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PRELIMINARY MINERALOGIC, FLUID INCLUSION, AND STABLE ISOTOPE STUDY OF THE MAHD ADH DHAHAB GOLD MINE, KINGDOM OF SAUDI ARABIA

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PRELIMINARY MINERALOGIC, FLUID INCLUSION, AND STABLE ISOTOPE STUDY OF THE MAHD ADH DHAHAB GOLD MINE, KINGDOM OF SAUDI ARABIA

by

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ABSTRACT

The Mahd adh Dhahab mine, located about 280 km northeast of Jiddah, Kingdom of Saudi Arabia, has yielded more than 2 million ounces of gold from periodic production during the past 3,000 years. A new orebody on the southern side of the ancient workings, known as the South orebody, is being developed by Gold Fields-Mahd adh Dhahab Limited. A suite of samples was collected from the newly exposed orebody for preliminary mineralogic, stable isotope, fluid inclusion, and geochemical studies.

The Mahd adh Dhahab deposit is in the carapace of a Proterozoic epizonal rhyolite stock that domed pyroclastic and metasedimentary rocks of the Proterozoic Halaban group. Ore of gold, silver, copper, zinc, tellurium, and lead is associated with north-trending, steeply dipping quartz veins in a zone 1,000 m long and 400 m wide. The veins include an assemblage of quartz-chlorite-pyrite-hematite-chalcopyrite-sphalerite-precious metals, which is similar to the mineral assemblage at the epithermal deposit at Creede, Colorado.

The primary ore contains abundant chalcopyrite, sphalerite, and pyrite in addition to a complex precious metal assemblage. Gold and silver occur principally as minute grains of telluride minerals disseminated in quartz-chlorite-hematite and as inclusions in chalcopyrite and sphalerite. Telluride minerals include petzite, hessite, and sylvanite. Free gold is present but not abundant.

All of the vein-quartz samples contained abundant, minute inclusions of both low-density, vapor-rich fluids and liquid-rich fluids. Primary fluid inclusions yielded homogenization temperatures of from 110° to 238° C. Preliminary light-stable isotope studies of the sulfide minerals and quartz showed that all of the $\delta^{34}S$ values are between 1.2 and 6.3 per mil, which is a typical range for hydrothermal sulfide

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minerals that derive their sulfur from an igneous source. The data suggest that the sulfide sulfur isotope geochemistry was controlled by exchange with a large sulfur isotope reservoir at depth.

The $\delta^{18}O$ values of all stages of vein quartz in the South orebody range between 8.5 and 11.1 per mil. This range is similar to that for quartz from the North orebody and indicates that the hydrothermal system consisted of dominantly exchanged meteoric water, which was uniform in temperature and $\delta^{18}O$ content throughout the area during the entire period of mineralization.

Lead isotope analyses of two galena samples indicate that the lead in the South orebody is less radiogenic than that from the North orebody and confirm that the lead was derived from oceanic crust approximately 700 Ma ago.

INTRODUCTION

The Mahd adh Dhahab ("Cradle of Gold") mining area, located about 280 km northeast of Jiddah, Kingdom of Saudi Arabia (fig. 1), has produced gold and silver periodically for more than 3,000 years. Probably more than 1 million ounces of gold were produced in ancient times from eluvial deposits and quartz veins, and an additional 1 million ounces were produced between 1934 and 1954 by the Saudi Arabian Mining Syndicate (SAMS). The area to the south of the ancient and SAMS workings is under evaluation by Gold Fields-Mahd adh Dhahab Limited (GFMAD). Previous geological and geochemical studies of the Mahd adh Dhahab district include geologic maps, cross sections, diamond drilling reports, and preliminary geochemical investigations (Dirom, unpub. data, 1947; Luce and others, 1976, 1979; Roberts and others, 1978; Worl, 1978, 1979).

Members of the U.S. Geological Survey (USGS), including the authors of this report, visited the Mahd adh Dhahab area from January 25 to 30, 1981, to collect a suite of samples from surface and underground exposures in the South orebody (fig. 2). These samples were used as the basis of a feasibility study to decide whether to proceed with a detailed modern geochemical study of the deposit that would lead to a genetic model of mineralization when integrated with detailed field studies. The genetic model would be used in part as a basis to evaluate the area's resource potential and in part to develop exploration parameters to assess the economic potential of other similarly mineralized areas.

This report presents the results of four elements of the feasibility study by various members of the USGS and recommends that the detailed study be conducted. The work on which this report was based was performed in accordance with

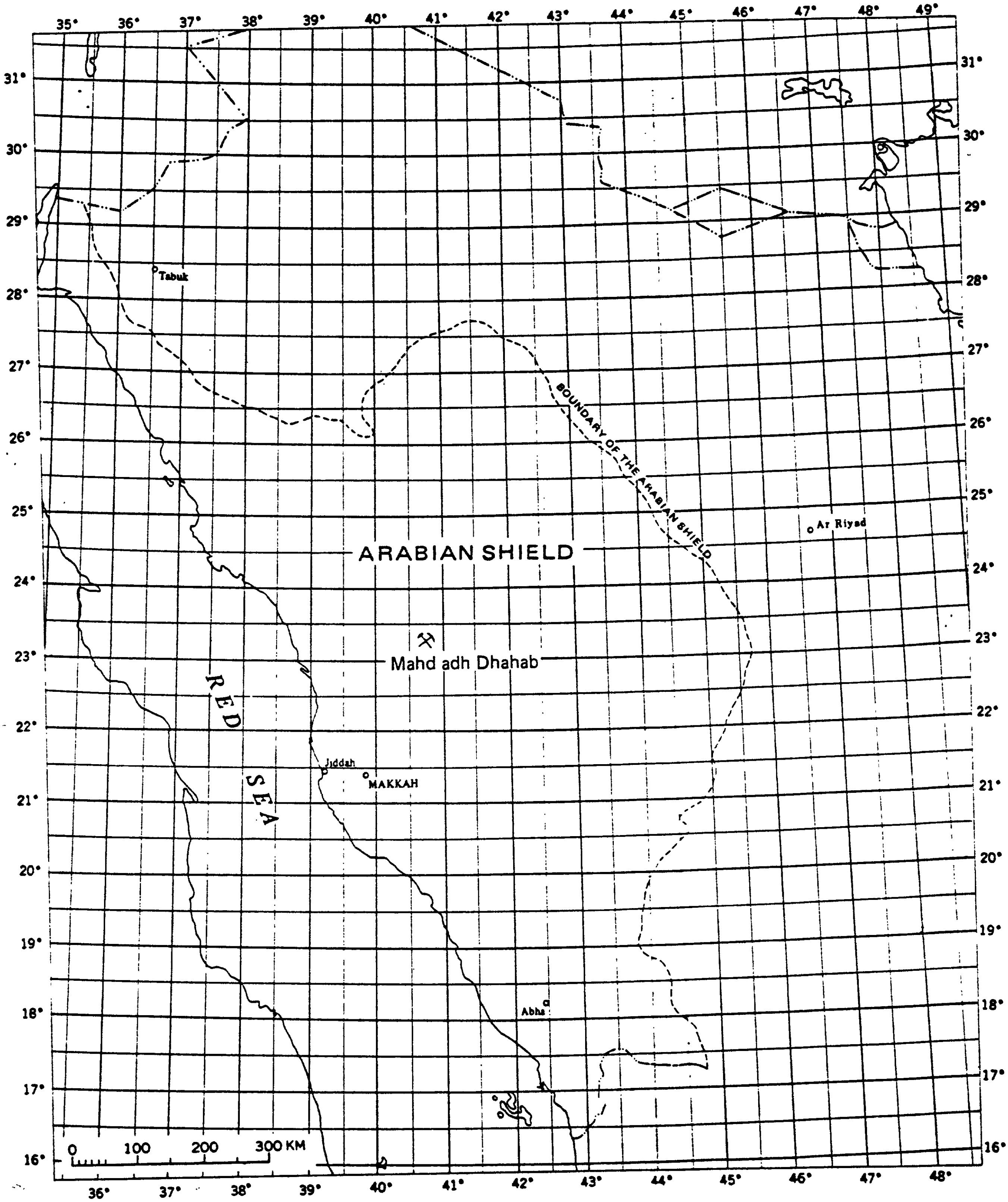


Figure 1.--Index map showing location of Mahd adh Dhahab area.

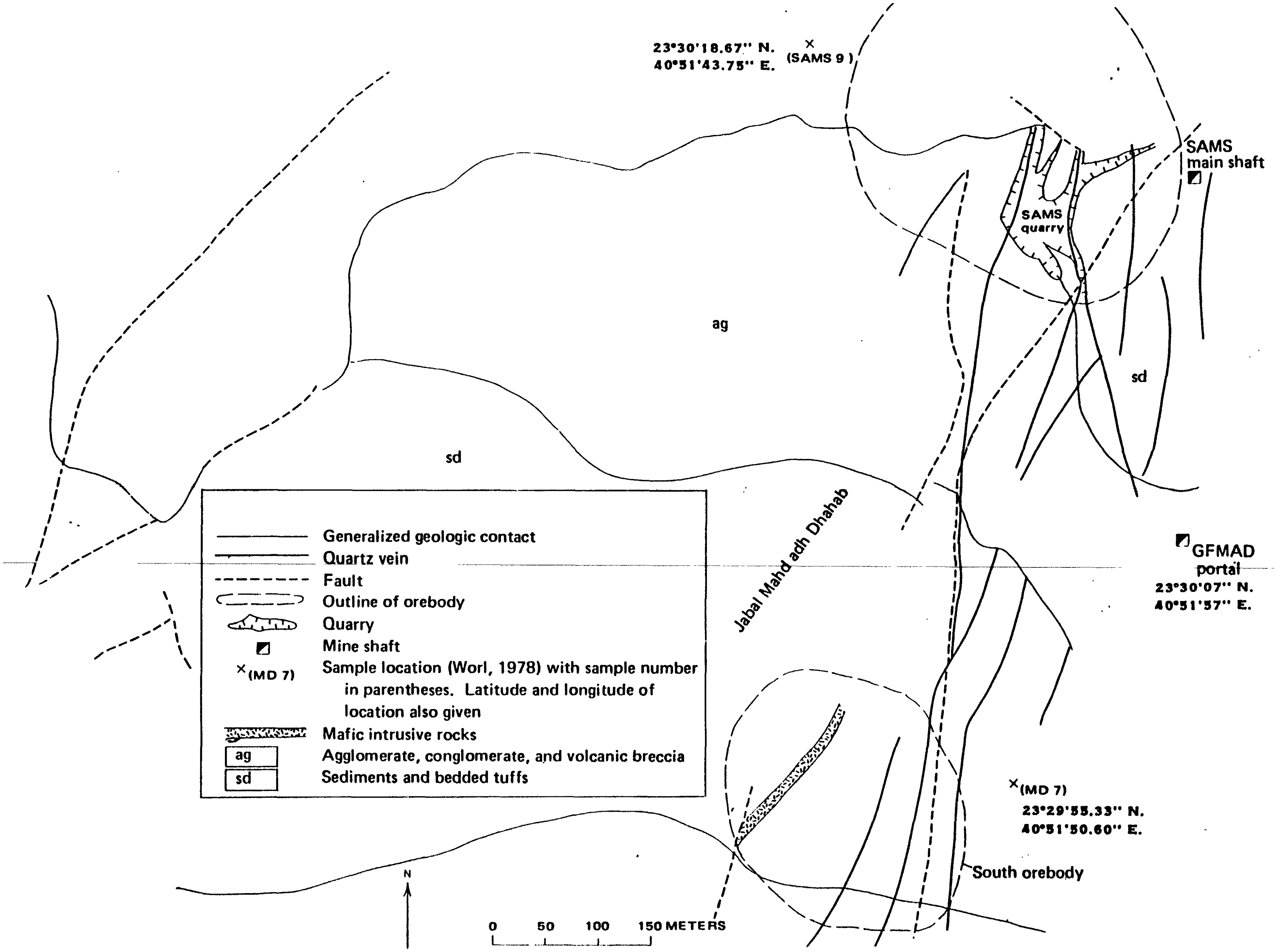


Figure 2.--Geologic sketch map of the Mahd adh Dhahab area (adapted from Worl, 1978).

a work agreement between the Saudi Arabian Ministry of Petroleum and Mineral Resources and the U.S. Geological Survey as part of subproject 3.31, special studies of mineralization. The authors are indebted to the officers and personnel of GFMAD, Limited, for access to the site, logistic support, and for their cooperation and encouragement of this program.

Geologic and mineralogic setting

Reconnaissance surface and underground mapping in this study indicates the Mahd adh Dhahab deposit is in the carapace of a Precambrian epizonal rhyolite stock and associated wall rocks. The emplacement of the stock domed lava flows and agglomerates of the Proterozoic Halaban (Hulayfah) group, which may have accumulated in a rift-related trough or caldera environment (Luce and others, 1979). A hornfelsic metamorphic aureole formed and xenoliths were incorporated in the stock. A pervasive crackle-breccia zone at the margin of the stock extends into the country rock. At the highest levels of the dome, spalled slabs of metamorphosed country rock and solidified rhyolite produced a breccia zone that filled with clastic debris.

Ore of gold, silver, copper, zinc, tellurium, and lead (listed in apparent order of economic importance) is associated with north-trending, steeply dipping quartz veins in a zone 1,000 m long and 400 m wide that cuts the pyroclastic and fine-grained sedimentary rocks. At the surface, individual barren quartz veins are mostly from 10 to 50 cm thick (Worl, 1978), but in the underground workings of GFMAD, the ore is located in a stockwork of anastomosing veinlets and incrustations of quartz and locally in areas of intense silicification and jasperization.

The ore is in shattered and intensely altered metasedimentary and pyroclastic rocks above the contact with the rhyolite stock, and it consists of veinlets, disseminations, and irregularly shaped masses of sulfide and telluride minerals in a stockwork gangue of altered host rock. The sulfide minerals have replaced the altered host rock and filled open spaces between brecciated rock fragments. Open-space filling is evidenced by well-developed banding as well as by cockade and comb structures. Repetition of banded mineral sequences indicate successive periods of fracturing and reopening.

The veins include an assemblage of quartz-chlorite-pyrite-hematite-chalcopyrite-sphalerite-precious metals that is similar to the mineral assemblage in the epithermal deposit at Creede, Colorado (Steven and Eaton, 1975; Bethke and others, 1976; Barton and others, 1977). Pervasive silicification, potassium feldspar alteration, and sericitization grade into massive chlorite-quartz replacement as the dominant alteration type in the ore zone.

Luce and others (1979) recognized four stages of quartz veins. Stage 1 quartz veins consist of massive, milky white quartz that contains sparse pyrite and has low precious metal values. Stage 2 quartz veins contain banded and crustified, milky to clear quartz, principally with comb or cockade structures. Massive sulfide ore bodies and precious metals are associated with this stage. Stage 3 veins are characterized by comb quartz, sphalerite, and chalcopyrite, with associated ankerite, manganiferous calcite, or calcite. Stage 4 veins contain only sparse sulfide minerals.

Sampling program

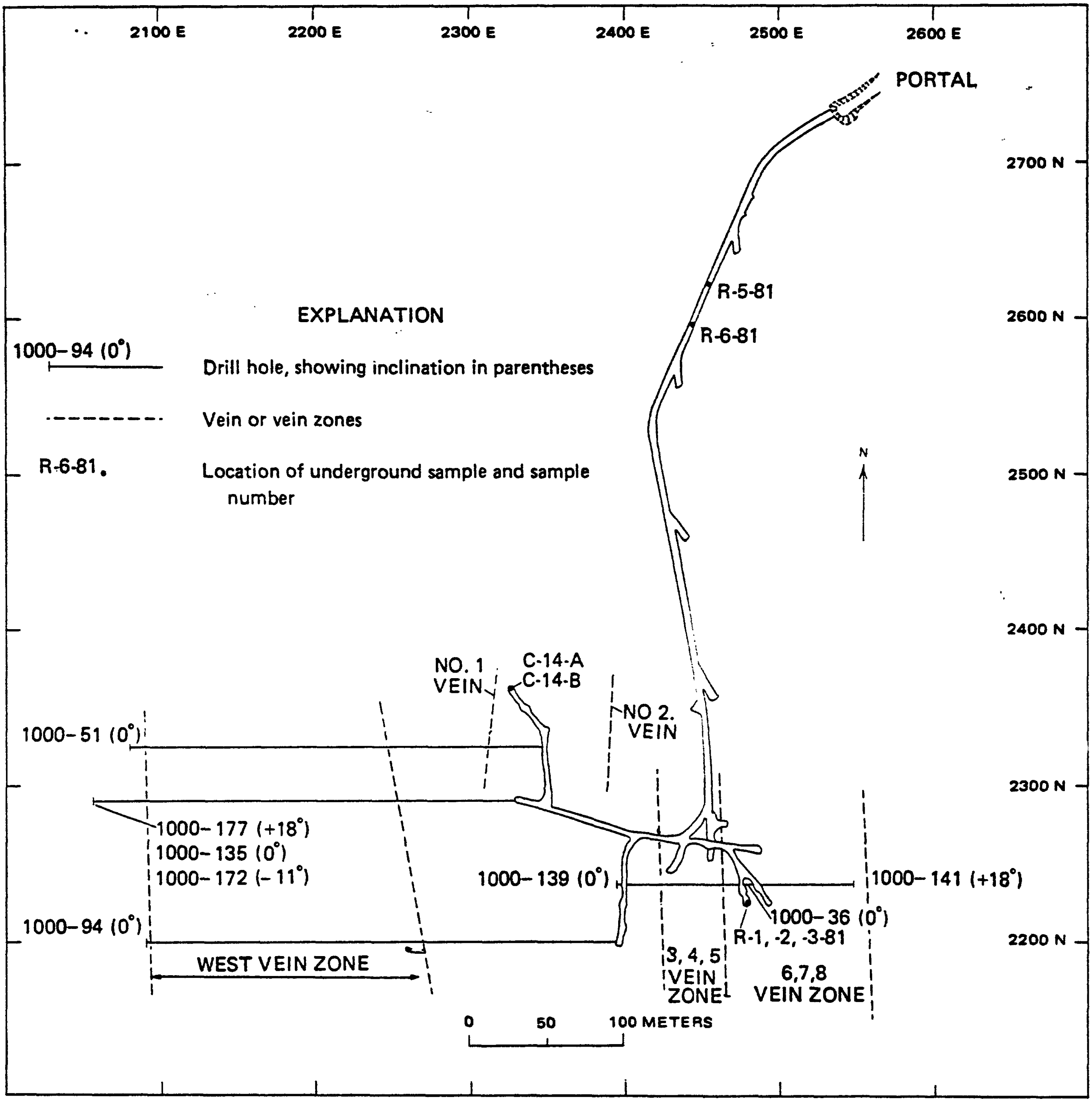
Most samples studied came from drill core or the underground workings of GFMAD, located about 30 to 40 m below the surface (figs. 2, 3). At the time of our fieldwork the company had concluded an exploratory drilling and tunneling program in the South orebody, and GFMAD provided access to the new underground decline and workings and to splits of drill core that intersected the various vein systems. A plan view of the new decline into the South orebody and workings, together with the location of the sampled drill holes and their relationship to veins and vein zones, is shown in figure 3. The underground workings and the diamond drill cores were sampled to obtain a representative suite of the veins covering as wide a horizontal and vertical distribution as possible. Dump samples from the development workings were also collected. In addition, samples of barren and mineralized veins were collected from the surface for isotope and fluid-inclusion studies. The locations of these samples are described later in table 4 (p. 19). This sample collection should be an excellent suite for future detailed geochemical studies.

MINERALOGY

by

Wayne E. Hall and G. K. Czamanske

Polished slabs of random samples collected underground and on the dump from the development workings in the South orebody were examined under an ore microscope for textures, structures, and a very preliminary determination of mineralogy and paragenetic sequence. No samples were collected from the oxidized zone. Fifteen polished thin sections of primary ore were studied; three of these were selected for electron microprobe study at the USGS, Menlo Park, facility.



Rye and others

Figure 3.--Schematic plan view of the decline in South orebody at Mahd adh Dhahab showing location of sampled drill holes, underground sample sites, and veins or vein zones (after Gold Fields-Mahd adh Dhahab Ltd. (GFMAD) mine maps).

A list of minerals identified in the primary ore is given in table 1. The principal sulfide minerals, in order of abundance, are sphalerite, chalcopyrite, and pyrite, and they characterize all samples. Galena is common, but its distribution is much more limited. Supergene copper sulfide minerals, including bornite, chalcocite, and covellite, are present in minor amounts along fractures in and along the margins of some chalcopyrite grains.

Primary sulfide minerals

Pyrite

Pyrite is a common mineral throughout the orebody. It occurs mostly as subhedral to euhedral cubes from 5 microns to 1 mm on an edge. It is the earliest sulfide mineral and occurs disseminated throughout the quartz-chlorite gangue and as corroded or relict grains in chalcopyrite and galena. Some pyrite grains contain blades of hematite that apparently crystallized contemporaneously with the enclosing pyrite. Much of the pyrite is crackled, and the fractures are filled with chalcopyrite and sphalerite. Few minerals containing precious metals were observed in the pyrite.

Chalcopyrite

Chalcopyrite, along with sphalerite, is abundant in the primary ore. Chalcopyrite occurs disseminated in quartz-chlorite rock, in fractures cutting quartz-chlorite rock, and in bands in crustified ore. Precious metal mineralization is associated with this stage of large-scale introduction of chalcopyrite and sphalerite.

Sphalerite

Sphalerite has the same distribution as chalcopyrite and, because it contains inclusions similar to those in chalcopyrite, is an important source of precious metals. The sphalerite has a low iron content, with FeS ranging from 0.39 to 2.17 weight percent, although most sphalerite contains from 0.44 to 0.67 weight percent FeS. Typically, the rims of sphalerite grains and masses are enriched slightly in iron relative to the cores.

Galena

Galena was introduced during the later stages of chalcopyrite-sphalerite mineralization and is present locally along grain boundaries and in fractures in both minerals. Precious metals are present in minor phases included in galena, but, because galena is not abundant, it is not an important source of these metals.

Table 1.--Ore and gangue minerals identified in this study

Ore minerals

Primary sulfide minerals

Pryite (FeS_2)
Chalcopyrite ($CuFeS_2$)
Sphalerite (ZnS)
Galena (PbS)

Native metals

Gold (Au)

Supergene sulfide minerals

Bornite (Cu_5FeS_4)
Chalcocite (Cu_2S)
Covellite (CuS)

Telluride minerals

Altaite ($PbTe$)
Bismuth-lead telluride
Hessite (Ag_2Te)
Petzite (Ag_3AuTe_2)
Sylvanite ($AgAuTe_4$)

Gangue minerals

Calcite
Chlorite
Hematite
Quartz

Precious metal assemblage

The precious metals, gold and silver, occur principally as telluride minerals in or near masses or bands of chalcopyrite and sphalerite, in disseminated form as wispy grains, rods, or anhedral grains from 5 to 50 microns in diameter within vein quartz and quartz-chlorite rock, or as minute fracture fillings. With one exception, free gold was not abundant in the polished sections prepared. One other thin section had minute grains of free gold in chalcopyrite. Most gold is present as a gold-silver telluride. Silver is present as hessite (Ag_2Te) and in gold-silver tellurides. A lead-bismuth telluride is present as minute inclusions in hessite; it contains no measurable amounts of gold or silver. The following description of the precious metal mineral assemblage is based upon ore microscopy and electron microprobe analysis. Ag_2Te, $AuTe_2$, Au, Au_{90}, and Au_{10} were used as internal standards.

Petzite (Ag_3AuTe_2)

Petzite is the principal gold-bearing phase in the primary ore from the South orebody. It occurs as irregularly shaped grains and shreds associated with other telluride minerals and hematite, as disseminated discrete grains in quartz-chlorite rock, and as inclusions in chalcopyrite and sphalerite (fig. 4). Grains are mostly from 5 to 20 microns in diameter but range to as much as 50 microns. Petzite is steel gray to brownish gray and apparently isotropic, although Schneiderhohn and Ramdohr (1931) have reported it to be anisotropic in part. Petzite can be distinguished from other telluride minerals by its slightly brownish color and by its poorer polish. Petzite composition varies both within individual grains and between grains as shown in table 2. Silver contents ranged from 38.4 to 47.2 weight percent, gold from 16.8 to 27.2 weight percent, and tellurium from 30.6 to 36.4 weight percent.

Hessite (Ag_2Te)

Hessite and petzite are closely associated as disseminated minute grains in quartz-chlorite rock and as inclusions in sphalerite and chalcopyrite. In polished section hessite has a slightly higher reflectivity than petzite and takes a smoother polish (fig. 5). It is isotropic to very slightly anisotropic. The composition of hessite in the South orebody ranged from nearly pure silver-telluride to as much as 10.3 weight percent gold (table 2), more than twice the amount listed as average for hessite by Dana and Dana (1944; table 2).

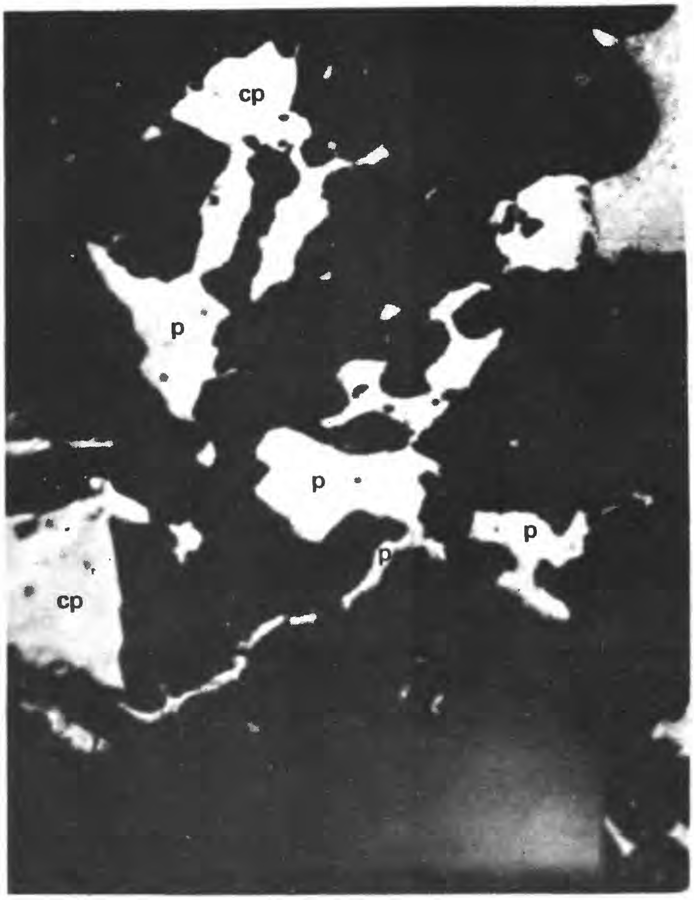


Figure 4.--Photomicrograph showing quartz-chlorite rock with disseminated petzite (p). The two grains having the smoother polish are chalcopyrite (cp). Width of photograph represents approximately 300μ.

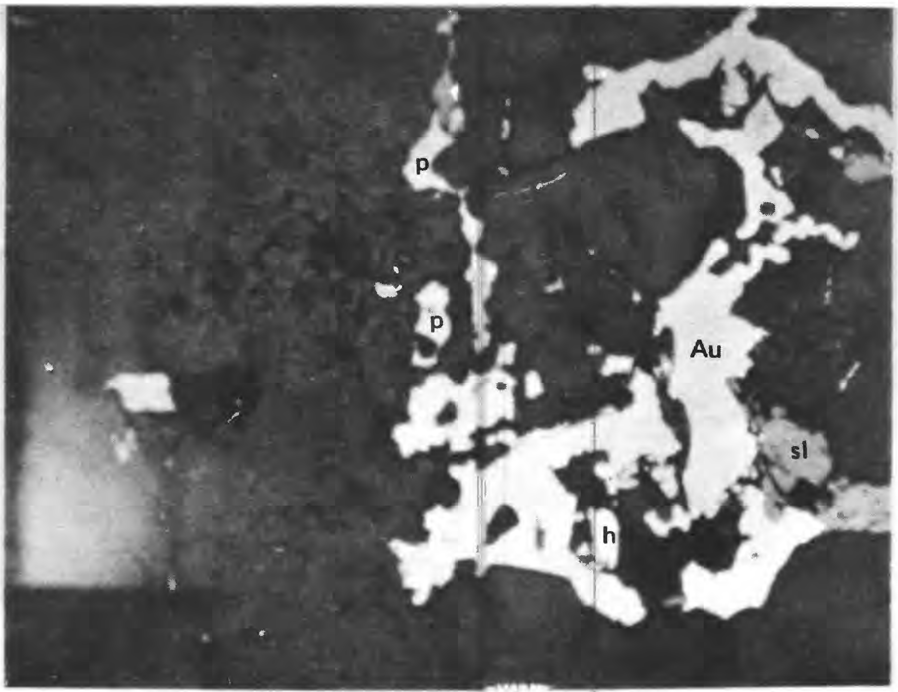


Figure 5.--Photomicrograph showing free gold in a quartz veinlet cutting quartz-chlorite rock. The gold (Au) shows as bright-white grains. Petzite (p) is in a tiny veinlet and as minute grains in quartz-chlorite rock. Sphalerite (sl) is in the lower right. Hessite (h) is in quartz encircled by gold. Width of photograph represents approximately 700 μ.

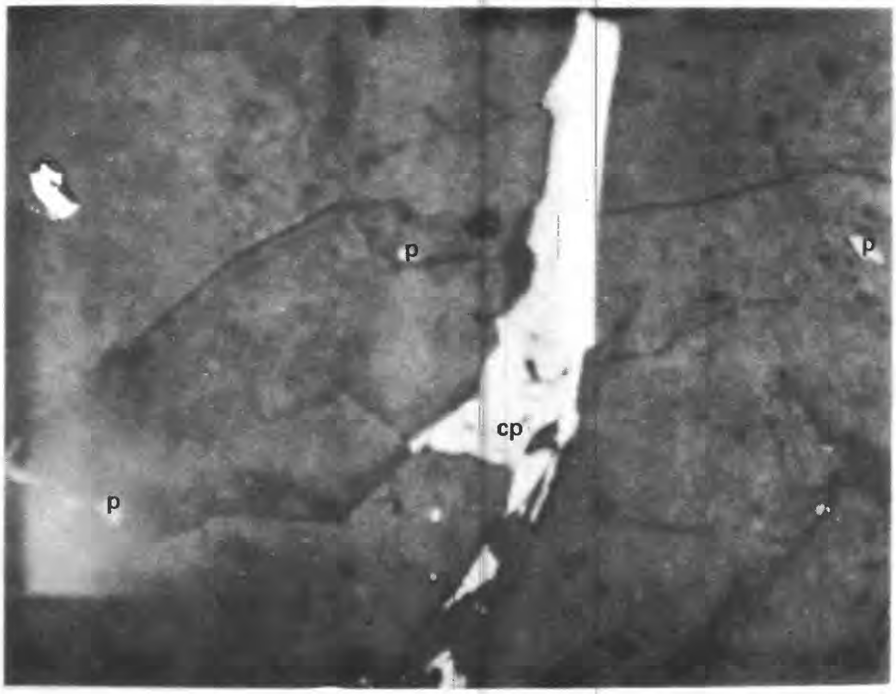


Figure 6.--Photomicrograph showing lath of bismuth-lead telluride (bright) in quartz-chlorite rock. Chalcopyrite (cp) is at the end of the blade. All the wispy grains and the thin fracture coating are petzite (p). Width of photograph represents 750 μ.

Table 2.--Composition of petzite, hessite, and sylvanite in the South orebody

[Results in weight percent. Analyses using electron microprobe, USGS, Menlo Park]

	Silver	Gold	Tellurium	
Pure petzite	41.71	25.39	32.90	Ag_3AuTe_2
Grain 1, pt. 1	42.6	22.1	35.0	$Ag_{2.88}Au_{0.82}Te_2$
Grain 1, pt. 2	41.9	19.9	35.4	$Ag_{2.80}Au_{0.73}Te_2$
Grain 2, pt. 1	47.2	16.8	34.1	$Ag_{3.26}Au_{0.64}Te_2$
Grain 3, pt. 1	43.2	22.7	33.9	$Ag_{3.18}Au_{0.84}Te_2$
Grain 4, pt. 1	42.8	22.7	30.6	$Ag_{3.08}Au_{0.83}Te_2$
Grain 5, pt. 1	38.4	26.3	35.3	$Ag_{2.70}Au_{0.93}Te_2$
Grain 6, pt. 1	40.9	27.2	32.0	$Ag_{3.17}Au_{1.06}Te_2$
Grain 7, pt. 1	42.6	22.1	35.0	$Ag_{2.87}Au_{0.87}Te_2$
Grain 7, pt. 2	43.2	20.5	36.4	$Ag_{2.82}Au_{0.73}Te_2$
Pure hessite	62.83	0	37.17	Ag_2Te
Grain 1, pt. 1	62.1	0.1	37.8	$Ag_{2.03}Te$
Grain 2, pt. 1	56.0	7.8	36.3	$Ag_{1.91}Au_{0.13}Te$
Grain 3, pt. 1	53.2	10.3	36.5	$Ag_{1.81}Au_{0.18}Te$
Pure sylvanite	13.23	24.14	62.61	$AgAuTe_4$
Grain 1	9.3	29.9	67.1	$Ag_{0.68}Au_{1.11}Te_4$
Grain 2	10.5	28.8	68.0	$Ag_{0.76}Au_{1.06}Te_4$

Sylvanite ($AgAuTe_4$)

Sylvanite is a minor telluride mineral in the South orebody. It is cream white in reflected light, has a much higher reflectivity than petzite or hessite, and is strongly anisotropic. Sylvanite is present mainly as minute, equant grains in sphalerite and chalcopyrite, but it also occurs sparsely as discrete, minute grains in quartz-chlorite-hematite rock. The composition of the sylvanite (table 2) shows that both grains contain more gold and less silver than pure sylvanite. However, they are within the range of compositions of sylvanite given by Dana and Dana (1944; table 2).

Gold

Free gold was observed only in two polished sections. It is abundant in a quartz veinlet that cuts quartz-chlorite rock, and in sphalerite, chalcopyrite, and pyrite (fig. 5). Because petzite and hessite are finely dispersed through the quartz-chlorite rock and within the base metal sulfide minerals, the gold presumably formed slightly later in the paragenetic sequence than the telluride minerals. If the samples, which total several hundred pounds, are representative of the primary ore in the South orebody, free gold will be a significantly smaller source of gold than petzite. The free gold contained only small amounts of silver; its fineness (parts per thousand pure gold) in two different grains was 954 and 935.

Altaite (PbTe)

Altaite is present in very small quantities as bright-white, cubic, isotropic inclusions in hessite. Electron microprobe analysis indicated the altaite contained a small amount of iron.

Lead-bismuth telluride

An unidentified lead-bismuth telluride is present in quartz-chlorite rock (fig. 6). It is a bladed, cream-colored, slightly anisotropic mineral. A cleavage surface displayed two sets of striations at an angle of approximately 60° to each other. A qualitative analysis indicated a major amount of tellurium, approximately 39 weight percent bismuth, and approximately 14 weight percent lead. The properties are similar to the description of tellurobismuthite (Dana and Dana, 1944).

Other minerals

Hematite (Fe_2O_3)

Hematite is closely associated with the precious metal telluride minerals disseminated in quartz-chlorite rock. It is present in the underground workings as irregularly shaped patches and as thin red veinlets in the chloritized host rock. Microscopy indicates that hematite occurs as tiny, gray, foliated or radial blades and shreds disseminated in the chlorite-quartz rock or as inclusions with pyrite.

Supergene minerals

Minor amounts of supergene copper minerals are present as thin bands around, and coating fractures within, chalcopyrite. They include bornite, chalcocite, and covellite.

STABLE ISOTOPE STUDIES

by

Robert O. Rye

Preliminary stable isotope analyses were made on sulfide minerals and quartz in order to determine the general sulfur and oxygen isotope systematics of the Mahd adh Dhahab mineralization and especially to compare the isotope systematics of the North and South orebodies. The data indicate that the North and South orebodies formed from the same large hydrothermal system, and the geologic and geochemical reasons for their separation must be determined in order to construct a model of ore deposition and to properly evaluate the resource potential of the area.

Sulfur isotope studies of sulfides

More than 75 sulfur isotope analyses were made on samples of pyrite, chalcopyrite, sphalerite, and galena collected from drill core and the underground workings in the South orebody. The results are summarized in table 3. Only coarse mineral phases were analyzed, and, although coexisting minerals were analyzed from most samples, little attention was given to paragenetic relationships. The data, however, should be representative of the time-space variations in sulfur isotopes during the main stage of coarse sulfide mineralization.

The following observations can be made. First, the total range of $\delta^{34}S$ values for all minerals is from 0.5 to 6.3^{o}/oo (parts per mil), whereas individual minerals have smaller ranges: 0.5 to 1.2^{o}/oo for galena, 1.0 to 4.3 ^{o}/oo for sphalerite, 1.4 to 5.7^{o}/oo for chalcopyrite, and 2.0 to 6.3^{o}/oo for pyrite. Second, there appears to be no significant spatial variation in the $\delta^{34}S$ values within the South orebody. Third, the $\delta^{34}S$ values fall in the range of those previously determined from samples collected at the SAMS workings in the North orebody (Luce and others, 1979).

Table 3.--$\delta^{34}S$ values of sulfide minerals from the South orebody, Mahd adh Dhahab
[Drill locations and sample sites shown on figure 3. Results in $^{0}/_{00}$, CDT (Canon Diablo Troilite meteorite standard). Leaders indicate not determined]

Drill core location	Distance from collar (meters)	Pyrite	Chalcopyrite	Sphalerite	Galena
1000-51	14.02	3.0	1.5	1.4	--
	77.09	--	--	1.6	--
	121.01	--	--	--	--
	125.98	2.5	--	4.3	--
	127.18	--	3.8	2.4	--
	185.00	--	2.9	2.8	--
	241.54	--	2.7	3.0	--
	242.67	--	2.6	3.4	--
	244.52	--	2.9	2.6	--
1000-177	170.11	--	--	2.9	--
	173.33	--	2.5	4.1	--
1000-135	186.90	--	3.9		0.5
	188.90	--	2.8	4.2	--
	193.18	--	3.1	3.8	--
	197.00	6.3	5.7	--	--
1000-172	205.10	--	2.3	--	--
	211.12	--	2.7	3.0	--
	213.43	--	2.6	--	1.2
	208.56	--	--	--	--
	215.32	--	2.9	2.6	--
	215.86	--	4.0	2.7	--
1000-94	264.21	--	3.7	2.9	--
	249.67	--	3.7	2.9	--
1000-139	2.15	6.1	2.9	--	--
	16.91	--	3.5	1.7	--
	24.27	--	2.9	2.6	--
	32.70	--	2.6	2.0	--
	35.74	--	4.2	1.8	--
	39.60	--	1.7	--	--
1000-36	1.68	2.7	2.0	--	--
	3.78	--	3.3	3.8	--
1000-141	10.64	3.8	4.7	3.6	--
	12.76	2.2	2.8	--	--
	15.24	2.0	3.8	2.1	--
	16.13	2.1	1.8	1.2	--
	19.70	--	1.4	--	--
	21.88	--	3.0	1.7	--
R-4-81*	--	2.2	1.9	--	--
R-6-81	--	3.2	2.2	--	--
R-3-81	--	--	--	1.5	--

* Sample R-4-81 collected from the dump of the development workings in the South orebody; not on figure 2.

The rather narrow range of slightly positive $\delta^{34}S$ values is typical of hydrothermal sulfide minerals that have derived their sulfur from igneous sources (Rye and Ohmoto, 1974). In particular, values as large as 6.3°/oo in pyrite are consistent with isotope effects related to the derivation of sulfur from rhyolite magmas (Ohmoto and Rye, 1979).

The narrow range of $\delta^{34}S$ values for the deposit, however, is unusual in that the principal mineral assemblage, pyrite-hematite-chlorite-quartz, indicates a high fO_2 environment for ore deposition in which the dominant sulfur species in the hydrothermal solution would be sulfate (Barton and others, 1977). Under such conditions the $\delta^{34}S$ values of sulfide minerals would normally be much lower than observed at Mahd adh Dhahab. The fact that they are higher indicates that the sulfide sulfur isotope geochemistry was probably controlled by exchange with a large sulfur isotope reservoir at depth rather than by equilibrium reactions at the site of ore deposition. A similar situation has been observed for the ore deposits at Creede, Colorado (R.O. Rye and others, unpublished data) where the epithermal veins may be underlain by a large sulfide (porphyry?) system. Careful attention should be given in future studies to determine if the sulfur isotope data for the Mahd adh Dhahab deposit can be interpreted to imply a large sulfide reservoir at depth.

Oxygen isotope studies

Representative samples of different generations of quartz from the surface, from the underground workings in the South orebody, and from the SAMS workings in the North orebody were analyzed for oxygen isotope composition (table 4). The $\delta^{18}O$ values of all generations of quartz range from 8.5 to 11.1°/oo.

Because of the reconnaissance nature of the sampling, detailed time-space relations of the various quartz stages throughout the area are not known (see the section on geologic and mineralogic setting in Luce and others, 1979). The $\delta^{18}O$ of quartz samples has a narrow range similar to that obtained by Luce and others (1979) for the North orebody. This similarity suggests that all generations of quartz, including the youngest barren veins, were related to fluids that had a very similar temperature and isotopic composition and were obviously all related to a single hydrothermal system.

Using the temperature range of from 150° to 250°C obtained from fluid-inclusion homogenization measurements (see the following section) and previous sulfur isotope measurements (Luce and others, 1979), the $\delta^{18}O_{H_2O}$ of the

Table 4--$\delta^{18}O$ values of quartz veins at Mahd adh Dhahab
[Results in °/oo, SMOW. cpy=chalcopyrite, py=pyrite, sph=sphalerite]

Sample number	Location*	Description	Quartz stage**	$\delta^{18}O$
SA-1	Ridge between SAMS workings and summit of Jabal Mahd adh Dhahab	Barren, north-trending quartz vein	4	10.3
SA-2	Hill above SAMS mill in ancient workings	Copper sulfides and secondary mineralization in large quartz vein	2 or 3	11.1
S-1-A	150-foot level of SAMS mine	Brecciated, stage 2 quartz with chlorite-sph-py-cpy cut by stage 3 quartz	3	8.5
S-4-A	SAMS dump	Stage 2 quartz-chlorite-cpy-sph grading into stage 3 vuggy quartz-calcite	2	9.7
S-4-A	SAMS dump	Stage 2 quartz-chlorite-cpy-sph grading into stage 3 vuggy quartz-calcite	3	10.0
C-14-A	#1 drive in barren area of GFMAD development	Milky quartz with minor chlorite-sph-cpy cut by stage 4 quartz	1	10.7
C-14-B	#1 drive in barren area of GFMAD development	Milky quartz with minor chlorite-sph-cpy cut by stage 4 quartz	4	9.4
R-1-81A	High-grade area #6 vein drift	Multiple generations of quartz in mineralized rock	1 2	9.5 9.4
R-1-81B	High grade area #6 vein drift	White quartz vein with chlorite selvage, sph, py-cpy and precious metals	2	10.1
R-1-81B	High grade area #6 vein drift	Late-forming pink crystals	3	11.0
R-2-81	High grade area #6 vein drift	Hematite-rich quartz, stage 2 quartz vein cut by stage 3 quartz	2	10.5
R-2-81	High grade area #6 vein drift	Hematite-rich quartz, stage 2 quartz vein cut by stage 3 quartz	3	10.0
R-5-81	GFMAD decline	Barren quartz vein	4	10.0
R-6-81	GFMAD decline	Quartz vein with sulfide minerals	2 or 3	9.0

* All samples except SA-1 and -2, S-1-A located on figure 3.

**Described in text.

hydrothermal fluids is calculated to range from -6.0 to 1.5°/oo. This wide range is probably not real and probably results from the uncertainty in temperatures used in the calculations. The actual range in the $\delta^{18}O_{H_2O}$ of the fluids was probably less than the 2.6°/oo range observed in quartz.

These $\delta^{18}O_{H_2O}$ values indicate that the fluids were dominantly exchanged meteoric waters, which is not unusual for an epithermal vein system. What is unusual is that the ^{18}O exchange in the meteoric water was so uniform throughout the entire period of quartz deposition, which spans the period of ore deposition. This uniformity implies that the hydrothermal fluids had a very large and very stable plumbing system throughout the period of mineralization.

The oxygen isotope study should be extended to the west side of Jabal Mahd adh Dhahab to determine if the alteration and quartz veins in that area are also related to the same system.

FLUID INCLUSION STUDIES

by

Charles G. Cunningham

A suite of samples representing suitable quartz and sphalerite host material from various geologic environments within the deposit was selected for detailed fluid inclusion studies. Twenty doubly polished plates and thin sections were prepared, from which hundreds of fluid inclusions were studied to relate fluid composition, phase relationships, and relative age to the host material and to mineralization. Quartz crystals were cut both parallel and perpendicular to the C-axis to examine changes in inclusion composition and temperature as a function of time. Homogenization temperatures were measured on a modified Chaix Meca fluid inclusion stage (Cunningham and Carollo, 1980) and are reported in table 5. The principles, assumptions, and procedures used in the study are reviewed by Cunningham (1977) and Roedder (1972, 1976, 1979).

All of the vein-quartz samples contained abundant, tiny (less than 3-micron diameter) fluid inclusions; rare inclusions as large as 15 microns are present locally. Internal phase and relative age relationships were usually observed at 1250X magnification using a 100X oil-immersion objective. The quartz was intensely sheared, and fluids introduced into the fractures formed myriad secondary inclusions. Primary fluid inclusions were discriminated from secondary and pseudosecondary inclusions by the relationship to primary growth

Table 5.--Homogenization temperatures of fluid inclusions, Mahd adh Dhahab

Sample*	Homogenization temperature (in °C)
SA-1	110-125
SA-2	125-154
R-1-81B, stage 2	160
R-1-81A, stage 1	208
R-1-81A, stage 2	195-238
R-2-81	135
R-5-81	(no workable fluid inclusions)
R-6-81	171-180

* Sample locations described in table 4.

Table 6.--Lead isotope analyses of galenas from the South and North orebodies

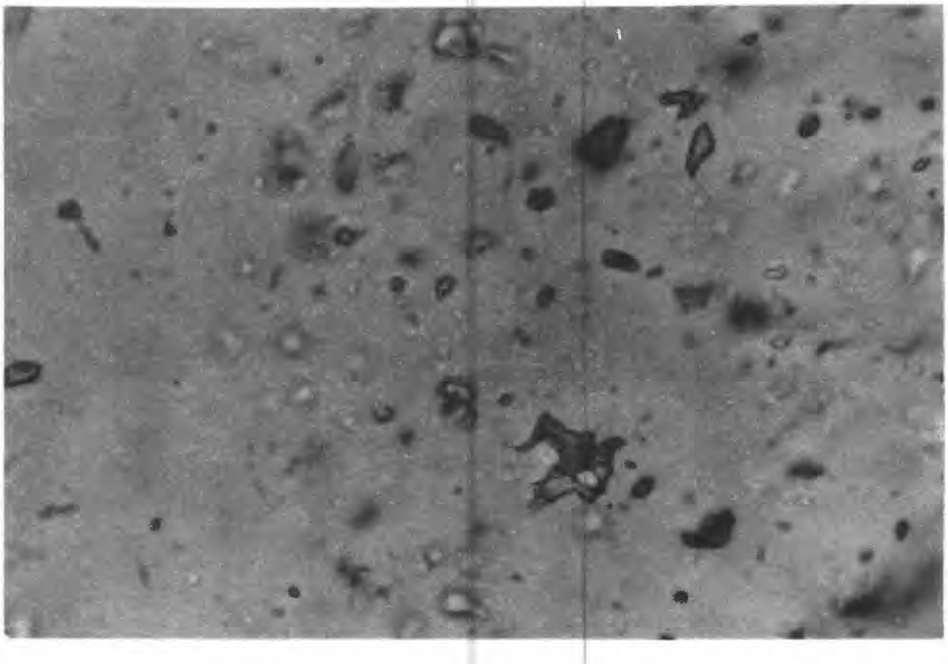
Sample	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
R-81-A	17.381	15.423	36.953
R-81-B	17.365	15.415	36.758
DDB-11	17.406	15.477	26.959

zones in quartz crystals, proximity to secondary shear planes, and internally consistent phase ratios. Homogenization temperatures reported in table 5 were determined for primary, representative, liquid-rich fluid inclusions as much as 10 microns in diameter. No primary inclusions were found that were large enough to determine equivalent salinity by means of freezing-point depression, but, the absence of daughter crystals in the inclusions suggests that the salinity is below the saturation level of NaCl at room temperature (about 26 weight percent).

The observed homogenization temperatures (100° to 238° C) have not been corrected for pressure, but, observation of coexisting vapor-rich fluid inclusions suggests to me that the confining pressure at times probably equaled the vapor pressure of the solution and that the pressure correction would be small. The temperature range, gangue-quartz morphology, and stability-range data for the coexisting mineral assemblage all indicate that the veins formed in an epithermal environment.

One of the potentially most important observations that arises from this feasibility study is the recognition of abundant, low-density, vapor-rich fluid inclusions in mineralized quartz from the ancient workings (fig. 7). This vapor-rich assemblage contrasts with the assemblage dominated by liquid-rich inclusions (fig. 8) in the barren veins to the west on the ridge connecting the SAMS workings and the summit of Jabal Mahd adh Dhahab. Although both mineralized and barren quartz veins contain vapor-rich fluid inclusions, they are significantly more abundant in the mineralized veins. The vapor-rich inclusions can form in several ways: they could contain a low-density vapor representing steam bubbles trapped from a boiling hydrothermal fluid; they could contain low-density carbon dioxide representing unmixed carbon dioxide effervescing from the fluid; or they could represent primary inclusions that were opened during later shearing events.

It is important from an economic and scientific standpoint to determine the extent and cause of the vapor-rich fluid inclusions. Boiling of a hydrothermal fluid will cause selective partitioning of various chemical components between the liquid and vapor phase (Cunningham, 1978; Roedder and Bodnar, 1980; Drummond, 1981). Because effervescence of carbon dioxide changes the pH of the hydrothermal fluid and gold in many instances is transported as a pH-sensitive chloride or bi-sulfide complex, the presence of carbon dioxide-bearing fluid inclusions may have a direct bearing on the means for depositing the gold. Although carbon dioxide was not observed in any fluid inclusions examined in this study, it was noted in other samples from Madh adh Dhahab (Luce and



e 7.--Photomicrograph showing abundant vapor-rich fluid inclusions in mineral-d quartz vein from the vicinity of the ancient workings near the SAMS mine in al Mahd adh Dhahab (sample SA-2). Average size of inclusions is 5μ .

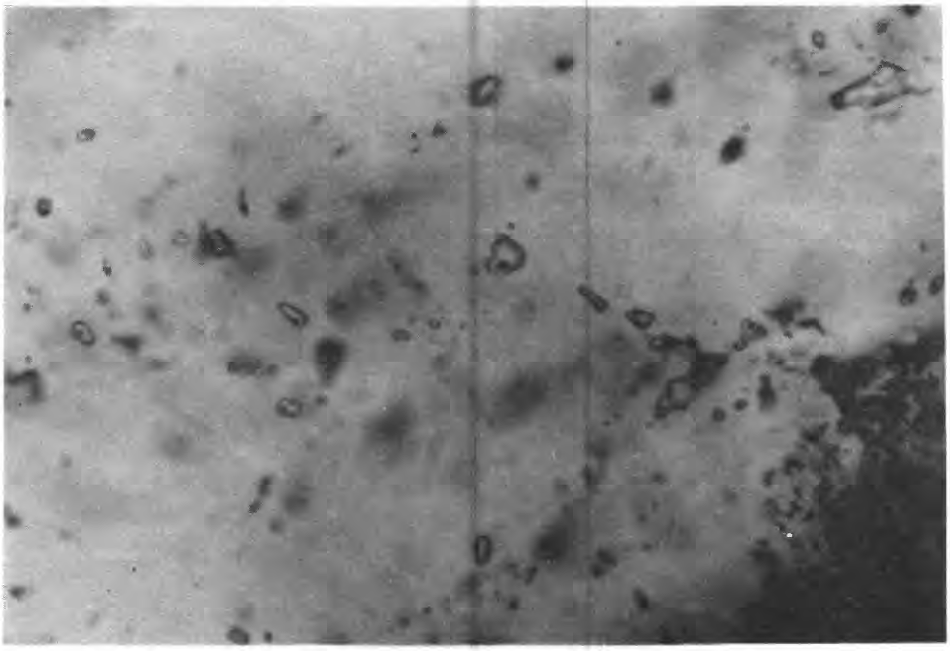


Figure 8.--Photomicrograph showing dominantly liquid-rich fluid inclusions in barren quartz vein from Jabal Madh adh Dhahab (sample SA-1). Average size of inclusions is 5μ .

others, 1979, p. 22). Furthermore, understanding of the vertical distribution of vapor-rich or carbon dioxide-bearing fluid inclusions could help to evaluate the location of gold in this deposit and the economic potential of other, similar deposits.

U-Pb ZIRCON AND COMMON LEAD STUDIES

by

John S. Stacey

Three 40-kg samples of volcanic rocks ranging in composition from andesite to rhyodacite were collected from the GFMAD development workings in an attempt to directly date the rocks in which the South orebody is found. No zircons were recovered from any of these fine-grained samples. Further work must await completion of the mapping program for the Mahd adh Dhahab region.*

Two galena samples collected underground (R-81-A and R-81-B) were analyzed for their lead isotope compositions. The data are shown in table 6 along with data for sample DDB-11 collected from the North orebody at Mahd adh Dhahab (Stacey and others, 1980).

The samples from the South orebody are significantly less radiogenic than the sample from the North orebody, and the data indicate that lead isotope compositions might be used to distinguish trends within the deposit. The data also confirm that the lead was derived from oceanic crustal material approximately 700 Ma ago*, as suggested by Stacey and others (1980).

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* Editorial note added during proof: A recent report by J. Y. Calvez and J. Kemp (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., contains results that bear on the age of Mahd adh Dhahab mineralization. Layered rocks that enclose the deposit (Mahd group of Calvez and Kemp) define a Rb-Sr whole-rock isochron age of 772±28 Ma. The oldest plutonic rock that intrudes the Mahd group (Halaban group of this report) was emplaced 760±10 Ma ago on the basis of U-Pb (zircon) measurements. Mineralization is believed by the present authors to be broadly coeval with the Mahd group.

CONCLUSIONS

The purpose of this investigation was to evaluate the feasibility of a detailed integrated geologic, mineralogic, isotopic, and geochemical study of the mineralization at Mahd adh Dhahab and the potential of such a study as an aid to evaluating the resource potential of the area and adjacent prospects. We believe the detailed study should proceed. Reconnaissance mapping indicates that the deposit is in the carapace of a rhyolite intrusion and associated brecciated wall rocks. This mode of occurrence needs to be further documented by detailed mapping both on the surface and underground. Detailed mineralogic studies should be continued on a larger scale to fully characterize the time-space distribution of the ore and gangue minerals. Stable isotope studies indicate that all mineralization in the North and South orebodies resulted from a single, large meteoric-water hydrothermal system that was probably part of a larger system at depth. Further stable isotope studies should be undertaken to define the nature of the deep system and to determine if mineralization on the west side of Jabal Mahd adh Dhahab is also related to the same system. Finally, fluid inclusion studies, although difficult to perform because of the small size of individual inclusions and the difficulty in separating individual generations, may help define the actual mechanism of mineralization.