

Gold-Bearing Mesothermal Veins from the Gubong Mine, Cheongyang Gold District, Republic of Korea: Fluid Inclusion and Stable Isotope Studies

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Abstract

The Gubong deposit consists of five massive, gold-bearing mesothermal quartz veins that fill fractures oriented northeast and northwest along fault shear zones over an area of 14 km² in Precambrian metasedimentary rocks of the Gyeonggi massif. The veins are divided into three groups, based on their orientation and location. They have a ribbon texture that is interpreted to result from repeated hydraulic fracturing events. Mineral deposition was associated with hydrothermal fluid overpressuring within and below the active fault shear zones. The vein mineralogy and paragenesis of the veins allow two separate discrete mineralization episodes to be recognized, separated by a major faulting event. The ore minerals are contained within quartz and calcite associated with fracturing and healing of veins that occurred during both mineralization episodes. Wall-rock alteration minerals during stage I, the main ore stage, include sericite, chlorite, and minor pyrite and carbonates. Sulfide minerals deposited along with electrum during this stage include arsenopyrite, pyrite, pyrrhotite, sphalerite, marcasite, chalcopyrite, galena, and argentite. Electrum also was deposited during stage II mineralization in the one group of veins, along with pyrite, sphalerite, chalcopyrite, and galena, but the second stage of deposition in other veins was barren.

Petrographic examination of textural relationships among sulfides, fluid inclusions, microfracturing, and quartz shows chronological and genetic relationships between gold deposition and fluid entrapment. Systematic studies of fluid inclusions in stage I vein indicate two contrasting events: a relatively high temperature (203°–432°C) and pressure (943–2,098 bars) event related to early sulfide deposition and associated with H₂O–CO₂–CH₄–NaCl ± N₂ fluids (less than about 13.4 wt % NaCl), and a lower temperature (202°–399°C) and pressure (670–850 bars) late sulfide depositional event involving H₂O–NaCl fluids (3.9–17.3 wt % NaCl). The H₂O–NaCl fluid involved in ore-related stage II mineralization had a salinity of 0.4 to 4.2 wt percent NaCl and a homogenization temperature of 201° to 378°C.

The calculated sulfur isotope compositions of hydrothermal fluids from the stage I veins ($\delta^{34}\text{S}_{\text{H}_2\text{S}}$ = 3.5–10.5‰) indicate that ore sulfur was derived mainly from a magmatic source but also in part from sulfur contained in the host rocks. The calculated and measured oxygen and hydrogen isotope compositions of the ore-forming fluids (stage I: $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ = 1.1–9.0‰, δD = –92 to –21‰; stage II: $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ = –0.1 to +0.3‰, δD = –95 to –93‰) indicate that the fluids were derived from magmatic and/or deep-seated metasedimentary rocks (stage I) and evolved by mixing with local meteoric water (stage II), by limited water-rock exchange and by degassing during mineralization in uplift zones.

The H₂O–NaCl fluids involved in the stage I development of these veins represent fluids that evolved either through unmixing of H₂O–CO₂–CH₄–NaCl ± N₂ fluids following a decrease in fluid pressure or through mixing with deeply circulating meteoric waters, possibly as a result of uplift and/or unloading during mineralization. The H₂O–NaCl fluid involved in stage II was derived from meteoric water.

Early deposition of gold in stage I was caused by a decrease in sulfur fugacity (H₂S loss) that accompanied the immiscible separation of carbonic vapor from H₂O–CO₂–CH₄–NaCl ± N₂ fluids. Gold in late stage I and stage II veins was precipitated from H₂O–NaCl fluids by cooling and by dilution caused by mixing with meteoric water.

Introduction

THE GUBONG MINE is located in the Cheongyang gold district, one of the major areas of mesothermal gold-bearing quartz mineralization in the Republic of Korea (Fig. 1). This mineralized district is one of ten metallogenic provinces in the Republic of Korea recognized by Kim (1970) and designated the Cheonan metallogenic province. Most gold-silver deposits in the Cheonan metallogenic province are associated closely with major Jurassic and Cretaceous igneous activity (Choi et al., 2001). These deposits can be divided into mainly gold-rich mesothermal deposits of Jurassic age, “Korean-type” Early

Cretaceous gold-silver deposits, and silver-rich epithermal deposits emplaced in the Late Cretaceous (Shelton et al., 1988). Gold deposits associated with Jurassic igneous activity (Daebo orogeny, 200–150 Ma) generally have a massive vein morphology, simple mineralogy, and low Ag/Au ratios (Shelton et al., 1988). Gold deposits associated with Cretaceous igneous activity (110–65 Ma) commonly show complex vein morphologies, complex mineralogy, and high Ag/Au ratios (Choi et al., 2001).

Although associated with Jurassic and Cretaceous igneous activity, the gold deposits are hosted in Precambrian metasedimentary rocks (So and Shelton, 1987; Shelton et al., 1988; So et al., 1995; Choi et al., 2001). In the Cheonan metallogenic

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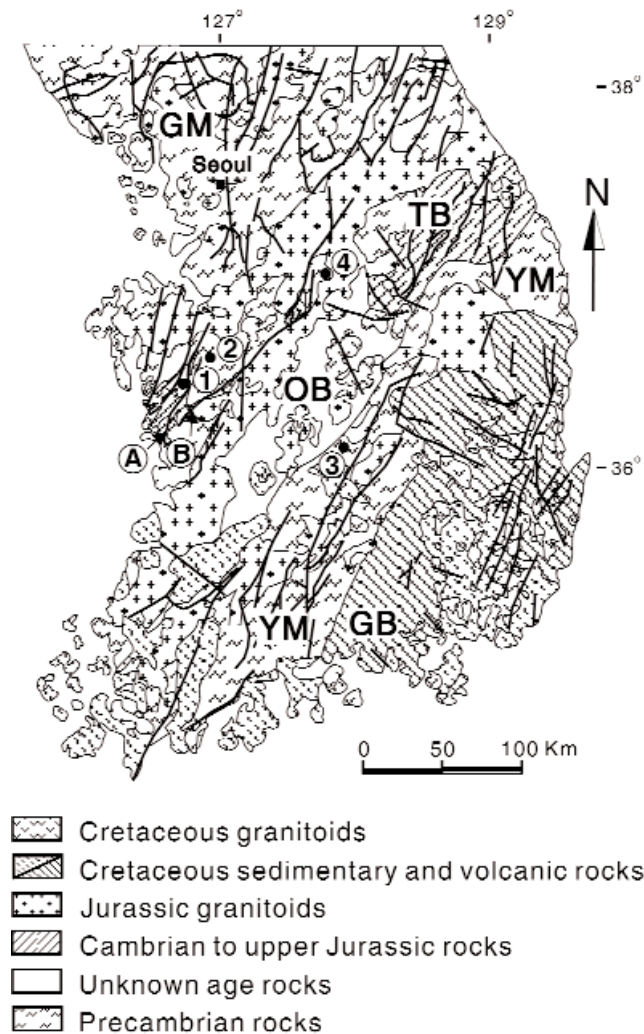


Fig. 1. Simplified geologic map of the Republic of Korea, showing the location of Cheongyang (1 = Gubong, 2 = Samgwang), Youngdong (3 = Samdong) and Jungwon (4 = Taechang) gold districts and Jurassic and Cretaceous granitoids, and major faults (A = thrust fault, B = sinistral strike-slip fault). GB = Gyeongsang basin, GM = Gyeonggi massif, OB = Ogcheon belt, TB = Taebaeg belt. Solid circles indicate mines, YM = Yeongnam massif. Black lines indicate faults.

province, the ore-related magmatic episode occurred during the Jurassic to Cretaceous (195–127 Ma) orogeny, some 120 m.y. after a regional 212 to 192 Ma metamorphic event had affected the Precambrian basement.

The Gubong mine operated intermittently from 1908 to 1940. In 1988, it was incorporated by the Youngpung Company and mined continuously until 1991. The mine was the largest gold producer in the Republic of Korea, with over 100 kg of gold produced per year from 1930 to 1943. The ore had an average grade of about 6.4 g/t Au and an average Au/Ag ratio of about 3:1. Remaining ore reserves are estimated at about 150,000 metric tons (t). In previous investigations of the Gubong mine, Cheon and Oh (1970) and Lee et al. (1992) examined the general geology and ore mineralogy. In this study, detailed mineralogical, fluid inclusion, and stable isotope studies of the gold quartz veins were undertaken to ascertain the conditions of mineralization and the potential

sources of the vein-forming fluids. The results have several implications for genetic models of mesothermal gold quartz vein systems in this region.

Geologic Setting

The general geology of the Republic of Korea is composed of the Precambrian Gyeonggi massif (GM), the Paleozoic Ogcheon belt (OB), the Paleozoic Taebaeg belt (TB), the Precambrian Yeongnam massif (YM), Jurassic granitoids, the Cretaceous Gyeongsang basin (GB), and Cretaceous granitoids (Fig. 1). The Gyeonggi and Yeongnam massifs consist of gneiss and schist. The Ogcheon belt consists of low- to medium-grade metasedimentary and metavolcanic rocks. The Taebaeg belt consists of non- or weakly metamorphosed sedimentary rocks. The Jurassic granitoids are distributed along northeast- or north-northeast-trending batholithic belts. They occur mainly in the Gyeonggi and Yeongnam massifs and locally in the Ogcheon and Taebaeg belts. They are characterized by meso- or katazone emplacement and no major volcanic activity. The Gyeongsang basin consists of sedimentary and calc-alkaline volcanic rocks deposited in a continental arc setting. The Cretaceous granitoids occur mostly in the Gyeongsang basin and partially in the central part of Ogcheon and Taebaeg belts.

The main structural feature in the Cheongyang gold district is a series of major north-northeast-trending faults and folds (Figs. 1, 2). These faults crosscut Precambrian metasedimentary rocks, Jurassic granitoids, and partly the Jurassic Daedong Supergroup. The Daechon, Maginsan, and Woosan faults are thrust faults with 30 to 80 km of strike length. These faults are considered to have been active after deposition of the Jurassic Daedong Supergroup (Fig. 2). The sinistral strike-slip faults are believed to have been active from the Late Jurassic to Early Cretaceous. The quartz veins in the Gubong mine occurred parallel or subparallel to the main faults and fold axes of the major syncline and anticline and strike mainly N2° to 34°E and N5° to 35°W.

The oldest rocks in the Gubong mine are Precambrian metasedimentary rocks of the Gyeonggi massif (Fig. 2). They occupy most of the mine area and consist of mainly banded gneiss or granitic paragneiss and partly migmatitic gneiss. Granitic paragneiss and migmatitic gneiss bodies that exhibit gradational contacts occur within the banded gneiss, which is the most abundant rock in the area and is commonly intercalated with hornblende schist, serpentinite, and marble. These bodies strike N20° to 80°E and vary in dip from 30° to 70°SE to 30° to 70°NW. The banded gneiss is composed of quartz, biotite, muscovite, plagioclase, orthoclase, microcline, hornblende, sericite, and epidote. The granitic paragneiss that occurs within the banded gneiss commonly has poorly defined contacts as a result of migmatitization. It is composed mainly of quartz, plagioclase, and biotite. The hornblende schist is composed principally of hornblende with minor quartz, orthoclase, plagioclase, biotite, muscovite, and sericite. Na (1992) argued that two episodes of amphibolite facies metamorphism affected the metasedimentary rocks of the Gubong mine at 2370 to 2572 and 1350 to 1420 Ma, followed by a Triassic to Jurassic greenschist facies metamorphic event. Kwon et al. (1997) presented evidence that the metasedimentary rocks of the Gyeonggi massif cooled from upper greenschist

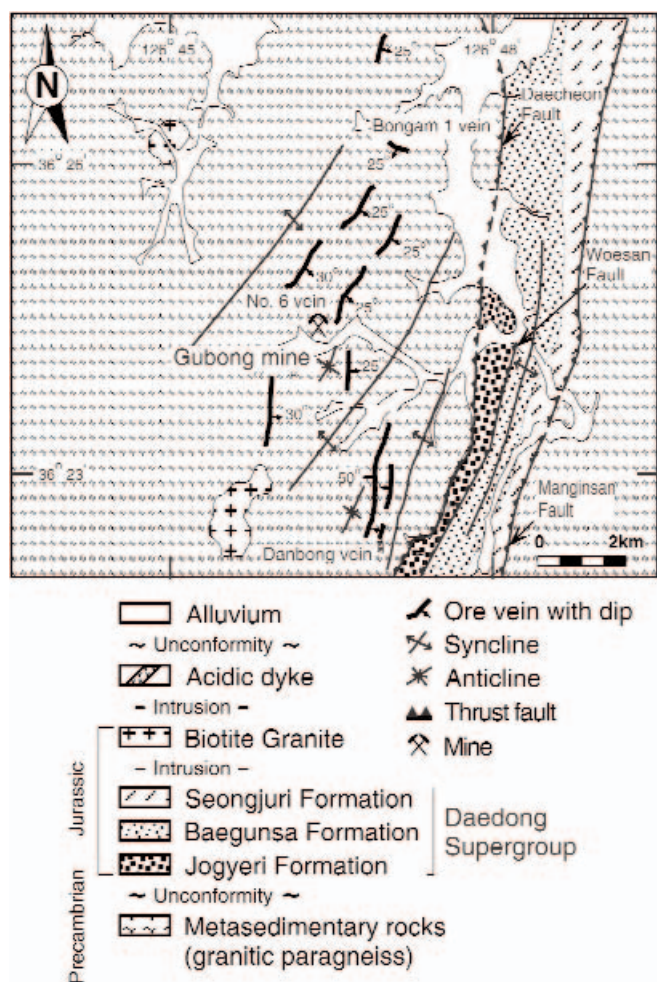


Fig. 2. Generalized geologic map of the Gubong mine, showing the orientation of the principal quartz veins.

metamorphic conditions to below about 300°C at some interval between 192 and 212 Ma and were subsequently subjected to localized heating above 300°C during the Middle-Late Jurassic and Cretaceous. Kwon et al. (1997) reported Permian to Cretaceous Rb-Sr biotite ages from the metasedimentary rocks and suggested that the massif may have been involved in continental collision during the early Jurassic (174–188 Ma). They suggested that the Gyeonggi massif had been uplifted rapidly, resulting in isothermal decompression of earlier formed amphibolite facies metasedimentary rocks. Serpentinite occurs along northeast-southwest-trending antichinal or synclinal axes in the Danbong vein area. It is composed of antigorite, chrysotile, and opaque minerals. Woo and Suh (2000) considered the serpentinite to be an Alpine type, which originated from upper mantle that had been emplaced into the crust along prominent fault zones. Serpentinization took place during greenschist and/or amphibolite facies regional metamorphism.

The Jurassic Daedong Supergroup, which unconformably overlies the Precambrian metasedimentary rocks, consists of sedimentary rocks and is distributed along a north-northeast trend east of the mine (Fig. 2). It consists of the Jogyeri, Baegunsu, and Seongjuri Formations. The Jogyeri Formation

contains breccia-bearing sandstone and conglomerate zones that are in faulted contact with the Precambrian banded gneiss. The breccia-bearing sandstone is very poorly sorted and is intercalated with black shale and sandstone. Its groundmass varies from fine to coarse, and clasts within it are mainly feldspar breccia with some black shale and quartzite. Minor sandstone and shale are included in the conglomerate zone. The conglomerate pebbles vary in size, are well rounded, and comprise quartzite and sandstone. The Baegunsu Formation is composed of sandstone, mudstone, and shale intercalated with conglomerate containing pebbles about 1 cm in diameter. The Seongjuri Formation consists of sandstone, siltstone, and shale intercalated with conglomerate and coal.

Jurassic granite intruded the Precambrian gneiss and consists of a small northeast-southwest-trending stock of biotite granite composed of quartz, orthoclase, plagioclase, microcline, biotite, sericite, and calcite. Tsusue et al. (1981) suggested that the Jurassic granite could have originated either by partial melting of lower crust or by partial crystallization of hornblende from quartz diorite magma. Hong (1987) argued in favor of formation by partial melting of lower crust metasedimentary rocks and considered the granite to belong to the ilmenite series.

Veins

The orebodies in the Gubong mine area consist of five lens-shaped, gold-bearing quartz veins that occupy faults and are locally both concordant and discordant with the foliation of the Precambrian gneiss. The quartz veins can be divided into three groups on the basis of their orientation and location: Danbong veins, No. 6 veins, and Bongam 1 vein (Fig. 2).

The Danbong veins consist of two parallel gold-bearing quartz veins that strike N 10° to 20° E and dip 40° to 60° NW. The veins can be followed for about 900 m along strike and extend to more than 130-m-vertical depth. They vary from 0.3 to 2.0 m in thickness and contain up to 33 g/t gold and 228 g/t silver. Neither of the two parallel, gold-bearing quartz veins that compose the No. 6 veins is continuous along strike. These two veins strike east-west to N 20° to 60° E and dip 20° to 50° S to 25° to 35° SE. The segments are about 400 to 500 m in strike length and extend to more than 600-m-vertical depth. They vary from 0.6 to 1.5 m in thickness and contain up to 80 g/t gold and from 5 to 229 g/t silver. Bongam 1 vein consists of one discordant gold-bearing quartz vein that is about 300 m in strike length, extends to over 100-m-vertical depth, and strikes N 50° to 70° W, dipping 25° W.

All the veins hosting gold mineralization in the Gubong mine are gray to white in color. Their widths are generally less than a meter and commonly vary over short distances both along strike and up- and down-dip. The variation in thickness is commonly the result of shear zones parallel to the vein margins, especially where faults cut the veins. The veins typically are laminated and up to a centimeter thick (Fig. 3A-F). In hand specimens, the laminations appear as dark gray or black planar zones separated by domains of pure white quartz. In the thinner veins, laminations are confined to the vein margins. Elongate, tabular fragments of country rocks are infrequently included in the veins, particularly close to the wall-rock contact. The extremities of these fragments commonly

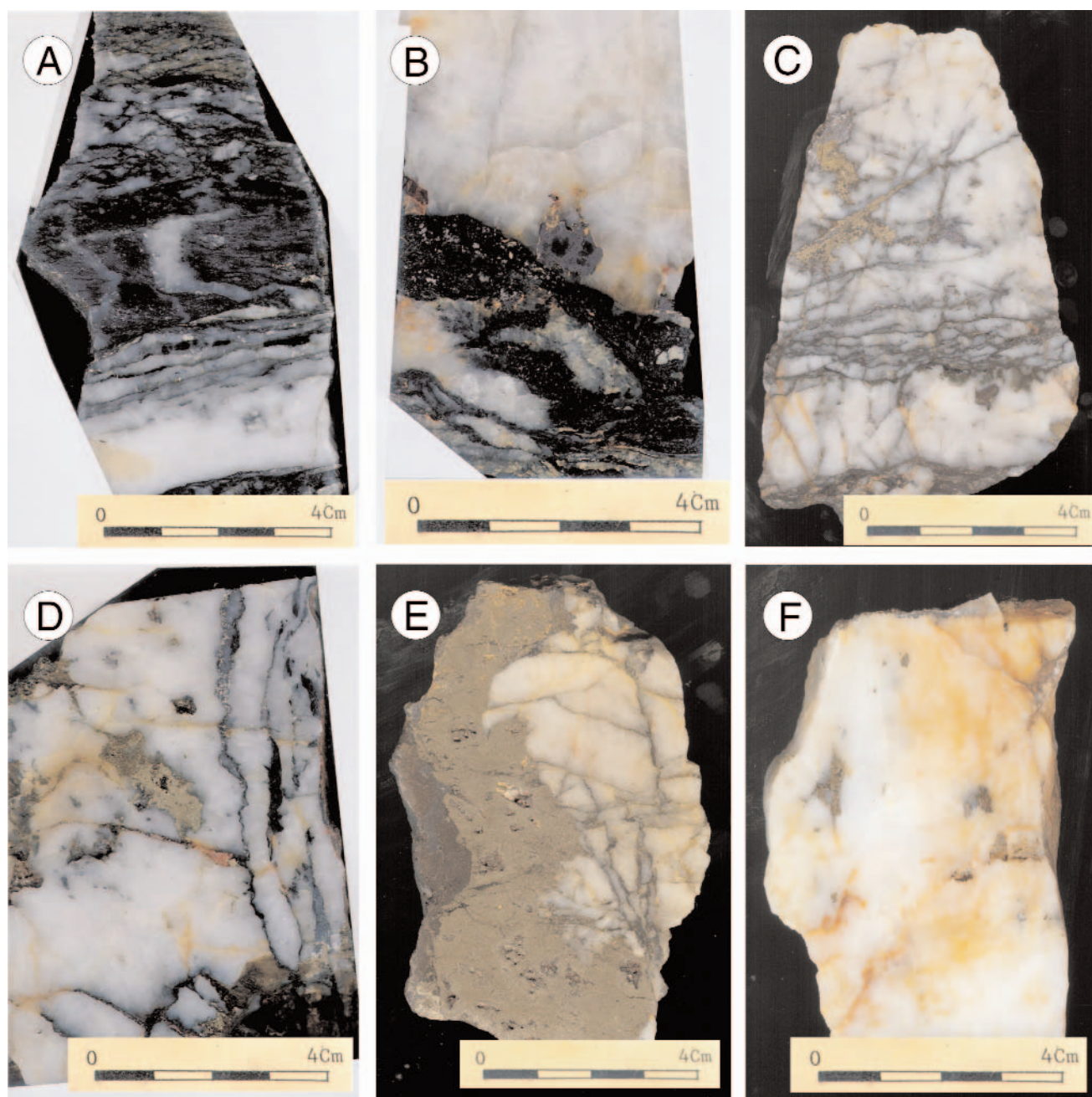


Fig. 3. Photographs of quartz vein samples from the Gubong mine. A. Laminations and elongate clasts of wall rock in quartz from the Danbong vein. B, C, and D. Laminations of wall rock and subgrain development that has fractured preexisting ore minerals and quartz in a No. 6 vein. E. Early massive quartz vein and fracture-filled ore minerals in the Danbong vein. F. Early massive quartz vein and seams of wall rock in the Bongam 1 vein.

display continuity with the laminations in the veins. The dark gray to black laminations consist of graphite with minor carbonates, biotite, and sulfides. The principal sulfides are arsenopyrite and pyrite, with sphalerite and galena also present. The veins are characterized by ribbon-banded quartz in which the sulfides are typically fractured, rotated, or attenuated, depending on whether their behavior has been ductile or brittle.

Laminations tend to be most concentrated where the vein walls are sheared. Adjacent to a vein margin, the laminations

are parallel to the vein margin and display continuity with mesoscopic fault planes parallel to the vein margins in the country rock.

Mineralogy and Paragenesis

Although the proportions of different minerals in the veins of the Gubong mine vary, the mineralogy of the veins is simple. At depth in the veins, pyrrhotite abundance increases and the abundance of galena, chalcopyrite, and ore grade decrease, but the mineralogy is uniform along strike.

Two stages of vein fill within the Danbong and No. 6 veins can be recognized, separated by a major faulting event. These are illustrated schematically in Figure 4. In the Bongam 1 vein, only one stage has been recognized. Quartz, sulfides, and economic concentrations of gold were deposited in the Danbong and No. 6 veins during stage I. During stage II, quartz, calcite, sulfides, and gold were precipitated in the Danbong veins, but, in the No. 6 veins, stage II deposition was confined to barren quartz and calcite.

Stage I veins consist mainly of white massive quartz associated with arsenopyrite, pyrite, sphalerite, galena, minor pyrrhotite, magnetite, chalcopyrite, marcasite, electrum, and argentite. Textural relationships indicate that at least one or two episodes of fracture opening and vein filling occurred during stage I. This stage began with the deposition of massive, gray to white quartz containing rare arsenopyrite, pyrite, sphalerite, magnetite, and pyrrhotite. Pyrite is the most abundant sulfide and occurs as coarse to fine grains or as cataclastic aggregates closely intergrown with arsenopyrite and sphalerite near vein margins. It also occurs as euhedral masses closely intergrown with other sulfides in vein centers. Arsenopyrite, the earliest sulfide, occurs as disseminated, coarse or fine grains near vein margins and as euhedral or anhedral masses that are closely intergrown with pyrite and sphalerite near vein centers. The arsenopyrite from these veins contains from 27.2 to 33.7 at. percent As (Danbong veins: 30.2–33.7 at. % As; No. 6 veins: 27.2–32.7 at. % As; Bongam 1 vein: 27.3–32.4 at. % As). Pyrrhotite occurs disseminated or as fine grains intergrown closely with pyrite and sphalerite near vein margins. Dark brown sphalerite is abundant and occurs as anhedral masses and as coarse to fine grains closely intergrown

with arsenopyrite, pyrite, chalcopyrite, and galena. The FeS contents of sphalerite range from 4.35 to 18.52 mol percent (Danbong veins: 5.23–18.52 mol % FeS; No. 6 veins: 4.35–15.95 mol % FeS; Bongam 1 vein: 11.47–14.75 mol % FeS), with the FeS content tending to decrease throughout the paragenetic sequence. Sphalerite contains high concentrations of cadmium (Danbong veins: <6.2 wt % Cd; No. 6 veins: <3.2 wt % Cd; Bongam 1 vein: <2.3 wt % Cd). Rare marcasite occurs as irregular masses intimately intergrown with earlier pyrite.

Stage I sulfide minerals were deposited mainly after fracturing of the first generation of vein quartz. Early arsenopyrite, pyrite, and sphalerite are also intensely fractured and healed by later pyrite, sphalerite, chalcopyrite, and galena. Chalcopyrite occurs within microfractures in arsenopyrite, pyrite, and sphalerite and is infrequently intergrown with sphalerite. Galena is intimately intergrown with chalcopyrite and sphalerite and also fills microfractures in arsenopyrite, pyrite, and sphalerite. Gold is present as native gold and electrum and was recognized only in the Danbong and No. 6 veins in this study, where it is microscopic. It is commonly intergrown intimately with both early and late arsenopyrite, pyrite, and sphalerite, but it also occurs alone in quartz grains. It is also present as irregular and/or subrounded grains, commonly associated with chalcopyrite and galena. In the Danbong veins, 3.8 modal percent of gold is associated with pyrite, 8.0 percent is associated with sphalerite, 22.6 percent is associated with galena, and 65.6 percent occurs as free gold in quartz. In the No. 6 veins, 12.6 percent of gold is associated with pyrite, 5.1 percent is associated with sphalerite, 11.0 percent is associated with galena, 24.3 percent occurs as free gold in quartz, 2.5 percent is associated with chalcopyrite, and 44.5

Minerals	Danbong vein			No. 6 vein			Bongam 1 vein	
	Stage I		Stage II	Stage I		Stage II	Stage I	
	Gray/White	Transparent gray		Gray/White	Transparent gray		Gray/White	Transparent gray
Quartz								
Chlorite	—	—		—	—		—	—
Sericite	—	—		—	—		—	—
Epidote	—	—		—	—		—	—
Rutile	—	—		—	—		—	—
Magnetite	—	—		—	—		—	—
Ilmenite	—	—		—	—		—	—
Arsenopyrite	—	—	Fault	—	—	Fault	—	—
Pyrrhotite	—	—		—	—		—	—
Pyrite	—	—		—	—		—	—
Marcasite	—	—		—	—		—	—
Sphalerite	—	—		—	—		—	—
Chalcopyrite	—	—		—	—		—	—
Galena	—	—		—	—		—	—
Electrum	—	—		—	—		—	—
Argentite	—	—		—	—		—	—
Calcite	—	—		—	—		—	—

Fig. 4. Paragenetic sequence of minerals from the Danbong, No. 6, and Bongam 1 veins in the Gubong mine.

percent is associated with arsenopyrite. Gold grains range from <30 to $>177\ \mu\text{m}$ in their largest dimension. The grains contain 36.6 to 81.4 at. percent Au in the Danbong veins and 26.4 to 72.5 at. percent Au in the No. 6 veins. The Au content of electrum decreases toward the No. 6 veins from the Danbong veins and throughout the paragenetic sequence.

Stage II in the Danbong veins corresponds to the introduction of transparent quartz, massive and/or rhombohedral calcite, pyrite, sphalerite, chalcocopyrite, galena, and gold. Stage II in the No. 6 veins consists of barren quartz. Stage II sphalerite in the Danbong veins contains from 5.8 to 8.5 mol percent FeS and <3.5 wt percent Cd. The gold composition of electrum ranges from 52.6 to 62.1 at. percent Au.

Fluid Inclusion Studies

Fluid inclusions in gray, white, and transparent samples of both stage I and stage II quartz and calcite from the Danbong, No. 6, and Bongam 1 veins were investigated by microthermometry. The lack of growth zonation in the quartz makes it difficult to classify fluid inclusions as primary, pseudosecondary, or secondary in veins that have undergone multiple intracrystalline deformations and fracturing, but the relative timing and trapping history of the inclusions can be estimated using usual criteria (Roedder, 1984). Microthermometric data were obtained on a Linkam THMSG 600 and Fluid Inc. gas flow-type heating-freezing stage attached to a Nikon transmitted light microscope and calibrated with synthetic H_2O and CO_2 inclusions. Heating rates were maintained near $2^\circ\text{C}/\text{min}$ for measurements of

total homogenization temperatures ($T_{\text{h}(\text{total})}$). Many inclusions decrepitated upon heating, and their decrepitation temperatures have been taken to represent a minimum value for $T_{\text{h}(\text{total})}$. During freezing experiments, a sequential freezing technique was employed (Haynes, 1985). The $T_{\text{h}(\text{total})}$ values and homogenization temperatures of the $\text{CO}_2 + \text{CH}_4$ carbonic phase ($T_{\text{h}(\text{CO}_2)}$) have standard errors of $\pm 0.5^\circ\text{C}$.

Fluid inclusion petrography

The quartz samples contain only a very small amount of gold, and fluid inclusions and gold have not been found in physical contact. Rather, all quartz examined in this study was intergrown intimately with sulfides. It is assumed, therefore, that such quartz was deposited during the same mineralization event as the sulfides, which are assumed to have been coeval with the gold.

Approximately 50 doubly polished sections ($30\ \mu\text{m}$ thick) were prepared from both stages of quartz and calcite. Unfortunately, no suitable fluid inclusions were found in quartz from stage II of the No. 6 veins. The massive white quartz samples proved to be inclusion rich, probably owing to repeated fracturing and healing. Leakage and decrepitation were common features among the inclusions of all samples, indicating that deformation continued after many of the secondary inclusions had been trapped.

Fluid inclusions in quartz and calcite samples from stage I and stage II veins consist of three compositional types. In order of decreasing abundance these are: aqueous-carbonic, carbonic, and aqueous inclusions (Fig. 5). The various types

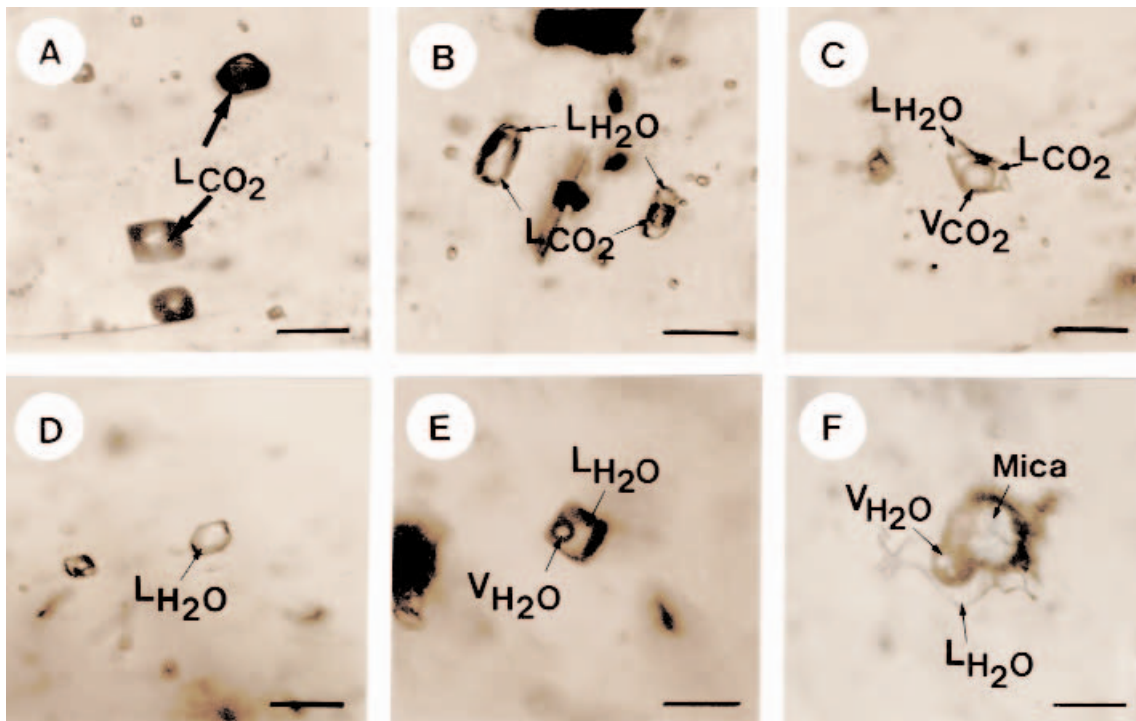


Fig. 5. Photomicrographs of representative types of fluid inclusions in quartz and calcite from both stage I and stage II veins of the Gubong mine. A. Type I inclusion in stage I white quartz. B. Type IIa inclusion in stage I white quartz. C. Type IIb inclusion in stage I white quartz. D. Type IIIa inclusion in stage I and stage II white and transparent quartz and calcite. E. Type IIIb inclusion in stage I and stage II white and transparent quartz and calcite. F. Type IIIc inclusion in stage II transparent quartz from the Danbong vein. Scale bar is $20\ \mu\text{m}$ in length.

of inclusions were distinguished on the basis of their appearance at room temperature (25°C), combined with their cooling behavior down to about -50°C and their low-temperature response on heating to about +32°C. The carbonic inclusions were recognized by their lack of clathrate formation during cooling. Three primary fluid inclusion assemblages using the criteria of Roedder (1984) were defined on the basis of their appearance at room temperature and the quartz phase in which they were hosted, crosscutting relationships, and optical microthermometric properties (Roedder, 1984).

Type I inclusions are carbonic and occur in quartz from stage I of the Danbong, No. 6, and Bongam 1 veins. These inclusions range in size from <2 to 144 μm and consist of a single phase (liquid CO_2 or vapor CO_2) at room temperature. No visible liquid water was found in these inclusions. They commonly have negative crystal shapes (Fig. 5A) and are distributed in clusters with aqueous-carbonic inclusions. They are considered to be primary in origin.

Type II inclusions are aqueous-carbonic inclusions that occur in stage I quartz from the Danbong, No. 6, and Bongam 1 veins. They range in diameter from <2 to 56 μm and most commonly are 13 to 25 μm . They are the most abundant of the three types of inclusions, making up more than 75 percent of all primary inclusions. At room temperature, type II inclusions consist of two phases (liquid water + liquid CO_2 = type IIa) or in some cases three (liquid water + liquid CO_2 + vapor CO_2 = type IIb; Fig. 5B-C). Type IIb inclusions occur only in quartz from the Danbong and No. 6 veins. Type II inclusions occur as negative crystals or as subrounded or elongate shapes in three-dimensional clusters that are generally confined to individual quartz grains. They are considered to be both primary and pseudosecondary. Their CO_2 volumetric proportion ranges from 5 to 90 percent, with most having from 35 to 60 vol percent CO_2 . Diamond (1990, 2001) classified aqueous-carbonic inclusions into low X_{CO_2} inclusions consisting of 15 to 25 vol percent carbonic liquid, high X_{CO_2} inclusions consisting of 85 to 95 vol percent carbonic liquid, and variable X_{CO_2} inclusions containing from 15 to 85 vol percent carbonic liquid. Accordingly, type II inclusions from the these veins are of the variable X_{CO_2} type.

Type III inclusions are aqueous inclusions and occur in a variety of different associations in both quartz and calcite of both stage I and stage II veins from Danbong, No. 6, and Bongam 1. Typical associations include trails along healed fractures, isolated inclusions, and coexistence with type II inclusions. Aqueous inclusions along healed fractures that cut across different quartz grains are common. At room temperature, aqueous inclusions consist of one (liquid water, type IIIa), two (liquid water + vapor water, type IIIb), or three (liquid water + vapor water + mica, type IIIc) phases (Fig. 5D-F). Type IIIa inclusions occur only in quartz and calcite from the Danbong vein. These inclusions range from 1 to 80 μm along their longest diameter with common values in the range 17 to 25 μm . They typically have irregular, elongate, or tabular shapes and are considered secondary in origin as a result of apparent necking down. Isolated aqueous inclusions or those coexisting with type II inclusions are rare but possess negative crystal or round shapes. Such inclusions range from 2 to 28 μm in diameter and are interpreted as primary. Their volumetric

proportion of water vapor calculated from the equation of Bodnar (1983) ranges from 2 to 48 percent.

Fluid inclusion microthermometry

More than 700 fluid inclusions in quartz and calcite were examined, but, as a result of their small size and the decrepitation of many on heating, only about one-third of the inclusions yielded both freezing and homogenization data; freezing experiments were performed first on all sections. Fluid salinities were estimated from clathrate melting temperatures ($T_{\text{m}(\text{clathrate})}$) for type II inclusions corrected for the effect of CH_4 (Brown, 1989; Darling, 1991; Ridley and Hagemann, 1999) and from the final melting temperature of ice ($T_{\text{m}(\text{ice})}$) in the system $\text{H}_2\text{O}-\text{NaCl}$ for type III inclusions (Brown, 1989; Davis et al., 1990). The final melting temperature of CO_2 ($T_{\text{m}(\text{CO}_2)}$) was also measured to evaluate the purity of the CO_2 phase. Attempts were made to measure the homogenization temperature of the CO_2 ($T_{\text{h}(\text{CO}_2)}$) during heating, in order to ascertain the density of CO_2 and the total homogenization temperature ($T_{\text{h}(\text{total})}$).

Type I inclusions in stage I veins: During cooling to -180°C, a vapor bubble nucleated at temperatures from -127° to -92°C. On reheating, $T_{\text{m}(\text{CO}_2)}$ for type I inclusions fell within the range -67.2° to -56.2°C for the Danbong vein, -62° to -57°C for the No. 6 vein, and -63.1° to -58.3°C for the Bongam 1 vein (Table 1), indicating that small concentrations of other gases were probably present (Fig. 6; Burruss, 1981). The homogenization temperatures of CO_2 in the type I inclusions into liquid ($T_{\text{h}(\text{CO}_2)(\text{l})}$) ranged from -65.2° to +28.4°C (Danbong vein: -65.2° to +14.6°C to a liquid; No. 6 vein: +2.2° to +28.4°C; Bongam 1 vein: -9.9° to +16.2°C) and into vapor ($T_{\text{h}(\text{CO}_2)(\text{v})}$), from -1.3° to +26.3°C (No. 6 vein: -1.3° to +26.3°C; Bongam 1 vein: +1.3° to +13.5°C; Table 1). The carbonic-phase molar volume of type I inclusions lie within a wide (Danbong vein) or narrow (No. 6 and Bongam 1 veins) range from about 25 to 70 cm^3 , irrespective of X_{CH_4} . No clathrate formation was noted during the freezing of type I inclusions, and no melting of such compounds was observed during subsequent heating. Some inclusions from the Danbong vein exhibit the same phase behavior as described in the CO_2 - CH_4 - N_2 system by Van Den Kerkhof (1990) and Van Den Kerkhof and Thiery (1994). For example, type H4 phase behavior in the CO_2 - CH_4 - N_2 system involves solid (s) + liquid (l) + vapor (v) $\rightarrow$ partial homogenization into liquid ($T_{\text{h}(\text{s})(\text{v})}$) at -98.9°C, solid (s) + liquid (l) $\rightarrow$ initial melting into vapor ($T_{\text{i}}(\text{v})$) at -65.9°C, solid (s) + liquid (l) + vapor (v) $\rightarrow$ final melting of solid (T_{m}) at -64.8°C, liquid (l) + vapor (v) $\rightarrow$ homogenization into liquid ($T_{\text{h}}(\text{l})$) at -58.5°C. Type S2 behavior involves solid (s) + liquid (l) + vapor (v) $\rightarrow$ partial homogenization into liquid ($T_{\text{h}(\text{s})(\text{v})}$) at -103.3°C, solid (s) + liquid (l) $\rightarrow$ sublimation of solid ($T_{\text{s}}(\text{l})$) at -66°C. These phase changes indicate that some type I inclusions from the Danbong vein contain N_2 in addition to CO_2 .

Type II inclusions in stage I veins: Upon cooling, an initial vapor bubble nucleated in the CO_2 phase within the temperature range -121° to -93°C. The final melting temperature of the CO_2 phase lay within the range -63.7° to -56.2°C (type IIa = Danbong vein: -62° to -56.2°C; No. 6 vein: -63.2° to -56.2°C; Bongam 1 vein: -63.7° to -58°C, type IIb = Danbong vein: -57.8° to -56.4°C; No. 6 vein: -57.4° to -56.6°C;

TABLE 1. Summary of Microthermometric Data for Measured Fluid Inclusions from the Gubong Mine

Inclusion type	Type I			Type IIa			Type IIb			Type IIIa			Type IIIb			Type IIIc
	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	
Vein	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong	No. 6	Bongam 1	Danbong
Stage	I	I	I	I	I	I	I	I	I	I	I	I	II	I	I	II
Vol % CO ₂	100	100	100	5 to 90	10 to 85	20 to 80	15 to 90	10 to 80	10 to 80	I	I	I	II	I	I	II
$T_{m(CO_2)}(^{\circ}C)^1$	-67.2 to -56.2	-62 to -57	-63.1 to -58.3	-62 to -56.2	-63.2 to -56.2	-63.7 to -58	-57.8 to -56.4	-57.4 to -56.6	-57.4 to -56.6	-2.2 to -0.3	-6.2 to 0	-2.5 to 0	-13.7 to -1.3	-13.4 to 0	-13.7 to -1.3	-0.8 to -0.2
$T_{m(clathrate)}(^{\circ}C)^2$				1.9 to 12.1	3.2 to 10.2	3.5 to 9.4	7.9 to 9.4	4.2 to 8.9	4.2 to 8.9							
$T_{h(CO_2)}(^{\circ}C)^3$																
$T_{h(CO_2)}(^{\circ}C)$	-65.2 to 14.6	-1.3 to 28.4	-9.9 to 16.2	-13.2 to 24.9	-16.4 to 24.9	7.6 to 21.2	25.3 to 27	25.2 to 28.4	25.2 to 28.4							
$T_{h(CO_2)}(^{\circ}C)^4$	-65.2 to 14.6	2.2 to 28.4	-9.9 to 16.2	-13.2 to 24.9	-16.4 to 24.9	7.6 to 18.8	25.3 to 27	25.2 to 28.4	25.2 to 28.4							
$T_{h(CO_2)}(^{\circ}C)^5$	-1.3 to 26.3	1.3 to 13.5		2.4 to 24.5	10.5 to 21.1		240 to 320	272 to 349	272 to 349							
$T_{h(ice)}(^{\circ}C)$				203 to 388	257 to 432	244 to 384	240 to 320	272 to 349	272 to 349							
$T_{h(ice)}(^{\circ}C)^6$				203 to 388	257 to 432	244 to 384	240 to 320	272 to 349	272 to 349							
$T_{h(ice)}(^{\circ}C)^7$				258 to 322	263 to 386	320 to 364	240 to 320	305 to 336	305 to 336							

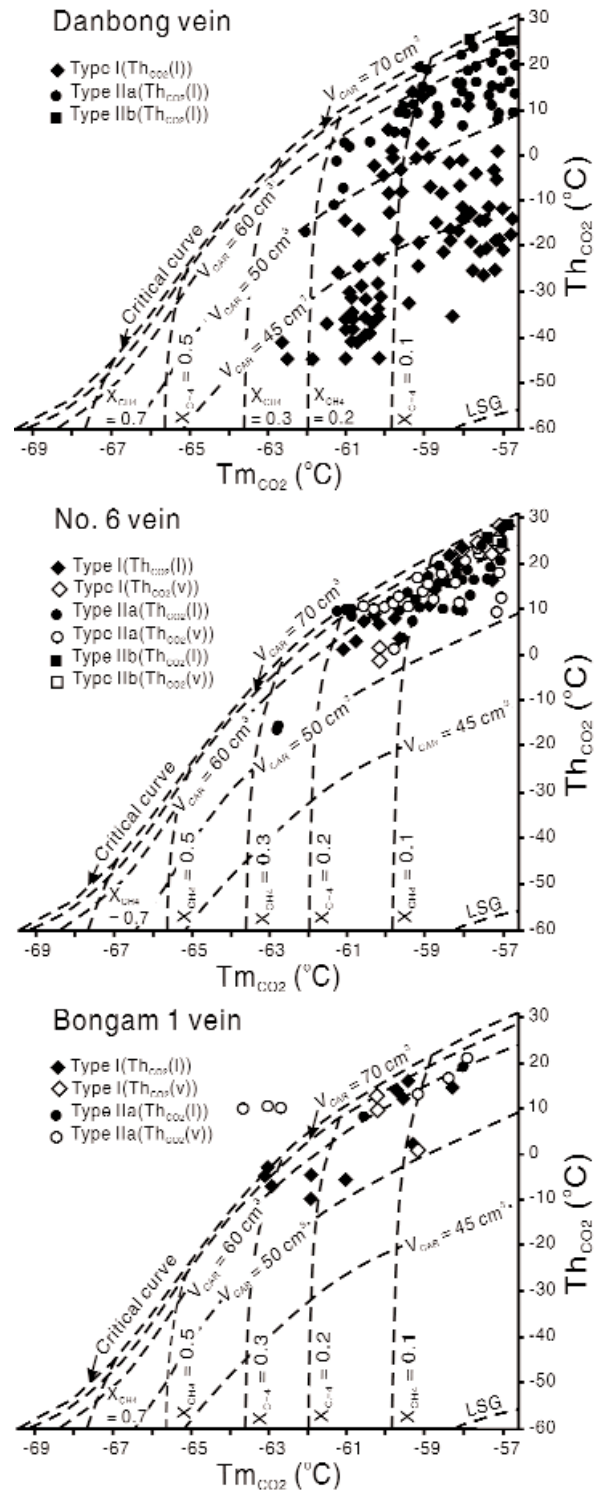
¹ Final melting temperature CO₂ in the type I, IIa, and IIb inclusions² Final melting temperature clathrate in the type IIa and IIb inclusions³ Final melting temperature ice in the type IIIa, IIIb, and IIIc inclusions⁴ CO₂ in the type I, IIa, and IIb inclusions homogenized to liquid⁵ CO₂ in the type I, IIa, and IIb inclusions homogenized to vapor⁶ Total homogenization temperature of type IIa, IIb, IIIb, and IIIc inclusions homogenized to aqueous phase⁷ Total homogenization temperature of type IIa, IIb, IIIb, and IIIc inclusions homogenized to CO₂ phase

Fig. 6. Final melting temperature of CO₂ ($T_{m(CO_2)}$) vs. homogenization temperature of CO₂ ($T_{h(CO_2)}$) of type I, IIa, and IIb inclusions at the Danbong, No. 6, and Bongam 1 veins. Contours of mole fraction of CH₄ (X_{CH_4}) and molar volume of carbonic phase (V_{CAR}), critical curve, and liquid-solid-gas (LSG) univariant curve constructed assuming homogenization to the liquid from figures in Thiery et al. (1994) and Ridley and Hagemann (1999). Note type I inclusions have lower $T_{m(CO_2)}$ and $T_{h(CO_2)}$ values than type II, reflecting higher contents of CH₄, and in some cases, high density with no CH₄. Also note the clustering by composition and molar volume, and relatively narrow range of V_{CAR} (No. 6 and Bongam 1 veins).

Table 1). The $T_{h(CO_2)}$ of type II inclusions homogenized to a liquid ($T_{h(CO_2)(l)}$) or vapor ($T_{h(CO_2)(v)}$) range from -16.4° to $+24.9^\circ\text{C}$ for type IIa inclusions ($T_{h(CO_2)(l)}$, -16.4° to $+24.9^\circ\text{C}$; $T_{h(CO_2)(v)}$, -1.3° to $+24.5^\circ\text{C}$) and from 25.2° to 28.4°C for type IIb inclusions ($T_{h(CO_2)(l)}$, 25.2° – 28.4°C ; $T_{h(CO_2)(v)}$, 25.8° – 28.4°C ; Table 1). Type IIb inclusions yielded higher $T_{m(CO_2)}$ and $T_{h(CO_2)}$ values than did type IIa inclusions (Fig. 6). The ranges of $T_{m(\text{clathrate})}$ values for type IIa and type IIb inclusions are 1.9° to 12.1° and 4.2° to 9.4°C , respectively (Table 1). Using the equations of Brown (1989) and Darling (1991), and the graph of Ridley and Hagemann (1999), the salinities of these veins have less than about 13.4 wt percent NaCl within the aqueous phase because of CH_4 or N_2 (Fig. 7). Collins (1979) suggested that $T_{m(\text{clathrate})}$ values of $>10^\circ\text{C}$ for $\text{H}_2\text{O}-\text{CO}_2$ inclusions indicate the presence of minor amounts of other volatiles such as CH_4 or N_2 . Type II inclusions generally decrepitate before total homogenization owing to high internal pressures arising from their high CO_2 contents (Burruss, 1981). However, about 120 $T_{h(\text{total})}$ values were recorded from negative crystal or regular shaped inclusions by slow heating. When decrepitation occurred, the decrepitation temperature was taken as the minimum value of $T_{h(\text{total})}$. Type II inclusions mostly homogenized to the aqueous phase between 203° and 432°C (type IIa, 203° – 432°C ; Type IIb, 272° – 349°C) and partly to the CO_2 phase between 240° and 349°C (type IIa, 263° – 386°C ; type IIb, 240° – 336°C ; Fig. 8). So et al. (1988) recorded 264° to 324°C of CO_2 - H_2O inclusions in the Samgwang deposits which are located at 11 km apart northeast from this deposit, Cheongyang gold district.

Type III inclusions in stage I veins: Measurements of initial ice melting for type III inclusions are -26.6° to -15.7°C (type IIIb = Danbong vein: -25.7° to -23.8°C ; No. 6 vein: -26.6° to -15.7°C ; Bongam 1 vein: -24.2° to -23.1°C), indicating a dominance of NaCl and KCl and low contents of divalent cations among the dissolved salts (Davis et al., 1990). The $T_{m(\text{ice})}$ values range from -13.4° to -2.3°C (type IIIb) for primary inclusions and from -13.7° to 0°C (type IIIa, -2.2° to -0.3°C , type IIIb, -13.7° to 0°C) for secondary inclusions (Table 1). Using the computer program of Brown (1989) and equations of Davis et al. (1990), the salinities are estimated to be 3.9 to 17.3 wt percent NaCl for primary inclusions and within 0 to 17.5 wt percent NaCl (type IIIa, 0.5–3.7 wt % NaCl, type IIIb, 0–17.5 wt % NaCl) for secondary inclusions. The $T_{h(\text{total})}$ values of type III inclusions in stage I quartz are between 130° and 399°C for the liquid phase (Table 1). Some type III inclusions occur along healed fractures parallel to gold-bearing sulfide veinlets cutting gray to white massive quartz; it is noteworthy that these inclusions have $T_{h(\text{total})}$ values between 202° and 399°C (Danbong vein: 202° – 361°C ; No. 6 vein: 203° – 350°C ; Bongam 1 vein: 316° – 399°C ; Fig. 8). Some type III inclusions homogenized initially to a liquid phase and then formed a new phase that finally homogenized to vapor upon heating. This phenomenon could be the result of partial decrepitation or can be explained by the formation of a new phase of <10 vol percent by unmixing from the liquid phase upon heating (Roedder, 1984).

Type III inclusions in stage II veins: These inclusions in transparent quartz and calcite from the Danbong vein have $T_{m(\text{ice})}$ values from -2.5° to -0.2°C (type IIIb, -2.5° to -0.2°C ; type IIIc, -0.8° to -0.2°C ; Table 1) for primary inclusions and

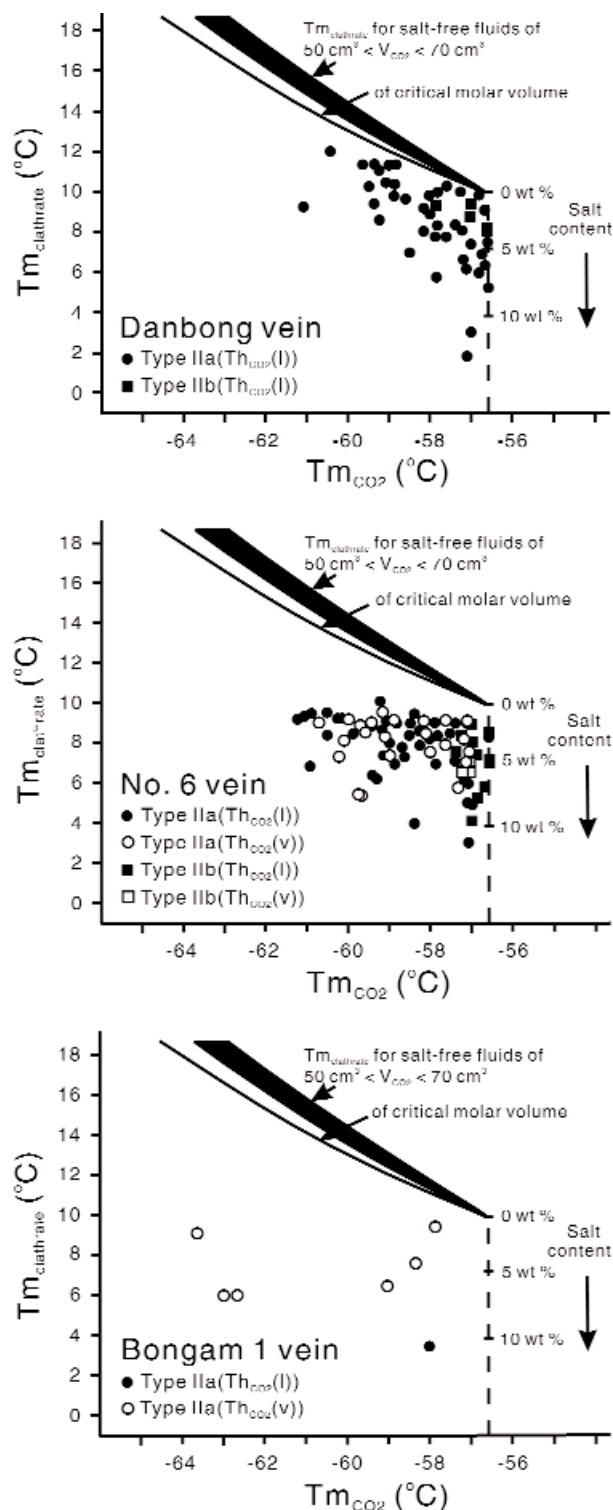


Fig. 7. Final melting temperature of clathrate ($T_{m(\text{clathrate})}$) vs. final melting temperature of CO_2 ($T_{m(\text{CO}_2)}$) of type IIa and IIb inclusions at the Danbong, No. 6, and Bongam 1 veins. The shaded area shows final melting temperature of clathrate and final melting temperature of CO_2 of salt-free $\text{H}_2\text{O}-\text{CO}_2-\text{CH}_4$ mixtures with carbonic molar volumes of the range shown from data in Seitz and Pasteris (1990). The Q_2 invariant clathrate melting point for the $\text{H}_2\text{O}-\text{CO}_2$ -NaCl system is after Diamond (1994). Note the clustering by sample with salinities of less than about 10 wt percent NaCl equiv and the wide range of $T_{m(\text{CO}_2)}$, indicating the presence of variable amounts of CH_4 .

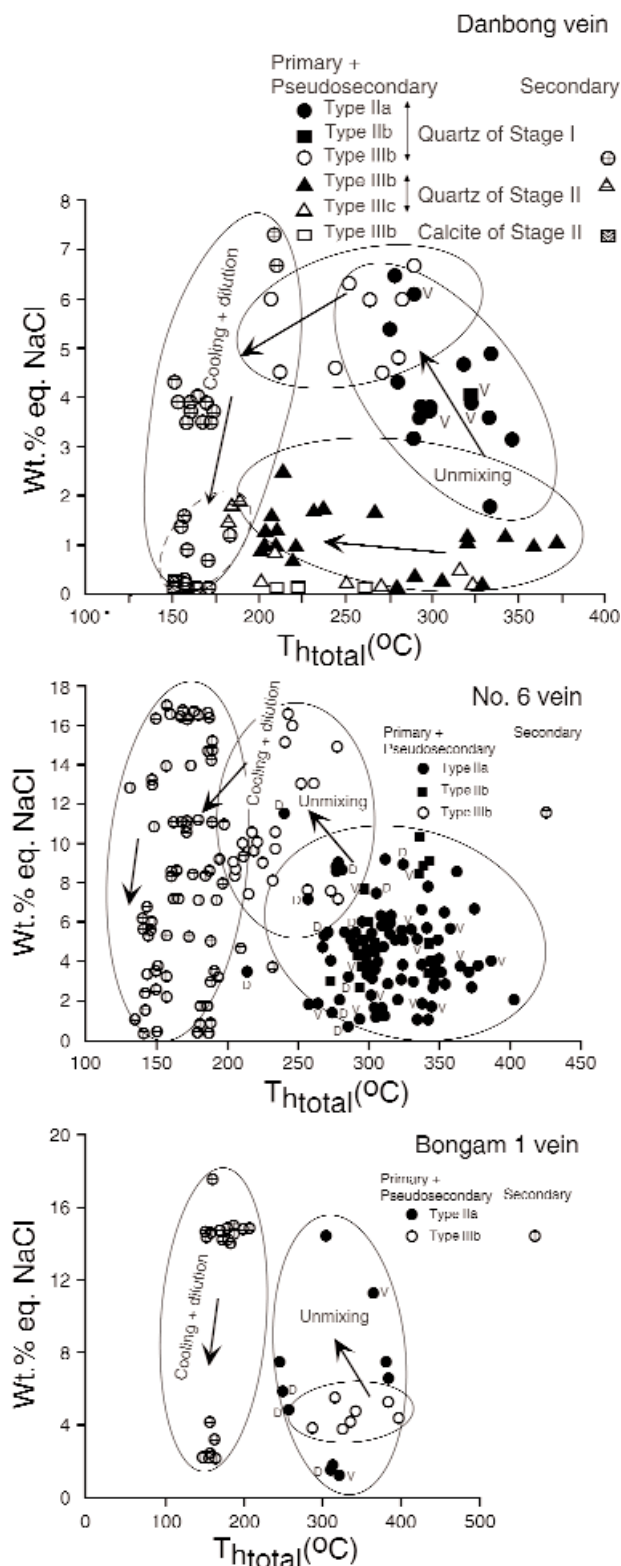


Fig. 8. Salinity vs. homogenization temperature diagram for fluid inclusions in stage I and stage II vein quartz and calcite from the Danbong, No. 6, and Bongam 1 veins. D = decrepitation temperature. V = homogenization temperature of type II inclusions. Circles enclose inclusions of the same type and letter indicates evolution of hydrothermal fluids. Type II inclusions represent unmixing of a low-salinity $\text{H}_2\text{O}-\text{CO}_2$ fluid, but type III inclusions are later inclusions with variable salinities.

from -0.7° to 0°C (type IIIb) for secondary inclusions, with corresponding salinities in the ranges of 0.4 to 4.2 and 0 to 1.2 wt percent NaCl, respectively (Fig. 8). They all homogenized into a liquid phase at temperatures ranging from 201° to 378°C (type IIIb, 201° – 378°C ; type IIIc, 201° – 323°C ; Table 1) for primary inclusions and from 151° to 208°C for secondary inclusions (Fig. 8).

Stable Isotope Studies

We measured the sulfur isotope compositions of sulfide minerals, the oxygen isotope compositions of quartz, and the hydrogen isotope compositions of inclusion waters. Standard techniques of extraction and analysis were used as described by Hall and Friedman (1963). Data are reported in standard δ notation relative to the Canyon Diablo troilite (CDT) standard for S and the Vienna SMOW for O and H. The standard errors of each analysis are approximately ± 0.1 per mil for S and O, and ± 2 per mil for H.

Sulfur isotope data

Sulfur isotope analyses were performed on 51 monomineralic samples from the Danbong, No. 6, and Bongam 1 veins (Table 2). The $\delta^{34}\text{S}$ values are similar among the same sulfide minerals in each of the veins: 4.7 to 9.4 per mil for pyrite, 5.8 per mil for pyrrhotite, 4.6 to 9.5 per mil for sphalerite, 6.4 to 8.4 per mil for chalcocopyrite, and 3.9 to 8.6 per mil for galena. Spatial or vertical covariation of $\delta^{34}\text{S}$ values with homogenization temperature was not observed (Table 2). Sphalerite-galena and chalcocopyrite-galena pairs that exhibited textures consistent with coprecipitation have $\Delta^{34}\text{S}$ values of 1.9 to 2.7 and 2.1 per mil, respectively, and yield equilibration isotopic temperatures of 245° to $343^\circ \pm 21^\circ\text{C}$ and $285^\circ \pm 6^\circ\text{C}$, respectively (Kajiwara and Krouse, 1971; Ohmoto and Rye, 1979), in agreement with the fluid inclusion homogenization temperatures in associated quartz. The presence of pyrrhotite and the alteration assemblage quartz + sericite indicates that sulfur was present in the hydrothermal fluids mainly as reduced sulfur (H_2S). Assuming depositional temperatures from 250° to 350°C , based on fluid inclusion and paragenetic constraints, the $\delta^{34}\text{S}$ values of H_2S in the hydrothermal fluids were calculated following Ohmoto and Rye (1979) and are listed in Table 2. The $\delta^{34}\text{S}$ values of H_2S generally increase from the Danbong veins toward the Bongam 1 vein, and we interpret this range in calculated $\delta^{34}\text{S}_{\text{H}_2\text{S}}$ values to indicate two distinct sources of sulfur in the hydrothermal fluids: light sulfur with a $\delta^{34}\text{S}$ value of <4.0 per mil, which was probably derived from a subjacent granitic melt (e.g., with $\delta^{34}\text{S}$ value of 2–5‰; So et al., 1988), and heavier sulfur with a $\delta^{34}\text{S} > 8.0$ per mil, probably derived from the local metasedimentary rocks (Shelton et al., 1988).

Oxygen and hydrogen isotope data

The $\delta^{18}\text{O}$ values of one gray and 22 white quartz samples from stage I of the Danbong, No. 6, and Bongam 1 veins range from 6.4 to 14.8 per mil (Danbong veins: 6.4–14.8‰; No. 6 veins: 8.4–14.3‰; Bongam 1 vein: 10.0–12.5‰). The values from two transparent quartz specimens from stage II of a Danbong vein are 8.8 to 9.2 per mil (Table 3). No spatial or vertical variation in $\delta^{18}\text{O}$ values was observed. Using the quartz-water isotope fractionation equation of Matsuhisa et

TABLE 2. Sulfur Isotope Data of Sulfide Minerals from the Gubong Mine

Vein	Stage	Sample no.	Sea level	Min.	$\delta^{34}\text{S}$ (‰)	$\delta^{34}\text{S}_{\text{H}_2\text{S}}$ (‰) ¹	$\Delta^{34}\text{S}$	T (°C) ²
Danbong	I	D.B.100-2	+100 m	Py	9.4	7.9		
	I	D.B.100-2	+100 m	Sp	5.8	5.4		
	I	D.B.100-2	+100 m	Gn	5.3	7.6		
	I	D.B.100-9	+100 m	Py	8.2	6.7		
	I	D.B.100-9	+100 m	Sp	6.1	5.7		
	I	D.B.100-9	+100 m	Gn	4.8	7.1		
	I	D.B.100-12	+100 m	Sp	6.0	5.7		
	I	D.B.100-12	+100 m	Gn	4.8	6.7		
	I	D.B.910121-6	+130 m	Sp	6.1	5.8		
	I	D.B.910121-6	+130 m	Gn	5.0	6.9		
	I	D.B.910121-10	+130 m	Po	5.8	5.5		
	I	D.B.910121-10	+130 m	Py	4.7	3.5		
	I	D.B.910121-10	+130 m	Gn	3.9	5.8		
	I	D.B.890427-4	+150 m	Py	5.9	4.9		
	I	D.B.890427-4	+150 m	Sp	4.6	4.3		
	I	D.B.890427-4	+150 m	Gn	5.1	7.0		
	I	D.B.910122-6	+150 m	Sp	6.4	6.1		
	I	D.B.910122-6	+150 m	Gn	5.2	7.1		
	I	D.B.910122-16	+150 m	Py	6.2	5.0		
	I	D.B.910122-16	+150 m	Sp	4.8	4.5		
		DB-03 ³		Py	6.8			
		DB-03 ³		Sp	6.6		Sp-Gn	
		DB-03 ³		Gn	3.9		2.7	245
		DB-21 ³		Cp	5.6			
		DB-21 ³		Sp	6.0		Sp-Gn	
		DB-21 ³		Gn	4.1		1.9	343
No. 6	I	D.S.97126-14		Sp	8.0	7.7		
	I	D.S.97126-14		Gn	6.7	8.6		
	I	D.S.97126-20		Sp	8.5	8.3		
	I	D.S.97126-20		Cp	7.4	7.6		
	I	D.S.97126-20		Gn	7.1	8.0		
	I	D.S.97126-7		Sp	7.3	7.1		
	I	D.S.97126-7		Gn	5.9	7.8		
	I	D.S.97126-21		Sp	5.2	4.9		
	I	D.S.97126-22		Cp	6.4	6.6		
	I	B.A.97724-3-1		Sp	9.5	9.2		
	I	B.A.97724-3-1		Cp	7.3	7.5		
	I	B.A.9827-10		Py	8.6	7.1		
	I	B.A.9827-10		Sp	6.9	6.5		
	I	B.A.9827-10		Cp	6.5	6.7		
	I	B.A.9827-10		Gn	5.3	7.6		
	I	B.A.9827-11		Py	8.3	6.8		
	I	B.A.9827-11		Gn	6.7	9.0		
	I	G.R.9827-8		Sp	8.4	8.1	Sp-Gn	
	I	G.R.9827-8		Gn	6.4	8.3	2.0	319
	I	G.R.9827-10		Py	8.6	7.6		
	I	G.R.9827-10		Sp	8.0	7.7		
	I	G.R.9827-10		Gn	6.8	8.7		
	I	G.R.97724-5-3		Py	7.8	6.8		
	I	G.R.97724-5-3		Gn	8.6	10.5		
	I	G.R.97724-5-5		Sp	7.8	7.5		
	I	G.R.97724-5-5		Cp	8.4	8.6	Cp-Gn	
	I	G.R.97724-5-5		Gn	6.3	8.2	2.1	285
Bongam 1	I	B.A.97724-5		Sp	8.0	7.7	Sp-Gn	
	I	B.A.97724-5		Gn	6.1	7.7	1.9	338
	I	B.A.9827-3		Sp	7.8	7.5	Sp-Gn	
	I	B.A.9827-3		Gn	5.8	7.4	2.0	337

Abbreviations: Cp = chalcopyrite, Gn = galena, Min = minerals, Py = pyrite, Po = pyrrhotite, Sp = sphalerite

¹ $\delta^{34}\text{S}_{\text{H}_2\text{S}}$ (‰) calculated following the equation given by Ohmoto and Rye (1979)

² Isotopic temperature calculated from fractionation factors given by Kajiwar and Krouse (1971) and Ohmoto and Rye (1979)

³ Data from Yoon and Shimazaki (1993)

al. (1979), coupled with the measured fluid inclusion temperatures, the calculated $\delta^{18}\text{O}$ values of water from stage I quartz samples range from 1.1 to 9.0 per mil and that of the stage II quartz sample is -0.1 to +0.3 per mil (Table 3).

Fluid inclusion water was extracted from 25 quartz samples by crushing and from a smaller number of quartz samples by decrepitation. Samples of stage I and stage II quartz were carefully selected to maximize the percentage of CO_2 -bearing,

TABLE 3. Oxygen and Hydrogen Isotope Data from Gubong Mine Quartz

Vein	Stage	Sample no.	Sea level (m)	Min	$\delta^{18}\text{O}$ (‰)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰) ¹	δD (‰)
Danbong	I	D.B.100-2	+100	Qz	10.5	3.6	-86
	I	D.B.100-6	+100	Qz	8.0	1.1	-90
	I	D.B.100-9	+100	Qz	8.7	1.8	
	I	D.B.910121-6	+130	Qz	14.8	7.9	-92
	I	D.B.910121-9	+130	Qz	7.0	1.7	-90
	I	D.B.910121-10	+130	Qz	14.8	9.0	
	I	D.B.150-1	+150	Qz	6.4	1.1	
	I	D.B.89427-4	+150	Qz	14.8	7.9	-92
	I	D.B.910122-5	+150	Qz	8.7	3.4	
	I	D.B.910122-6	+150	Qz	10.8	5.5	-87
	II	D.B.100-6	+100	Qz(t)	9.2	0.3	-93
	II	D.B.100-8	+100	Qz(t)	8.8	-0.1	-95
No. 6	I	D.S.97126-21		Qz	8.7	3.4	-89
	I	D.S.97126-22		Qz	8.4	3.1	-73
	I	D.S.97126-7		Qz	13.6	8.3	-44
	I	D.S.97126-14		Qz	12.6	7.3	-31
	I	D.S.97126-20		Qz	12.2	6.9	-31
	I	B.A.97724-3-1		Qz	13.5	8.2	-42
	I	B.A.9827-10		Qz	14.3	9.0	-48
	I	G.R.9827-8		Qz(g)	13.0	6.1	-46
	I	G.R.9827-8		Qz	12.1	6.8	-22
	I	G.R.9827-10		Qz	13.6	3.7	-54
	I	G.R.97724-5-5		Qz	12.9	7.6	-21
Bongam 1	I	B.A.9827-3		Qz	12.5	7.2	-38
	I	B.A.97724-5		Qz	10.0	4.7	-40

Abbreviations: Sample no. = sample number; Min = minerals; Qz = white quartz; Qz (g) = gray quartz; Qz(t) = transparent quartz

¹ $\delta^{18}\text{O}_{\text{H}_2\text{O}}$ (‰) calculated from the equation of Matsushita et al. (1979)

types I and II inclusions and to minimize the percentage of secondary inclusions. Monitoring of the mole fractions of CO_2 in the extracted fluids, together with fluid inclusion petrology of each sample, indicate that the extracted fluids and their hydrogen isotope compositions are representative of ore fluids. The $\delta\text{D}_{\text{SMOW}}$ values of the extracted waters for stage I and stage II quartz samples range from -95 to -21 and -95 to -93 per mil, respectively (Table 3).

Discussion

Estimation of fluid compositions

Two hydrothermal fluids appear to be contained in the quartz and calcite samples of the stage I and stage II veins of the Gubong mine: an earlier CO_2 -bearing and a later aqueous fluid. The earlier fluid is represented by coexisting CO_2 -rich, CO_2 - H_2O , and primary aqueous inclusions that unmixed from a single parent fluid. The later fluid is represented by the secondary aqueous inclusions.

Most type I and II inclusions in the stage I veins have $T_{\text{m}(\text{CO}_2)}$ values below -56.6°C , which are interpreted to result from the presence of other species such as CH_4 and N_2 (Burruss, 1981). Furthermore, $T_{\text{h}(\text{CO}_2)}$ values of most type I and II inclusions are lower than $T_{\text{m}(\text{clathrate})}$ and also indicate that significant CH_4 is present. Plots of the low-temperature behavior of the CO_2 phases ($T_{\text{m}(\text{CO}_2)}$ and $T_{\text{h}(\text{CO}_2)}$) of type I and II inclusions are presented in Figure 6 and show a positive correlation between the $T_{\text{m}(\text{CO}_2)}$ and $T_{\text{h}(\text{CO}_2)}$ values. Also, it shows that some inclusions with no CH_4 have high density. A volume versus X_{CH_4} projection in the CO_2 - CH_4 system allows the relative proportions of CH_4 and CO_2 present in the CO_2 phases of types I and II inclusions to be estimated semiquantitatively

using the method of Brown (1989), Thiery et al. (1994) and Ridley and Hagemann (1999), assuming that CH_4 is the only additional component present. The approximate X_{CH_4} values of the CO_2 phases estimated from the $T_{\text{m}(\text{CO}_2)}$ and $T_{\text{h}(\text{CO}_2)}$ values of the stage I veins are listed in Table 4. The calculated X_{CO_2} values for stage I inclusions from these veins are also given.

As noted above, some type I inclusions from the Danbong vein exhibit the same phase behavior as that described by Van Den Kerkhof and Thiery (1994). Consequently, the type H4 and type S2 stable phase transitions of some type I inclusions are taken to indicate that they are CO_2 - N_2 and N_2 rich, respectively. Using the methods of Thiery et al., (1994) and Van Den Kerkhof and Thiery (1994), the X_{N_2} content of the type I inclusions with type H4 and type S2 behavior from the Danbong veins is calculated to be within the range of 0.51 to 0.53.

The bulk densities and chemical compositions of types I and II inclusions were calculated from microthermometric and volumetric data using a simplification of the method described by Bodnar (1983), Ramboz et al. (1985), Brown (1989), and Van Den Kerkhof and Thiery (1994), and also the graphical method of Schwartz (1989). In order to estimate the bulk composition of type II inclusions, the volume ratio of CO_2 to H_2O must be determined. The mol percent CO_2 of carbonic-aqueous inclusions can be ascertained from $T_{\text{h}(\text{CO}_2)}$, $T_{\text{m}(\text{clathrate})}$, and $T_{\text{h}(\text{total})}$, and the mol percent CO_2 can then be converted to the vol percent CO_2 . The calculated total density values for stage I and II inclusions from these veins are listed in Table 4. It is noteworthy that the calculated fluid density increases in the order: type I < type IIa < type IIb < type IIb (Table 4) and probably indicates that trapping of fluid inclusions followed this same order with a progressive increase in

TABLE 4. Summary of Compositions, Molar Volumes, and Densities of Fluid Inclusions in Quartz and Calcite from Stage I and Stage II Veins in the Gubong Mine

Vein	Stage	Inclusion type	Bulk inclusion composition				Carbonaceous phase composition			Aqueous phase volume	Molar (g/cm ³)	Density
			X _{H₂O}	X _{NaCl}	X _{CO₂}	X _{CH₄}	X _{N₂}	X _{CO₂}	X _{CH₄}			
Danbong No. 6	I	I			0.49 to 1.00	0.00 to 0.24	0.51 to 0.53	0.76 to 1.00	0.00 to 0.24		41.2 to 68.9	0.60 to 1.05
Bongam 1	I	I			0.82 to 0.98	0.02 to 0.18		0.82 to 0.98	0.02 to 0.18		53.4 to 72.2	0.58 to 0.78
Danbong	I	I			0.68 to 0.94	0.06 to 0.32		0.68 to 0.94	0.06 to 0.32		51.9 to 73.3	0.48 to 0.78
No. 6	I	IIa	0.25 to 0.98	<0.01 to 0.01	0.02 to 0.73	0.00 to 0.05		0.79 to 1.00	0.00 to 0.21	0.2 to 13.4 ¹	18.8 to 42.7	0.79 to 1.03
Bongam 1	I	IIa	0.45 to 0.98	<0.01 to 0.01	0.01 to 0.51	<0.01 to 0.05		0.74 to 0.98	0.02 to 0.26	1.2 to 11.7 ¹	19.3 to 38.5	0.62 to 1.00
Danbong	I	IIa	0.69 to 0.85	<0.01	0.13 to 0.29	0.02 to 0.03		0.80 to 0.95	0.05 to 0.20	1.2 to 11.2 ¹	29.7 to 40.4	0.55 to 0.89
Danbong	I	IIb	0.27 to 0.95	<0.01	0.05 to 0.73	0.00 to 0.01		0.95 to 1.00	0.00 to 0.05	1.2 to 4.2 ¹	20.3 to 31.4	0.82 to 0.97
No. 6	I	IIb	0.49 to 0.97	<0.01 to 0.01	0.03 to 0.50	<0.01 to 0.02		0.95 to 0.99	0.01 to 0.05	4.5 to 10.2 ¹	19.6 to 49.4	0.54 to 1.01
Danbong	I	IIIb								0.2 to 9.5 ²	19.5 to 23.5	0.79 to 0.99
No. 6	I	IIIb								0.4 to 17.0 ²	19.3 to 27.7	0.67 to 1.04
Bongam 1	I	IIIb								2.2 to 17.5 ²	19.5 to 33.7	0.55 to 1.03
Danbong	II	IIIb								0.4 to 4.2 ²	19.6 to 30.5	0.60 to 0.92
	II	IIIc								0.4 to 1.4 ²	20.8 to 27.6	0.65 to 0.87

¹ Salinity calculated from the equations of Brown (1989) and Darling (1991) and Ridley and Hagemann (1999)² Salinity calculated from the equations of Brown (1989) and Davis et al. (1990)

fluid density from the early to the later stages of mineralization. This conclusion is consistent with the evolution of inclusions toward H₂O-rich and CO₂-poor compositions throughout the mineralization sequence.

In summary, the parental fluids that deposited quartz in the stage I veins are similar. They had approximate salinities of less than about 13.4 wt percent NaCl, X_{CO₂} + X_{CH₄} ± N₂ contents of 0.02 to 1.00, and total densities in the range of 0.48 to 1.04 g/cm³. In contrast, the stage II fluids responsible for depositing quartz and calcite in the Danbong vein contained 0.4 to 4.2 wt percent NaCl and had total densities ranging from 0.60 to 0.92 g/cm³.

Fluid immiscibility

Petrographic and freezing-heating data suggest that coexisting type I, II, and III inclusions may have been trapped coevally both as primary and as secondary inclusions. All assemblages of primary and secondary inclusions have variable salinities, CO₂ contents, and homogenization temperatures. Inasmuch as coexisting inclusions within the same cluster or along the same microfracture display variation in their properties, the contents of the inclusions reflect the operation of either secondary processes, such as unmixing after trapping and subsequent necking during annealing of microfractures, or primary processes such as heterogeneous trapping of immiscible fluids. Although some of the variation can be attributed to necking or analytical errors, heterogeneous trapping of immiscible fluids can also produce variability in phase relationships, in homogenization temperatures, and in compositions of simultaneously trapped fluid inclusions (Ramboz et al., 1982). Several features suggest immiscibility as a mechanism responsible for producing the fluids in some inclusions. The Danbong, No. 6, and Bongam 1 veins all have carbonic-aqueous inclusions coexisting with all aqueous and carbonic inclusions, either in clusters or rarely along the same trail, and thus are interpreted to have been trapped contemporaneously. This is generally regarded as evidence for fluid immiscibility (Roedder, 1984; Hagemann and Luders, 2003). Variable X_{CO₂} type II inclusions homogenize both to the vapor and liquid at about the same temperature (Fig. 8, see also So et al., 1995), which indicates unmixing and cooling + dilution. If type I, II, and some of type III inclusions trapped in stage I quartz are the result of fluid immiscibility processes during entrapment, the fluid inclusions were trapped on or near the solvus of the CO₂-H₂O-NaCl system. The relationship between the estimated bulk compositions of type II fluids and their behavior in the H₂O-CO₂ ± (CH₄)-NaCl system at different pressures and salinities support the interpretation of fluid immiscibility (Fig. 9). Most type II inclusions plot on or near the solvus of the H₂O-CO₂-6 wt percent NaCl system at 1.5 to 2 kbars. For fluids trapped on the solvus, homogenization temperatures will be approximately equal to or higher than the trapping temperature. The presence of these assemblages with inclusions of different aqueous-carbonic ratios suggests that mechanical mixtures have been trapped.

The fabric and structures within the veins suggest that they were emplaced under conditions near the brittle-ductile transition. Brittle failure would have favored rapid pressure changes conducive to immiscibility within an H₂O-CO₂ fluid. Most type III inclusions appear to be secondary and display a

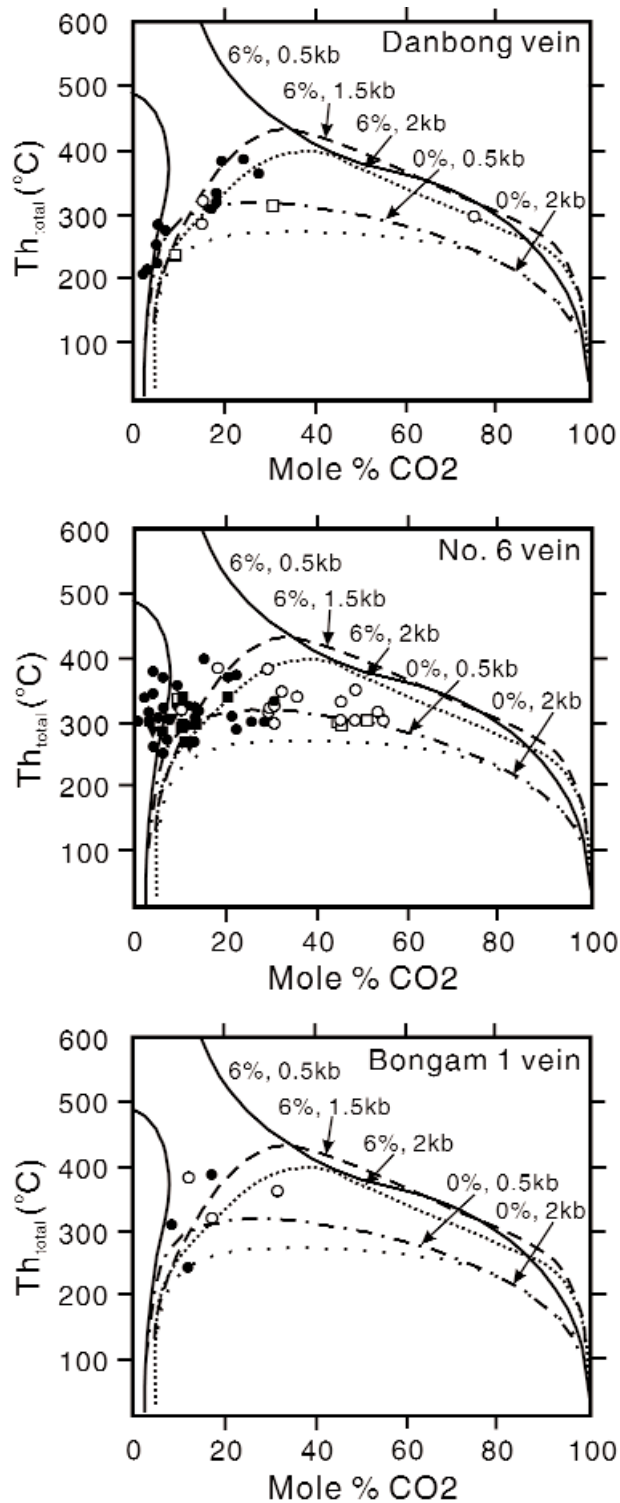


Fig. 9. Total homogenization temperature ($T_{h(\text{total})}$ ($^{\circ}\text{C}$)) vs. calculated equivalent mole fraction CO_2 of type II fluid inclusions from the Danbong, No. 6, and Bongam 1 veins in the Gubong mine. The curves for 0 to 6 wt percent NaCl are modified from Bowers and Helgeson (1983) and Brown (1998). Note most type II inclusions plot on or near the solvus of the $\text{H}_2\text{O}-\text{CO}_2$ -6 wt percent NaCl system 1.5 to 2 kbars. Solid circles = homogenization to liquid of type IIa inclusions, open circles = homogenization to vapor of type IIa inclusions, inverted solid triangles = decrepitation of type IIa inclusions, solid squares = homogenization to liquid of type IIb inclusions, open squares = homogenization to vapor of type IIb inclusions.

trend of decreasing salinity with decreasing temperature (Fig. 8). This may indicate later cooling and dilution of ore fluids, probably as a result of mixing with deeply circulating meteoric waters. If this is correct, the majority of aqueous type III inclusions may be unrelated to the early fluid unmixing within the hydrothermal system. Some stage I aqueous inclusions in quartz, such as those formed at high temperatures and having high salinity, may represent remnants of early fluids which also evolved through fluid unmixing. Probable causes of mixing include fluid decompression and changes in the magnitude of the principal stresses leading to repetitive opening of fractures and subsequent fluid ascent along these structures (Sibson et al., 1988; Wilkinson and Johnson, 1996).

Estimation of pressure

Trapping pressures for types I and II inclusion fluids were estimated by the construction of two-phase curves and bulk fluid isochores by combining the present compositional data and trapping temperature estimates with the data of Kerrick and Jacobs (1981), Bowers and Helgeson (1983), and Brown (1989). Fluid trapping pressures for type III inclusions were estimated by constructing two-phase curves and isochores for aqueous solutions of the appropriate salinity (5.4–7.9 wt % NaCl), using the data of Zhang and Frantz (1987) and Knight and Bodnar (1989). In both cases, trapping temperatures were estimated from the results of the fluid inclusion study and sulfur stable isotope thermometry.

The $T_{h(\text{total})}$ values of the immiscible aqueous and carbonic inclusions are interpreted to correspond to their trapping temperatures. Most type II inclusions from these veins fall between solvus for the $\text{H}_2\text{O}-\text{CO}_2$ -6 wt percent NaCl at 1.5 and 2 kbars at temperatures of 300° to 400°C (Bowers and Helgeson, 1983; Brown, 1989; Fig. 9). In the absence of independent temperature estimates for type I and II inclusions in veins of the Gubong mine, it was assumed that trapping temperatures were at least equal to the average homogenization temperatures measured (i.e., 315° – 389°C) and, in all pressure calculations for these veins, an arbitrary trapping temperature of 350°C was used. The calculated trapping pressures for all veins range from 943 to 2,098 bars (Danbong veins: 1,082–2,098 bars; No. 6 veins: 943–1,954 bars; Bongam 1 vein: 1,036–1,881 bars) and correspond to minimum depths of unmixing of 3.4 to 7.6 km, assuming that lithostatic conditions prevailed. These values are similar to those (1,300–1,900 bars) of the massive, mesothermal quartz veins of the Samdong deposit (So et al., 1995; Table 5). Based on the average homogenization temperature and salinity of type III inclusions from stage I, the calculated trapping pressures range from 670 to 850 bars (Danbong veins: 670 bars; No. 6 veins: 850 bars; Bongam 1 vein: 740 bars) and correspond to minimum depths of 2.4 to 3.0 km for lithostatic conditions. So et al., (1988) estimated 500 to 700 bars for Samgwang deposits based on CO_2 -bearing inclusions (Table 5).

Fluid evolution and gold deposition

Gold in hydrothermal fluids is mostly transported as gold bisulfide and chloride complexes (Shenberger and Barnes, 1989; Hayashi and Ohmoto, 1991; Benning and Seward, 1996; Stefansson and Seward, 2003, 2004). Experimental studies have demonstrated that gold is soluble as bisulfide

TABLE 5. Characteristics of Au-Ag Vein Deposits of the Republic of Korea

Mine	Gubong	Sangwang ¹	Samdong ²	Taechang ³
Age		Early Cretaceous (127 Ma)	Late Jurassic	Jurassic (146–156 Ma)
Depth of formation	>2.4 km (670–2,098 bars)	1.5 km (<200–700 bars)	>5 km (1,300–1,900 bars)	>4.5 km (1,200–1,500 bars)
Petrology of host units	Granitic paragneiss	Granitic gneiss	Banded biotite gneiss	Granitic paragneiss
Ore mineralogy	Simple, massive quartz vein (0.3–2.0 m wide), sulfides, argentite, electrum = 26–81 at. % Au	Simple, massive quartz vein (0.1–15 m wide), sulfides, argentite, argentian tetrahedrite, pyargyrite, electrum = 40–67 at. % Au ⁴	Simple, massive quartz vein (0.2–1.2 m wide), sulfides, argentite, electrum = 28–42 at. % Au	Simple, massive quartz vein (0.1–1.0 m wide), sulfides, native gold and electrum = 61–76 at. % Au ⁵
Cumulative production (kg)	13,446 Au, 4,578 Ag (1932–1970) ⁶	2,181 Au, 0.4 Ag (1938–1942, 1952–1959, 1984–1996) ⁶	123–223 Au (1938–1942)	194 Au, 32 Ag (1936–1942)
Ore grades (g/t)	6.4 Au	9–11 Au	5.5–13.5 Au	8–737 Au
Ore reserves (t)	150,000	72,000	132,400	50,000
Hydrothermal alteration	Weak, silicification, sericitic, chloritic	Weak, silicification, potassic, sericitic, argillic	Weak, silicification, sericitic, chloritic, argillic	Weak, sericitic, propylitic, chloritic
Fluid inclusion	201°–432°C, 0.4–17.3 wt % NaCl	180°–340°C, 1.2–7.9 wt % NaCl	188°–426°C, 4.5–13.8 wt % NaCl.	276°–394°C, 0.2–8.5 wt % NaCl
Stable isotope data (‰)	$\delta^{18}\text{O}$ (–0.1 to +9.0), δD (–92 to –21), $\delta^{34}\text{S}$ (3.9–9.5)	$\delta^{18}\text{O}$ (–5.9 to +0.1), δD (–102 to –90), $\delta^{34}\text{S}$ (0.6–5.2)	$\delta^{18}\text{O}$ (6.8–7.6), δD (–80 to –74), $\delta^{34}\text{S}$ (–3.0 to +5.3)	$\delta^{18}\text{O}$ (5.0–7.7), δD (–113 to –78), $\delta^{34}\text{S}$ (3.7–11.1)
Ore deposition mechanism	Unmixing (CO ₂ effervescence), cooling	Boiling (and CO ₂ effervescence), cooling	Unmixing (CO ₂ effervescence), cooling	Unmixing (CO ₂ effervescence)
Districts	Cheongyang	Cheongyang	Youngdong	Jungwon

Data sources: ¹So et al. (1988), ²So et al. (1995), ³Shelton et al. (1988), ⁴Lee et al. (1998), ⁵Choi and Wee (1992), and ⁶Choi et al., (2004)

complexes at low salinities and low f_{O_2} but at variable pH conditions. The $Au(HS)_2^-$ complex is predominant at near-neutral to weakly acidic pH, reduced sulfur-bearing solutions, and at relatively low temperatures (Renders and Seward, 1989; Shenberger and Barnes, 1989; Benning and Seward, 1996; Stefansson and Seward, 2003; Tagirov, et al., 2005), whereas the $AuHS^0$ and $HAu(HS)_2^0$ complexes are stable under acidic condition. The chloride complex of gold is predominant in more acidic and high-salinity, H_2S -poor fluids at relatively high f_{O_2} . The pH of the Gubong fluids, based on the stable coexistence of K-feldspar and sericite (muscovite) in the Danbong, No. 6, and Bongam 1 veins, was between 5 and 6. The f_{O_2} values can be estimated from the CH_4 - CO_2 equilibrium as 10^{-28} and 10^{-35} atm at 430° and 220°C, respectively. The lack of sulfate minerals and hematite, and the presence of CH_4 in the inclusions in these veins, indicate that the fluids were reduced, which is consistent with their estimated f_{O_2} values plotting below the field in which hematite is in equilibrium with pyrite. It would therefore seem likely that gold was transported as the $Au(HS)_2^-$ in the ore-forming fluids.

Gold deposition from the $Au(HS)_2^-$ may be caused by several mechanisms (Seward, 1984; Cole and Drummond, 1986; Hayashi and Ohmoto, 1991; Benning and Seward, 1996; Gilbert, et al., 1998). These include (1) pH change from near-neutral to more acidic or alkaline conditions; (2) change in f_{O_2} from redox reactions and/or CO_2 immiscibility; (3) decrease in the activity of reduced sulfur species as a result of sulfide precipitation, wall-rock alteration, and/or H_2S loss accompanying fluid unmixing; and (4) cooling and dilution of ore-forming fluids. A change in pH within the Gubong veins could not have been an effective cause of gold deposition. Not only is gold contained in restricted fracture fillings in quartz veins, but the wall-rock alteration is too limited to have brought about an effective change in pH. On the other hand, a decrease in fluid f_{O_2} may well have occurred as a result of interactions with the wall rocks, albeit limited, and thus caused a reduction in the $Au(HS)_2^-$ solubility. Fluid inclusions in stage I quartz show evidence of fluid immiscibility and partial cooling, resulting from mixing with meteoric water during the mineralization sequence. Those found in stage II quartz and calcite from the Danbong veins show evidence only of cooling. Gold was deposited during stages I and II as inclusions in sulfides or as fracture fillings accompanying sphalerite, chalcopryrite, and galena, most likely as a result of fluid immiscibility and cooling, and it is possible that type III inclusions may also have trapped gold-bearing fluids. The H_2O - $NaCl$ fluid represents either fluid that evolved through unmixing of an H_2O - CO_2 - CH_4 - $NaCl \pm N_2$ fluid owing to a decrease in fluid pressure or from mixing with meteoric water as a result of uplift and/or unloading during mineralization, which could have caused gold deposition from aqueous sulfur complexes (Seward, 1984; Drummond and Ohmoto, 1985; Cole and Drummond, 1986).

We suggest that gold was deposited in the stage I veins as a result of a decrease in sulfur fugacity/ H_2S loss that accompanied CO_2 separation from the H_2O - CO_2 - CH_4 - $NaCl \pm N_2$ fluid. Precipitation also occurred from the aqueous fluid during cooling and dilution caused by mixing with meteoric water. Gold in the stage II Danbong vein precipitated as a

result of cooling of the aqueous fluid at temperatures between 201° and 378°C.

Possible sources and evolution of ore-forming fluids

The fluids of the Danbong, No. 6, and Bongam 1 veins in the Gubong mine are very similar to those of the Jurassic gold deposits in Cheongyang, Youngdong, and Jungwon gold districts of the Republic of Korea (Shelton et al., 1988; So et al., 1988, 1995; So and Yun, 1997), which are interpreted to be of meteoric and/or magmatic origin (Table 5, Fig. 10). These fluids are also similar to those of mesothermal gold deposits in the Shaanxi, Henan, Jiaodong, and Hebei provinces, China (Neng et al., 1999; Yao et al., 1999), which are interpreted to be of mainly magmatic origin and involving minor mixing with local meteoric water. The Gubong deposits are also comparable to mesothermal lode gold deposits found in Archean greenstone terranes worldwide. The source of ore-forming fluids of many Archean mesothermal gold deposits is considered to be metamorphic, but magmatic sources have also been proposed by Hattori (1987). Kwon et al. (1997) reported Permian to Cretaceous Rb-Sr biotite ages from the metasedimentary rocks of the Gyeonggi massif range and suggested that the massif may have been involved in continental collision during the early Jurassic (174–188 Ma). Therefore, regional metamorphic fluids could well have contributed to the mineralization at Gubong.

The cluster of $\delta^{18}O_{\text{quartz}}$ values from 12.1 and 14.8 per mil and the calculated $\delta^{18}O_{\text{water}}$ values of 6.8 to 9.0 per mil are typical of most mesothermal vein systems, which generally display a regional homogeneity in their $\delta^{18}O_{\text{water}}$ values (Shelton et al., 1988; Nesbitt and Muehlenbachs, 1989; So and Yun, 1997). Although some calculated $\delta^{18}O_{\text{water}}$ values from the Danbong veins are lower than those from the No. 6 and Bongam 1 veins, $\delta^{18}O_{\text{water}}$ values calculated from the three veins overlap and are therefore compatible with a fluid of

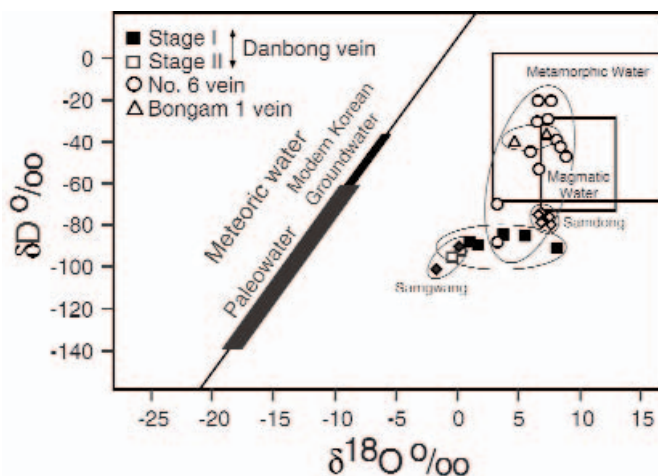


Fig. 10. Hydrogen vs. oxygen isotope diagram showing stable isotope hydrothermal fluid compositions from the Danbong, No. 6, and Bongam 1 veins in the Gubong mine. Also shown are the isotopic fields for Paleowater (Shelton et al., 1988, 1990) and modern Korean ground water (Kim and Nakai, 1988). Note data from the Samdang (open diamonds) and Samgwang (solid diamonds) that are interpreted to be magmatic (Samdang) and meteoric (Samgwang). The magmatic and metamorphic water boxes are from Ohmoto (1986) and Sheppard (1986).

deep crustal origin. Both magmatic and metamorphic reservoirs are possible sources. However, the lower oxygen isotope values probably reflect fluids of a meteoric origin. The δD_{water} values of the No. 6 and Bongam 1 veins have a wide range (-89 to -21‰) and may indicate either a probable magmatic and/or metamorphic signature for a component of these ore-bearing fluids, whereas the δD_{water} values of the Danbong veins have a limited range (-95 to -86‰) and may be consistent with a meteoric signature (Fig. 10). However, decrepitation may release fluid from secondary inclusions that contain low δD meteoric water and mask primary ore fluids. Further, deep-sourced, nonmeteoric ore fluids may react with δD -depleted organic matter and acquire a low δD signature that mimics meteoric water (Goldfarb et al., 1989; McCuaig and Kerrich, 1998). As Figure 10 shows, the fluids from the Gubong veins plot in two distinct yet partly overlapping regions. For comparison, data from mesothermal (Samdong) and Korean-type (Samgwang) gold deposits (So et al., 1988, 1995) are also shown. In this plot, the fluids that deposited the gold-bearing stage I veins may be interpreted to be mainly magmatic or derived in part from deep-seated metasedimentary rocks. They evolved by mixing with local meteoric water, by exchange of low water/rock ratio, and by degassing during mineralization within uplift zones. In contrast, the fluid that precipitated the gold-bearing, stage II Danbong vein was predominantly of meteoric origin similar to that documented by So et al., (1988) for the Samgwang mine, Cheongyang gold district.

Conclusions

Gold-bearing mesothermal veins (Danbong, No. 6, and Bongam 1 veins) from the Gubong mine at Cheongyang gold district occur in Precambrian metasedimentary rocks and include two stages of quartz veins separated by fracturing and faulting events. Stage I quartz veins contain arsenopyrite, pyrite, pyrrhotite, marcasite, chalcopyrite, galena, electrum, and argentite. In the stage II Danbong quartz vein, pyrite, sphalerite, chalcopyrite, galena, and electrum were deposited, but in the No. 6 vein stage II quartz was barren.

Three types of fluid inclusions are present in the quartz and calcite of the Danbong, No. 6, and Bongam 1 veins. Type I inclusions from these veins are CO_2 rich and occur in stage I quartz. Type II CO_2 - H_2O inclusions are also present in stage I quartz. Type III inclusions are aqueous and occur in the quartz and calcite of both stage I and stage II veins. Type I inclusions have variable CH_4 content and abundant N_2 . Type II inclusions contain minor CH_4 and have variable salinities and variable homogenization temperatures that are taken to represent minimum trapping temperatures. Type III inclusions have low to moderate salinities and moderate homogenization temperatures. Microthermometric results indicate that fluid inclusions from stage I quartz veins of the Danbong, No. 6, and Bongam 1 veins represent two contrasting sets of fluid compositions: H_2O - CO_2 - CH_4 - $\text{NaCl} \pm \text{N}_2$ fluids (943–2,098 bars) related to early sulfide deposition and H_2O - NaCl fluids (670–850 bars), which either evolved through immiscibility of H_2O - CO_2 - CH_4 - $\text{NaCl} \pm \text{N}_2$ fluids as a result of a decrease in fluid pressure or from mixing with deeply circulated meteoric waters as a result of uplift and/or unloading during mineralization related to late sulfide deposition. The H_2O - NaCl fluid

responsible for stage II of the Danbong vein was an evolved meteoric water.

Gold from the Danbong and No. 6 veins occurs as electrum associated with the early and late sulfides in stage I and as electrum in stage II. $\text{Au}(\text{HS})_2^-$ was the dominant complex responsible for gold transport during both stage I and stage II mineralization of the Danbong and No. 6 veins. Gold deposition associated with early sulfides in stage I was mainly caused by a decrease in sulfur fugacity/ H_2S loss accompanying immiscible phase separation from H_2O - CO_2 - CH_4 - $\text{NaCl} \pm \text{N}_2$ fluids. Stage I gold precipitated with late sulfides from H_2O - NaCl fluids as a result of cooling and dilution on mixing with meteoric water. Gold in stage II precipitated from H_2O - NaCl fluid by cooling.

Stable isotope results from the Gubong mine samples indicate that ore sulfur was derived mainly from a magmatic source but also partly from sulfur in the host rocks. The ore-forming stage I fluids came from magmatic and/or deep-seated metasedimentary rocks and evolved by mixing with local meteoric water, by low water/rock ratio exchange, and by degassing during mineralization in uplift zones. The stage II fluid of the Danbong vein originated from meteoric water.

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