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A Fluid Inclusion Study on Mahd Adh Dhahab Gold Deposit, Saudi Arabia

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ABSTRACT. Mahd adh Dhahab, the oldest gold mine in Saudi Arabia, is situated at the central part of the Arabian shield. It consists of an upper Proterozoic rock sequence of andesite, agglomerate, lower rhyolitic tuff, lithic crystal tuff, upper rhyolitic tuff and a late small porphyritic rhyolite intrusion. Four generations of quartz veins cut through the sequence with three generations mineralized. The area has been regionally metamorphosed to low-grade green schist facies. To date, Mahd adh Dhahab has estimated ore reserves of 1.45 million tons, grading 26 g/t Au and 92 g/t Ag, and a further 109,000 tons of oxide ore with an average of 77 g/t Au.

The majority of the fluid inclusions in quartz from quartz veins at Mahd adh Dhahab are very small. However, primary fluid inclusions of larger sizes (5 to 15 U) were chosen and analyzed. All the analyzed fluid inclusions are two phase (gas and liquid) inclusions. Upon heating, they all homogenized into a liquid phase. The final melting temperatures of ice from the analyzed fluid inclusions fall between –0.3 and –2.2°C whereas, the final homogenization temperatures of bulk composition fall between + 100 and + 380°C. The calculated compositions of the fluid are 99.21 to 99.33% of H_2O and 0.67 to 0.79% of NaCl.

A microthermometric study of the fluid inclusions suggests that there are at least two stages of quartz deposition, one at about 100-210°C and another at about 340-380°C. Quartz deposited at low temperature is considered to be barren or contain minor amount of mineralization, whereas quartz deposited at high temperature is postulated to be mineralized and economically important.

It is concluded that the mineralizing fluid at Mahd adh Dhahab consisted mainly of meteoric water with a possible minor amount of sea water. The mineralization is postulated to have been deposited at a shallow depth in the earth's crust to form a typical epithermal deposit.

Introduction

The Mahd adh Dhahab gold deposit is located in the central part of the Arabian shield, approximately 300 km NE of Jeddah (Fig. 1). It is the oldest gold mine in Saudi Arabia and has been mapped and investigated by many geologists (Dirom 1946, 1947, Playter 1953, Brown *et al.* 1962, Theobald Jr. 1965, Davis *et al.* 1965, Goldsmith and Kouther 1971, Robert *et al.* 1975, Hakim 1978, USGS 232/78, 1978, USGS 265/79, 1979, Riofinex 1981). For the last five years, consolidated Gold Fields is carrying out a detailed investigation and evaluation of the deposit. The potential ore at the southern mineralized zone is 1.45 million tons with 26 g/t of Au and 92 g/t of Ag, and a further 109,000 tons of oxide ore with an average gold content of 77 g/t from the Open Pit (Petromin 1988). Petromin is at present preparing to mine and extract gold from Mahd adh Dhahab.

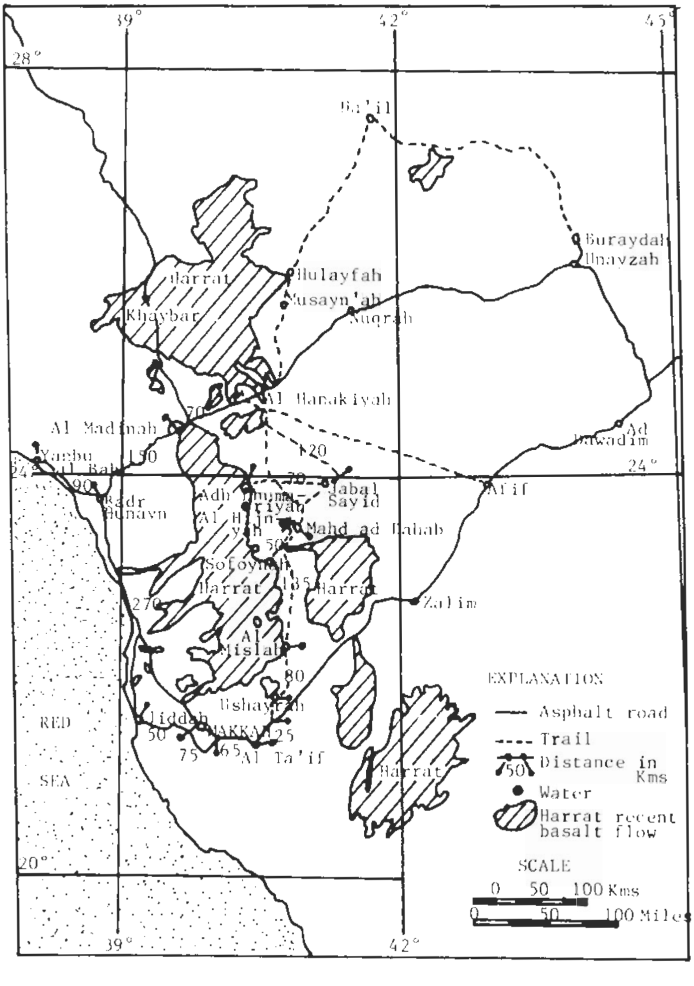


FIG. 1. Location map of Mahd adh Dhahab.

Geology

Rocks in the area consist of a west striking, north dipping volcanic sequence with the lowest 300 m comprising a massive dark green andesite conformably overlain by 90 to 120 m of thick agglomerate (Fig. 2). It is followed by a 270 m thick layer of "lower" rhyolitic tuff, mainly thick bedded, very siliceous and intercalated in its lower part with sandstone and siltstone. This again is overlain by 140 m of lithic crystal tuff (Hakim 1978). The uppermost layer is a fine grained rhyolitic tuff intercalated with thin bedded chert and siltstone.

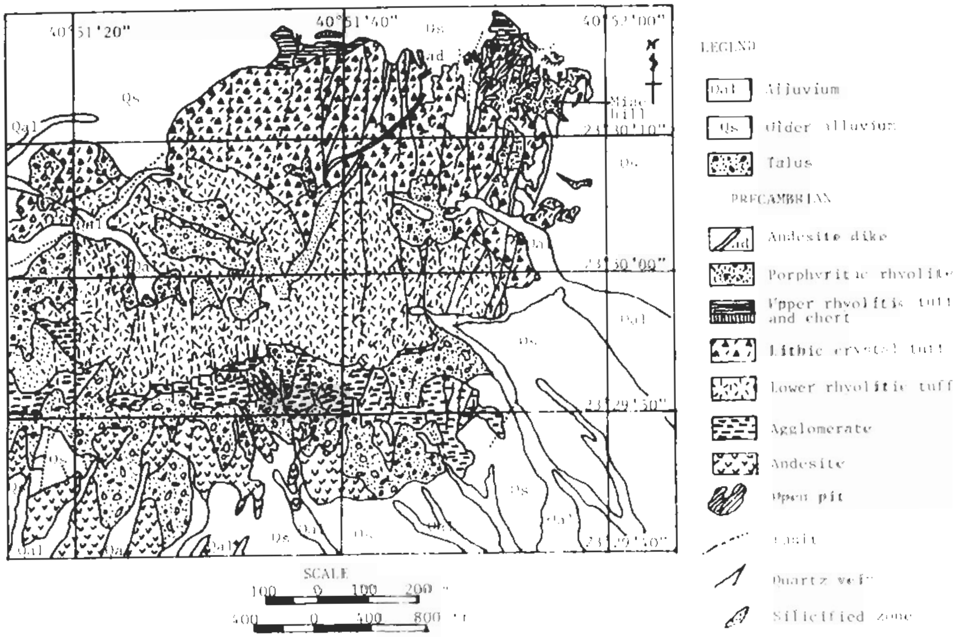


FIG. 2. Geologic map of Mahd adh Dhahab (Hakim 1978).

An elliptical body of porphyritic rhyolite 350 m by 260 m occurs within the upper part of this layered sequence at the northeast corner of Jabal Al-Mahd (Hakim 1978).

Quartz veins cut all the layered units and the porphyritic rhyolite. Because of the impervious nature of the lower and upper rhyolitic tuffs and the intercalated massive thick bedded chert, quartz veins observed in these rocks are thin and not abundant. The veins terminated in the upper rhyolite tuff intercalated with chert. Andesite dykes, the youngest rock unit, cut all other units of the area, including the quartz veins. However, they are not as common as the quartz veins. The andesite dykes appear to be the feeders for the next cycle of volcanism.

There is an excess of silica throughout the lower rhyolitic tuff, the upper rhyolitic tuff and porphyritic rhyolite. This is accompanied by a large increase in K_2O and a decrease in Na_2O as is evidenced by late growth of orthoclase and sericite after plagioclase in the rocks and in selvages of quartz veins (Hakim 1978).

Isotopically, the age of the Mahd adh Dhahab volcanic sequence has not been established. However, Brown (1973) measured a Rb/Sr whole rock age of 6% ma on appearing rhyolite body, 12 km NE of Mahd adh Dhahab. In light of this, the Mahd adh Dhahab volcanic sequence is postulated to be upper Proterozoic in age.

Structure

The area has a homoclinal structure with a general east-west trending strike and a northerly dip varying from moderately steep to vertical. A prominant N 45 W, steeply dipping fault system cuts the rock units. There are two main fracture systems, trending N 10 W to N 20 E and N 30-75 W, the majority of them steeply dipping. The N 10 W to N 20 E fracture system may be attributed to the Hijaz Tectonic Cycle, whereas the N 45 W fault system coincides with the Najd Fault System.

Mineralization

An oxidized zone at the surface and along fractures penetrates to a maximum depth of about 8-10 m and comprises quartz veins intergrown with limonite, malachite and chrysocolla. Copper, zinc and silver have been leached from this zone. Remnants of primary and supergene sulphides which contain gold and tellurides, occur in some areas of the oxidized zone (Lewis and Martin 1983).

Four generations of quartz veins are present at Mahd adh Dhahab. These are crustified quartz veins (Plate 1-A), massive quartz veins (Plate 1-B), quartz cemented breccia veins (Plate 1-C) and barren quartz is milky white in colour, but some is rosy pink (Plate 1-D). The veins are crypto-crystalline, fine to medium grained quartz. Barren quartz veins have characteristic prismatic quartz crystals grown perpendicular to the length of cavities.

Mineralized quartz veins trend between N 10 W to N 20 E and N 30 to 70 E, and are essentially vertically dipping. Barren quartz veins trend N 10 E, N 30 to 70 E and N 30 W and are also steeply dipping (Hakim 1978). Ratios of FeO/Fe_2O_3 from metal-bearing and barren quartz veins and host rock samples showed increases down stratagraphic section, and the vein material has the greatest relative amount of oxidized iron.

The mineralized quartz veins contain pyrite, chalcopyrite, bornite, covellite, chalcocite, neodigenite, galena, sphalerite, calaverite plus malachite and azurite. At the southern mineralized zone, where Petromin is mining gold, the host rock to mineralization is agglomerate.

Twenty to thirty percent of the Au and Ag occurs as native metals (electrum) with their sizes ranging between 1 to 10. Seventy to eighty percent of the precious metals occur as tellurides (hessite, petzite) with their sizes ranging between 10 to 30 (Petromin 1983).

The metal bearing and barren quartz veins were estimated to have an age of 690 ± 35 m.y. by the Rb/Sr method (Routhier and Delfour 1975) using the pink orthoclase which occurs either as elongated crystals or thin layers along vein selvages. This age corresponds to the postulated age of the porphyritic rhyolite.

Metamorphism and Hydrothermal Alteration

Mineralogically, it has been established that the metamorphic minerals present in the rocks at Mahd adh Dhahab area are quartz, cholorite (chamosite, penninite), orthoclase, calcite, ankerite, epidote and sericite (Hakim 1978). This mineral assemblage represents low-grade greenschist facies metamorphism.

Hydrothermal alteration in the wall rocks and the immediate vicinity of quartz veins in propylitic (chlorite, calcite, epidote), phyllic (quartz, sericite) and potassic (orthoclase, quartz, sericite) (Hakim 1978). Generally, propylitic alteration is the most widespread, phyllic alteration is dominant where quartz veining and sulphide mineral content is greatest, and potàssic alteration is localized and inter-related to veined and metal-bearing areas.

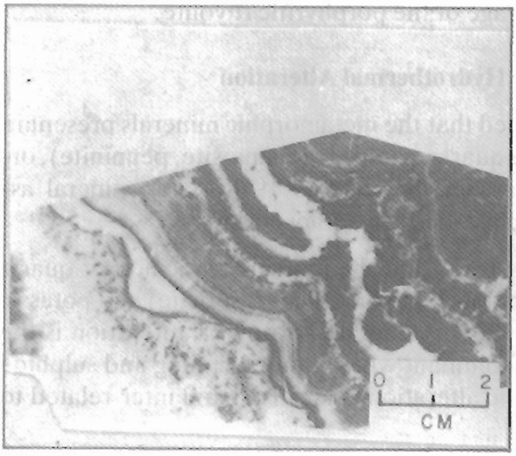
Hydrothermal alteration and regional metamorphism mineral assemblages in rocks in the Mahd adh Dhahab area are very similar. Thus, it is difficult to differentiate between the two. Geochronogically, the ages of the regional metamorphism and the hydrothermal alteration have not been established. Therefore, it is not known which event took place first. Nevertheless, from the postulated and determined ages of the porphyritic rhyolite and the quartz veins, it is assumed that the two events took place within a short period hiatus or at the same time.

Fluid Inclusion Study

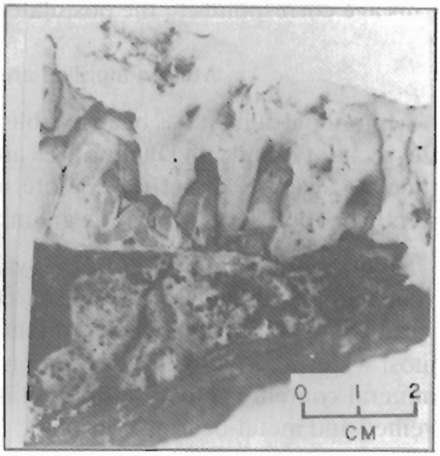
Doubly polished sections were prepared at the thin section laboratory of the Faculty of Earth Sciences, King Abdulaziz University, Jeddah, Saudi Arabia. A microthermometric study of the fluid inclusions was carried out at the fluid inclusion laboratory of the Faculty. Calibration of the Chiax Meca heating and cooling stage was made with standard chemicals and the fluid inclusion measurements were corrected according to a standard calibration curve (Fig. 3)

Forty fresh representative samples from the three types of mineralized quartz veins, namely, crystified quartz veins, massive quartz veins and quartz cemented breccia veins, were taken from the underground tunnel of the soůthern mineralized zone. They were cut into 1 mm thick doubly polished sections and fluid inclusions were examined under a polarizing microscope. A majority of the fluid inclusions were less than 5 in size, especially those in samples from quartz cemented breccia veins, and were considered too small for microthermometric study. Notwithstanding, 69 fluid inclusions were analyzed from the crustified quartz veins samples and 22 fluid inclusions from the massive quartz veins samples. For comparison, 32 fluid inclusions were analyzed from quartz samples of the last stage cavity filling barren quartz veins.

PLATE 1

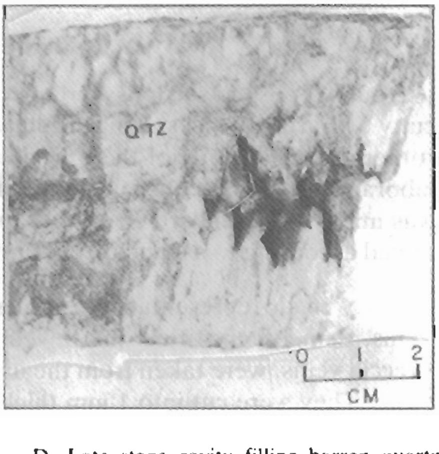


A. Crustified quartz vein.



B. Massive quartz vein.

C. Quartz-cemented breccia vein.



D. Late stage cavity filling barren quartz vein.

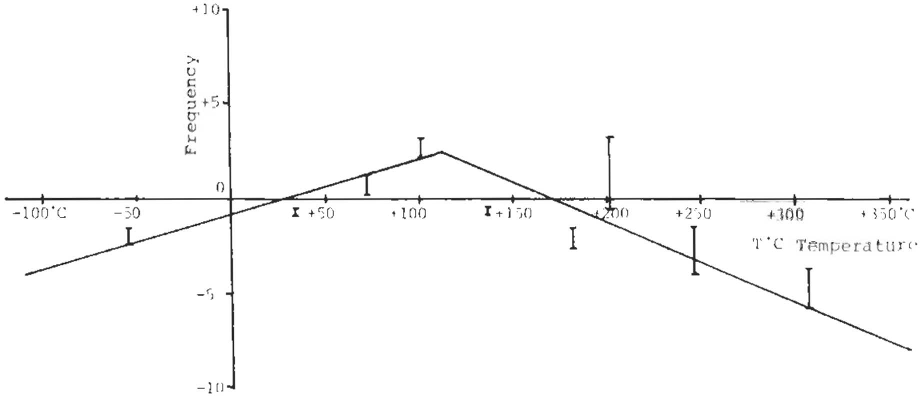


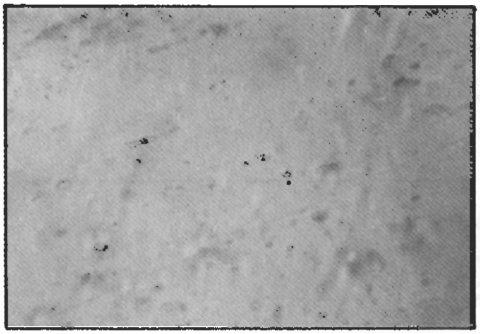
FIG. 3. The calibration curve.
$T_{actual} = T_{measured} + T_{correction}$

The analyzed fluid inclusions had sizes ranging between 5 to 15 and the majority of them had elongated, oval, semi-euhedral and semi-round shapes (Plate 2 A-B-C). Irregular and also euhedral shaped inclusions were observed in quartz samples of the last stage cavity filling barren quartz veins (Plate 2 D-E). To avoid fluid inclusions that were trapped at a later stage, those that were formed along healed crack planes, and those that were very irregular in shape, were neglected. Fluid inclusions with regular shape that where away from healed crack planes and isolated randomly were microthermometrically analyzed by the Chiax Meca heating and cooling stage.

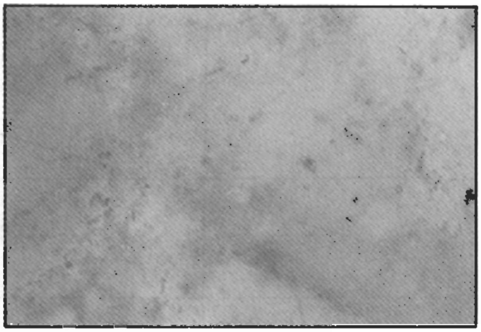
At room temperature, no carbonate gas or liquid was observed in the fluid inclusions. Nonetheless, all the analyzed fluid inclusions were frozen to –120°C and reheated in order to check for any presence of carbonate liquid. No sign of it was observed. Thus, it is postulated that no hydrocarbon content was involved, or was involved in a negligible amount in the mineralization depositional fluid. All the analyzed fluid inclusions are two-phase (gas and liquid).

The analyzed fluid inclusions from the mineralized quartz veins were composed of aqueous solutions with 20 to 30% of gas and 70 to 80% of liquid. Final melting temperatures of ice in the fluid inclusions from mineralized quartz veins fell between –0.5 to –2.2°C (Fig. 4) yielding an equivalent weight percent of NaCl between 1 to 4 (Fig. 5). Final melting temperatures of ice in the fluid inclusions from the barren quartz veins fall in a range of –0.3 to 1.6°C (Fig. 6) with an equivalent weight percent of NaCl ranging between 0.6 to 3 (Fig. 7). Final homogenization temperatures of fluid inclusions from mineralized quartz veins fall between 100 and 38°C (Fig. 8), and those from barren quartz veins fall between 130 and 200°C (Fig. 9). All the analyzed fluid inclusions homogenized into a single liquid phase.

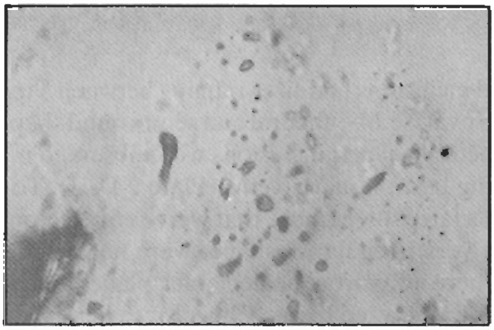
PLATE 2



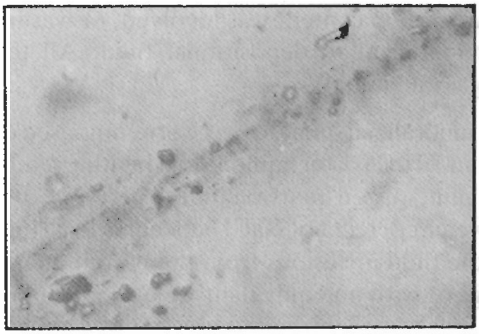
A. Elongated 2-phase fluid inclusion.



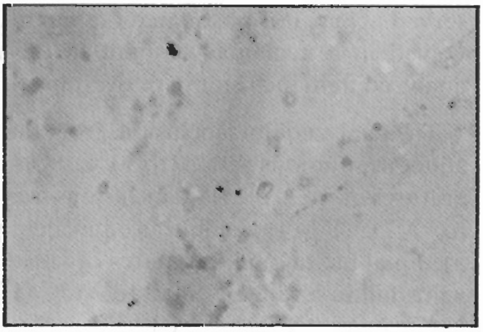
B. Elongated and semi-oval 2-phase fluid inclusions.



C. Semi-euhedral, semi-rounded and oval 2-phase fluid inclusions.



D. Irregular and euhedral 2-phase fluid inclusions.
A-B and C are mineralized quartz veins.



E. Irregular and euhedral 2-phase fluid inclusions.
D and E are late stage cavity filling quartz vein.

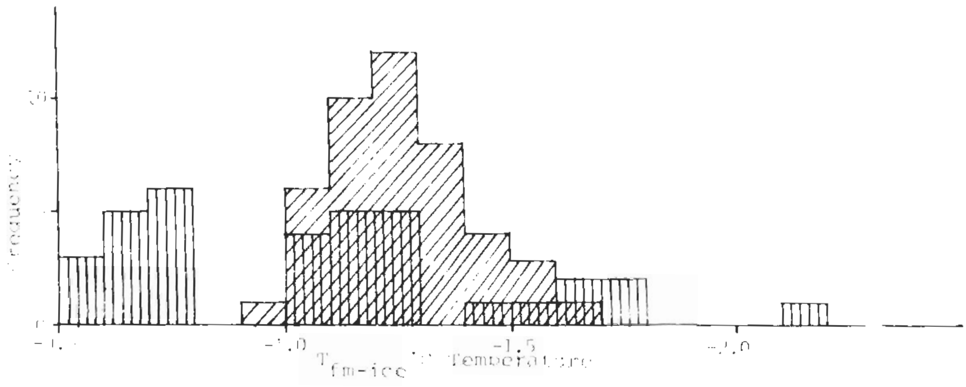


FIG. 4. Histogram of final melting temperatures of ice in fluid inclusions from mineralized crustified and massive quartz veins.

= Mineralized crustified quartz vein.

= Mineralized massive quartz vein.

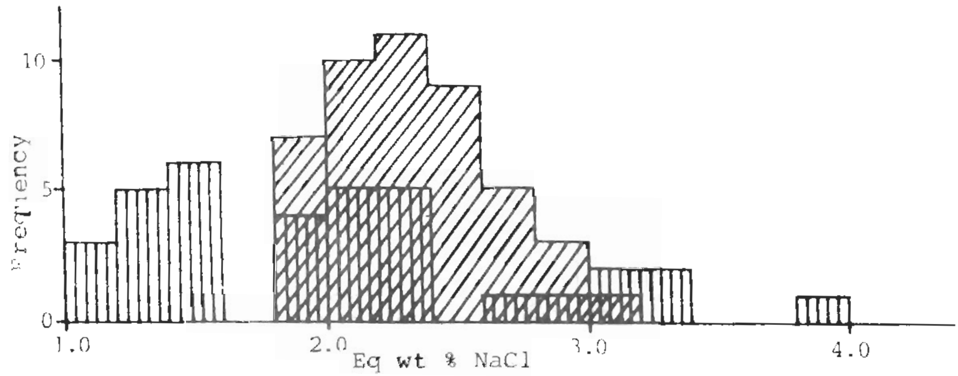


FIG. 5. Histogram of equivalent weight % NaCl of fluid inclusions from mineralized crustified and massive quartz veins.

= Mineralized crustified vein

= Mineralized massive quartz vein

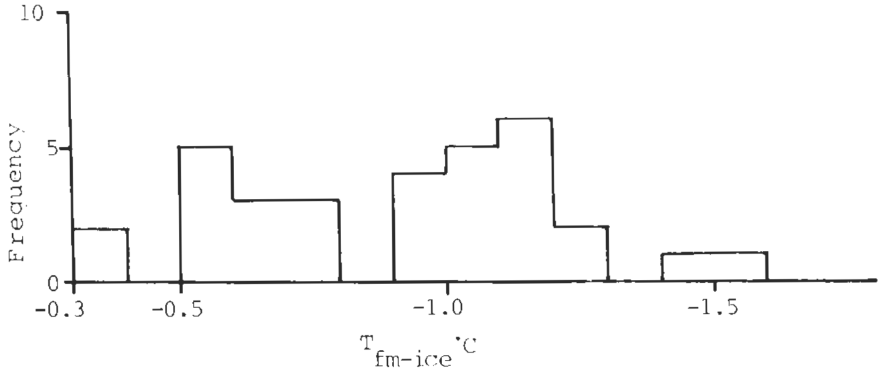


FIG. 6. Histogram of final melting temperatures of ice in fluid inclusions from barren quartz vein.

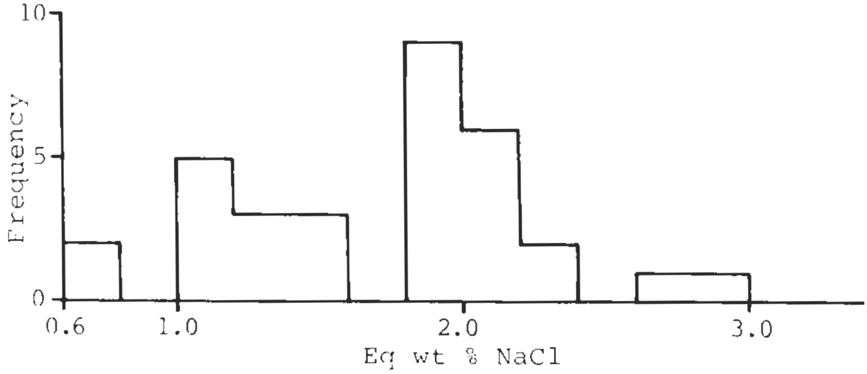


FIG. 7. Histogram of equivalent weight % NaCl of fluid inclusions from barren quartz vein.

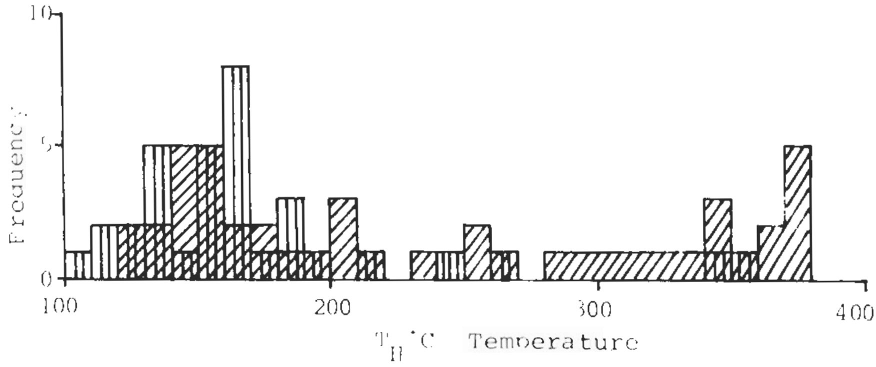


FIG. 8. Histogram of final homogenization temperatures of bulk composition of fluid inclusions from mineralized crustified and massive quartz veins.

= Mineralized crustified quartz vein.

= Mineralized massive quartz vein.

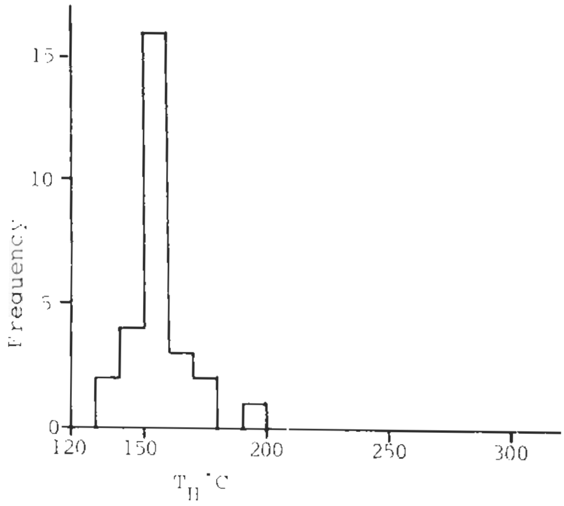


FIG. 9. Histrogram of final homogenization temperatures of bulk composition of fluid inclusions from barren quartz vein.

The final homogenization temperatures of fluid inclusions from mineralized quartz veins (Fig. 8) and the histogram between their final melting temperatures of ice versus their final homogenization temperatures of bulk composition (Fig. 10) indicate that there are two possible depositional stages, one at lower temperature with the peak at about 150°C. The histogram of the homogenization temperatures versus

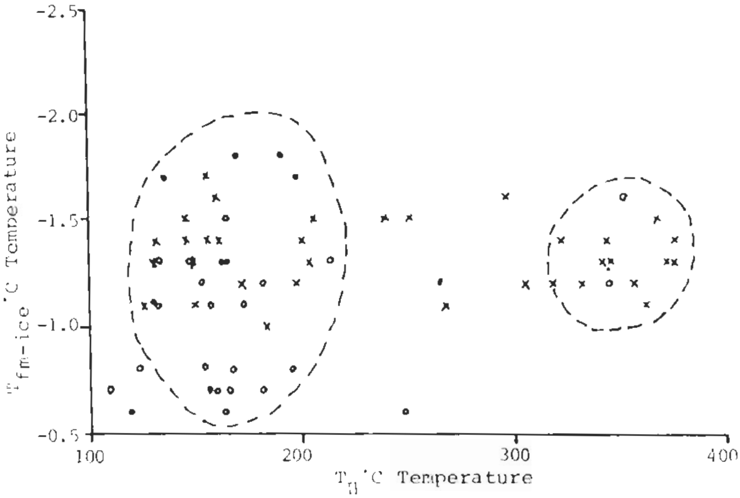


FIG. 10. A composite diagram of fluid inclusions from mineralized crustified and massive quartz veins as a function of their bulk homogenization temperature (T_H) and final melting temperature of ice ($T_{fm\text{-}ice}$). It indicates two possible stages of fluid inclusions entrapment.

× = Mineralized crustified quartz vein.

○ = Mineralized massive quartz vein.

the final melting temperatures of ice of the barren quartz veins (Fig. 11) suggests that there was only depositional stage and that they were deposited at low temperature with the peak temperature at about 150°C, corresponding to the lower temperature depositional stage of the mineralized quartz veins. In light of that, it is assumed that

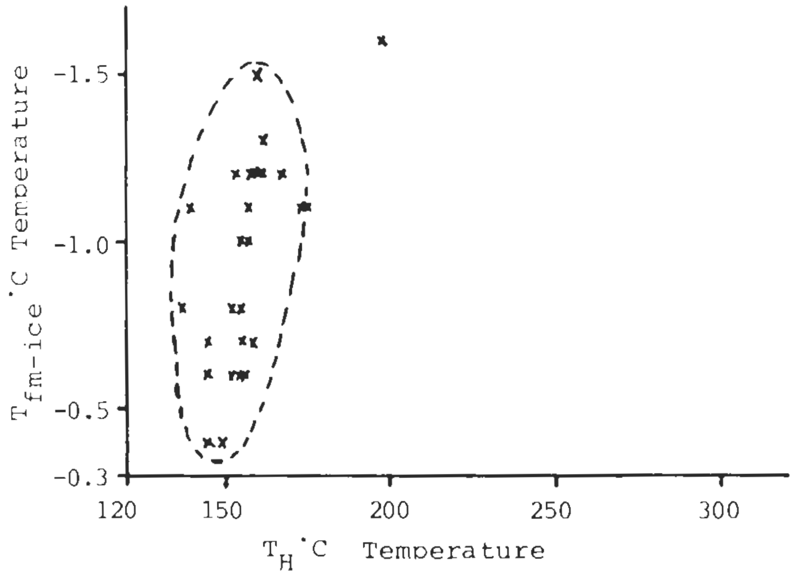


FIG. 11. Diagram of fluid inclusions from barren quartz vein as a function between their bulk homogenization temperatures (T_H) and their final melting temperatures of ice ($T_{fm\ ice}$). It indicates only one stage of fluid inclusions entrapment.

low temperature quartz from the mineralized quartz veins may be barren or contain only a negligible amount of precious metals. Whereas, high temperature depositional stage of quartz is postulated to be important and essential for the gold mineralization at Mahd adh Dhahab.

Mole percents of H_2O and NaCl in the fluid inclusions were calculated according to Ramboz (1980), Potter and Brown (1977) and Chinkul (1983) and they fall in the range of:

99.33% of H_2O and 0.67% of NaCl
99.30% of H_2O and 0.70% of NaCl

for low-temperature fluid inclusions and

99.27% of H_2O and 0..73% of NaCl
99.21% of H_2O and 0.79% of NaCl

for high-temperature fluid inclusion.

These data on NaCl in the fluid inclusions indicate that sea water involvement in the mineralization fluid may not be of significant importance. Together with the fact that no carbonate liquid was observed in the analyzed fluid inclusions, it is postulated that water in the mineralization fluid would mainly have been meteoric water with possibly a minor amount of sea water.

It has been established that low-grade greenschist facies metamorphism has little to no effect on fluid inclusions (Chinkul 1983, Al-Zubeidi 1984). In the present study, the wide range of the homogenization temperatures of the fluid inclusions in mineralized quartz veins (Fig. 8) also indicate that the regional low-grade greenschist metamorphism has little to no effect on the fluid inclusions.

No indication of fluid boiling was observed from the analyzed fluid inclusions. Therefore, isochore lines were established according to Potter and Brown (1977) and pressure corrections were made. Three isochore lines were established from three representative low temperature fluid inclusions and two isochore lines were established from two representative high temperature fluid inclusions (Fig. 12). The im-

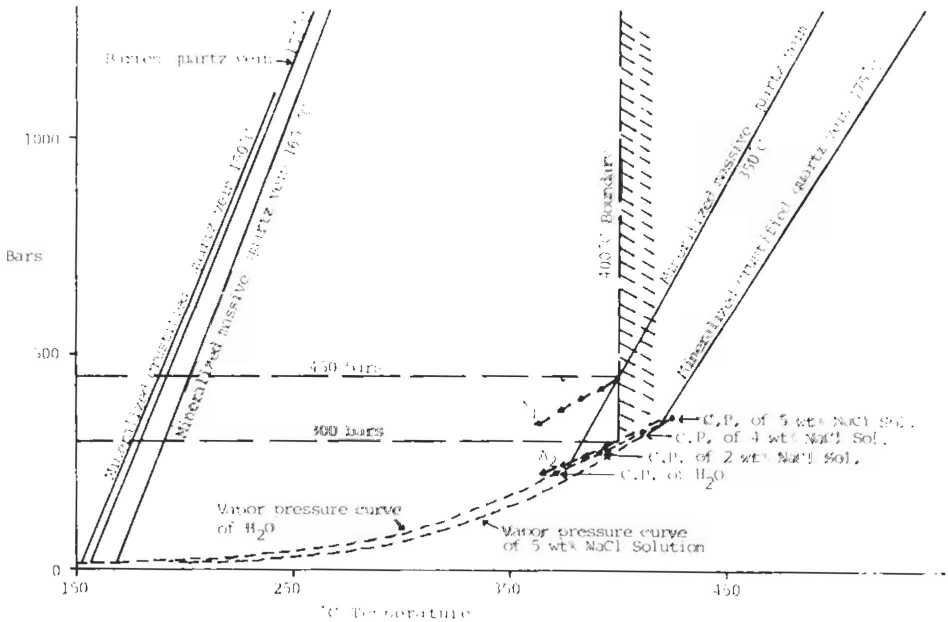


FIG. 12. Representative isochores of mineralized crustified quartz vein, mineralized massive quartz vein and barren quartz vein. The maximum mineralization depositional temperature is taken as 400°C (see text). Vapor pressure curves and critical points (C.P.) of H_2O, 2 wt %, 4 wt % and 5 wt % NaCl solutions are after Takenouchi and Kennedy (1965). Trapping paths A_1 and A_2 are suggested.

portant mineralization deposition occurred at higher temperature and the highest measured homogenization of the fluid inclusions is about 380°C which is close to the estimated depositional temperature (400°C) of Hakim (1978) from the mineral assemblage study. Thus, taking the maximum mineralization depositional temperature as 400°C, the depositional pressure during that time was established to be about

300-450 bars (Fig. 12). In estimating the 300 bars pressure, the critical points of 2-3-4 and 5 weight percent NaCl solutions and their vapor pressure curves (Takenouchi and Kennedy 1965) were taken into accounts. Fluid inclusions trapping paths A_1 and A_2 have been suggested. In light with the estimated depositional pressure, Mahd adh Dhahab gold mineralization is assumed to have been deposited in a high temperature (400°C) low pressure (500 bars) shallow depth environment.

Conclusion and a Proposed Model

Microthermometric study of the fluid inclusions from the mineralized quartz veins indicates two possible stages of trapping. The low temperature (150°C) trapping stage corresponds to the fluid inclusions trapped in barren quartz veins, which likewise may not be of significant importance. It is postulated that the high temperature (400°C) fluid inclusions trapping stage of the mineralized quartz veins is important and essential for the deposition of the Mahd adh Dhahab vein type gold mineralization.

All the analyzed fluid inclusions are two-phase (gas and liquid) and consist of aqueous solutions with mole percent of H_2 falling between 99.21 to 99.33% and NaCl 0.67 to 4.0%. Weight percent NaCl of fluid inclusions are found in the range of 0.6 to 0.79% with the average at 2.3. No hydrocarbon gas or liquid has been observed in the analyzed fluid inclusions. These data suggest that the contribution of magmatic water in the mineralization fluid is negligible, sea water contribution is minor, and meteoric water contribution is the most abundant.

The maximum bulk composition homogenization temperature of the fluid inclusions is 389°C close to the estimated depositional temperature (400°C) of Hakim (1978). Thus, assuming 400°C as the maximum depositional temperature, the established isochores of the representative fluid inclusions indicate the mineralization depositional pressure to be less than 500 bars (300-450 bars, Fig. 12).

The Mahd adh Dhahab vein type gold deposit is very similar to the vein type deposits in the Baguio district, Philippines and the Tayoltita silver-gold vein deposit at Durango, Mexico. Fluid inclusion studies on quartz from vein gold deposits at Baguio indicate deposition throughout the vein systems in the range 250 to 300°C by low salinity fluids (0-6 equivalent wt % NaCl) (Sawkins *et al.* 1979). Similarly, filling temperatures for quartz from the Tayoltita silver-gold vein deposit at Durango fall between 250 to 300°C with salinities from 1.9 to 9.7 equivalent wt % NaCl (Smith *et al.* 1982). Studies of precious metal deposits in both areas suggest that meteoric water dominated the hydrothermal system. The Mahd adh Dhahab vein type gold deposit has a higher depositional temperature (400°C) and lower salinities (0.6 to 4 eq wt % NaCl) than the precious metals of these two areas. Nonetheless, the indication of the abundance involvement of meteoric water in the hydrothermal system is identical.

In summary, using all the information a depositional model (Fig. 13) for the Mahd adh Dhahab vein type gold mineralization is proposed as follows :

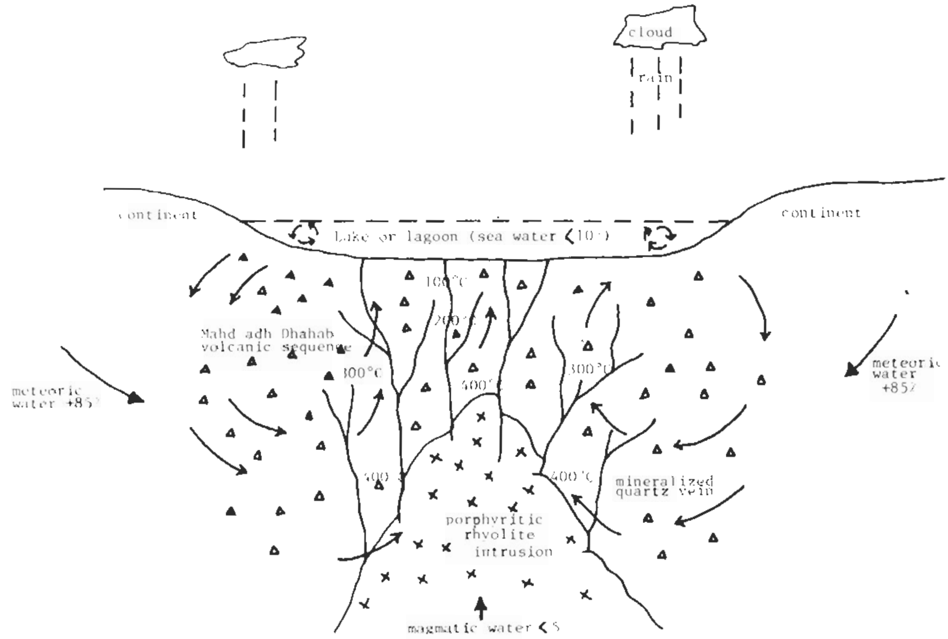


FIG. 13. A schematic diagram of the proposed model for the Mahd adh Dhahab vein type gold deposit.
ΔΔΔ = Mahd adh Dhahab volcanic sequence. ××× = Porphyritic rhyolite intrusion.
↻ = Hydrothermal convective system.

The intrusion of the porphyritic rhyolite into the Mahd adh Dhahab volcanic sequence caused meteoric water, (85%) with possibly less than 10% of sea water, and less than 5% of magmatic water, to circulate through the fractures and cracks of the rocks. When these water were percolated downward they were heated up, transformed into hot hydrothermal solution of about 400°C and leached the metals from the Mahd adh Dhahab volcanic sequence. The ascending metal impregnated hydrothermal solution encountered descending oxygenated cold water and temperature of the solution was decreased. As the temperature dropped and the chemical environment changed, the metals in the hydrothermal solution were precipitated together with quartz in the fractures and cracks of the rocks, forming mineralized quartz veins at shallow depth under a pressure of less than 500 bars.

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دراســة المـكتنـفــات الســائــلة في تمعــدن الــذهب في مهــد الــذهب المملــكة العربيــة السعوديــة

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مستخلص . يقـع منجم المهـد ، الـذي يعـد أقـدم منجم ذهب في المملكة العربية السعـودية ، في الجـزء الأوسط من الـدرع العـربي . ويتكـون من صخور تابعة للعصر البروتيروزوي الأعلى من الأنديزيت والأجلومريت وجسم عدسي من الريوليت . وتقطع هذه الصخور أربعة أجيال من عروق المرو ، ثلاثة منها متمعدنة . وقد تعرضت المنطقة إلى تحول إقليمي ذي درجة منخفضة من سحنة الشيست الأخضر .

يقدر احتياطي الخام في منجم مهد الذهب بـ ١,٤٥ مليون طن رتبته ٢٦ جراما في الطن ذهبًا و ٩٢ جرامًا في الطن فضة بالإضافة إلى ١٠٩,٠٠٠ طن خام مؤكسد يصل الذهب فيه إلى ٧٧ جرامًا في الطن .

وغالبية المكتنفات السائلة في عروق المرو صغيرة جدًا وقد جرى اختيار وتحليل مكتنفات أولية - غازية وصلبة - يتراوح حجمها بين ٥ - ١٠ ميكرونًا . وعند التسخين أصبحت متجانسة في حالة السيولة . وقد كانت الدرجة النهائية التي سُجلت لذوبان الثلج مابين ٠,٣ و ٢,٢ درجة مئوية . وكانت درجة التجانس النهائية بين ١٠٠ و ٣٨٠ درجة مئوية . ويتراوح تكـوين السـائل بين ٩٩,٢١٪ إلى ٩٩٫٣٣٪ ماء و ٠,٦٧ إلى ٠,٧٩ كلوريد صوديوم . تشير نتائج التحاليل إلى عدم وجود أي كربونات سواء في الحالة الصلبة أو الغازية .

وقد دلت دراسة المقاييس الحرارية تحت الميكروسكوب للمكتنفات السائلة على وجود حالتين على الأقل لترسيب عروق المرو . إحداها عند درجة حرارة تتراوح بين ١٠٠ إلى ٢١٠ درجة مئوية ، والأخرى مابين ٣٤٠ إلى ٣٨٠ درجة مئوية . ويعتبر المرو الذي ترسب في درجة حرارة منخفضة غير متمعدن ، بينما الذي ترسب في درجة حرارة عالية متمعدنًا و ذا قيمة اقتصادية .

ويستنتج من ذلك أن السائل الممعدن في مهد الذهب يكون أساسًا من ماء سطحي مع احتـمال مشاركة كمية قليلة من ماء البحر . ويُفترض أن التمعدن قد حصل القرب من سطح الأرض لكي يكون تمعدنًا من النوع السطحي .