Fluid Inclusion Study of the Mamut Porphyry Copper Deposit, Sabah, Malaysia*

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Abstract: The fluid inclusion study of the Mamut porphyry copper deposit, Sabah, Malaysia was carried out as part of studies of the ore-forming fluids and mineralization of porphyry copper deposits from the Southwestern Pacific island arcs. Polyphase fluid inclusions which contain halite, sylvite, hematite, anisotropic unidentified minerals, and opaque minerals, are observed abundantly in the vein quartz. Gaseous inclusions are also abundant, but liquid inclusions are few. It is inferred from the disappearance temperature of halite that the salinity of fluid would have been in a range between 35 to 55 wt.% NaCl equivalent concentration. The homogenization temperature of polyphase inclusion ranges from 300° to 480°C, whereas that of liquid inclusion is between 280° and 325°C. The “boiling” of the fluid is manifested by an intimate coexistence of gaseous and polyphase inclusions, in some samples. The numeral ratio of polyphase inclusion to the total number of inclusion becomes higher in the ore-shell or biotite zone, and at lower levels of the orebody. A low value of the ratio from the core of the orebody is attributable to the abundance of gaseous inclusions. An intimate relation between the abundance of chalcopyrite in sulfide minerals and polyphase inclusions suggests an important role of highly saline fluids in the copper mineralization. It is concluded that the ore-forming fluids at the Mamut porphyry copper deposit were rich in non-volatile materials including chlorides and that the pressure of the fluids was low enough to emanate the vapor phase. Such characteristics of fluids at the Mamut deposit are similar to those of the porphyry copper deposits in the southwestern United States.

Introduction

The Mamut porphyry copper deposit is located about 65 km to the east of Kota Kinabalu, Sabah, Malaysia. The operation of the mine has been commenced in May, 1975, processing 16,000 tons of 0.61% Cu ore per day.

The orebody is located on the southeastern flank of Mt. Kinabalu at heights of about 1,300 m above the sea level. The deposit was found in 1965 by means of a series of geochemical prospecting undertaken by the Labuk Valley Project of the United Nations, started in March, 1963. The ore reserve is estimated at 179 million tons of 0.476% Cu (Kosaka and Wakita, 1975).

Geology

The regional geology of the Kinabalu area is reported by Collenette (1958, 1965), Kirk (1968), and Jacobson (1970). This area lies in the Northwest Borneo Geosyncline which had developed in late Cretaceous to early Tertiary age for the extent about 800 km long and 300 km wide with NE-SW trend.

Mitchell and Garson (1972) considered this area as a possible example of an ancient island arc underthrust by the older microcontinent of Kalimantan. Deformed ophiolite and chert are considered to be the remnants of late Cretaceous ocean floor lost along a northward-dipping Benioff zone.

At the earliest stage of geosyncline, chert, shale, sandstone and limestone were deposited together with the extrusion and intrusion of basic rocks, forming a chert-splilite formation. In Paleocene to early Miocene epoch, eugeosynclinal flysch-type sediments were deposited. These sedimentary rocks are
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MINING GEOLOGY:

Fig. 1 Geologic map of the Mt. Kinabalu area, Sabah, Malaysia (after JACOBSON, 1970).

The geology, ore deposit, and mineralogy of the Mamut mine were already reported by KOSAKA and WAKITA (1975).

The country rocks of the ore deposit consist of sandstone and siltstone of the Trusmadi Formation, serpentinite and adamellite porphyry. The adamellite porphyry extending generally north-south and dipping 40° eastward, intruded into the sedimentary rocks and serpentinite. The elongation of the stock is parallel to the tectonic trend of the area. The stock branches into many dikes forming complicated boundaries. Some of these dikes are recognized on the surface trending in N–S and NE–SW directions. The adamellite porphyry consists of phenocrysts of K-feldspar, plagioclase and hornblende, and the groundmass of fine-grained quartz and K-feldspar (Fig. 2).

A fine-grained granodiorite porphyry...
(granophyre) dike intrudes the stock, siltstone and serpentinite in the western part of the deposit. The dike strikes N35°E and dips 45°SE. This intrusive rock has been altered hydrothermally but poorly mineralized, and is regarded as an intrusive at a late stage of the mineralization. The porphyry consists of phenocrysts of plagioclase and hornblende, and the groundmass of fine-grained K-feldspar, plagioclase and a small amount of quartz.

The copper grade of ore is high in the marginal parts of the adamellite porphyry stock but low in the core. Within the ore-shell, the copper grade is high even in siltstone and serpentinite, suggesting that the copper mineralization has had little control from the kind of wall-rock. In the ore-shell, biotitization and silicification are predominant and the low-grade core corresponds to the tremolite-actinolite zone where K-feldspar is also recognized in the alteration products.

The following ore minerals are identified microscopically; chalcopyrite, pyrite, pyrrhotite, cubanite, mackinawite, galena, sphalerite, molybdenite, magnetite and native gold as primary minerals, and bornite, chalcocite (digenite) and covellite as secondary minerals.

Chalcopyrite, pyrite and pyrrhotite are the principal primary minerals. They occur in quartz veinlets and wall-rocks as disseminated grains. Chalcopyrite and pyrite occasionally occur as separated single grains, but pyrrhotite occurs intimately associated with chalcopyrite. In some cases chalcopyrite grain contains a pyrite core, suggesting that the crystallization of some pyrite preceded the chalcopyrite deposition (Fig. 3).

Magnetite occurs mostly as isolated grains, but, in some cases, it is coated by sulfide

Fig. 3 Microphotograph of pyrite grain wrapped by chalcopyrite (G-10, 160m). Cp: chalcopyrite, Py: pyrite

Fig. 4 Microphotograph showing the occurrence of cubanite at the boundary between chalcopyrite and monoclinic pyrrhotite (E-8, 53m). Cb: cubanite, Po: pyrrhotite

Fig. 5 Microphotograph showing the occurrence of native gold in pyrrhotite. Au: native gold

Fig. 6 Chalcopyrite bleb in pyrite associated with exsolved mackinawite. Mk: mackinawite
minerals. Cubanite is recognized along the boundaries between chalcopyrite and pyrrhotite (Fig. 4), and mackinawite rarely occurs as lamellae in chalcopyrite blebs formed in pyrite (Fig. 6).

Wall-rock Alteration

Alteration of the adamellite porphyry is identified by the alteration products of hornblende phenocrysts. Fresh hornblende, tremolite-actionolite, and biotite zones are successively distributed from the lower core to the outermost part of the stock. Silicification is remarkable in the ore-shell regardless of the kind of wall-rock.

In the tremolite-actionolite zone, hornblende phenocrysts are replaced by the aggregate of tremolite, actionolite and K-feldspar (Fig. 7), while in the biotite zone, hornblende is replaced by flakes of biotite (Fig. 8). Epidote, carbonate and chlorite which are the characteristic minerals of the propylitic zone, are occasionally recognized in both of the above-stated alteration zones, suggesting the telescoping of alteration. Sericitization is locally recognized but not pervasive.

In serpentinite of the ore-shell, talc, phlogopite and tremolite are the main constituents (Fig. 9). These minerals would have been the products of alteration and mineralization.

In sedimentary rocks of the ore-shell, aggregates of biotite flakes and, in some parts, mosaic aggregates of K-feldspar are recognized. It is likely that the biotite-K-feldspar

Fig. 7 Hornblende phenocryst in adamellite porphyry is completely replaced by an aggregate of fine-grained actinolite and K-feldspar (Actinolite-tremolite zone, C-14, 100 m). Ac: actinolite, Kf: K-feldspar, Pl: plagioclase

Fig. 8 Hornblende phenocryst in adamellite porphyry is completely replaced by an aggregate of fine-grained biotite (Biotite zone, A-6, 73 m). Bi: biotite

Fig. 9 Altered serpentinite consists of fine-grained talc, tremolite and phlogopite with intense silicification (E-12, 210 m). Tc: talc, Tr: tremolite, Qz: quartz

Fig. 10 Sericitized siltstone (E-16, 64 m). Sr: sericite
alteration of sedimentary rocks corresponds to that of adamellite porphyry. Outside the ore-shell, the sericitization is predominant (Fig. 10).

In fine-grained granodiorite porphyry (granophyre), the hydrothermal alteration is intensive but the copper mineralization is poor. Biotite, chlorite, epidote and carbonate replace hornblende phenocrysts. In some parts, pyritization is remarkable.

**Fluid Inclusion Study**

Three types of fluid inclusions are recognized in quartz from the Mamut deposit, that is, polyphase, gaseous and liquid inclusions. As the size of these inclusions is generally less than 10 micrometers, it was necessary to use objectives of 40 or 100 magnifications for the observation of inclusion.

**Polyphase fluid inclusion:** Polyphase fluid inclusions generally contain a cubic crystal of halite and occasionally minute opaque minerals. Sylvite is often observed as a small rounded crystal in association with halite. Some inclusions occur in the shapes of negative crystal, but others which distribute especially along a supposed plane suggesting their formation along healed fractures, are irregular. In many samples, polyphase inclusions coexist intimately with gaseous inclusions (Fig. 11).

Besides the above-stated chloride crystals, a solid having a rhombohedral shape and high birefringence color and a prismatic solid having parallel extinction and low birefringence color are occasionally observed in the inclusions. It is supposed that the former phase is probably a carbonate and the latter anhydrite. Small non-magnetic opaque minerals, considered to be sulfide minerals, are common in these polyphase inclusions. Several other minerals are observed less frequently but their small sizes prevent identification.

**Gaseous inclusion:** Gaseous inclusions are the most common in quartz crystals. They generally show shapes of negative crystal or simpler shapes and often occur with polyphase inclusions. In some cases, however, they are found along curved planes. The bubble in gaseous inclusions occupies 70–90 percent of the volume of inclusion at room temperatures. Small minerals are sometimes observed in the aqueous phase of this type of inclusion.

**Liquid inclusion:** The degree of filling of the liquid inclusion is generally from 0.75 to 0.90. The shapes of inclusion are mostly irregular and they distribute along supposed healed fractures suggesting the secondary origin. This type of inclusion is the least common among the three types of inclusion.

**Homogenization temperature and salinity:** Homogenization temperatures were determined on liquid and polyphase inclusions.

Liquid inclusions are generally homogenized at temperatures between 280° and 325°C. On the other hand, homogenization temperatures of polyphase inclusions range from 300° to 480°C, much higher than those of liquid inclusions.
Fig. 12  Disappearance temperature of sylvite, halite and bubble in polyphase inclusions. The upper line represents the temperature for sylvite, the middle line for halite, and the lower line for bubble. Broken line ties the data obtained from the same inclusion. The combination of alphabet and figure on the left side represents the location of drilling (see Fig. 2), and the figures in meters show the depth of sample from the surface.
The homogenization of polyphase inclusions is attained by the disappearance of either bubble or halite. In cases, the disappearance of bubble precedes that of halite, even under a very slow heating-rate. This means that the dissolution of halite occurs under a higher pressure than the vapor pressure of the system and, in such cases, it is not appropriate to estimate the salinity of inclusion from the disappearance temperature of halite using Keevil's data (1942). Because Keevil's data have been obtained under the vapor pressure of the system, the estimated value of salinity would be higher than the true value. Approximate values, however, will be obtained from the disappearance temperatures. The salinity estimated thus indicates the range of 33–53 weight percent NaCl equivalent.

From the disappearance temperature of halite and sylvite, it is also possible to estimate the approximate concentration of NaCl and KCl using the phase diagram of the ternary system H₂O–NaCl–KCl (Roedder, 1971). Table 1 shows the concentration of NaCl and KCl, and the mole ratio of Na and K. The Na/K ratio in polyphase inclusions from the Mamut deposit is much lower than those for the waters from geothermal areas. This suggests that the hydrothermal fluids would have been in contact with rocks at considerably high temperatures (approximately 400°C) if the exchange equilibrium of Na and K was maintained between the fluids and rocks (Fournier and Truesdell, 1973, Fig. 6).

An intimate coexistence of gaseous and polyphase inclusions suggests that there was "boiling" in the fluid at the time of inclusion formation, inferring that the prevailing pressure would have been close to the vapor pressure of the system. In such cases, the dissolution of halite in polyphase inclusion should precede the disappearance of bubble.
Fig. 13 Distribution of polyphase inclusions in the ore deposit (Horizontal plans). Number in a circle represents the relative abundance of polyphase inclusion in parts per ten.
upon heating, but this is not the case in many samples of the present study. It is necessary to carry out a long-term heating experiment in order to check the abnormal dissolution temperature of halite at a temperature higher than the disappearance temperature of bubble. CHIVAS and WILKINS (1977) indicated that the dissolution temperature of halite and disappearance temperature of bubble became almost identical after heating for a sufficient length of time. This check has not yet been done in the present work, but it is expected that the range of dissolution temperature of halite will become lower and narrower than the present result.

The dissolution temperature of halite appears to have no remarkable difference between the core and the ore-shell of the orebody, but the disappearance temperature of bubble is slightly higher at the core than in the ore-shell.

**Distribution of fluid inclusions in orebody:** The numeral ratio of polyphase inclusion to the total number of inclusions, expressed in parts per ten, was determined under the microscope in order to know the distribution of polyphase inclusion in the orebody. As the number of liquid inclusion very small, the ratio may approximate the relation between polyphase and gaseous inclusions. The results are plotted in Figs. 13 and 14. Though the data are still few to draw any conclusion, some trend may be pointed out.

**Fig. 14** Distribution of polyphase inclusions in the ore deposit Vertical section. Number in a circle represents the relative abundance of polyphase inclusion in parts per ten.

**Fig. 15** Relation between the abundances of chalcopyrite and polyphase inclusions observed in the same specimen.
out. The ratio is higher in the marginal zone of adamellite porphyry, that is, in the ore-shell or biotite zone, and at the lower levels of the deposit. The low values from the core is attributable to the abundance of gaseous inclusions.

The volume ratio of chalcopyrite to the total sulfide minerals was determined by the modal analysis on the polished thin sections, on which the determination of numeral ratio of polyphase inclusion had been carried out. Fig. 15 shows that at the high volume ratio of chalcopyrite the numeral ratio of polyphase inclusion ranges widely from 1 to 5 in parts per ten, but at the low chalcopyrite ratio the inclusion ratio is limited narrowly in the lower range.

Though the scarcity of data from the low grade ore zone make the picture uncertain, it is inferred from Fig. 15 that the high saline fluids represented by polyphase inclusions might have played an important role in the copper mineralization.

**Nungkok Porphyry Copper Deposit**

The Nungkok deposit, the geology of which is briefly reported by Lewis (1967) and Saegusa (1973), is located about 22 km to the westnorthwest of the Mamut deposit. The Nungkok deposit consists of two orebodies. The northern body, consisting of fine networks of chalcopyrite-pyrrhotite-quartz veinlets, is formed in a stock of quartz diorite porphyry, and the southern orebody is found in thermally metamorphosed quartzite. The geologic age of the porphyry is reported as 8 m.y.B.P. It is also reported that the Nungkok deposit is smaller in scale than the Mamut deposit but the content of molybdenum is higher. Sericitization and silicification are widespread in the porphyry and sedimentary rocks.

Quartz from a drilling core contains a great number of polyphase fluid inclusions. In general, they accompany halite, sylvite, anisotropic prismatic crystal, hematite flake and some opaque minerals and occur intimately with gaseous inclusions. In general, bubble disappeared between 250° and 380°C, and halite between 230° and 320°C. Both of these temperatures are slightly lower than those of the Mamut deposit.

**Conclusion**

The study of fluid inclusions at the Mamut porphyry copper deposit revealed that the ore-forming fluids of the deposit were high in temperature and salinity, similar to the features of the porphyry deposits in the southwestern United States. Large solid phases observed in polyphase inclusions indicate that the fluids would have been very rich in metals and other materials.

The results of recent experiments on the chlorine concentration of the aqueous phase equilibrated with granitic melts, suggest that chlorine in the aqueous phase increases during the course of crystallization of silicate melts when the pressure is lower than 500 bars (Kiling and Burnham, 1972), and that chlorine increases remarkably in late stages of crystallization resulting in high concentrations of metals, when the initial content of water in silicate melts is low (Holland, 1972). Burnham (1967) attributed the mineralization of porphyry copper deposits to a result of a rapid shallow intrusion of granitic magmas under-saturated in water.

The mode of occurrence of fluid inclusions in the Mamut deposit seems to support these experimental results and considerations. The "boiling" phenomena of the fluids suggest a relatively high temperature condition in a rather low pressure condition.

An intimate genetic relation between the copper mineralization and polyphase fluid inclusions of high salinity would indicate an important role of highly saline fluids in the mineralization of the Mamut deposit.

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References


SAEGUSA, M. (1973): Relationship between copper contents in soil and copper grade of ore bodies calculated by drill core assay of some porphyry copper deposits in tropical terrain. Mining Geol., 23, 283 ~ 294.

Appendix Table showing the sample number, level and alteration zone

<table>
<thead>
<tr>
<th>Sample*</th>
<th>Level**</th>
<th>Zone of Alteration</th>
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<td>A-6, 40-55m</td>
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<td>Biotite zone</td>
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<td>A-6, 125-135m</td>
<td>-110~120m</td>
<td>Tremolite-actinolite zone</td>
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<td>A-10, 80m</td>
<td>-15m</td>
<td>Serpentinite</td>
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<tr>
<td>A-10, 195m</td>
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<td>Adamellite porphyry</td>
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<td>B-8, 15-30m</td>
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<tr>
<td>B-8, 108m</td>
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<td>Tremolite-actinolite zone</td>
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<tr>
<td>C-8, 44-67m</td>
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<td>C-8, 178m</td>
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<td>G-14, 179m</td>
<td>7m</td>
<td>Biotite zone</td>
</tr>
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</table>

* The combination of alphabet and figure on the left side represents the location of drilling (see Fig. 2), and the figures in meters show the depth of sample from the surface.

** The height of the Om level of the mine is 1,323m above the sea level.
マレーシア、サバ州マムート斑岩銅鉱床の流体包有物の研究

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要　旨

南西太平洋島弧に胚胎する斑岩銅鉱床の鉱化流体の研究の一環として、マレーシア、サバ州のマムート鉱床の流体包有物の研究を行なった。鉱体中には気相包有物と共に、岩塩・カリ岩塩・赤鉄鉱・不透明鉱物などを伴う多相流体包有物が多数観察される。岩塩の消失温度から流体の塩濃度は35～55重量％と推定される。また、多相包有物の均質化温度は300～400℃であるが、液体包有物の均質化温度は280～325℃である。試料の一部には多相包有物と気相包有物が共存し、“満とう”現象があったことを示している。流体包有物総数中に占める多相包有物数の割合は鉱石帯（黒雲母帯）と下部で高くなっている。鉱体の核には気相包有物が多い。青銅鉱の量と多相包有物との関係は、鉱鉱化に高温度流体が重要な役割を果したことを示している。流体包有物の研究から、マムート鉱床の鉱鉱化流体は塩化物その他の物質に富み、その系の蒸気圧に近い条件にあったものと推定される。マムート鉱床の鉱鉱化流体のこののような特色は米国南部の斑岩銅鉱床の特色と類似のものである。