging about 90 cents a cu m (gold at $140 an ounce).

SUMMARY AND RECOMMENDATIONS

The productive ore bodies in Mine Hill are mostly in quartz-sulfide veins that cut the upper agglomerate and rhyolite porphyry. Geochemical sampling in this area indicates that mineralization extends well beyond the principal productive veins along fractured and silicified rock into the intervein zones. The mineralized block is about 300 m long and as much as 200 m wide. The mineralized block warrants further testing to determine whether it can be mined profitably by open pit methods.

Geochemical sampling of the lower agglomerate, south of the main mine, along and between north-trending veins (plate 1) also has revealed gold mineralization in a block of rock, the surface trace of which is about 150 m on a side. Further exploration of this block should determine whether it contains material of adequate tonnage and grade to be mined by open pit methods.

A third target that warrants exploration is along the north side of the mine at the junction of the north-trending veins and below the north-dipping upper tuff unit. Examination of the SAMS underground maps indicates that the vein-tuff intersection controls ore bodies that plunge north. Deep drilling along the projected plunge should determine whether these ore bodies are minable at lower depths and whether base metal and silver content of the ores will increase with depth, as is expected. The Mahd adh Dhahab deposits were being diamond drilled in 1974 as a first step in testing these exploration targets.

About 800,000 tons of tailings remain after SAMS 1939-1954 operations. These were sampled and found to average 0.07 oz/t gold and 0.26 oz/t silver, 0.51 percent copper, 1.89 percent zinc, and 0.60 percent lead (Goldsmith, 1971). Preliminary tests by the Newmont Company indicate that cyanide leaching will remove about half the gold and silver in the tailings (A. A. Brant, written commun., 1973). Additional tests should be made to determine whether the base metals can also be recovered.

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