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Sulfide Assemblages and Metamorphic Episodes at Mahd Adh Dhahab Gold Mine, Kingdom of Saudi Arabia

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ABSTRACT. The Mahd Adh Dhahab gold mine is located in the west central part of the Arabian Shield and has been the most productive gold mine in Saudi Arabia in both ancient and recent times. Textural and mineralogical features observed in the ore deposits at Mahd Adh Dhahab indicate that the deposits have been subjected to metamorphism.

Three main effects were recognized. Recrystallization of the ores during regional metamorphism resulted in changes mainly in the fabrics, but also in the mineralogy, of the ores. With increasing metamorphism: a) there is a general increase in grain size, b) growth of pyrite as porphyroblasts, and c) presence of triple junction point texture. Deformational effects present varied from none, through brittle cataclasis to ductile deformation. The features observed include: a) fracturing, brecciation and mylonitization of fine-grained sulfides and porphyroblasts, b) deformation twinning, c) folding and disruption of cleavage traces, d) rotation of pyrite crystals, and e) stretching and elongation of soft sulfides. Remobilization produced irregular bodies of vein quartz and ore minerals, either within the deposits or in their immediate country rocks. The remobilization distances are limited, either within parent body or in restricted halo surrounding it (up to some tens of meters). The remobilization is selective and proceeded by creep or fluid-phase transport. The apparent order of decreasing mobility is: galena, chalcopyrite, sphalerite, pyrite. Certain replacement phenomena observed between the euhedral-subhedral pyrite grains and the base metal sulfides could be ascribed to metamorphism.

At Mahd Adh Dhahab area, successive episodes of low grade metamorphism prevailed during a long time span. Intermittent with such pervasive regional metamorphism, the ores were subjected to short periods of essentially dynamic and thermal metamorphism.

Introduction

The Mahd Adh Dhahab gold mine is located in the west central part of the Arabian Shield (Fig. 1) about 275 km northeast of Jeddah (23 30′N and 40 52′E). The mine is

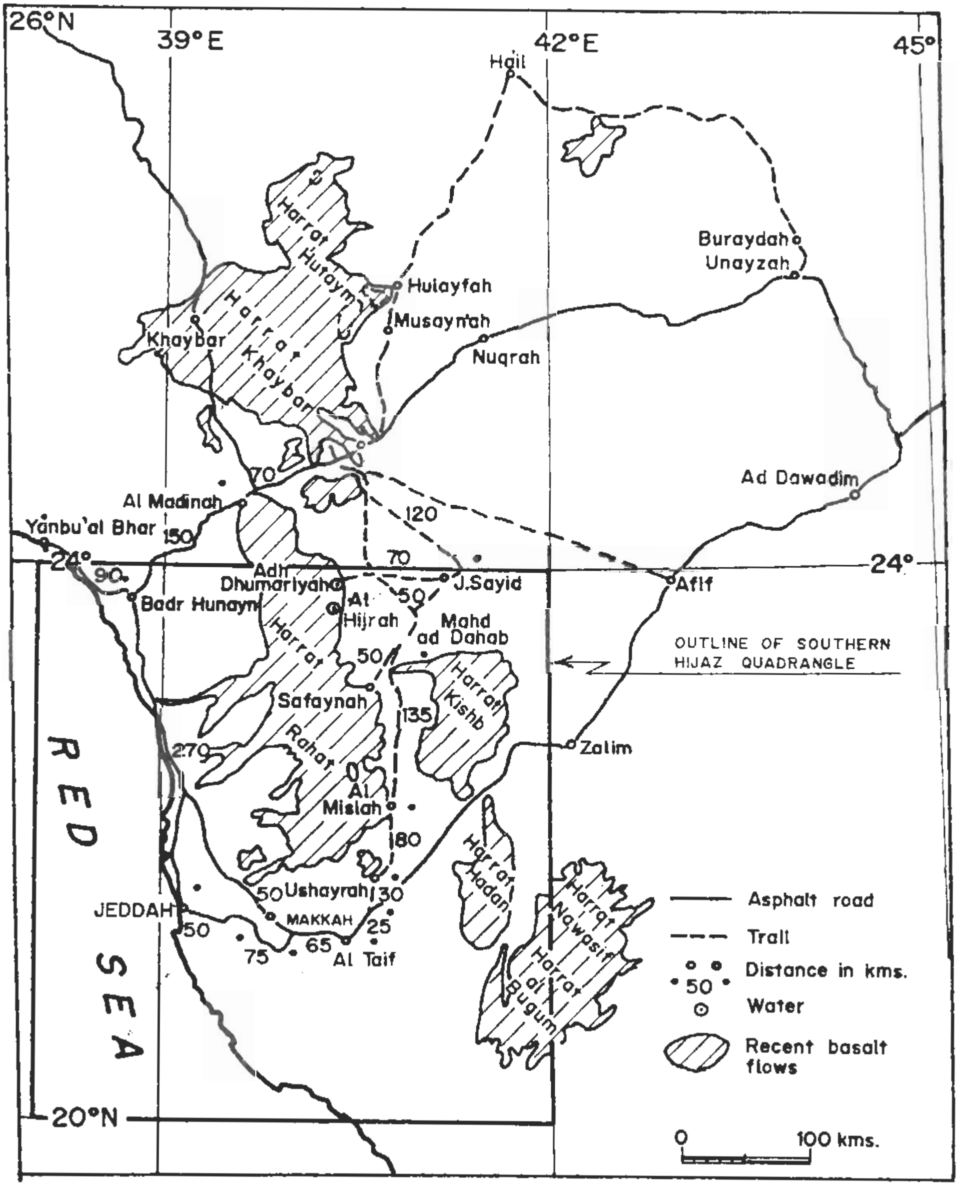

FIG. 1. Location map of Mahd Adh Dhahab.

situated at the northern part of an isolated hill, Jabal Al-Mahd, covering an area of about 2.2 km^2 to an altitude of 1238 m which is the highest peak in the area.

The Mahd Adh Dhahab mine in the Mine Hill area has had by far the largest production of any gold mine in the Arabian Shield. It has also been the most productive mine in Saudi Arabia in both ancient and recent times. At present, the mine is reopened and an exploratory decline has been completed and consists of about 1100 meters of adits and crosscuts.

Ancient mining and smelting in the area is evidenced by intricate workings that extend to a depth of 85 meters along major veins and by several thousands tons of waste and artifacts and ruins.

Previous Work

A program of detailed mapping and geochemical sampling was carried out from 1974 to 1977 (Luce *et al.* 1975, 1979; Roberts *et al.* 1978; and Worl 1978, 1979). This led to the discovery of the southern mineralized zone (SMZ) 700 meters south of the ancient workings. Diamond drilling in the SMZ intercepted wide veins that averaged as much as 60 gm per ton (Worl 1978). Reserves in the Southern Ore Zone are estimated at 1.1 million tons of approximately one oz. of gold per ton (Doebrich and Le Anderson 1984 and Hilpert *et al.* 1984).

Geology

The country rocks belong to the Upper Proterozoic (800-780 Ma) Mahd Group and consist of a thick-layered succession of volcanic and sedimentary rocks unconformably overlying granite and granodiorite (Fig. 2). From base to top, the local stratigraphic sequence is composed of andesite, andesitic tuff, lower agglomerate, lower tuff, lithic crystal tuff, and upper tuff (Hakim 1978). The layered rocks are cut by two generations of intrusives. The earliest consists of plugs or domes of porphyritic rhyolite, and the latter of andesite dikes. The porphyritic rhyolite outcrops in the northeast part of Jabal Al-Mahd. A series of andesite dikes occupy northeasterly and northwesterly faults in the Mine Hill area. The dikes cut and displace the mineralized veins.

Structure

The layered rocks dip mostly to the north except locally in the northeast part of Jabal Al-Mahd where the rocks have been folded by the rhyolite intrusion. The dips in the southern part of the Jabal are 35 to 40 N and generally steepen northward to 60-80 N. This monocline is cut by several fracture systems (Hakim 1978 and Hilpert *et al.* 1984). These are N15W to N30W, dipping 25-45W; N45-75E, dipping 45-60NW; N10W to N20E dipping steeply westward; N30W dipping steeply to the west or southwest; N45E dipping steeply to the west; and N30W, vertical. The north or north-easterly-trending faults belong to the older Hijaz Tectonic Cycle, while the northwest-trending faults belong to the younger Najd Fault System.

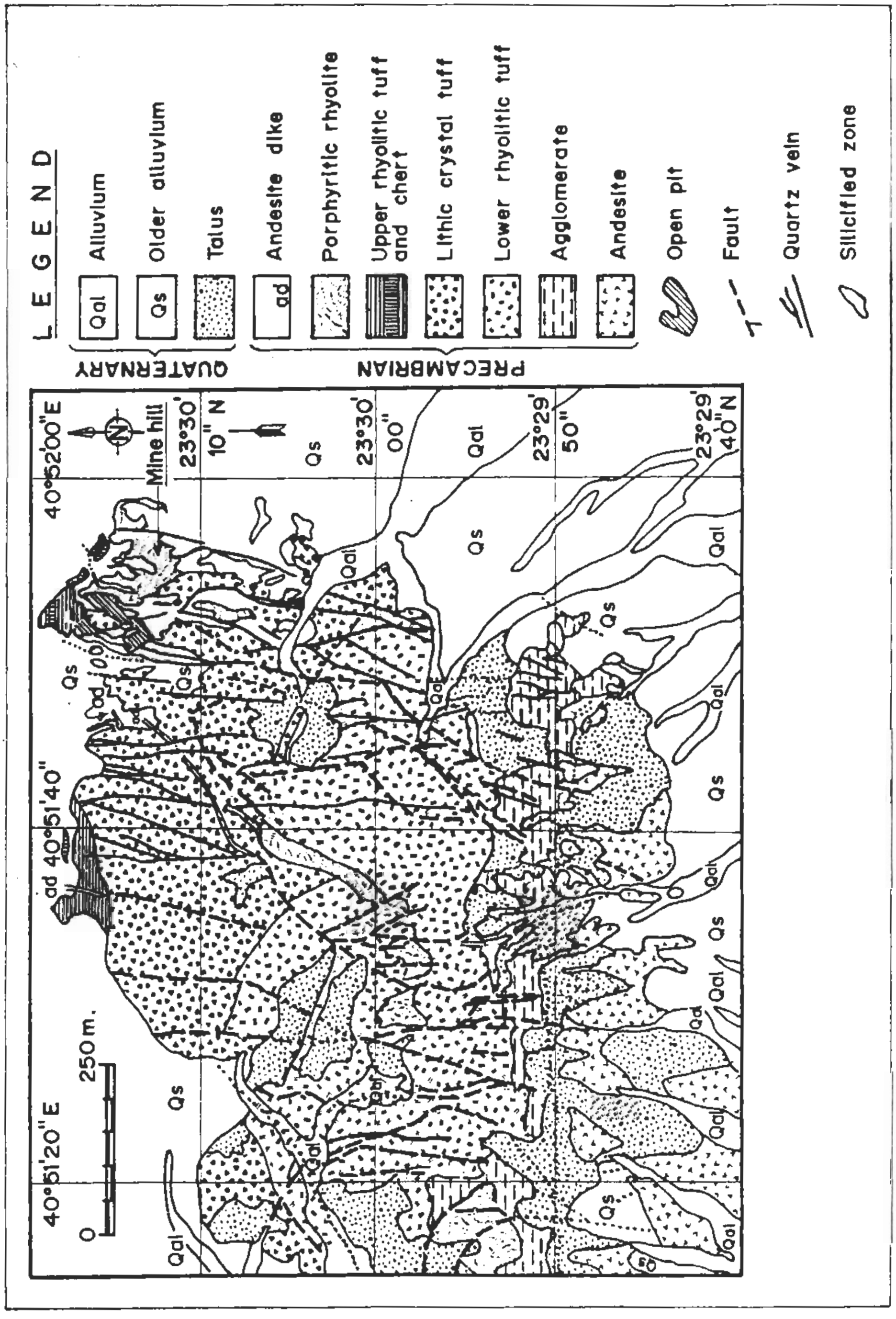

FIG. 2. Geologic map of Mahd Adh Dhahab (Hakim 1978).

Ore Deposits

Gold mineralization occurs as disseminations, quartz veins, and stockworks. Thus far, most of the gold production came from the quartz veins. There are two separate ore zones; the northern zone includes ancient workings at the northeastern part of Jabal Al-Mahd; and the southern zone along the southern side of the Jabal.

The quartz veins cut across the steeply dipping layered rocks and the rhyolite. The veins strike N10W to N20E, and N30E to N70E and are essentially vertical. The veins are divided into four types, three are metal-bearing and the fourth is barren.

The metal bearing quartz veins are divided as follows :

1 – Milky Quartz Veins

These are sharp walled veins of white, milky, fine- to medium-grained quartz. Comb structure is common. A thin film of chlorite envelops the quartz crystals and, near vein margins. Patches of calcite are randomly distributed in the fine-grained quartz. Sphalerite, chalcopyrite and galena are dispersed along the vein margins. These veins are ½ to one meter thick.

2 – Crustified Milky Quartz Veins

These are medium-grained quartz veins 5 cm to one meter thick with crustified bands of galena, chalcopyrite, sphalerite and chlorite alternating with chalcedony.

3 – Quartz-Cemented Breccia Veins

This type contains breccia fragments mostly of chert, rhyolite, and quartz. Quartz cement makes up about 40% of the veins. Sphalerite and galena are the common sulfide phases in these veins.

The stockwork mineralization occurs as intricate, thin, crisscrossing veinlets of quartz traversing the chloritized and silicified country rocks. They form irregular patches and contain thin veinlets and disseminations of sulfides. Disseminated pyrite occurs in the wall rocks particularly in the nothern area.

Ore Minerals

The primary ore minerals include, in order of abundance, pyrite, sphalerite, chalcopyrite, galena, hessite, altaite, argentite, pyrargyrite, polybasite, petzite, tetradymite, tellurobismuthite, calaverite, gold, electrum and specular hematite. Secondary minerals include covellite, chalcocite, neodiginite, bornite, malachite, azurite, specular hematite, geothite, lepidocrosite, and amorphous hydrated ferric oxides.

Metamorphic Features

The ore deposit at Mahd Adh Dhahab exhibits a number of textural and mineralogical features which indicate that the deposit has been subjected to effects of low grade metamorphism. The metamorphic features described in this work are mainly concerned with the smaller-scale, predominantly microscopic effects. The pervasiveness of metamorphism in terms of sulfide mineral re-equilibration often inhibited determination of the original ore mineral paragenesis.

The metamorphic effects observed in the sulfides at Mahd Adh Dhahab generally resemble those that can be observed in the enclosing rocks (pumpelleyite facies).

Barton and Skinner (1979) discussed the tendency of ore minerals to re-equilibrate at various temperatures. They demonstrated that the respond threshold for ore minerals corresponds, in general, with bond strength and hardness. Thus minerals such as pyrite, magnetite and arsenopyrite have the greatest tendencies to retain their original texture and composition during mild metamorphism. If, however, these minerals are re-equilibrated during the metamorphism, they are also most likely to preserve some record of the metamorphic peak rather than totally re-equilibrating during the subsequent retrograde metamorphism. On the other hand, soft sulfides (e.g. chalcopyrite, galena) and native metals (e.g. gold, electrum, bismuth), may readily re-equilibrate during the thermal rise to the metamorphic maximum and during the retrograde cooling and hence may retain little or no evidence of their origin. Sphalerite behaves in a different way because although it is soft, it is sufficiently refractory to retain original growth features through mild metamorphism, and to retain metamorphically equilibrated compositions through retrograde cooling periods.

The metamorphic features observed at Mahd Adh Dhahab are related to: (i) thermal or contact, (ii) dynamic or stress, and (iii) dynamothermal or regional effects. All the ore minerals reveal effects of regional metamorphism; contact and stress effects are present but have commonly been overprinted by regional effects.

Megascopic Ore Textures

The principal megascopic effects are increase in grain size, and injections of the plastic sulfides into crosscutting apophyses.

The pyrite- and sphalerite-rich veins may contain nearly undistributed primary sulfide banding with inclusions of undeformed volcanoclastic fragments. They may also display thorough destruction of the original texture. During plastic deformation of the soft sulfides, included layers and even portions of the wall rocks, which are more brittle, are broken and rotated in the sulfide matrix. Chalcopyrite, sphalerite and galena are commonly injected into fractures and cleavages of the accompanying silicates. Mobilization of chalcopyrite is suggested by its common presence in cross cutting features and its concentration along grain boundaries of, and fractures in, large pyrite crystals. Part of the texture observed in chalcopyrite may result from its precipitation late in the paragenetic sequence and replacement of pre-existing minerals.

The degree of homogenization and recrystallization varies greatly from one vein to the other and even in the same vein. The grain size of pyrite averages approximately 1 mm but over a distance of few cm it may vary from 0.1 mm to 1 cm. In places, pyrite has grown into cubes 2 cm across that are intermixed with pyrite crystals barely 0.1 mm across.

Microscopic ore textures

Pyrite

Pyrite is the most abundant ore mineral. The behavior of pyrite during metamorphism is determined by its abundance and its strong force of crystallization. Pyrite locally displays considerable cataclasis on account of its brittleness. The effects range from slight to intense fracturing (Fig. 3) culminating in pronounced brecciation and mylonitization (Fig. 4). Rectangular sections of pyrite cubes are common

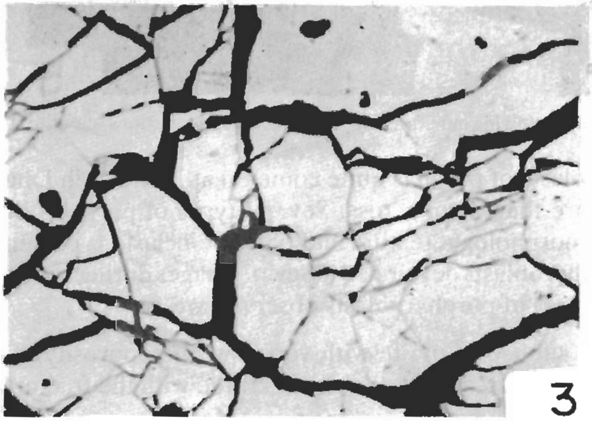

FIG. 3. Photomicrograph illustrating moderate to intense fracturing in pyrite. Incident light, × 308, oil.

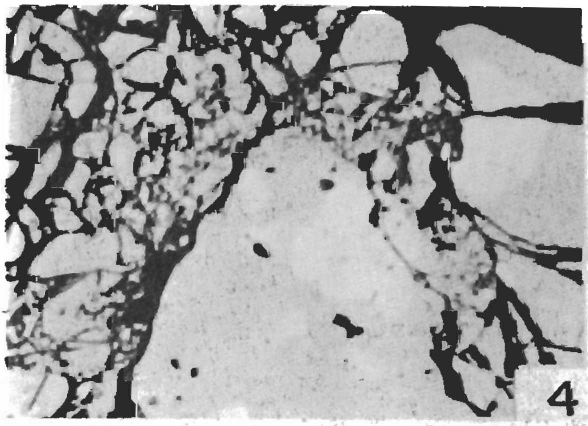

FIG. 4. Photomicrograph illustrating brecciation of pyrite crystals. Incident light, × 308, oil.

in polished sections (Fig. 5). Pressure shadows were also observed. The development of porphyroblasts of pyrite is quite common at Mahd Adh Dhahab. The crystals may reach more than 2 cm across. Several types of porphyroblasts are distinguished based on morphology, texture and types of inclusions present. They probably represent porphyroblasts developed at several stages during successive periods of metamorphism. Types of porphyroblasts observed are :

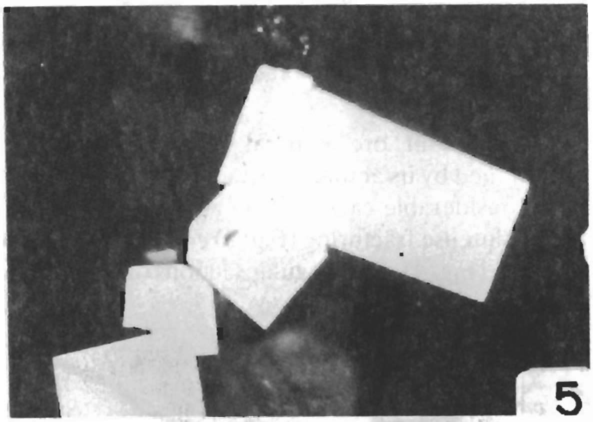

FIG. 5. Photomicrograph showing euhedral cubes and rectangular sections of pyrite. Incident light × 190 oil.

1 – Euhedral to subhedral pyrite with very low microporosity. The porphyroblasts are either unfractured or very slightly fractured with the fractures vacant or filled by gangue (Fig. 5).

2 – Subhedral porphyroblasts with relatively high microporosity. The core of the crystal is often occupied by anhedral to subhedral quartz (Fig. 6). Fracturing is slight to absent.

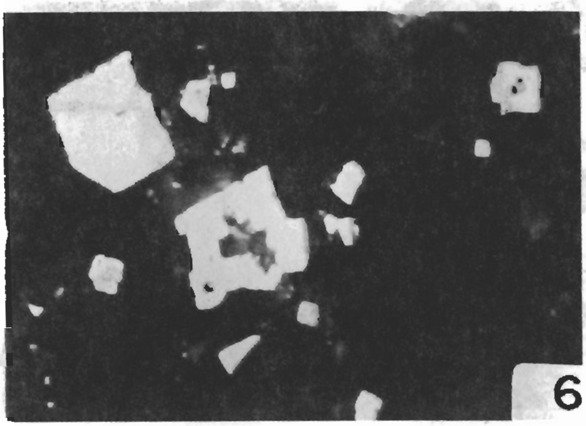

FIG. 6. Photomicrograph of subhedral to euhedral pyrite porphyroblasts with cores occupied by anhedral quartz. Incident light, × 190, oil.

3 – Anhedral, rounded and rotated pyrite porphyroblasts. In some crystals the rounding is almost perfect, and few exhibit "tails" or curved inclusion trails depicting effects of rotation. Syntectonic growth of rotating pyrite porphyroblasts with curved inclusion-trails was first described by Carstens (1944). Ramdohr (1969) emphasized that such inclusions, still retaining the orientation and grain size they had before being captured, offer most valuable information regarding the metamorphic history of ore bodies. The porphyroblasts are commonly traversed by veinlets of chalcopyrite and sphalerite. The crystals may be devoid of inclusions, or contain varying amounts of small rounded, curved or irregularly shaped inclusions of base metal sulfides. These inclusions are usually restricted to the core of the porphyroblast, but in some instances they may delineate part of the growth pattern of the pyrite (Fig. 7).

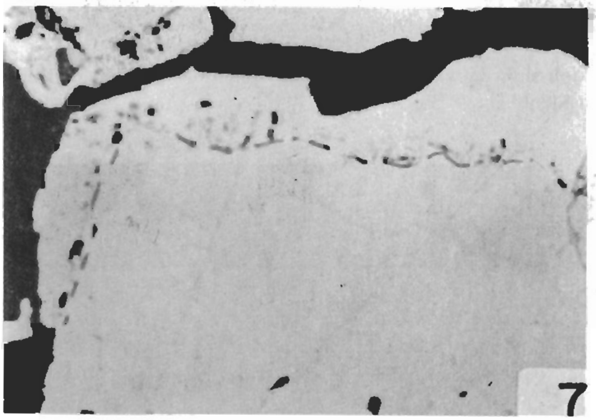

FIG. 7. Photomicrograph illustrating two generations of pyrite delineated by a zone of inclusions. Incident light, × 309, oil.

Another type of inclusions present are those of acicular crystals of specularite that are usually aligned parallel to the growth lines of the growing pyrite porphyroblast (Fig. 8). Some of the pyrite porphyroblasts are strained causing slight anomalous anisotropism.

Under thermal metamorphism, pyrite recrystallizes with the development of 120 triple junctions characteristic of equilibrated annealed textures (Fig. 9). Minute films of chalcopyrite tend to collect along such junctions and/or spread along pyrite interfaces. The recrystallization effects are also apparent where the growth of pyrite grains during metamorphism has trapped base metal sulfide grains (Fig. 10).

Growth textures, probably reflecting metamorphic development, are abundant in pyrite but usually requires etching to be made readily visible. Many pyrite crystals, with or without discernible growth zoning, possess a polycrystalline internal texture (brought about by etching) in spite of their external appearance as single crystals. Initially polycrystalline aggregates are unlikely to have grown into a form which possessed the external morphology of a single crystal (Craig 1983). Thus the polycrystalline

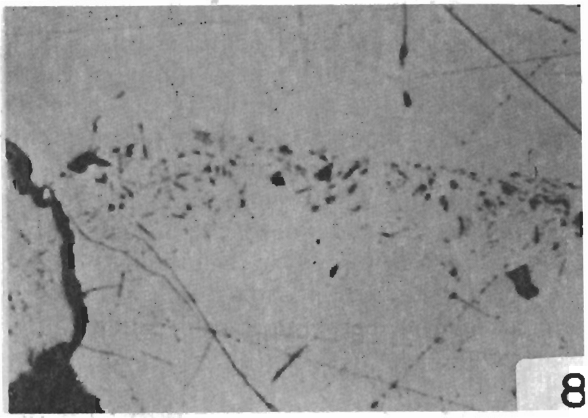

FIG. 8. Photomicrograph showing growth of pyrite porphyroblasts delineated by acicular crystals of specularite. Incident light, × 308, oil.

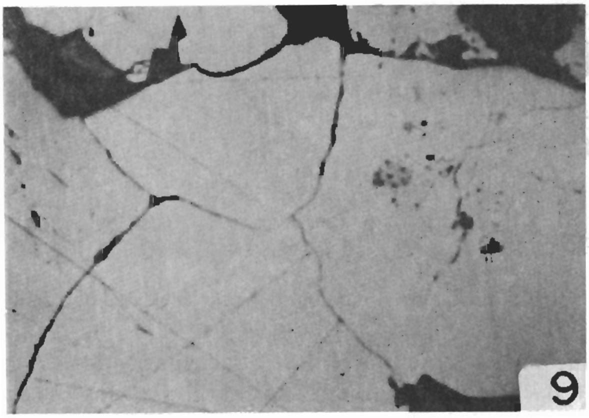

FIG. 9. Photomicrograph showing development of triple junctions in recrystallized pyrite. Incident light, × 308, oil.

nature may be due to recrystallization at the metamorphic maximum.

Pyrite sometimes occurs as aggregates of fine cubes < 50 µm in size, whereas in other instances, it occurs as single grains of a larger size. The differences in size could be explained in terms of the rate of nucleation and precipitation. It is also a function of temperature and cooling rate. When the rates of precipitation were high, this resulted in rapid deposition of abundant clots or masses of FeS_2 which subsequently recrystallized to form the present fine-grained aggregates. On the other hand when the temperature is high, the nucleation rate is low and the result is the growth of fewer and larger single crystals. These changes in rates of pyrite precipitation and crystallization probably also reflect intermittent discharge of the hydrothermal solutions.

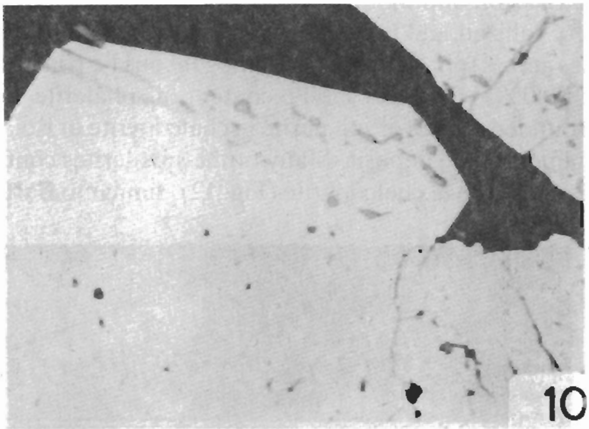

FIG. 10. Photomicrograph showing minute inclusions of galena trapped during recrystallization of pyrite. Incident light, × 308, oil.

Spheroidization (*i.e.* attainment of near-minimum surface area in order to minimize surface free energy) is also noticed in pyrite grains embedded in equant quartz grains. The pyrite also form botroydal or colloform bands up to few mm in length (Fig. 11). This texture is similar to what Ramdohr (1969) calls bird's eye structure formed by alteration of pyrrhotite along (0001) to produce fine grained pyrite + marcasite.

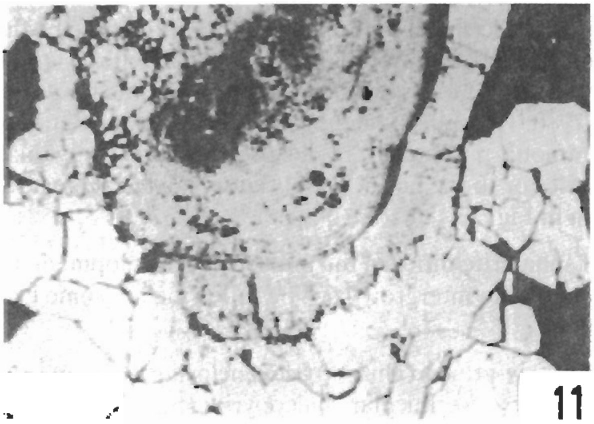

FIG. 11. Photomicrograph showing colloform banding in pyrite. Incident light, × 308, oil.

Sphalerite

Sphalerite is the most abundant of the base metal sulfides at Mahd Adh Dhahab deposit, and generally ranges between 1 to 15 volume % of all vein sulfides but may locally reach up to 70%. Although sphalerite is known as one of the more refractory sulfide minerals (Barton and Skinner 1979), some of the sphalerite at Mahd Adh Dhahab has recrystallized and homogenized during metamorphism. Electron microprobe traverses across sphalerite reveal homogeneous Fe contents within the same grain averaging 0.60%. However, the Fe content of sphalerite varies from 0.00 to 2.65%. Highly rounded islands of sphalerite in chalcopyrite or isolated in pyrite crystals are very common in the deposit. Many of the sphalerites contain randomly disseminated or aligned blebs of chalcopyrite (Fig. 12), similar to Barton's (1987) "chalcopyrite disease". These chalcopyrite grains, once thought to be the result of exsolution, are now interpreted as replacement or epitaxial features; the solubility of Cu in sphalerite is not sufficient for exsolution to be responsible for its development (Wiggins and Craig 1980; Hutchinson and Scott 1981). During metamorphism, the chalcopyrite has commonly migrated from the interiors of the individual sphalerite grains to grain boundaries or to the periphery of the sphalerite aggregate where it remains as rims as shown in Fig. 13.

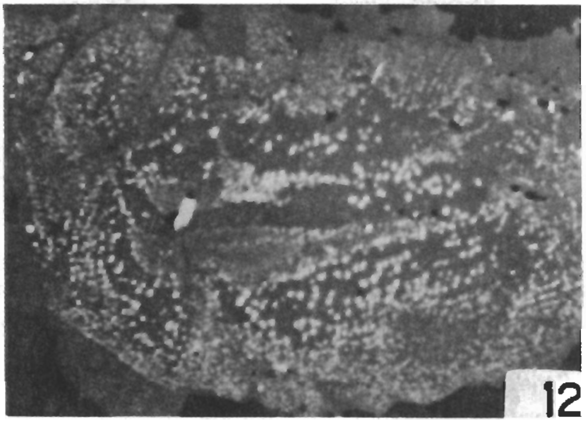

FIG. 12. Photomicrograph of randomly oriented blebs of chalcopyrite in sphalerite. Note the rind of fine-grained chalcopyrite enclosing fewer and coarser chalcopyrite. Incident light, × 308, oil.

The grains of sphalerite differ in the intensity of development and patterns of distribution of chalcopyrite intergrowths. The following are some examples of the patterns observed :

1 – A "ring" of fine-grained chalcopyrite enclosing a core of sphalerite containing a central zone of coarse, vermicular chalcopyrite (Fig. 12).

2 – Unusually coarse and anhedral chalcopyrite in the outer periphery of sphalerite passing gradually into much finer chalcopyrite in the core (Fig. 14).

3 – Chalcopyrite aggregates showing strong resemblance to myrmekitic intergrowths.

4 – Fine anhedral, irregularly shaped blebs of chalcopyrite that show parallel alignment within the same sphalerite crystal.

5 – Fine acicular plates that are arranged along one or more directions.

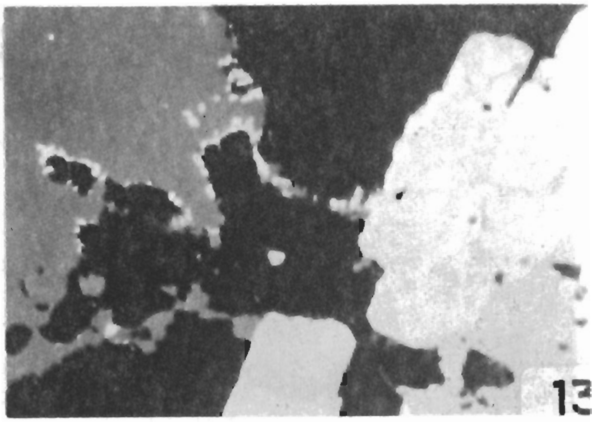

FIG. 13. Photomicrograph of chalcopyrite blebs occupying rims of sphalerite. Incident light, × 308, oil.

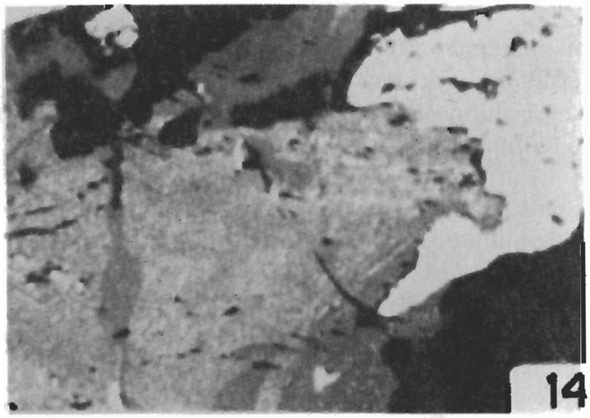

FIG. 14. Photomicrograph of coarse and anhedral chalcopyrite in the outer periphery of sphalerite passing into much finer chalcopyrite in the center. Incident light, × 308, oil.

Sphalerite with no chalcopyrite intergrowths can be found encrusting chalcopyrite-diseased sphalerite as well as other clasts containing chalcopyrite. Clear (and undiseased) sphalerite also overgrows (Fig. 15) and fills cracks in diseased sphalerite. The chalcopyrite-free areas may be due to annealing which locally drove the chalcopyrite inclusions out of the sphalerite. Also some of the apparently undiseased sphalerite may contain submicroscopic chalcopyrite disease that is only apparent in transmitted light. Some zones within sphalerite are more strongly diseased than others. The chalcopyrite disease has not been observed in any mineral other than sphalerite.

Several processes may be considered to explain the development of chalcopyrite disease in sphalerite :

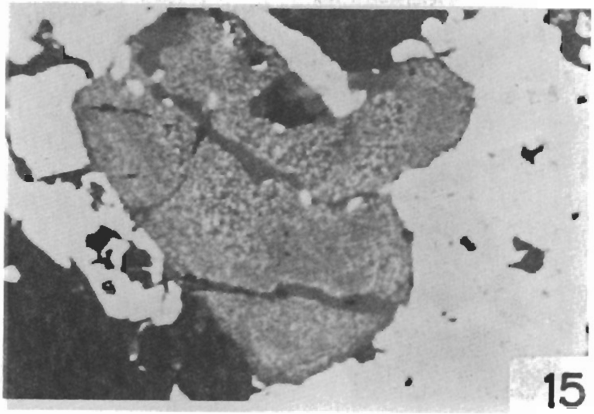

FIG. 15. Photomicrograph illustrating clear sphalerite filling cracks in diseased sphalerite. Incident light. × 308,oil.

(1) Exsolution phenomena: This is unlikely because it was shown experimentally that exsolution is not a viable mechanism (Hutchinson 1978; Eldridge *et al.* 1983).

(2) Physical segregation of remnants of a primitive stage of ore formation (Yui 1983): This process implies that sphalerite and chalcopyrite formed contemporaneously as small (< 1 μm) blebs and that sphalerite grew to its present grain size (up to 3 mm) while pushing and squeezing the small chalcopyrite blebs to grain boundaries. Though some coprecipitated sphalerite and chalcopyrite intergrowths are observed, this process is incapable of explaining the vast majority of the textures.

(3) Supergene phenomena (De Waal and Johnson 1981): This process is inapplicable since the disease show no relationship to covellite, neodiginite or any other possible supergene mineral.

(4) The breakdown of a metastable Cu-Zn-Fe-S phase such as that found by Clarck (1970) in the supergene enrichment zone of a porphyry copper deposit: This possibility entails growth of a metastable CuZnFeS mineral which will breakdown to yield $CuFeS_2 + ZnS$.

(5) Interaction of sphalerite with later ore forming fluids (Eldridge *et al.* 1983; Barton 1987): One of the possible mechanisms (Eldridge *et al.* 1983) involves removal of Cu originally dissolved in sphalerite by interaction with fluids of higher sulphur fugacity such as:

$$Zn_{0.09}Fe_{0.05}Cu_{0.05}S + 0.04S = Zn_{0.98}Fe_{0.01}Cu_{0.01}S + 0.04\,CuFeS_2.$$

The initial Cu content of sphalerite is the limiting factor of the extent of the disease. However, the initial sphalerite is unlikely to have contained sufficient Cu to form chalcopyrite.

Another mechanism suggested by Eldridge *et al.* (1983) is the reaction between sphalerite and Cu-bearing fluids. It may begin as a replacement of the FeS component of sphalerite in reactions such as:

$Zn_{0.95}Fe_{0.05}S + 0.048\,Cu^{+} + 0.048H_2S = 0.952\,(Zn_{0.998}Fe_{0.002}S) + 0.048CuFeS_2 + 0.048H^{+} + 0.024H_2$.

(6) Metamorphic recrystallization: This invokes the action of metamorphic remobilization and re-equilibration. During the low grade metamorphism to which the deposit and enclosing country rocks were subjected, Cu-bearing solutions were generated and move along microfractures. These solutions replaced the FeS and ZnS components in sphalerite. This process occurred at several episodes during the metamorphism of the deposit with the result that there are multiple stages of chalcopyrite disease superimposed on each other. In other words, the chalcopyrite disease was a series of repeated events occurring during successive periods of metamorphism. During the slow and intermittent permeation of such solutions within sphalerite, there developed a multitude of nucleation centers around which blebs of chalcopyrite were formed. It must be noted, however, that examples of the disease process going to complete replacement of sphalerite have not been found. Only examples of intensely diseased sphalerite have been observed. It is conceivable that the chalcopyrite disease represents a part of the processes that caused the wholesale replacement of the other sulfides by chalcopyrite.

Localized effects of dynamic metamorphism are evident through the presence of intensely fractured and/or mylonitized sphalerite (Fig. 16). In addition, deformation along faults or shear zones has locally lead to ductile flow of the softer sulfides (sphalerite, galena, and chalcopyrite). Such differentiation products are recognized by an extremely deformed fabric unless later modified by annealing. Thus sphalerite commonly forms stretched and irregularly elongated patches that occupy microfractures or line cavities and spaces between gangue minerals. The elongation of sphalerite has been ascribed to twin gliding during deformation.

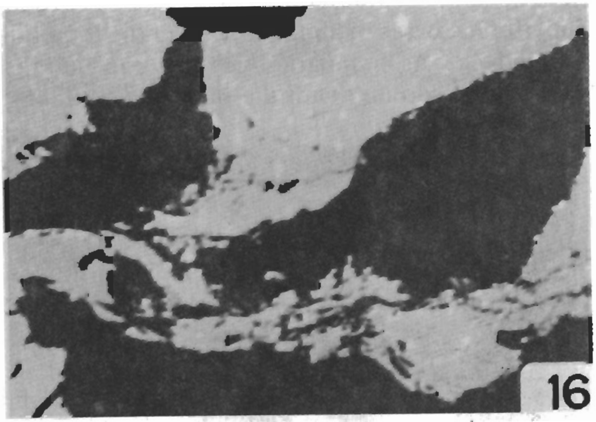

FIG. 16. Photomicrograph illustrating intensely fractured sphalerite. Incident light, × 308, oil.

With increasing depth, sphalerite becomes coarser and more euhedral. It is commonly seen as subhedral to euhedral crystals lining former cavities or as crystal fragments. Etching reveals that the largest sphalerite grains (up to 3 mm) consist of clusters of smaller subgrains. Crystals may grow together to form semilinear to curved bands. Sphalerite crystals at Mahd Adh Dhahab do not show any discernible growth banding on close examination of doubly polished thin sections. This is attributed to recrystallization during metamorphism. Few examples of framboidal sphalerite were observed in the upper parts of the deposit. Three processes make it very difficult to correlate growth stratigraphy of one sphalerite crystal to another :

1 – Coarse-grained sphalerite crystals may have been broken and mixed with other mineral fragments. Homogeneous aggregates of crystals were also recemented by late sulfides or gangue minerals.

2 – Hydrothermal dissolution may have removed part of the growth history of sphalerite, creating a microkarst texture (Barton 1987) similar to those described in sphalerite from Mississippi Valley-type deposits and vein deposits.

3 – Partial replacement of sphalerite by chalcopyrite (chalcopyrite disease) masks the initial character of much of the sphalerite.

Chalcopyrite

Chalcopyrite is the second most abundant base metal sulfide in the veins. It occurs as disseminated anhedral grains or irregular patches interstitial to pyrite and silicates. In contrast to the other sulfides, the chalcopyrite is nearly always massive and anhedral. Chalcopyrite increases in abundance from the top of the ore downward. With increasing abundance, its boundaries with the other sulfides become increasingly cuspate (Fig. 17). Associated with the increased rounding of other sulfides against chalcopyrite is an increase in the porosity. The migration of chalcopyrite to low pressure areas during metamorphism is evidenced by its abundant occurrence in fractures and cracks in pyrite grains and in the silicates included within, and

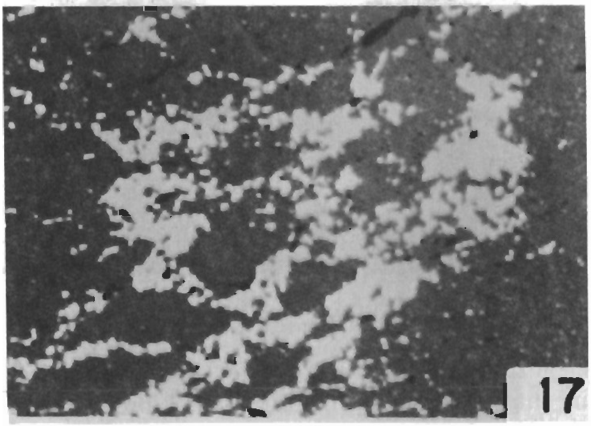

FIG. 17. Photomicrograph illustrating cupsate boundaries of chalcopyrite. Incident light, × 308, oil.

peripheral to the ore deposit. Chalcopyrite also commonly occurs as randomly, or aligned disseminated grains and rods dispersed within sphalerite.

The typical textural relationships between chalcopyrite and the other base metal sulfides in the deposit can be summarized as follows :

1) Chalcopyrite fills gaps in the outer shell of pyrite cubes and often penetrates to the interior of cubes to form atoll texture;

2) Chalcopyrite engulfs small rounded islands separate from peninsulas or scalloped masses of sphalerite, pyrite or galena (Fig. 18);

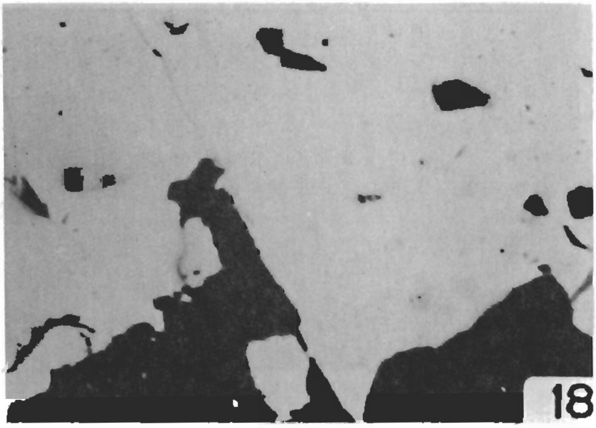

FIG. 18. Photomicrograph of chalcopyrite engulfing islands of base metal sulfides. Incident light, × 308, oil.

3) Chalcopyrite surrounds highly rounded crystals of pyrite, sphalerite and galena (Fig. 19);

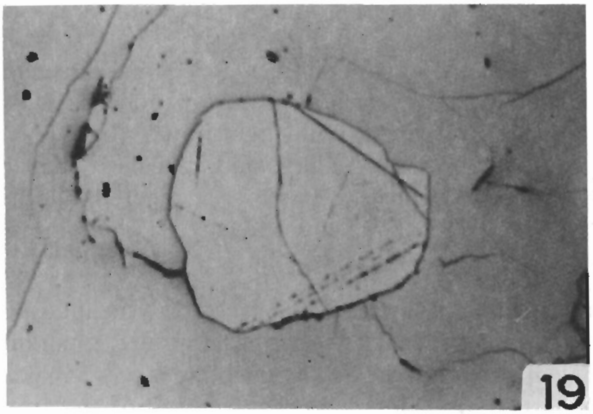

FIG. 19. Photomicrograph showing round pyrite surrounded by chalcopyrite. Incident light, × 308, oil.

4) Chalcopyrite forms the chalcopyrite disease in sphalerite; and

5) Chalcopyrite appears in some cases to have coprecipitated in minor amounts with the other sulfides either as small "tacks" along growth horizons or as patches with mutual boundaries.

Deformation twins are commonly developed in patches of anhedral to subhedral chalcopyrite (Fig. 20). Slight to moderate fracturing are observed occasionally and reflect effects of dynamic metamorphism.

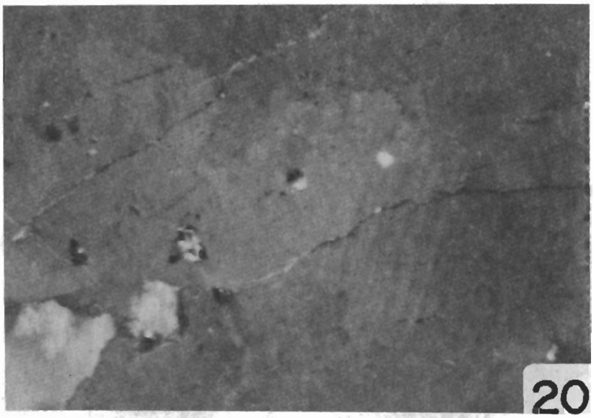

FIG. 20. Photomicrograph of deformation twinning in chalcopyrite. Incident light, crossed polars, × 308, oil.

Fine lamellae of bornite are often observed in some chalcopyrite grains, particularly along fractures and cracks. They are probably the result of weathering of chalcopyrite.

Galena

Galena is the least abundant of the sulfides. It occurs as disseminated grains and in cross cutting veinlets. It also forms anhedral to subhedral blebs and irregularly shaped patches. These forms are typically tightly intergrown with sphalerite and pyrite. Galena is found occasionally as large and irregularly shaped patches that are abundantly intergrown with sphalerite and pyrite. There is multiplicity in the direction of cleavage traces in these patches, indicating that several individual crystals may be contained in each galena mass.

Galena is often crosscut by and enclosed in chalcopyrite indicating that the majority of the galena formed before chalcopyrite. However, small quantities of galena formed after chalcopyrite, as indicated by the occurrences of galena encrusted on or filling cracks in clasts of ore containing chalcopyrite. As the average ore grain size and chalcopyrite content increase with depth, the abundance of galena decreases, and the abundance of rounded galena inclusions in chalcopyrite increases. In relatively sphalerite-rich ore galena is present in large enough masses that are highly rounded and there are numerous islands of galena in the chalcopyrite nearby.

All of the galena has no doubt been recrystallized, but curved cleavages resulting from late stage deformation are common. The recrystallization is also apparent where the growth of pyrite grains during metamorphism has trapped base metal sulfide grains. Among the base metal sulfides, galena is one of the most ductile sulfides under effects of regional metamorphism (Vokes 1969). Thus the galena is readily mobilized by creep forming irregularly shaped and elongated streaks. Kinking is locally observed (Fig. 21) as a consequence of dynamic metamorphism. The galena contains trace amounts of Ag (0.1-0.5%), possibly in solid solution.

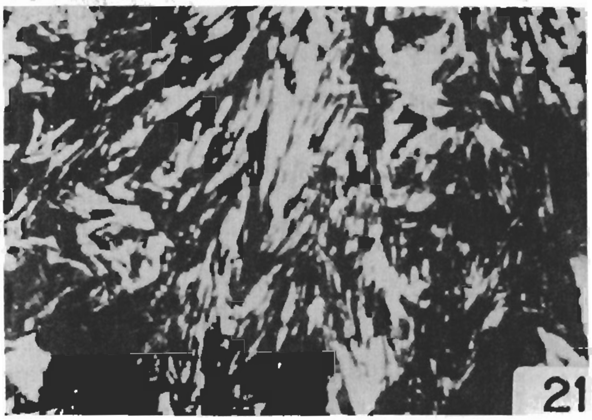

FIG. 21. Photomicrograph showing development of kinking in galena. Incident light, × 308, oil.

Tellurides

Minerals of the telluride group are less abundant than galena. The tellurides have poorly developed crystal outlines and typically occur as irregularly shaped patches intergrown with the sulfides described above. Small islands of tellurides surrounded by chalcopyrite are very common (Fig. 22).

Precious metals

The behavior of the precious metals during metamorphism is not well understood. Gold is present almost entirely as disseminated fine grains of electrum in close association with chalcopyrite, sphalerite, galena and quartz. Substantial Au occurs as petzite, Ag_3AuTe_2 (Afif 1990). It also occurs as very thin irregular streaks and veinlets that have irregular mutual boundaries with the associated sulfides and gangue. Due to the unique physical and chemical characteristics of gold (e.g. extreme softness, low power of crystallization, and resistance to chemical reactions) it is difficult to assess effects of metamorphism on gold. Mobilization of gold usually occurs at high metamorphic grades. However, it is reasonable to assume that at least part of the

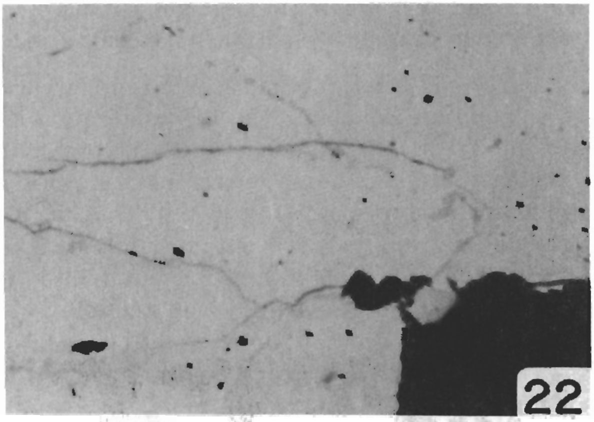

FIG. 22. Photomicrograph illustrating small rounded islands of tellurides in chalcopyrite. Incident light, × 308, oil.

originally disseminated gold has been remobilized during metamorphism. This would probably involve coalescence of the fine-grained gold into irregular patches, or its physical migration into elongated streaks within microfractures in the associated sulfides.

Summary and Conclusions

Textural and mineralogical features observed in the ore deposits at Mahd Adh Dhahab indicate that the deposits have been subjected to metamorphism.

Three main effects were recognized. *Recrystallization* of the ores during regional metamorphism resulted in changes mainly in the fabric of the ores. With increasing metamorphism: a) there is a general increase in grain size, b) growth of pyrite as porphyroblasts, c) presence of triple junction point texture and d) sulfidation of iron-bearing minerals.

Deformational effects present varied from none, through brittle cataclasis to ductile deformation. The features observed include: a) fracturing, brecciation and mylonitization of fine-grained sulfides and porphyroblasts, b) deformation twinning, c) replacement, d) folding and disruption of cleavage traces, e) rotation of pyrite crystals, and f) stretching and elongation of soft sulfides.

Remobilization produced irregular bodies of vein quartz and ore minerals, either within the deposits or in their immediate country rocks. The remobilization distances are limited, either within parent body or in restricted halo surrounding it (up to some tens of meters). The remobilization is selective and proceeded by creep or fluid-phase transport. The apparent order of increasing mobility is: most mobile (galena and chalcopyrite), mobile (sphalerite), least mobile (pyrite). Certain replacement phenomena observed between the euhedral-subhedral pyrite grains and the base metal sulfides could be ascribed to metamorphism.

The multitude of metamorphic features observed and their varied nature suggest that the ores at Mahd Adh Dhahab area were subjected to polymetamorphic episodes. Successive episodes of low grade metamorphism prevailed during a long time span. Intermittent with such pervasive regional metamorphism, the ores were subjected to short periods of essentially dynamic and thermal metamorphism.

References

Afifi, A.K. (1990) *Environments of gold telluride mineralization in the Mahd Adh Dhahab district, Arabian Shield.* Ph.D. Thesis, University of Michigan, Ann Arbor, Michigan, 285 p.

Barton, P.B., Jr. (1987) Chalcopyrite disease in sphalerite, pathology and epidemiology. *American Mineralogist,* **72:** 451-467.

Barton, P.B., Jr. and **Skinner, B.** (1979) Sulfide mineral stabilities, *In:* **Barnes, H.L. (ed.)** *Geochemistry of Hydrothermal Ore Deposits,* 2nd. edn., Wiley-Interscience, New York, 278-403.

Carstens, C.W. (1944) Om dannelsen av de norske svovelkisforekomster, *K. Nor. Vidensk. Selsk. Forh.,* **17:** 27-54.

Clarck, A. (1970) Native Zn and a-Cu, Zn from Mina Dulcinea de Llampos, Copiapo, Chile. *Am. Mineralogist,* **55:** 1019-1025.

Craig, J.R. (1983) Metamorphic features in Appalachian massive sulfides. *Mineralogical Magazine,* **47:** 515-525.

De Waal, S.A. and **Johnson, J.A.** (1981) Chemical heterogeneity of sphalerite in a base metal sulfide deposit. *Econ. Geol.* **76:** 694-705.

Doebrich, J.L. and **LeAnderson, P.J.** (1984) Geology and hydrothermal alteration at the Mahd Adh Dhahab epithermal precious metal deposit, Kingdom of Saudi Arabia. *U.S. Geological Survey, Saudi Arabian Mission, Open File Report,* **USGS-OF-04-32,** 33 p.

Eldridge, C.S., Barton, P.B., Jr. and **Ohmoto, H.** (1983) Mineral textures and their bearing on formation of Kuroko orebodies. *Econ. Geol. Monograph* **5:** 241-281.

Hakim, H.D. (1978) *Geology and the genesis of gold-silver base metal sulfide-bearing veins at Mahd Adh Dhahab, Kingdom of Saudi Arabia.* Ph.D. Thesis, University of Western Ontario, London, Ontario, Canada, 182 p. (Unpublished).

Hilpert, L.S., Roberts, R.J. and **Dirom, G.A.** (1984) Geology of the Mine Hill and the underground workings, Mahd Adh Dhahab. Kingdom of Saudi Arabia. *U.S. Geological Survey Saudi Arabian Mission, Open File Report.*

Hutchinson, M.N. (1978) *Refinement and application of the sphalerite geobarometer,* Ph.D. Thesis, University of Toronto, 159 p. (Unpublished).

Hutchinson, M.N. and **Scott, S.D.** (1981) Sphalerite geobarometry in the Cu-Fe-Zn-S system. *Econ. Geol.,* **76:** 143-153.

Luce, R.W., Bagdady, A.Y. and **Roberts, R.J.** (1975) Geology and ore deposits of the Mahd Adh Dhahab district, Kingdom of Saudi Arabia. *U.S. Geological Survey Saudi Arabian Project Report* **195,** 29 p.

Luce, R.W., O'Neil, J.R. and **Rye, R.O.** (1979) Mahd Adh Dhahab–Precambrian epithermal gold deposit, Kingdom of Saudi Arabia. *U.S. Geological Survey Saudi Arabian Project Report* **256,** 33 p.

Ramdohr, P. (1969) *The Ore Minerals and Their Intergrowths,* New York, Pergamon, 1174 p.

Roberts, R.J., Bagdady, A. and **Luce, R.W.** (1978) Geochemical investigations in the Mahd Adh Dhahab district, Kingdom of Saudi Arabia. *U.S. Geological Survey Saudi Arabian Project Report* **231,** 34 p.

Vokes, F.M. (1969) A review of metamorphism of sulfide deposits, *Earth Sci. Rev.,* **5:** 99-143.

Wiggins, L.B. and **Craig, J.R.** (1980) Reconnaissance of the Cu-Fe-Zn-S system: Sphalerite phase relationships. *Econ. Geol.* **75:** 742-751.

Worl, R.G. (1978) Mineral exploration–Mahd Adh Dhahab district, Kingdom of Saudi Arabia. *U.S. Geological Survey Saudi Arabian Project Report 233,* 85 p.

World, R.J. (1979) Ore controls at the Mahd Adh Dhahab gold mine, Kingdom of Saudi Arabia, *In:* Evolution and mineralization of the Arabian-Nubian Shield, King Abdulaziz University. *Institute of Applied Geology, Bulletin* **3**(2): 93-106.

Yui, S. (1983) Textures of some Japanese Besshi-type ores and their implications for Kuroko deposits. *Econ. Geol. Monograph* **5:** 231-240.

صحبات الكبريتيدات وأزمنة التحول في منجم مهد الذهب بالمملكة العربية السعودية

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المستخلص . يقع منجم مهد الذهب في وسط الجزء الغربي من الدرع العربي ويعتبر أكثر منجم منتج للذهب في المملكة العربية السعودية في الماضي والحاضر . تدل المعالم النسيجية والمعدنية التي لوحظت في الخام على أن تلك الرواسب قد تعرضت لعمليات تحول إقليمي نتجت عنها ثلاثة أنواع من مظاهر التحول هي إعادة التبلور والتشوه وتحريك الخام .

نتج عن إعادة تبلور الخام تغييرات أساسية في الأنسجة وكذلك في معادن الخام ، وبزيادة درجة التحول لوحظ الآتي : أ - زيادة عامة في حجم الحبيبات ، ب - نمو البيريت على هيئة حبيبات بورفيروبلاست و ج - وجود نقاط التقاء ثلاثية . أما التأثيرات الناتجة عن التشوه فتتدرج من لاشيء إلى تشوه هش ثم إلى تشوه لدن وتتضمن : أ - تشقق وتهشم وتفتت الكبريتيدات دقيقة الحبيبات والبورفيروبلاست ، ب - توأمة تشوهية ، ج - تشوه وتمزق أسطح الانفصام ، د - إدارة حبيبات البيريت ، و هـ - تمدد واستطالة الكبريتيدات اللدنة .

نتج عن إعادة تحرك الخام نشوء أجسام غير منتظمة الشكل من عروق المرو ومعادن الخامات إما مع الرواسب المعدنية أو في الصخور الحاوية لها . وقد تحرك الخام لمسافات محدودة تقدر بعشرات الأمتار إما خلال جسم الخام الأصلي أو في المنطقة المحيطة به وعملية التحرك انتقائية وتتم إما بطريقة الزحف أو بطريقة انتقال الطور المائع . يقل مقدار التحرك من الجالينا إلى الكالكوبيريت إلى السفاليريت وأخيرًا البيريت . وتعزي بعض ظواهر الإحلال بين بلورات البيريت الكاملة الأوجه والنصف كاملة وكبريتيدات المعادن الأساسية إلى عملية التحول .

تعرضت منطقة مهد الذهب إلى أطوار متتابعة من التحول الإقليمي لسحنة الشيست الأخضر المنخفض على امتداد فترة طويلة من الزمن تخللها فترات قصيرة من التحول الدينامي والتحول الحراري .