Overview of Epithermal Gold-Silver Mineralization, Korea:

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Abstract The precious-metal mineralization of epithermal type in the Korean Peninsula, which is spread over a broader range of ca. 110 to 60 Ma with a major population between 90 and 70 Ma, mainly occurred along the NE-trending major strike-slip fault systems (i.e., the Gongju and Gwangju ones) that commonly include volcano-tectonic depressions and calderas. The occurrence of epithermal mineralization during Late Cretaceous clearly indicates that the geologic setting of the Korean Peninsula changed to the favorable depth of ore formation with very shallow-crustal environments (<1.0 kb) accompanied with gold-silver (-base-metal) mineralization. Epithermal gold-silver deposits in Korea are primarily distinguished as sediment-dominant and volcanic-dominant basins by using criteria of varying alteration, ore and gangue mineralogy deposited by the interaction of different ore-forming fluids with host rocks and meteoric waters. These differences between the central and southern portions are causally linked to the tectonic evolution of the Peninsula during the Cretaceous time.

In the Early Cretaceous, the sinistral strike-slip movements due to the oblique subduction of the Izanagi Plate resulted in the Gongju and Gwangju fault systems in the central portion of the Korean Peninsula, which was accompanied with a number of sediment-dominant basins formed along these faults. During the Late Cretaceous, the mode of convergence of the Izanagi Plate changed to northwestward so that orthogonal convergence occurred with a calc-alkaline volcanism. As results, volcanic-dominant basins were developed in the southern portion of the Peninsula, accompanied with volcano-tectonic depressions and caldera-related fractures. The magmatism and related fractures during Late Cretaceous may play an important role in the formation of geothermal systems. Thus, such fault zones may be favorable environments for veining emplacement that is closely related to the precious-metal mineralization of epithermal type in the Korean Peninsula.

INTRODUCTION

Epithermal deposits are an important class of hydrothermal deposits, that have recently seen an surge of exploration and research, principally as significant resources of gold and silver. Epithermal deposits form

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at shallow depths (surface to 1-2km) and temperatures less than 300°C (Hayba et al., 1985), and encompass a variety of low-sulfidation (near-neutral pH, reduced fluid; LS) and high-sulfidation (acidic and oxidized fluid; HS) deposits (Sillitoe, 1993; White and Hedenquist, 1995). In contrast to high-sulfidation epithermal deposits, magmatic signatures in low-sulfidation deposits are more elusive. Also, epithermal deposits are closely associated with subaerial, silicic volcanism or shallow intrusion in convergent margin settings, which generally forms in the late stages of arc evolution.

Recently, the gold-silver deposits in Korea have been classified into three types such as mesothermal, Korean-type, and epithermal deposits on the basis of the fluid inclusion and stable isotope data (Shelton et al., 1988). Whereas this makes the genetic criteria clear, it provides little regional information on ore genesis and classification of Korean gold-silver deposits using common mineral-deposit models. However, both the gold-silver lode deposits and the granitoids during Mesozoic time in the Korean Peninsula document a very close spatial and temporal relationship with syn-tectonic and post-tectonic magmatisms invariably controlled by changing convergent plate motions, suggesting the apparent overlap between Jurassic orogenic and Cretaceous volcano-plutonic-related deposits (Choi, 2001). The epithermal precious-metal deposits in Korea, which contain about one-third of the total gold resource, form important Cretaceous gold-silver provinces spatially associated with pull-apart basin and Bulgugsa volcano-tectonic depressions or calderas, although individual deposits are relatively small to medium-sized except for the Mugeug gold-silver metallogenic province (i.g., >30t Au). A principal aim of this paper is to provide a general overview of the genetic mode of epithermal deposits in Korea, and specifically to relate the gold-silver mineralization to the tectonic evolution in Korea during Cretaceous time.

TECTONIC FRAMEWORK

The tectonic framework in South Korea includes the Precambrian Gyeonggi massif (2.7~0.8 Ga), the Paleozoic Ogcheon-Taebaeg belt, the Precambrian Yeongnam massif (3.1~0.7 Ga), and the Cretaceous Gyeongsang basin from north to south. The Jurassic granitoid rocks (the older group) are the most abundant among the Mesozoic granitoids and are widely distributed along 200 km NE- or NNE-trending elongated batholithic belts. They occur mainly in the Gyeonggi and the Yeongnam massifs, and partially in the Paleozoic Ogcheon-Taebaeg belt. Sinistral, strike-slip, brittle shearing during the Early Cretaceous in the central portion of the Peninsula (e.g., Ogcheon belt and in the Gyeonggi massif) was accompanied by the formation of a number of pull-apart or trans-tensional basins (e.g., Pungam, Eumseong, Yeongdong, Gyeongsang, Haenam, Neungju etc.) along NE-trending faults, probably caused by the distal oblique (northward) subduction of the Izanagi Plate (Otoh and Yanai, 1996). During Late Cretaceous oxidized magma of the magnetite series intruded into the upper crust or extruded along the NE-trending subvolcanic belts in central area of Korea and ENE-trending volcanic belts in southern area. The younger, Cretaceous granitoid, which is characterized by stock-sized subvolcanic magma bodies, occurs mostly in the Gyeongsang basin, and partially in the central part of the Ogcheon belt.

The Cretaceous basins may be subdivided into two types of basin according to their geologic setting: the sediment-dominant and volcanic-dominant basins. The Gyeongsang, Neungju and Haenam basins in the southern district consist of dominantly nonmarine sedimentary rocks, felsic pyroclastics and andesitic pyroclastics and flows with shallow-level granitoids, whereas the Pungam, Eumseong and Yeongdong basins in the central district are mainly filled with nonmarine sedimentary sequences with lesser volcanics. Sedimentation in the basins was initiated in the Hauterivian, and continued into the Albian (Yang, 1992). Comparisons and contrasts between the central and southern districts in the Korean Peninsula may be evaluated to better establish significant spatial relationships between ore genetic type and tectonic event.

STYLE OF EPITHERMAL GOLD-SILVER MINERALIZATION

In spite of the favorable tectonic and geologic setting, the potential for epithermal gold-silver deposits in Korea was neglected until the early 1980s, when two main districts were recognized in the Mugeug province in the central portion of the Korean Peninsula and the Haenam-Jindo province in the southwestern portion. Although most of the mineralization in these areas is epithermal in nature, its style and geochemistry significantly vary from area to area. Low-sulfidation epithermal gold-silver deposits in Korea can be divided into two types, according to their geologic setting, common alteration, ore and gangue mineralogy, fluid inclusion, stable isotope and geochemical signatures. One type, typical of adularia-sericite type, is closely associated with Cretaceous volcano-tectonic terranes (e.g., pyroclastic rocks) in the southern Korea, whereas the other type formed in uplifted basement regimes in the central Korea, commonly hosted by granitoids, and older sedimentary and metamorphic units.

Mugeug mineralized area

The Eumseong basin within the Gyeonggi massif at the central Korea is located along the Gongju strike-slip fault systems that are bounded by two left-stepping sinistral master faults. The basin contains dominantly alluvial to lacustrine sedimentary rocks of the Hauterivian-Albian in age with locally younger volcanic rocks (Choi et al., 1995). The gold-silver veins in the Mugeug mineralized area along the Eumseong basin are emplaced in biotite granite. The Au-Ag-Sb veins in the Mugeug mineralized area probably resulted from multistage mineralization, i.e., an early gold-bearing assemblage dominated by base- metal sulfides and a late assemblage characterized by a variety of silver-bearing sulfides, sulfosalts, native silver or stibnite. The multistage mineralization is represented mainly by banded fissure veins that comprise predominantly quartz, sericite, chlorite and carbonate with lesser amounts of chalcedony, epidote, quartz pseudomorphing carbonate, fluorite and clay minerals, and commonly show relatively well-developed crustiform, drusy cavity, comb, breccia, feathery, lattice and cockade structures. The veins show extensive envelope of sericitic, argillic, propylitic and silicic alterations associated with mineralization that are represented mainly by sericite, K-feldspar, carbonate, chlorite, kaolinite and smectite(Choi, 2001).

A distinct feature of overall lateral and vertical zonation from Au-Ag through Ag to Sb deposits typifies variations in the relative abundance of gold and silver-antimony sulfosalts. The Mugeug mine at the northern mineralized area is composed of multiple veins that are characterized by relatively high gold fineness as well as sericitization, chloritization and epidotization. The ore-forming fluids formed at relatively high temperature and moderate salinity (280°C, 4~9 equiv. wt. % NaCl) with relatively deep circulating (more-evolved) groundwater ($\delta^{18}O_{H2O}$ = –0.7±6.0 ‰; δD = –73±8 ‰). Gold mineralization is closely associated with sulfides formed at temperatures between 260° and 220°C and from sulfur fugacity range of $10^{-11.5}$~$10^{-13.5}$ atm. In contrast, the Geumwang, Geumbong and Taegueg veins at the southern mineralized area represent the low fineness values and increasing tendency of brecciation or stockwork, and are characterized by kaolinitization, silicification, carbonatization and smectitization. The geothermal systems in the mining area were evolved by mixing event (dilution and cooling mechanism) at relatively low temperature and salinity (<230°C, <3 equiv. wt. % NaCl) from ore-forming fluids containing greater amounts of less-evolved meteoric waters ($\delta^{18}O_{H2O}$ = –2.5±5.0 ‰; δD = –73±8 ‰). Silver mineralization in these mines include various silver- bearing minerals that formed at temperatures between 200° and 150°C and from sulfur fugacity range of 10^{-15}~10^{-18}atm. Thus, it may suggest that they display later formed mineralization in shallow depth overprinting deeper levels, earlier formed mineralization in telescoped system. All of the isotopic data display various degrees of ^{18}O enrichment relative to local meteoric water, produced by exchange with igneous or metamorphic rocks at relatively shallow depths of formation (<1.0 kbar), the classic ^{18}O shift. The characteristics of these precious-metal deposits can be attributed to the complexities of mixing, cooling and boiling in the ore-precipitating mechanisms, typical of epithermal environments.

Haenam mineralized area

The Eunsan-Moisan and Gasado deposits, which occur in Late Cretaceous volcanic rocks, are the most economically feasible gold-silver mineralization found in recent years in Haenam-Jindo province, southwestern Korea. The Haenam Basin at the southwestern Korea is situated within the Gwangju strike-slip fault systems, and is filled with dominantly felsic pyroclastic rocks. The pyroclastic sequence in the basin can be divided into four litho-stratigraphic units in ascending order: the lower andesitic tuff with andesite intrusions and flows, the Uhangri formation, the Hwangsan tuff and the Jindo rhyolite (Chun and Chough, 1995). The general distribution of pyroclastic sequence suggests that the basin formed as volcano-tectonic depressions related to continental rift within magmatic arcs or bark arc environment. An abundance of subvolcanic to volcanic rocks necessitates that much of the veins are hosted in lithologies of roughly equivalent age.

The Eunsan and Moisan deposits occur as the colloform banded fissure veins and vein breccias that comprise predominantly chalcedony, fine-grained comb quartz, bladed quartz and carbonate minerals with lesser illite-smectite, adularia and dark sulfide bands with only trace base metals. The ore mineralogy of the veins is characterized by the dominance of silver-antimony sulfosalt minerals with silver selenides and tellurides over argentite. However, mineralogical differences between the Eunsan (e.g., naumanite, aguilarite) and Moisan deposits (e.g., sylvanite, altaite, tellurobismuthite, native tellurium) appear to reflect intrinsic geochemical characteristics. The Ag/Au ratios in the Eunsan veins exhibit a bi-modal distribution with Se-rich type, whereas the Moisan veins show an intermediate normal distribution in Ag/Au ratios with Te-rich type. The alteration, ore and gangue mineralogies of the Au-Ag-Se-Te deposits are typical of adularia-sericite-carbonate (low-sulfidation) class of volcanic-hosted epithermal deposits.

Adularia-sericite epithermal gold-silver deposits typically form within back-arc basins or rifts. They are characterized by deep-seated felsic intrusions that are set up circulating hydrothermal systems dominated by meteoric waters. Felsic volcanic and subvolcanic rocks are commonly spatially associated with mineralization as part of a bimodal suite of volcanic host rocks. The gold-silver systems commonly display a closer spatial relationship with volcano-tectonic depression and extensional structure rather than intrusive rocks, although subvolcanic acidic rocks of similar age may occur in the vincinity of some deposits (e.g. Moisan). The hydrothermal systems of the deposits are characterized at very shallow depth by neutral pH fluids of low temperature and salinity (<300°C, <4 equiv. wt. % NaCl) but variable gas content (CO_2 and H_2S). Stable isotope data of Eunsan-Moisan-Gasado veins commonly demonstrate the meteoric water dominance ($\delta^{18}O_{H2O}$ = −8.0±2.5‰; δD = −65±5‰), with O-isotope compositions of both water and rock modified to varied degrees by their mutual interaction (^{18}O shift). The range of the Gasado H- and O-isotope data is consistent with dominantly meteoric water as ore fluid compositions approach those of local unexchanged meteoric waters.

In general, low-sulfidation epithermal deposits form distant from inferred magmatic heat source at temperatures of 200°-300°C. Pressures are controlled by hydrostatic conditions, suggesting that the maximum temperature at a given depth is constrained by boiling. Boiling and mixing mechanism of hydrothermal fluid with meteoric water and associated loss of CO_2 and H_2S in the shallower part of the system control gold-silver mineralization in the Eunsan-Moisan deposits. The major epithermal gold-silver deposits, typically of the low sulfidation vein type and rarely the high sulfidation, occur in extinct geothermal systems of Late Cretaceous volcanic terrains, which are related to the overlying thick argillic alteration zones and nearby acid alteration associated with steam-heated acid hot springs. Thus, it suggests that a dilute fluid undergoes boiling and a loss of acidic volatile components with mixing of meteoric fluid or groundwater.

The Eunsan (Se-type) and Moisan (Te-type) veins may result from different parts of same geothermal system, according to their alteration, ore and gangue mineralogy, vein morphology, geochemical signatures and stable isotope data. Mineralogical and geochemical differences that exist in these deposits can be well explained by variations of the physicochemical conditions that existed during gold-silver deposition. The Eunsan deposit of Se-type formed at shallower crustal levels with relatively lower temperature conditions than the Moisan deposit of Te-type. It implies that the Moisan deposit display mineral association closer to the heat source than the Eunsan deposit.

DISCUSSION AND SUMMARY

Mineralogical and geochemical differences that exist in the Korean lode deposits can be explained by variations of the physicochemical conditions that existed during gold-silver deposition (Choi and Wee.

1992). The Cretaceous gold-silver deposits are characterized by variable averages and wide ranges of Au fineness values within individual deposits, suggesting differences in the mineralogy of these deposits. Most of the Au-Ag deposits probably resulted from several mineralization stages, i.e., an early gold-bearing assemblage dominated by base-metal sulfides and a late assemblage characterized by a variety of silver-bearing sulfides, sulfosalts, selenides, tellurides or native silver. Perhaps, the wide intra-vein variations of the Cretaceous deposits indicate that ore-forming fluids changed rapidly in composition by response to varying P-T-X parameters in the epithermal environment. Although a variety of classifications of this Cretaceous deposits type exist, a division based on ore assemblage appears to reflect intrinsic geochemical differences. The general characteristics of the Cretaceous precious-metal deposits can be attributed to the complexities in the ore-precipitating mechanisms (i.e., boiling, mixing and cooling), typical of the epithermal environments. The Cretaceous gold-silver mineralization in Korea may have occurred at PT conditions of approximately <1.0kb from a meteoric or less-evolved fluid with $\delta^{18}O_{H2O}$ values of –3.0±6.0‰ and $\delta^{18}D$ values of –70±20‰. Ore-forming fluids generally indicate relatively low to moderate temperature (150°~350°C), neutral to slightly alkaline, low salinity (<10 equiv. wt. % NaCl), and/or partly CO_2-bearing (<10 mole%) solutions, with sulfur species involved in the complexing of the gold.

The epithermal gold-silver deposits in Korea mainly occur in the Cretaceous pull-apart or trans-tensional basins. Most of the gold-silver mineralizations (90~70 Ma) are spatially associated with extensional features by strike-slip movement, as well as volcano-tectonic depression accompanied by major subvolcanic or volcanic activity. On the basis of variation in alteration, ore and gangue mineralogy as well as geologic setting, epithermal gold-silver deposits in Korea are primarily divided into sediment-dominant (Mugeug) and volcanic-dominant (Haenam) types. Stable isotope and fluid inclusion data of mineralizing fluids from the Gasado, Eunsan-Moisan and Tongyeong veins in southern Korea are similar to modern meteoric and hot spring waters ($\delta^{18}O_{H2O}$ values of –7.0±2.0‰ and $\delta^{18}D$ values of –50±20‰ (Shin and Chi, 1996)). The Gasado, Eunsan-Moisan and Tongyeong geothermal systems may represent an end member of high-level veining and alteration closely associated with Late Cretaceous volcanism in Korea whose ore fluid compositions commonly fall on the meteoric water line. Most of the Cretaceous gold-silver deposits in the central Korea, which can be closely associated with relatively deep-circulating (more-evolved) groundwater, may be genetically related to epithermal quartz-carbonate Au-Ag mineralization of low-sulfidation, transitional to relatively deeper mesothermal mineralization, implying a very steep geothermal gradient on the upper crust.

Epithermal gold-silver deposits of volcanic-dominant basin in the southern Korea generally formed at shallower crustal levels and relatively lower temperature conditions from the hydrothermal fluids containing more amounts of meteoric or less-evolved circulating waters than those along the sediment-dominant basin in the central portion, suggesting considerable differences in the physicochemical environment and fluid characteristics between geothermal systems formed in continental rift environments (e.g., the central portion) and volcanic arc environments (e.g., the southern portion).

During the Early Cretaceous in the Korean Peninsula, the NE-trending sinistral, strike-slip, brittle faults such as Gongju and Gwangju ones, which took place along the boundary of the Ogcheon belt and in the Gyeonggi massif, resulted in by a number of pull-apart or trans-tensional basins. The strike-slip faults are probably caused by the distal northward oblique subduction of the Izanagi Plate. During the Late Cretaceous, the NE-trending strike-slip faults ceased due to the change of oblique to orthogonal convergence of the plate. However, volcano-tectonic depressions or calderas related to Late Cretaceous calc-alkaline magmatism are locally developed with NE-trending strike-slip fault zones. Thus, such fault zones may be favorable environments for veining emplacement that is closely related to the epithermal gold-silver mineralization.

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