Econ. Environ. Geol.
Vol. 28, No. 2, p. 109-121, 1995.

Genetic Environments of Hydrothermal Vein Deposits in the Pacitan District, East Java, Indonesia

Seon-Gyu Choi*, Chil-Sup So*, Sang-Hoon Choi* and Jin-Kyun Han**

ABSTRACT: The hydrothermal vein type deposits which comprise the Kasihan, Jompong and Gempol mineralized areas are primarily copper and zinc deposits, but they are also associated with lead and/or gold mineralization. The deposits occur within the Tertiary sedimentary and volcanic rocks in the Southern Mountain zone of the eastern Java island, Indonesia. Mineralization can be separated into two or three distinct stages (pre-and/or post- ore mineralization stages and main ore mineralization stage) which took place mainly along pre-existing fault breccia zones. The main phase of mineralization (the main ore stage) can be usually classified into three substages (early, middle and late) according to ore mineral assemblages, paragenesis, textures and their chemical compositions. Ore mineralogy and paragenesis of the three areas in the district are different from each other. Pyrite, pyrrhotite (/arsenopyrite), iron-rich (up to 20.5 mole % FeS) sphalerite and (Cu-)Pb-Bi sulfosalts are characteristic of the deposits in the Kasihan (/Jompong) area. On the other hand, pyrite + hematite + magnetite + iron-poor (2.7 to 3.6 mole % FeS) sphalerite assemblage is restricted to the Gempol area. Fluid inclusion data suggest that fluids of the main ore stage evolved from initial high temperatures (near 350℃) to later lower temperatures (near 200℃) with salinities ranging from 0.8 to 10.1 equiv. wt. percent NaCl. Each area represents a separate hydrothermal system: the mineralization at Kasihan and Jompong were largely due to early fluid boiling coupled with later cooling and dilution, whereas the mineralization at Gempol was mainly resulted from cooling and dilution by an influx of cooler meteoric waters. Fluid inclusion evidence of boiling indicates that pressures of ≥95 to 255 bars (≥95 bars for the Gempol area : ≒120 to 170 bars for the Jompong area : ≒140 to 255 bars for the Kasihan area) during portions of main ore stage mineralization. Equilibrium thermodynamic interpretation indicates that the evolution trends of the temperature versus fs_2 variation of ore stage fluids in the Pacitan district follow two fashions: ore fluids at Kasihan and Jompong changed from the pyrite-pyrrhotite sulfidation stage towards pyrite-hematite-magnetite state, whereas those at Gempol evolved nearly along pyrite-hematite-magnetite reaction curve with decreasing temperature. The sulfur isotope compositions of sulfide minerals are consistent with an igneous source of sulfur with a $\delta^{34}S_{\Sigma S}$ value of about 3.3 per mil. The oxygen and hydrogen isotopic compositions of the fluids in each area indicate a progressive shift from the dominance of highly exchanged meteoric water at early hydrothermal systems towards an un- or less-exchanged meteoric water at later hydrothermal systems.

INTRODUCTION

Extensive base metal and/or gold bearing quartz veins have been found recently in the Pacitan district of East Java, Indonesia. This is one of new discoveries of hydrothermal gold and base metal occurrences made in the unexplored Southern Moutain zone of East Java in 1991 (Figs. 1 and 2). Most of the hydrothermal veins occur in three areas: Gempol, Kasihan and Jompong. The Southern Mountain zone (Van Bemmelen, 1949) lies on the southern margin of the eastern portions in the Java island and consits of mixed sequences of Tertiary to Quaternary sedimentary and volcanic rocks (Fig. 2). Enclosed within the volcanic rocks of Early Miocene age are a number of fissure-filling hydrothermal veins containing mainly copper, zinc, lead and gold minerals. These deposits are spatially related to several small subvolcanic dacitic and/or andesitic bodies intruded into a pile of volcanic and sedimentary (locally pyroclastic) rocks. The partial geological survey of the Pacitan and Ponorogo area has been carried out by many geologists since 1908 but the detailed mineralogy, paragenesis and physico-chemical conditions of ore mineralization have not been documented. This paper presents the results of our investigations of the nature of the vein mineralization in the Pacitan district and updates an earlier description of the deposits by KMPC (Korea Mining Promotion Corporation, 1991) which was based on exploration work undertaken in 1991. Since that time, an additional field survey with drilling of 1,005 m has been completed and a number of laboratory studies, including petrological, geochemical, fluid inc-

---

*Department of Earth and Environmental Sciences, Korea University, Seoul 136-701, Korea
**Korea Mining Promotion Corporation, Seoul 156-010, Korea

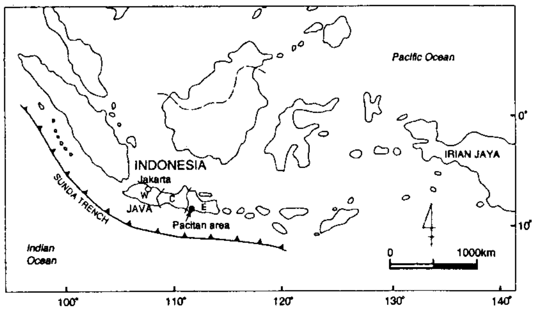

Fig. 1. Location of the Pacitan district. Abbreviations : C= Central Java; E=eastern Java; W=western Java.

lusion and stable isotope studies, have been carried out.

REGIONAL GEOLOGY

Java is situated on the southwestern edge of the Asian plate and has been formed as a part of a convergent margin since the Permian at least, inferring from the existence of volcano-plutonic rocks and arc-related lithologies along the length of the island (Katili, 1973). At least, during the past 100 million years, its geologic history has been governed by the northward motion of the Indian ocean plate relative to the Asian plate. The volcanic belt extended along the length of Java island represents the magmatism of the Sunda Arc System. During the Tertiary, the belt has moved toward the north, and now it is located on the main axial portion of Java island overlying Benioff zone which is emplaced at the depth of $\approx$ 200 km (Katili, 1973). East Java lies on the eastern portion of the Java island (Fig. 1) and is filled principally by sedimentary and volcanic rocks of the Cenozoic. East Java can be divided into five physiographic zones from north to south (Van Bemmelen, 1949): Renbang Zone (characterized by anticlinorium), Randublatung Zone (represented by synclinorium), Kendeng zone (characteristic of anticlines and fold-hills), Quaternary volcanic zone (dominated by Quaternary volcanoes), and Southern Mountain zone. Southern Mou-

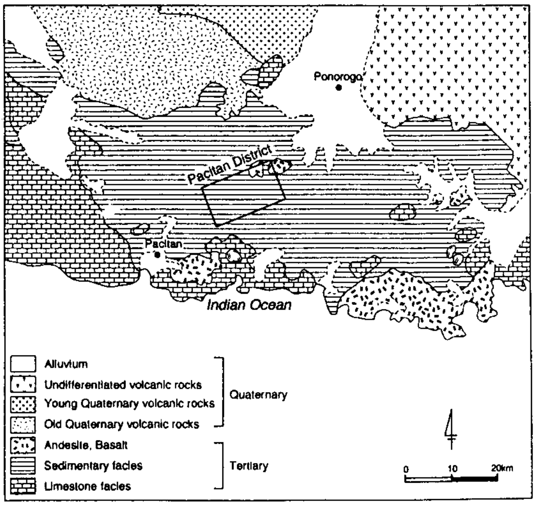

Fig. 2. Generalized geologic map of western portion of the Southern Mountain Zone, East Java, showing the location of the Pacitan district.

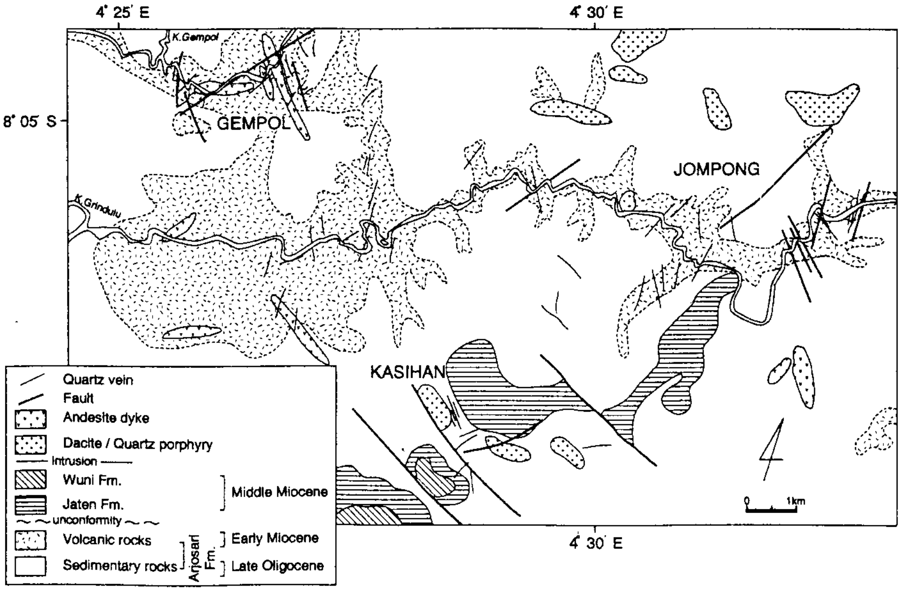

Fig. 3. General geology of the Pacitan district, and location of the each mineralized area and of the vein distributions.

ntain zone is mainly composed of Tertiary sedimentary and volcanic rocks and Quaternary volcanics (Fig. 2). The lower part of the zone is characterized by calcareous rocks of shallow marine sediments and the upper part is dominated by dacitic and andesitic rocks. The Pacitan district is located at the western portion of the Southern Mountain zone, East Java (Fig. 2).

LOCAL GEOLOGY

Geology of the Pacitan district is shown in Fig. 3. Three main lithostratigraphic units are recognized in the district: Late Oligocene to Early Miocene sedimentary and volcanic rocks of the Arjosari Formation, Middle Miocene sedimentary rocks of the Jaten and Wuni Formation, and younger intrusive rocks. The Arjosari Formation is largely composed of conglomerate, sandstone, siltstone, limestone, mudstone, tuff and volcanic lava and breccia with andesitic and dacitic rocks. The Jaten and Wuni Formation, which overlie unconformably the Arjosari Formation, consist of conglomerate, sandstone and siltstone. These sedimentary rocks represent marine sedimentary facies deposited in shallow sea and/or lagoon environments (KMPC, 1993).

The Arjosari Formation occupies most of the Pacitan district and is divided into the lower sedimentary rock member (Late Oligocene) and the upper volcanic rock member (Early Miocene). The sedimentary rock member generally consists of upwardly fining polymict conglomerate-sandstone-siltstone-mudstone sequences. It is interbedded with limestone which occurs as lenticular and/or thin bed with poor lateral continuity. A sequence of the sedimentary rocks contains a few intercalated volcanic horizons as volcanic breccias, tuffs, and lava with dacitic rocks. The upper volcanic rock member, which ovelies conformably the lower member, consists of andesitic lava and breccia intercalated with tuff. All the fossil (foraminifera in limestone) and sedimentary features of the Arjosari Formation indicate a Late Oligocene to Early Miocene and marine (shallow or steeply sloped marine) environment.

The Mandalika Formation occurs locally in the northern portion of the Pacitan district and is correlated with upper volcanic member of the Arjosari Formation. It mainly consists of andesitic or dacitic tuff, lava, and breccia. The volcanic lava is characterized by pillow structure at/near the K. Gempol and K.Grindulu River.

The Jaten Formation consists of siltstone, sandstone and conglomerate altenating each other. Compared with the sedimentary rocks of the Arjosari Formation, it has small amounts of volcanic material and shows typical clastic sedimentary facies (deposited in shallow marine or lagoonal environments).

A number of small porphyritic intrusions of dacitic to andesitic compositions crop out within the most of the Pacitan district. Many porphyritic intrusions and andesite dykes ubiquitously intrude the volcanics and sedimentary rocks. Later ore-bearing quartz veins crosscut the sedimentary rocks, volcanics, intrusions and andesite dykes. The lack of significant metamorphic aureoles around these intrusives and the fine grained nature of their groundmass imply they were relatively cool, shallow emplacements. As most of these intrusives occur within Late Oligocene to Early Miocene sediments, a Middle Miocene or younger age is inferred. The ore mineralization in the district is likely to be associated with those intrusives.

Map-scale faults run mostly in NW-SE, and locally NE-SW and N-S directions (Fig. 3). Minor faults show the same trend with higher angle dips, which include the mineralized vein systems.

HYDROTHERMAL ALTERATION AND MINERALIZATION

Alteration

The rocks in the Pacitan district are variably altered and mineralized. Wallrock alteration zones surrounding quartz veins show sericitic and/or argillic alteration and pervasive propylitization generally containing disseminated pyrite. Alteration minerals include sericite, kaolinite, chlorite, epidote, and rare rutile. Wallrock alteration adjacent to quartz veins at each mineralized area in the district is similar, commonly consisting of zonally arranged envelopes of propylitic, argillic, and sericitic alteration surrounding each vein (and/or vein system). Each of the zonal widths varies proportionally to vein size.

Generally, sericitic and argillic alterations terminate within (up to) a couple of meters of the veins, whereas the pervasive propylitization may extend several meters from larger veins. The most widespread propylitic alteration is characterized by dominant chlorite with quartz + epidote + sericite + pyrite assemblage. Silicification as alteration envelope typically occurs in the upper and central parts of the vein systems in the district.

In some areas adjacent to the quartz veins (vein systems), quartz was added directly to the country rock either as quartz veinlets or as quartz-filled pore space.

Ore Mineralization

The mineral deposits in the Pacitan district are mainly

Table 1. Chemical compositions of sphalerites from the ore veins in the Pacitan district.

Mineralized area	Paragenetic time	mole % FeS	mole % MnS	mole % CdS	N*
Kasihan	Early	15.16~20.46	0.24~0.48	0.16~0.51	7
	Middle	6.24~ 9.51	0.05~1.18	0.18~0.79	15
	Late	0.80~ 4.90	0.16~3.64	0.19~0.84	24
Jompong	Early	11.54~15.00	0.04~0.30	0.12~0.34	5
	Middle	4.35~ 5.84	0.00~0.13	0.25~0.38	6
	Late	0.65~ 1.92	0.00~0.26	0.17~0.56	12
Gempol	Middle	2.00~ 3.57	0.00~0.26	0.25~0.39	13
	Late	1.10~ 1.75	0.03~0.29	0.12~0.62	9

* Number of spot analyses

hydrothermal veins (quartz veins and/or veinlets), and locally disseminations and/or breccia pipes. They commonly occupied fractures (sometimes breccia-filled) in Tertiary sedimentary and volcanic rocks. The fractures (and/or breccia zones) can be divided into two sets according to their strike: one set striking NS to N50°E and the other striking N10°W to N40°W. The veins show textural evidence of open-space filling, extend several ten to hundred meters (up to ≈ 300 m) along strike, and vary in width from 0.1 to 10 m. Most of the hydrothermal mineralizations in the district, occur in three areas-Gempol, Kasihan, and Jompong-where they display some differences in paragenetic mineral assemblages (see, MINERALOGY and PARAGENESIS).

The veins are mineralogically polymetallic, consisting mainly of white, milky and gray quartz with base-metal sulfides, electrum, (Cu-)Pb-Bi sulfosalts and locally clear quartz. The main veins of each area have a higher concentration of pyrite, chalcopyrite, sphalerite, and galena than other sulfides and sulfosalts.

In the Kasihan area, ore deposits (mainly quartz veins with locally disseminations and/or breccia pipes) contain larger concentrations of sulfide and sulfosalts minerals than those of the Gempol and Jompong areas, including chalcopyrite, sphalerite, galena and aikinite with minor pyrrhotite, electrum and Pb-Bi sulfosalts. The ore mineralizations in the area occur in Late Oligocene lower sedimentary rock member of the Arjosari Formation. The ore veins generally display repeated pinching and swelling along strike and dip direction with concomitant lens-shaped ore shoot. The veins are often reopened and filled by clear euhedral quartz veining. Hematite occurs as specularite crystals, is commonly interstitial to euhedral quartz crystals and is characteristic of all the later mineralization in the area.

In the Jompong area, the quartz veins that occupy fractures in Early Miocene upper volcanic rock member of the Arjosari Formation splay into small stringers and numerous thin veins occur in sub-parallel orientation to the veins. The veins are commonly narrow and variable in thickness (up to 100 cm), but locally achieve a maximum thickness of 600 cm. Small vugs containing clear euhedral quartz are found locally. The ore veins contain dominantly pyrite, chalcopyrite, sphalerite, galena, and minor arsenopyrite with rare greenockite and electrum.

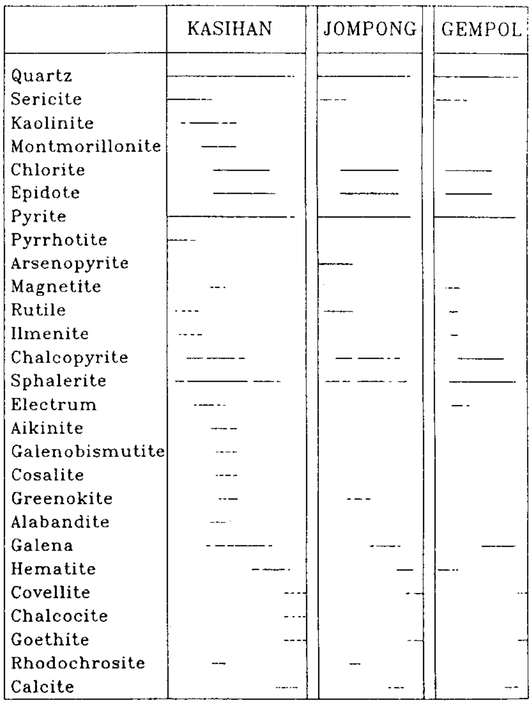

Fig. 4. Generalized paragenetic sequences of vein minerals from the ore veins of Kasihan, Jompong, and Gempol areas in the Pacitan district.

The veins in the Gempol area display a vertical distribution in the upper volcanics of the Arjosari Formation (from the highest level being 610 m above sea level to ≈ 200 m above sea level) and show slight vertical mineral variations relating vertical vein distribution. Although sphalerite and galena occur widely throughout the veins of each level, rich zones are restricted to the veins of upper levels. The occurrence of Fe-oxides (small inclusions in pyrite) is characteristic of the veins of lower levels. The veins locally display lateral asymmetrical zoning of sulfide minerals, from vein margins to centers: pyrite + Fe-oxides (+ rutile), chalcopyrite + sphalerite + galena.

MINERALOGY AND PARAGENESIS

Two or three vein stages are recognized within the study areas of the Pacitan district: pre- and/or post-ore mineralization stage barren quartz veins and ore-bearing main stage quartz veins. Each stage is separated from another by tectonic fracturing events. Pre- and/or post-ore mineralization stage quartz veins do not contain ore minerals and are best displayed in the Gempol area. Base metal and/or gold bearing hydrothermal quartz veins in three areas of the district have some differences in mineralogy, paragenesis (paragenetic mineral assemblages), and the variations of mineral chemistry (Fig. 4).

Kasihan area: The Kasihan area is the dominant ore mineralization area from volumetric standpoints. The ore mineralization in the area is the result of multiple episodes of vein opening and filling. It is characterized by abundant, massive white to grey quartz (with base metal sulfides, sulfosalts, and gold) and, locally, clear quartz containing Fe-oxides with minor sulfides. It also and frequently displays brecciated textures. Lesser amounts of coarse-grained euhedral, clear quartz occur as druses within rarer vuggy portions of veins. The mineral succession is, therefore, complicated by a history of multiple mineralization. Undisturbed veins can, however, be further divided into three substages of mineralization on the basis of mineral textures and assemblages combined with the variation of FeS contents of sphalerite (relating to its paragenesis): early substage represents pyrite + pyrrhotite + early sphalerite assemblage; middle substage is characterized by pyrite + chalcopyrite + massive sphalerite + galena assemblage; late substage is characteristic of hematite occurrence.

Pyrite within fine-grained white to grey quartz characterizes early veins in the area. Pyrite occurs as massive aggregates and as small isolated grains throughout the veins. Some anhedral lenticular pyrrhotites as isolated grains and/or displaying equigranular mosaic textures with early sphalerite are disseminated in pyrite. Sphalerite is distributed widely throughout the paragenesis of main stage vein mineralization and shows three types of occurrence. First, it is partly enclosed within pyrite in early substage, and this has the highest range of FeS contents (15.2 to 20.5 mole % FeS). Second, it occurs as exolutions in or intergrowths with chalcopyrite and as veinlets that cut euhedral pyrite in middle substage (6.2 to 9.5 mole % FeS). Third, it is present as anhedral masses associated with galena (0.8 to 4.9 mole % FeS and honey yellow colored) or as rare isolated grains in coarse-grained clear quartz (Table 1 and Fig. 4). Chalcopyrite occurs as irregular masses and is commonly associated with sphalerite and galena that cut pyrite along fractures. Sulfosalt minerals are aikinite, galenobismutite, and cosalite. Anhedral aikinite occurs as irregular masses along grain boundaries or in fractures of eu- to subhedral pyrite and intergrowths with chalcopyrite. Electrum which has a very high Au contents (91.4 to 94.0 atomic % Au; nearly pure gold) appears as ellipsoidal inclusions in aikinite or as single grains in quartz. Cosalite and galenobismutite occur as tiny inclusions in chalcopyrite or replace chalcopyrite. Hematite shows euhedral specularite crystals and is characteristic of all the later mineralization, which suggests a distinct change in fluid conditions later in ore mineralization in the area. Chalcocite, covellite and goethite occur as alteration products. Sulfides (especially, chalcopyrite and pyrite) were altered or replaced by those supergene minerals along grain margins, fractures, and cleavages. The supergene alterations of sulfides are similar in occurrences in all three areas of the district.

Jompong area: Ore-bearing hydrothermal quartz veins in the Jompong area display similarities in mineralogy (occurrences and morphologies) and paragenesis to those of the Kasihan area (Fig. 4). In detail, however, some of the paragenetic mineral assemblages and their chemistry are different. Compared with ore mineral succession of the Kasihan area, that of the Jompong area is characteristic of the presence of arsenopyrite and the absence of pyrrhotite, electrum, and (Cu-)Pb-Bi sulfosalts (Fig. 4). Therefore, the early substage of the vein deposits in the area represents pyrite + arsenopyrite (29.5~30.3 atomic % As) + sphalerite assemblage replacing pyrite + pyrrhotite + sphalerite assemblage like that in the Kasihan area. Sphalerite is also distributed widely throughout the paragenesis and has a tendency of decrease in FeS contents (11.5 to 15.0 mole %, for early pyrite + arsenopyrite + sphalerite assemblage; 4.4 to 5.8 mole %, for sphalerite associated with chalcopyrite and/or galena; 0.7 to 1.9 mole %, for late sphalerite; Table 1). The ore mineralization in the area is commonly accompanied by sulfide deposition (minor hematite occurs as later vein minerals). Sulfide mineralization is widespread throughout the white to gray quartz veins, but amounts of the base metal sulfides are smaller than the Kasihan area. It is dominated by pyrite, with lesser chalcopyrite, sphalerite, galena and minor covellite and goethite as products of supergene alteration. Greenockite rarely occurs as fine irregular inclusions with galena in sphalerite mass.

Gempol area: Textural relationships indicate that the vein mineralization in the Gempol area were locally formed in three stages of mineralization separated by tectonic fracturing events: stages I and III are barren quartz stage; stage II is quartz-sulfide stage. During the quartz-sulfide stage (as ore mineralization stage), grey to white quartz with concentrations of base metal sul-

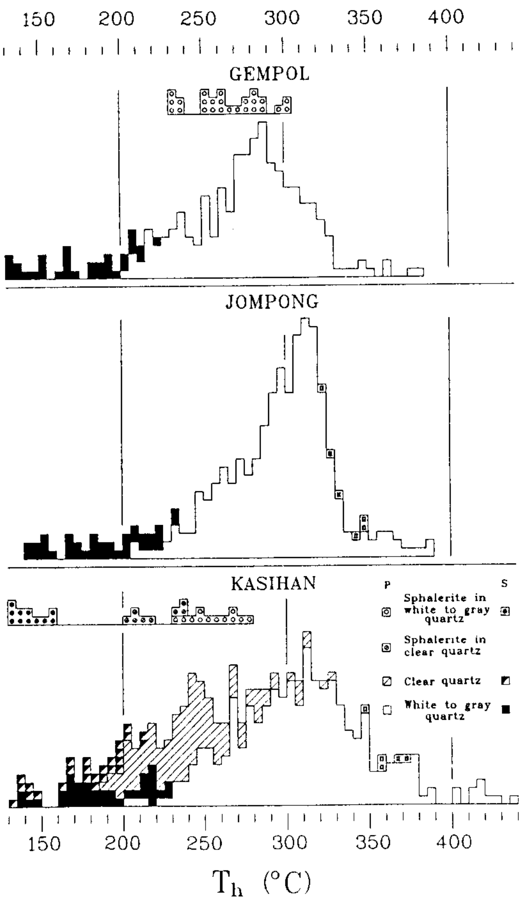

Fig. 5. Frequency diagram of homogenization temperatures of fluid inclusions in vein minerals from Kasihan, Jompong, and Gempol areas. Abbreviations: II=vapor-rich fluid inclusion; P=primary; S=secondary.

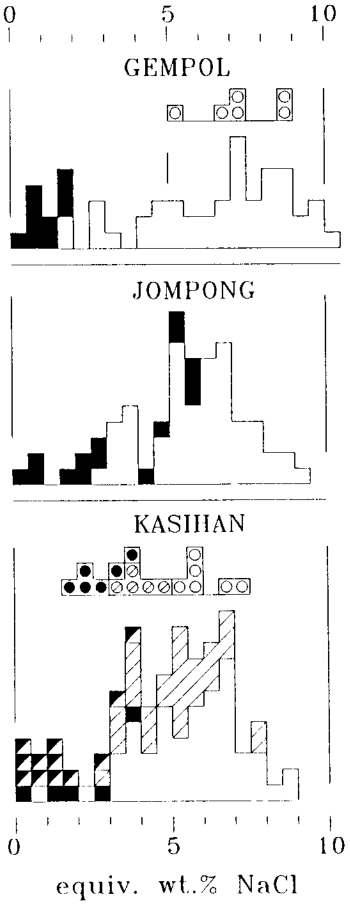

Fig. 6. Frequency diagram of salinities of fluid inclusions in vein minerals from Kasihan, Jompong, and Gempol areas. Symbols as in Figure 5.

fides, minor Fe-oxides and rutile, and rare electrum were deposited.

Pyrite, the most abundant sulfide, occurs mostly as euhedral to subhedral grains. It commonly forms massive aggregates or monominerallic bands at vein margins and small isolated grains throughout the veins. Some pyrite grains are brecciated and cemented by chalcopyrite, sphalerite and galena. Hematite and magnetite inclusions rarely occur within euhedral pyrite grains. Electrum rarely occurs as fine rounded or irregular inclusions in pyrite. Rutile is present mainly as anhedral single grains in quartz veins or rarely as inclusions in pyrite. Ore veins in the area as a whole are characterized by the occurrence of anhedral grains or masses of honey yellow sphalerite along with other sulfides and/or Fe-oxides deposited during early to late mineralization. It occurs as commonly polycrystalline aggregates and as inclusions in pyrite. The FeS contents are relatively lower (1.1 to 3.6 mole %) than those of other areas (Table 1). In summary, the ore mineral paragenesis in the Gempol area is characterized by pyrite + hematite + magnetite + sphalerite assemblages representing early mineralization, pyrite + chalcopyrite (+ galena) + sphalerite (2.0 to 3.6 mole % FeS) assemblage related to middle mineral deposition, and sphalerite having the lowest FeS contents (1.1 to 1.8 mole % FeS) with galena indicating late mineralization.

FLUID INCLUSIONS

Fluid inclusions were studied in outcrop and/or core (only in Kasihan area) samples from the ore veins of all three area in the Pacitan district which were suitable for measurement of homogenization temperatures (T_h) and/or melting temperatures (T_m); they are accurate to

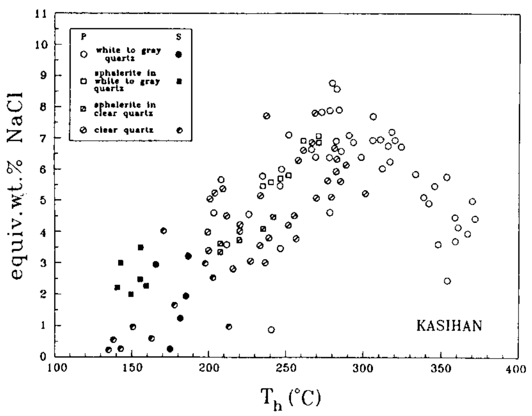

Fig. 7. Plots of homogenization temperature versus salinity for primary and secondary fluid inclusions in ore stage minerals from the ore veins in the Kasihan area.

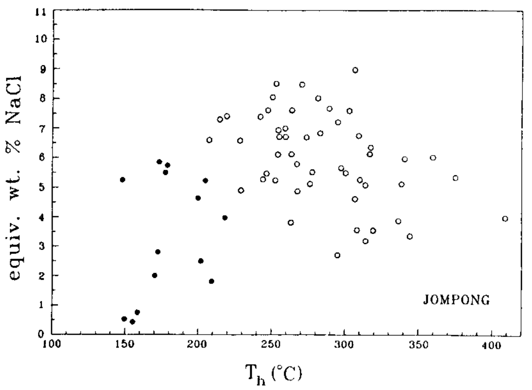

Fig. 8. Homogenization temperature versus salinity diagram for primary and secondary fluid inclusions in ore stage minerals from the ore veins in the Jompong area. Symbols as in Fig. 7.

± 2.0℃ and ± 0.2℃, respectively. Minerals hosting fluid inclusions include medium to coarsely crystalline quartz and translucent sphalerite. Most of the materials studied was obtained from ore mineralization stage veins (and/or vugs with locally disseminations or breccia pipes). In some cases, paragenetic relationships could not be precisely established. The fluid inclusions have been divided into primary (pseudosecondary) and secondary inclusions. The results of heating and freezing experiments are presented in Figs. 5 and 6. Salinities are based on freezing point depression in the system H_2O-NaCl (Potter et al., 1978). Two types of fluid inclusions were recognized, liquid-rich and vapor-rich, and their size ranges from ≤3 to 40 μm in diameter. No traces of gas hydrates were observed during freezing of samples, indicating that

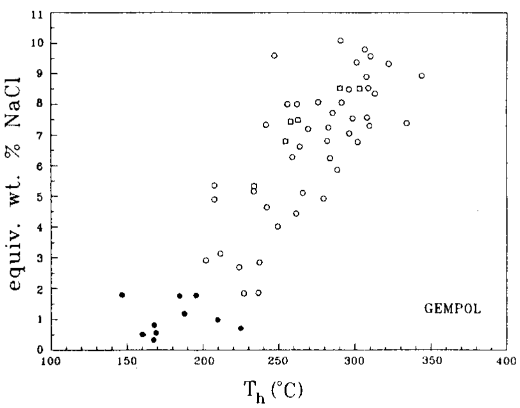

Fig. 9. Plots of homogenization temperature versus salinity for primary and secondary fluid inclusions in ore stage minerals from the ore veins in the Gempol area. Symbols as in Fig. 7.

CO_2 concentrations are below that required to form clathrates (≤0.85 molal; Hedenquist and Henley, 1985). The inclusions do not contain daughter minerals.

Liquid-rich inclusions are the dominant type and contain vapor bubble comprising ≤40 volume percent at room temperature. These inclusions were found in all samples as primary and secondary inclusions and homogenize to the liquid phase.

Vapor-rich inclusions occur only as primary inclusions in quartz samples from the veins in the Kasihan and Jompong area and contain liquid phase with a large vapor bubble comprising ≥70 volume percent. These inclusions are very small for fluid inclusion study (especially, for freezing experiment) and homogenize to the vapor phase.

Fluid Inclusions in Ore Mineralization Stage

Ore stage quartz veins mainly consist of white to grey quartz associated with ore minerals and locally clear quartz which occurs with hematite only in the Kasihan area.

Homogenization temperatures of primary liquid-rich inclusions in ore stage white to grey quartz range from 201° to 433°C. The ranges for individual area are similar (Fig. 5) : Kasihan area, 213° to 433℃; Jompong area, 207° to 409℃; Gempol area, 201° to 383℃. Primary liquid-rich inclusions in sphalerite from the Kasihan and Gempol area homogenize at temperatures of 203° to 287℃ and 234° to 302℃, respectively (Fig. 5). Sphalerite from the veins in the Kasihan area is generally divided into three types based on its paragenetic occurrence (such as paragenetic mineral assemblage) and chemistry (see, MI-

NERALOGY and PARAGENESIS, and Table 1). Only, the later two types of sphalerite from the area were possible for fluid inclusion study and have the ranges of homogenization temperature: 233° to 287℃ for the middle substage sphalerite; 203° to 239℃ for sphalerite of the late substage (Table 1 and Fig. 5). The homogenization temperatures of primary liquid-rich fluid inclusions in clear quartz (related to the late mineralization) from the veins of the Kasihan area range from 189° to 325℃. These are slightly lower than those of white to grey quartz of the stage. Vapor-rich fluid inclusions in ore stage white to grey quartz are observed only in Kasihan and Jompong area and homogenize at temperatures between 321° and 378℃ (Kasihan, 321° to 378℃; Jompong, 334° to 346℃; Fig. 5). Individual vapor-rich fluid inclusions homogenize at nearly the same temperature as coexisting liquid-rich inclusions, which suggests that the fluid boiled in those areas.

Salinities of primary liquid-rich inclusions in ore stage white to grey quartz range from 0.8 to 10.1 equiv. wt. percent NaCl (Kasihan area, 0.8 to 8.8; Jompong, 2.8 to 9.0; Gempol, 1.7 to 10.1); those in sphalerite range from 3.4 to 8.5 (5.4 to 7.0 for the middle substage; 3.4 to 4.5 for the late substage) equiv. wt. percent NaCl (Kasihan area, 3.4 to 7.0; Gempol, 5.4 to 8.5); those in clear quartz in the ore veins of Kasihan area range from 2.9 to 7.9 equiv. wt. percent NaCl (Fig. 6).

Variations in Temperature and Composition

The variations in temperature and composition of the hydrothermal fluids during episodes of mineralization are recorded by fluid inclusions. Fluid inclusion data indicate that the ore mineralization stage in each area of the Pacitan district evolved from initial high temperatures (≈370℃) to later lower temperatures (≈200℃).

The relationship between homogenization temperature and salinity in ore stage of each area (Figs. 7, 8, and 9) suggests a complex history of boiling, cooling and dilution. Although the temperature ranges of ore stage for the Kasihan, Jompong, and Gempol areas are similar, the relationship between homogenization temperature and salinity in ore stage suggests that the ore-forming fluids of the three areas evolved somewhat differently (Figs. 7, 8, and 9). The relationships at Kasihan and Jompong areas indicate a complex fluid evolution history dominated by boiling (Figs. 7 and 8), whereas the relationship at Gempol area indicates a dominant cooling and dilution of ore fluids (Fig. 9).

Kasihan and Jompong areas: During early quartz veining in these areas, boiling of ore fluids resulted in an increase in salinity (up to 9.0 equiv. wt. % NaCl) at initial high temperatures ranging from ≈400℃ to 270℃ (Figs. 7 and 8) and led to precipitation of early minerals mainly as pyrite(-pyrrhotite)(-arsenopyrite)-chalcopyrite-sphalerite. The salinity increase reflects the concentration of salts in the residual liquid as vapor was lost during boiling. During the early mineralization of ore stage the boiling of hydrothermal fluids led to high but variable salinities (Figs. 7 and 8). Later cooling and dilution of fluids (from ≈270℃ and ≈8.0 to 200℃ and 3.0 equiv. wt. % NaCl) which mainly deposited sphalerite, sulfosalts, galena, and hematite with clear quartz in middle to late ore veins in the areas, resulted in the positive linear relationship between temperature and salinity (Figs. 7 and 8). The data of secondary fluid inclusions suggest that cooling and dilution were continued, probably owing to repeated fracturing which allowed more dilute meteoric water into the systems of the areas. Such changes (by boiling and mixing) would be very likely to result in polymetallic mineralization in these areas (especially, Kasihan area).

Gempol area: Fluid inclusion data from the ore stage quartz vein in the Gempol area indicate that there is a tendency of progressive decrease in average temperature and salinity with increasing paragenetic time (Fig. 9). The nearly positive linear relationship between homogenization temperatures and salinities of fluid inclusions from early to late vein minerals (quartz and sphalerite) indicates a history of progressive cooling and dilution of ore-forming fluids. During the early portions of the ore stage, higher temperature and salinity fluids (≈320℃, ≈9.0 equiv. wt. % NaCl) mixed with cooler, less saline waters, resulting in most of ore deposition and later mineralization from fluids of intermediate to low temperature and composition (down to ≈200℃ and ≈2.0 equiv. wt. % NaCl).

In summary, the fluid inclusion data of the Pacitan district indicate that the main base-metal (Cu-Pb-Zn) and/or gold mineralization of the Kasihan and Jompong areas was led by the boiling coupled with later mixing of ore fluids, whereas that of the Gempol area was mainly a result of cooling and dilution of ore fluids.

Pressure Considerations

Vapor-rich and liquid-rich fluid inclusions are intimately associated in some sample of ore stage quartz from Kasihan and Jompong areas and homogenize at the same temperatures over a range from 321° to 378℃ (Kasihan, 334° to 378℃; Jompong, 321° to 346℃) (Fig. 5). At these temperatures the wide range of salinity of early ore stage fluids (Figs. 7 and 8) indicates that boiling occurred throughout early mineral deposition of ore stage, although there is some tendency of increase in salinity with nearly constant or decreasing temperature. Data for the system H_2O-NaCl (Hass, 1971; Cunningham, 1978), combined with temperature and salinity data of these inclusions, indicate pressures of ≈120 to 255 bars (Kasihan area, ≈140 to 255 bars; Jompong area ≈120 to 170 bars). These pressures correspond to depths of approximately 1200 to 2600 m (Kasihan, 1400 to 2600 m; Jompong, 1200 to 1700 m) assuming hydrostatic conditions, 460 to 960 m (Kasihan, 530 to 960 m; Jompong, 460 to 650 m) assuming lithostatic conditions.

Only liquid-rich fluid inclusions were observed at Gempol. The absence of vapor-rich inclusions and lack of other definitive evidence of boiling allow us to determine a minimun estimate of pressure at the time of mineralization. Data from Sourirajan and Kennedy (1962), Hass (1971), and Cunningham (1978) indicate that a minimum pressure of approximately 95 bars is necessary to prevent boiling of a 9.0 wt. percent NaCl fluid at 310℃.

GEOCHEMICAL ENVIRONMENTS

Equilibrium thermodynamics are used to estimate the changes in chemical conditions of the hydrothermal fluids during ore and gangue mineral deposition of ore mineralization stage in the hydrothermal systems of the Pacitan district.

Variations of fugacity of sulfur (fs_2) for ore mineralizations in the Kasihan, Jompong, and Gempol areas were estimated from phase relations and mineral compositions in the systems Fe-Zn-S (Scott and Barnes, 1971), Fe-As-S (Kretschmar and Scott, 1976), and Fe-O-S (Helgeson, 1969) (Fig. 10).

In the Kasihan area, pyrrhotite is closely associated with pyrite and sphalerite in the early mineralization of main ore stage. The FeS contents of sphalerite in this assemblage decrease from 20.5 to 15.1 mole percent (Table 1), and the homogenization temperatures of fluid inclusions in associated quartz during early mineralization are ≈290° to 360℃, corresponding to a decrease

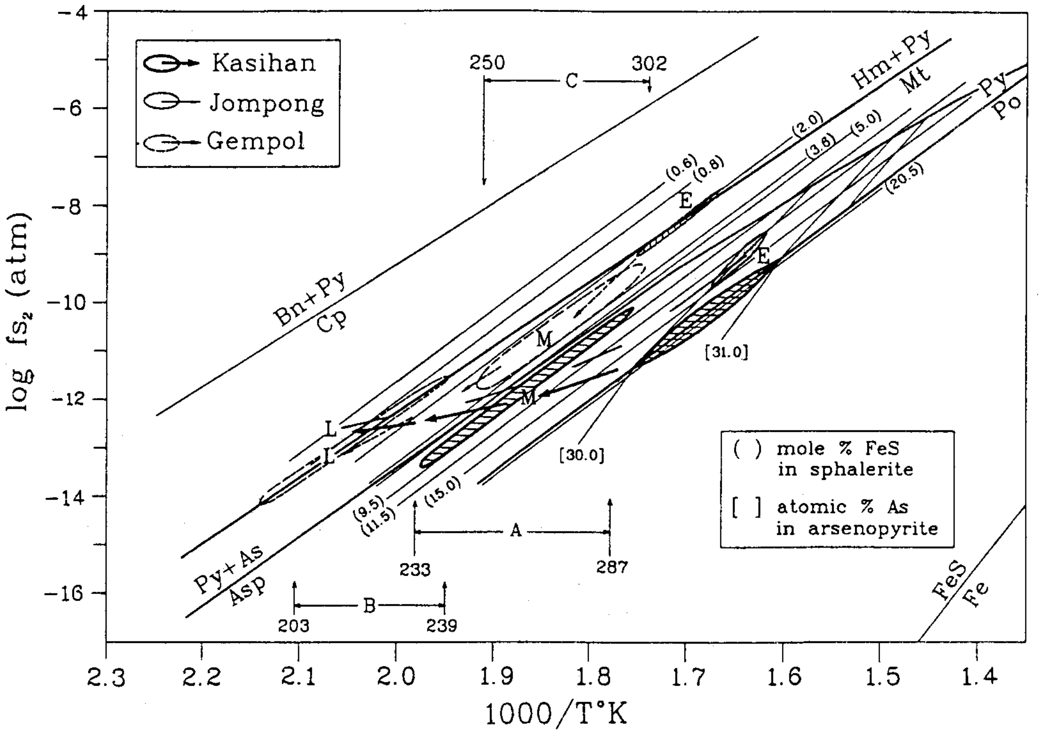

Fig. 10. Plot of temperature versus sulfur fugacity showing possible mineralization conditions and the evolution paths (represented by each arrow) for early, middle, and late mineralization of ore stage veining at each area in the Pacitan district. A and B represent homogenization temperature(℃) ranges of sphalerite from white to gray quartz veins and clear quartz veins, respectively, in the Kasihan area. C is the range of homogenization temperature(℃) of sphalerite (as early to middle mineralization) from the ore veins in the Gempol area. Abbreviations: As=native arsenic; Asp=arsenopyrite; Bn=bornite; Cp=chalcopyrite; E=early substage; Hm=hematite; M=middle substage; Mt=magnetite; L=late substage; Po=pyrrhotite; Py=pyrite.

in fs_2 values with time from $10^{-9.2}$ to $10^{-11.2}$ atm (Fig. 10). During the middle substage, pyrite + chalcopyrite + massive sphalerite assemblages (sphalerite, 6.2 to 9.5 mole % FeS) were precipitated. Based on homogenization temperatures of fluid inclusions in the sphalerite (233° to 287℃), log fs_2 values ranged between -10.0 and -13.2 during the middle substage. Honney yellow sphalerite associated with late mineral assemblage and/or hematite (see, MINERALOGY and PARAGENESIS) has a lower range of FeS contents between 0.8 and 4.9 mole percent (Table 1). Based on homogenization temperatures of fluid inclusions in sphalerite (203° to 239℃), the range of fs_2 values is $10^{-11.5}$ to $10^{-14.0}$ atm.

In mineral assemblages and the variations in FeS contents of sphalerite relating to paragenetic time, ore veins in the Jompong area are similar to those in the Kasihan area. In detail, however, the early mineral assemblage (pyrite + arsenopyrite + sphalerite; see, MINERALOGY and PARAGENESIS) and some FeS contents of sphalerite (Table 1) are different. During the early mineralization of the ore stage veins in the Jompong area, arsenopyrite (29.5~30.3 atomic % As) is closely associated with pyrite and early sphalerite (11.5 to 15.0 mole % FeS; Table 1). Therefore, the estimated initial log fs_2 values for early mineralization in the area ranged between -8.7 and -9.8 (Fig. 10) and the changes of log fs_2 values in the remaining mineralization after early mineralization in the Jompong area (represented light solid line arrows in Fig. 10) are similar to those in the Kasihan area.

For the ore stage mineralization in the Gempol area, the variation of fs_2 of ore-forming fluids cannot be investigated due to a lack of suitable data. However, the compositional change of sphalerite with paragenesis and mineral assemblages, combined with homogenization temperatures of fluid inclusions in sphalerite and associated quartz, provides an approximation of fs_2 variations with paragenetic time. In the early mineralization, the homogenization temperatures of early quartz and early sphalerite, suggest that formation temperatures were ≥300℃. Early hematite and magnetite occurrences (see, MINERALOGY and PARAGENESIS) combined with sphalerite compositions of the early mineralization in the area suggest that the lower limit of the fs_2 of ore fluids at this temperature condition is $\fallingdotseq 10^{-9.1}$ atm. During the middle substage, sphalerite (2.0 to 3.6 mole % FeS) is associated with pyrite and chalcopyrite. Based on homogenization temperatures of fluid inclusions in the sphalerite (250° to 302℃), log fs_2 values were estimated to range between -9.4 and -11.8 during the middle substage. In the late mineralization, late sphalerite (1.1 to 1.8 mole % FeS) is intergrown with galena or occur in vugs of the ore veins in the area. The compositional range of late sphalerite and the homogenization temperatures of fluid inclusions in sphalerite (234° to 239℃) and associated quartz (down to 200℃) also defined the lower limit of the fs_2 of the late ore fluids as $\geq 10^{-14.0}$ atm. The probable fs_2 variations of the ore veins in the Gempol area (represented dotted line arrows) are shown in Fig. 10.

In summary, the evolution of the fs_2 variations coupled with temperatures (as paragenesis) at each hydrothermal system in the Pacitan district shows two trends: 1) the ore fluids at Kasihan and Jompong, initially evolved nearly along the FeS_2-FeS sulfidation curve and evolved towards the FeS_2-Fe_2O_3-Fe_3O_4 reaction line at late mineralization; 2) for the Gempol hydrothermal system, the ore fluids chemically evolved nearly along the FeS_2-Fe_2O_3-Fe_3O_4 reaction curve throughout the paragenesis. These may represent the difference of oxygen states (fo_2) in the early ore-bearing fluids at each hydrothermal system.

It is possible to define the chemical changes that were responsible for mineral deposition further by using plots of fo_2 versus fs_2 (Fig. 11). The diagram, for convenience, has been constructed for 300℃ in order to compare oxygen states responsible for early ore fluids in the Kasihan, Jompong, and Gempol area.

The values of log fo_2 during the ore mineralization in the Kasihan area may be estimated from the occurrence of rhodochrosite and alabandite with pyrite. Assuming a log fo_2 value of 0.6 atm, the log fo_2 values for the ore mineralization in the Kasihan area range from -34.5 to -33.6. The minimum value of log fo_2 at Jompong may be estimated from the occurrence of rhodochrosite and absence of alabandite. The occurrence of pyrite and absence of magnetite in the ore mineralization stage of Jompong area indicates the maximum value of log fo_2 value. The maximum and minimum values of log fo_2 at Jompong hydrothermal system are -32.1 and -33.6, respectively. The assemblage magnetite-pyrite in the ore veins of the Gempol area indicates a log fo_2 value near -30.7 ± 0.3.

The differences of chemical conditions (fo_2 value and the evolution trend of the fs_2 variations coupled with temperatures) at each hydrothermal system in the Pacitan district reflect the different role of meteoric water at each hydrothermal system relating mainly mineralization depth (see, Pressure Considerations and Oxygen and Hydrogen Isotopes Study).

STABLE ISOTOPE STUDIES

In this study, oxygen and hydrogen, and sulfur isotope

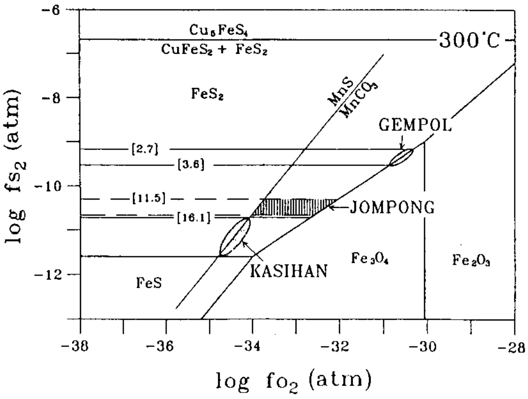

Fig. 11. Fugacity of oxygen (fo_2) versus fugacity of sulfur (fs_2) diagram at 300°C showing stability relationships of Kasihan, Jompong, and Gempol mineralizations of the Pacitan district. Stability of $MnCO_3$ is based on a fugacity of $CO_2=0.6$ atm. Ranges of fs_2 are calculated from FeS contents of sphalerite (numbers in square brackets) (Scott and Barnes, 1971).

Table 2. Sulfur isotope data for sulfide minerals from the ore veins in the Pacitan district.

Mineralized area	Sample no.	Mineral	$\delta^{34}S$(‰)	T(°C)[1]	$\delta^{34}S_{H_2S}$(‰)[2]
Kasihan	KS-1	Chalcopyrite	2.2	310	2.4
	KS-22	Chalcopyrite	2.7	310	2.9
	KS-42	Sphalerite	4.1	250	3.7
	KS-232	Chalcopyrite	1.6	270	1.8
Jompong	JP-1-1	Pyrite	7.9	320	6.8
	JP-1-2	Galena	0.1	250	2.4
	JP-2-1	Pyrite	4.1	290	2.8
	JP-2-2	Chalcopyrite	1.8	290	2.0
Gempol	GP-1	Pyrite	2.7	270	1.3
	GP-6	Pyrite	6.9	310	5.7
	GP-10	Pyrite	6.7	280	5.4
	GP-28	Pyrite	4.8	310	2.6

[1] Based on fluid inclusion temperatures and paragenetic constraints.
[2] Calculated using the sulfur isotope fractionation equations in Ohmoto and Rye (1979).

compositions of quartz samples and sulfides from the Pacitan district were measured to elucidate the origin and history of hydrothermal fluids. The oxygen isotope compositions of quartz, the hydrogen isotope compositions of fluid inclusion waters and the sulfur isotope compositions of sulfide minerals were determined. We used standard techniques of extraction and analysis described by Grinenko (1962), Hall and Friedman (1963), and Rye (1966). Data are reported in standard δ notation relative to the Canyon Diablo Troilite (CDT) standard for sulfur, and the Vienna SMOW for oxygen and hydrogen. The analytical error of each analysis is approximately ±0.1‰ for O and S, and ±1‰ for H.

Sulfur Isotope Study

Sulfur isotope analyses were performed on twelve sulfides from the ore stage sulfides of the Kasihan, Jompong, and Gempol areas (Table 2). Sulfur isotope compositions in pyrite, chalcopyrite, sphalerite, and galena from the ore veins have a narrow range of values between 0.1 to 7.9 per mil.

Using temperatures estimated from fluid inclusions and paragenetic constraints, calculated $\delta^{34}S$ values of H_2S in ore stage hydrothermal fluids are 1.3 to 6.8 per mil (Ohmoto and Rye, 1979). The overlap of the ranges suggests that a fluid with a $\delta^{34}S_{H_2S}$ value of around 3.3 per mil (mean value) was responsible for mineralization in the each area of Pacitan district. Ore mineral assemblages indicate that sulfur in the hydrothermal fluids was dominantly H_2S (see, Fig. 11). Therefore, the $\delta^{34}S$ values of H_2S ($\approx$3.3‰) may be taken as an approximate sulfur isotope composition of the entire solution ($\delta^{34}S_{\Sigma S}$). These data indicate that such a fluid was responsible for mineralization and that the sulfur had a local igneous source, either directly by magma devolatilization or by leaching from surrounding igneous rocks (see, LOCAL GEOLOGY).

Oxygen and Hydrogen Isotopes Study

The $\delta^{18}O$ values of twelve quartz samples from ore stage of the Kasihan, Jompong, and Gempol areas range from 5.9 to 13.3‰ (Table 3). Values of $\delta^{18}O_{H_2O}$ calculated using the quartz-water oxygen isotope fractionation equation of Matsuhisa et al. (1979) in conjunction with fluid inclusion temperatures range from −3.0 to 5.0 per mil.

Fluid inclusion waters were extracted by crushing eleven quartz samples and were analysed for their hydrogen isotope composition. The ranges of δD values for the each samples are from −65 to −88 per mil (Table 3).

To assess the importance of meteoric waters in the Kasihan, Jompong, and Gempol ore-mineralized hydrothermal systems in the Pacitan district and to interpret the measured δD values of inclusion waters, it is important to know the δD value of the local meteoric water at the time of mineralization. Unfortunately, the δD values of the local meteoric water at Miocene age are not known. In this study, the δD values are estimated from the δD values of the Porgera gold mine, Papua New Guinea (Richards and Kerrich, 1993). This mine is similar in mineralization age (Late Miocene), geographic location (6°S), and tectonic setting (an eastern

Table 3. Oxygen and hydrogen isotope data for inclusions fluids and quartz from the ore veins in the Pacitan district.

Mine	Sample no.	Mineral	$\delta^{18}O$(‰)	T(℃)[1]	$\delta^{18}O_{water}$(‰)[2]	δD_{water}(‰)	Substage
Kasihan	KS-1	quartz	7.0	280	−0.6	−69	M
	KS-2	quartz	7.4	320	1.2	−66	M
	KS-3	quartz	8.2	300	1.3	−71	M
	KS-4	quartz	9.0	350	3.7	−67	E
Jompong	JP-1	quartz	8.7	250	−0.2	−79	L
	JP-4	quartz	13.3	260	5.0	−76	M
	JP-6	quartz	10.2	270	2.2	−72	M
	JP-10	quartz	11.2	320	5.0	−65	E
Gempol	GP-6-1	quartz	10.0	290	2.8	−84	M
	GP-6-2	quartz	10.2	290	3.0	−79	M
	GP-10	quartz	5.9	250	−3.0	−88	L
	GP-28	quartz	9.9	310	3.4	−81	E

[1] Based on fluid inclusion temperatures and paragenetic constraints.

[2] Calculated using the quartz-water oxygen isotope fractionation equation of Matsuhisa et al. (1979).

Abbreviations : E = early substage, M = middle substage, L = late substage.

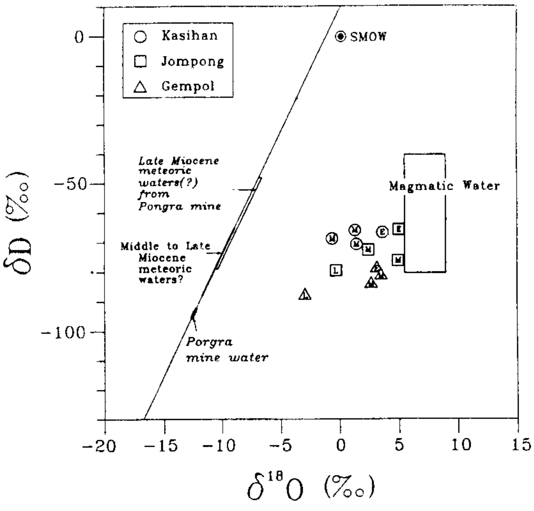

Fig. 12. Plot of oxygen versus hydrogen isotope compositions showing stable isotope systematics of hydrothermal fluid compositions in Kasihan, Jompong, and Gempol areas. Alphabets in symbols : E = early mineralization, M = middle mineralization, L = late mineralization at ore veins in each area. Meteoric water line from Craig (1961); magmatic water box from Taylor (1974). See text for explanation of isotopic compositions of meteoric waters.

portion of Irian Jaya Island, Indonesia) to Pacitan district (see, Fig. 1). The measured range δD values for fluid in vein minerals from the Porgera hydrothermal ore deposit of Late Miocene age is −48 to −78 per mil (Richards and Kerrich, 1993) which are assumed to represent the range of meteoric water compositions at the time of mineralization at Porgera. The δD values (−65 to −88‰) from the ore stage vein quartz in the Pacitan district are slightly lower than those of the Porgera mine.

Measured and calculated hydrothermal fluid compositions for the Kasihan, Jompong, and Gempol area are shown on a conventional oxygen versus hydrogen isotope diagram (Fig. 12). The $\delta^{18}O$ versus δD values for ore stage vein quartz indicate the ore-bearing hydrothermal fluids of each area in Pacitan district were derived from a paleometeoric water that became isotopically highly evolved through isotope exchange reaction with igneous rocks at variable temperatures under low water/rock ratios.

The δD values from early substage quartz at each hydrothermal system are variable (−65 to −81‰) at nearly constant $\delta^{18}O$ (3.4 to 5.0‰). These results reflect the differences of water/rock ratios at each hydrothermal system relating mainly mineralization depth. Therefore, the early ore-bearing fluids at relatively shallow Gempol hydrothermal system (See, Pressure considerations) evolved isotopically under relatively higher water/rock ratio than those of other hydrothermal systems (Jompong and Kasihan) in the Pacitan district.

Quartz from late substage yielded isotopic values that fall significantly towards the $\delta^{18}O$ and δD values of the estimated paleometeoric water (especially, Gempol area). This could signify a mixing of highly exchanged meteoric water with unexchanged meteoric water.

In summary, the isotopic composition of the fluids in each hydrothermal system indicate a progressive shift from dominance of highly exchanged meteoric water in early mineralization period towards an unexchanged meteoric water in late mineralization period.

ACKNOWLEDGEMENTS

This research was financially supported by a grant from the Center for Mineral Resources Research, Korea University.

REFERENCES

Craig, H. (1961) Isotopic variations in meteoric waters. Science, v. 133, p. 1702-1703.

Cunningham, C.G. (1978) Pressure gradients and boiling as mechanisms for localizing ore in porphyry systems. U.S. Geol. Survey J. Research, v. 6, p. 745-754.

Grinenko, V.A. (1962) Preparation of sulfur dioxide for isotopic analysis. Zhurnal Neorganicheskoi Khimii, v. 7, p. 2478-2483.

Hall, W.E. and Friedman, I. (1963) Composition of fluid inclusion, Cave-in-Rock fluorite district, Illinois and Upper Mississippi Valley zinc-lead district. Econ. Geol., v.

53, p. 886-911.

Hass, J.L. Jr. (1971) The effect of salinity on the maximum thermal gradient of a hydrothermal system at hydrostatic pressure. Econ. Geol., v. 66, p. 940-946.

Hedenquist, J. W. and Henley, R.W. (1985) The importance of CO_2 on freezing point measurements of fluid inclusions; Evidence from active geothermal systems and implications for epithermal ore deposition. Econ. Geol., v. 80, p. 1379-1406.

Helgeson, H.C. (1969) Thermodynamics of hydrothermal systems at elevated temperatures and pressures. Amer. J. Sci., v. 267, p. 729-804.

Katili, J. A. (1973) Geochronology of West Indonesia and its implication on plate tectonics. Tectonophysics, v. 19, p. 195-212.

KMPC (1991) Report on the joint mineral exploration in the Pacitan-Ponorogo area, East Java, the Republic of Indonesia, Phase I. Korea Mining Promotion Corporation, 299p.

KMPC (1993) Report on the joint mineral exploration in the Pacitan-Ponorogo area, East Java, the Republic of Indonesia, Phase III. Korea Mining Promotion Corporation, 255p.

Kretschmar, U. and Scott, S.D. (1976) Phase relations involving arsenopyrite in the system Fe-As-S and their application. Canadian Mineralogist, v. 14, p. 364-386.

Matsuhisa, Y., Goldsmith, R. and Clayton, R.N. (1979) Oxygen isotope fractionation in the system quartz-albite-anorthite-water. Geochim. et Cosmochim. Acta, v. 43, p. 1131-1140.

Ohmoto, H. and Rye, R.O. (1979) Isotopes of sulfur and carbon. In: Barnes, H.L. (ed.) Geochemistry of hydrothermal ore deposits (2nd ed.). John Wiely, p. 509-567.

Potter, R.W. III, Clynne, M.A., and Brown, D.L. (1978) Freezing point depression of aqueous sodium chloride solutions. Econ. Geol., v. 73, p. 284-285.

Richards J.P. and Kerrich R. (1993) The Porgera gold mine, Papua New Guinea: Magmatic hydrothermal to epithermal evolution of an alkalic-type precious metal deposit. Econ. Geol., v. 88, p. 1017-1052.

Rye, R.O. (1966) The carbon, hydrogen, and oxygen isotopic compositions of the hydrothermal fluids responsible for the lead-zinc deposits at Providencia, Zacatecas, Mexico. Econ. Geol., v. 61, p. 1399-1427.

Scott, S.D. and Barnes, H.L. (1971) Sphalerite geothermometry and geobarometry. Econ. Geol., v. 66, p. 653-669.

Sourirajan, S. and Kennedy, G.C. (1962) The system H_2O-NaCl at elevated temperatures and pressures. Am. J. Sci., v. 260, p. 115-141.

Taylor, H.P. Jr. (1974) The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition. Econ. Geol., v. 69, p. 843-883.

Van Bemmelen, R.W. (1949) The Geology of Indonesia. The Hague, Netherlands, 3 volumes.

Manuscript received 25 March 1995

인도네시아 동부자바 빠찌딴(Pacitan) 광화대 열수 맥상 광상의 성인 연구

최선규 · 소칠섭 · 최상훈 · 한진균

요　약: 인도네시아 빠찌딴 광화대 동-아연 광상은 금 또는 연 광화작용을 수반하여 동부자바 Southern Mountain zone내 제 3기 퇴적암류와 화산암류의 열극을 충진한 열수 석영 맥상광체로 까시한 (Kasihan), 점퐁 (Jompong), 금뽈 (Gempol) 지역에 밀집 분포한다. 주 광화시기의 광석광물로는 황철석, 황동석, 섬아연석, 방연석 등이 각 지역별로 특징적인 광석광물들과 공생관계로 보이며 산출한다. 즉 까시한 지역의 경우 초기 공생광물군으로써 황철석 자류철석 철함유량이 높은(약 20 mole % FeS) 섬아연석과 Au 함량이 매우높은 (91.4 to 94.0 atomic % Au) 에렉트럼 및 (Cu-)Pb-Bi계 유염광물 등이 산출하며, 점퐁지역은 황철석, 유비철석 (29.5~30.3 atomic % As), 섬아연석 등이 공생관계를 보여주며 산출된다. 반면, 금뽈지역의 경우 황철석, 자철석, 적철석 등의 초기 산출이 특징적이다. 광석광물의 침전은 0.8~10.1 wt. % NaCl 상당염농도를 갖는 광화유체로 부터 약 350℃에서 약 200℃에 걸쳐 진행되었으며, 까시한 및 점퐁지역의 경우 초기 광화유체의 비등현상과 이에 수반된 냉각 희석 작용에 기인한 광액 진화에 의하여, 금뽈지역의 경우 천수의 유입에 의한 냉각 희석작용이 우세하게 진행된 광액 진화에 기인하여 야기되었다. 광화유체의 비등현상 및 유체포유물 연구결과에 근거한 빠찌딴 광화대 주 광화시기의 압력조건은 약 ≥95~255 bars로, 까시한 (≈ 140~255 bar) → 점퐁(≈ 120~170 bar)→ 금뽈 (≥95 bar)의 순으로 광화대내 지역별 상대적인 광화심도 차이가 확인된다. 광물공생관계를 이용한 열역학적 연구결과, 온도감소에 따른 유황분압의 변화와 산소분압 조건이 각 지역별로 상이함은 광화대내 각 지역별 열수계에서 상기 광화심도에 관련한 천수의 역할 (water/rock 비등)차이에 기인된 결과로 해석된다. 유체내 산소 및 수소안정동위원소 연구결과, 이들 동위원소 값이 광화작용의 진행과 함께 점차 감소함은 상대적으로 낮은 water/rock 비 값은 갖는 환경하에서 동위원소 교환반응을 이뤄 평형상태에 이른 광화초기 열수계내에 광화작용의 진행과 함께 산화상태의 차갑고 동위원소적 교환반응이 적게 이뤄진 천수의 혼입이 점증하였음을 지시하며, 각 지역별 동위원소비 값의 차이는 광화심도에 관련된 water/rock비 및 동위원소 교환반응차 등에 의한 결과로 사료된다.