Evolution of subaerial magmatic-hydrothermal systems: A comparative study between Koryu Au-Ag deposit and Toyoha polymetallic deposit at Sapporo-Iwanai district, Hokkaido, Japan

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Abstract

Sapporo-Iwanai district is located at the intersection of the northeast Japan arc and Kuril arc, associated with the subduction zone. This area is characterized by Miocene submarine volcanism followed by Plio-Pleistocene subaerial volcanism.

Koryu, a small epithermal Au-Ag deposit, occurred in Pleistocene (1.4 - 0.85 Ma) within Miocene sedimentary rocks near a subaerial andesitic volcano, while Toyoha, a large epithermal Pb-Zn-Ag(-Au) deposit, also occurred near a subaerial andesitic volcano. Although most of the base metal deposits formed in middle~late Miocene, Toyoha formed in Plio-Pleistocene (2.93 - 1.60 Ma) within Miocene volcanic and sedimentary rocks. This epithermal mineralization was partly overprinted by xenothermal Cu-Sn-In(-Au) mineralization (2.68 - 0.49 Ma).

Hydrothermal alteration differs vastly between Koryu and Toyoha: host rocks at Koryu were not intensively altered, although wall rocks adjacent to veins were silicified, while those at Toyoha show intensive and extensive neutral-pH alterations. Geological and chronological studies show that middle~late Miocene (12.5 - 8.4 Ma) alteration was pervasive and overprinted by Plio-Pleistocene (2.93 - 0.49 Ma) alteration. The base metal veins in the middle~late Miocene were not well developed, but were large in number with great depth.

These studies show that the hydrothermal activity at Koryu is rather small and short-lived, while that at Toyoha is large, long-lived and characterized by overprinting of different hydrothermal systems. The subaerial magmatic activities yielded not only the andesite lavas, but also generated hydrothermal solutions for the formation of both Koryu and Toyoha. The metals were possibly derived from such magma. At Toyoha, the hydrothermal solutions could also remobilize metals from old ores.

The size, life span of magmatic-hydrothermal system, and overprinting on the old mineralizing systems could constrain the type of metal deposits (precious and polymetallic deposits) nearby subaerial andesitic volcanoes in Plio-Pleistocene.

Keywords: *Koryu Au-Ag deposit, Toyoha polymetallic deposit, epithermal, xenothermal, Plio-Pleistocene, hydrothermal alterations, overprinting of different hydrothermal systems, subaerial magmatic-hydrothermal systems*

Introduction

The Koryu deposit is a small epithermal Au-Ag vein-type deposit whereas the Toyoha deposit, located only 30 km northwest of Koryu, is Japan's biggest polymetallic Pb-Zn-Ag-Cu-Sn-In-Au vein-type deposit (Fig.1). The total metal production and ore grade for each deposit is shown in Table 1.

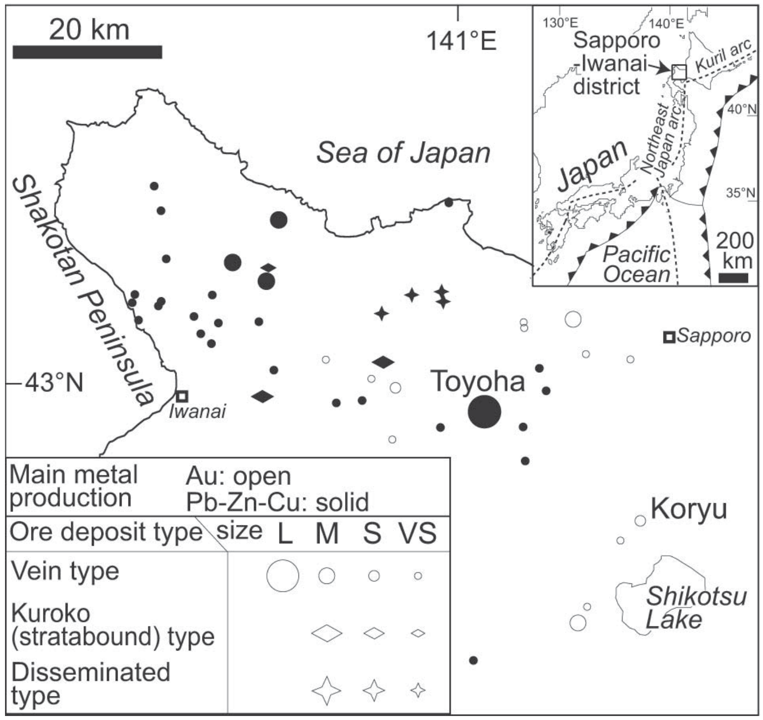

Figure 1. Au and Pb-Zn-Cu deposits at Sapporo-Iwanai district, Hokkaido, Japan (Modified after Watanabe, 2002). Dotted lines denote present volcanic front. Size of ore deposit, L: large, M: medium, S: small, VS: very small. Division of deposit size, Au: L > 100t > M > 10t > S > 1t > VS Cu-Pb-Zn: L > 1Mt > M > 10Kt > S > 1Kt > VS

Koryu and Toyoha have been the focus of extensive and intensive research on its geology, geochronology, hydrothermal alteration and vein mineralogy including phase relations, fluid inclusions, stable isotopes and genetic model (e.g., Yajima and Ohta, 1979; Sawai et al., 1989; Ohta, 1995; Shimizu et al., 1998). However a detailed comparative study in terms of ore genesis between these two deposits has never been conducted.

The aim of this study is to know how subaerial magmatic-hydrothermal systems differentiated precious metal and base metal deposits. This paper presents similarities and differences in the environment of ore formations between Koryu and Toyoha and reveals the important factors in the subaerial magmatic-hydrothermal systems responsible for precious and base metal mineralization. Although Toyoha veins were formed by three chronologically distinct hydrothermal systems (as described later), this study mainly focuses on the youngest hydrothermal system that occurred in Plio-Pleistocene.

Outline of geological setting

The Sapporo-Iwanai district is located at the intersection of the northeast Japan arc and Kuril arc near the subduction zone (Fig.1). This district is characterized by intermittent volcanic activities from early Miocene. These volcanic activities generated many hydrothermal ore deposits as shown in Fig. 1. The assemblage of host rocks of Koryu and Toyoha are summarized in Table 1.

Table 1. Characteristics of Koryu and Toyoha deposits

	Koryu	Toyoha
Production	Au: < 5 t [2]	Pb: 413000 t, Zn: 1230000 t, Ag: 2350 t, Au: >10 t [3, 16]
Ore grade	Au: 40 g/t [17]	Pb: 2.27%, Zn: 11.52%, Ag: 283 g/t, Au: 0.3-0.4 g/t [3, 19]
Host rocks	Early or middle Miocene sedimentary rocks consisting of mudstone and siltstone, overlain by andesitic pyroclastic rocks and Pleistocene subaerial andesite west of the mining area [1].	Early Miocene basalt and andesite, and middle Miocene mudstone in ascending order. These rocks are overlain by middle-to-late Miocene andesite, pyroclastics and andesitic hyaloclasite, and Pliocene subaerial andesite south of the mining area [4].
Hydrothermal alteration of host rocks	Presence of K-feldspar in silicified rocks adjacent to veins (a distance of approx. 4 m from veins) is indicative of hydrothermal alteration related to ore mineralization within an area of 1.2km east-west by 0.5 km north-south [5, 17].	Intense Neutral-pH alteration mainly composed of sericite, chlorite and quartz envelopes the ore veins around the area of at least 3 km east-west by 2.5 km north-south [11]. The intense Neutral-pH hydrothermal alteration is also present to a depth over 600 m below the surface [14].
Numbers of productive veins	Among veins 1-8, veins 1, 2 and 3 are the most productive [17].	More than fifteen veins in which Tajima (epithermal vein), Izumo and Shinano (xenothermal veins) are the most productive[11,20].
Area of vein swarm (km^2)	0.5(North-South) x 0.9(East-west) [17]	1.2(North-south) x 2.7(East-west) [13]
Main vein system	East-west trending dextral strike-slip shear veins [17]	East-west trending dextral strike-slip shear veins with northwest-southeast extensional veins [21]
Vein dips	70°N~65°S [17]	50°N~65°S [11,20]
Vein thickness	2.0 m (max.) [17]	25 m (max.) [11]
Elevation of exploitation	+420 ~ +600 m above sea level [12, 17]	-60 ~ +540 m above sea level [19]
Mineralization episode	Earlier episode (stages E-I~E-III) occurs in veins 1 and 2 whereas later episode (stages L-I~L-VII) mainly occurs in vein 3 [17].	Earlier episode (epithermal mineralization, stages I~II) occupies the northwestern half of the mining area whereas the later episode (xenothermal mineralization, stages III~VII) occurs in the southeastern half of the area [8].
Main ore mineral assemblage	Earlier veins: el, py, sp, gn, cp. Later veins: el, ac-ag, po-pe, py, sp, gn and cp [17].	Earlier veins: gn, sp, hm, mg, py Later veins: py, sp (In-sp), gn, cp, wt, pyrr, st, tet-ten, asp, ma [11]
Main gangue mineral assemblage	Earlier veins: qz, ad, cal and jo. Later veins: qz ad and chl/sm [17]	Earlier veins: qz, chl, cal, rho. Later veins: qz, pyro, ka, di, ser, cal, rho [11]
Charcteristics of mineralogy and metal zoning	On an ore deposit scale, the veins with abundant ad tend to be richer in el than those in qz-rich veins. However, on a hand specimen to microscopic scale, el is rare in bands of ad and qz but are abundant in aggregates of chl/sm at bonanza zones [17]. The upper limit of Au-Ag mineralization is not known due to erosion, but the lower end of the bonanza zones in the vein 3 extend to a depth of 420 m above sea level where high-grade Au ore abruptly decreased [12,17].	Calculated mineral-equlibrium temperatures from sp-st and ten-py-cp-asp in xenothermal veins were 350 - 400°C [8]. The upper and lower limits of mineable Toyoha veins become deeper southeastwards [4, 20]. The epithermal Pb-Zn-Ag veins are transitional to quartz-(Mn-)calcite veins at shallow depth whereas the xenothermal veins are transitional to quartz-pyrite network veins enveloped by sericite-dominant altered host rocks at shallow depth (300 m above sea level) [11, 23]. Au grade is locally up to several tens of g/t at shallow epithermal ores as well as deep high grade Cu zone of xenothermal ores [3].
Vein textures and subsidiary textures in bonanza zones	Textures: crustiform banding, colloform,cockade and brecciated. Subsidiary textures: comb, microcrystalline, colloform, fibrous, dendritic, flamboyant, ghost-sphere and pseudo-acicular [17]	Massive, crustiform banding, colloform, cockade, brecciated. Subsidiary textures: microcrystalline, colloform, fibrous, dendritic and replacement [9, 11, 18, 20]. Xenothermal veins commonly show fine-grained Kuroko-like ore with rhythmic zoning both in single crystal and in colloform aggregates [7].
Intepretation of vein textures and subsidiary-textures	Quartz morphology combined with fluid inclusion studies suggests that boiling of fluid occurred repeatedly, leading to silica-supersaturated conditions with respect to quartz and resulting in the formation of the various quartz textures and subsidiary textures [17].	Combined with a mineralogical study [9], the fine-grained Kuroko-like ores were interpreted as a result of ore precipitation from sulfide-supersaturated fluids caused by dynamic pulsating injections of ascending high-temperature (350-400°C) fluids just above the brittle-plastic transition zone [7].
Mineralization ages	1.4 - 0.85 Ma (Earlier veins: 1.4 Ma, Later veins: 1.2 - 0.85 Ma) [17, 18]	2.93 - 0.49 Ma (Epithermal veins: 2.93-1.60 Ma, Xenothermal veins: 2.68 - 0.49 Ma) [13].
Old mineralizing systems	None	Miocene Pb-Zn veins (12.5 - 8.4 Ma and 24.6 Ma) pervasively occurred south-to-southeast of Toyoha, especially at great depth, though these veins were not economical [14,16].
Contemporaneous volcanic rocks	Andesite (1.2 - 0.8 Ma) within 10 km west of the mine [17].	Andesite (3.2 - 2.9 Ma) within 5 km south of the mine [14, 22].

Table 1. (Continued)

	Koryu	Toyoha
Evidence of boiling of fluids	Presence of vapor-rich fluid inclusions in several minralization stages (17)	Fluid inclusions with variable vapor/liquid ratios existed in an epithermal quartz vein exposed to the surface (15)
Homogenization temperature	151 - 317 °C (17)	150 - 315°C Epithermal veins: approx. range of 150 - 250°C(10, 15, 20) Xenothermal veins: approx. range of 200 - 315°C (11, 20)
Intepretation of homogenization temperature	The formation temperatures of earlier veins show slightly higher temperatures (263 - 283°C) than those of later veins (206 - 260°C) (17).	Combined with the data of mineral-equilibrium temperatures (9), the formation temperatures of xenothermal mineralization could be up to 400°C (8). The shallow epithermal quartz veins (< 450m of paleodepth) formed at lower temperatures (157-219°C) (15).
Salinity	0.5 - 3.0 wt% NaCl equiv.except for the first stage of the later episode (L-I, 0.5 - 6.0 wt%) which was slightly enriched in base metals (17).	Epithermal veins: 0.0 - 6.7 wt% NaCl equiv. (10,11,15,20). The shallow level (< 450m of paleodepth) of epithermal quartz veins: 0.0 - 0.9 wt% (15). Xenothermal veins: 0.8 - 8.5 wt% (11,15,20).
Interpretation of salinity	Ore fluids were generally low-saline fluids (up to 3.0 NaCl wt% equiv.) (17).	Ore fluids were low to moderate saline fluids (up to 8.5 NaCl wt% equiv.) (10,11,15,20).
Paleodepth	430 - 850 m (17)	Epithermal veins: 450 - 850 m (15,18).
δD fuids	-85 ~ -78 (‰) (17)	n.d.
$\delta^{18}O$ fluids	-9.8 ~ -5.3 (‰) (17)	-10.5 ~ -3.2 (‰) (6,15).
Interpretation of stable isotope data	Ore fluids were dominantly meteoric water in origin (17).	Ore fluids were dominantly meteoric water in origin though the xenothermal fluids were more enriched in deep fluids (magmatic fluids ? and fluids that were well -interacted with $\delta^{18}O$-rich rocks ?) than the epithermal fluids (6,15).
Cause of metal precipitaion	Intermittent boiling of fluids (17).	Mixing of shallow meteoric water with deep fluids (6).

Abbreviations: ac-ag = acanthite-aguilarite, ad =adularia, asp = arsenopyrite, cal = calcite, chl/sm = chlorite/smectite interstratified minerals, di = dickite, cp = chalcopyrite, el = electrum, gn = galena, hm = hematite, In-sp = Indium bearing sphalerite, ka = kaolinite, ma = marcasite, mg = magnetite, po-pe = polybasite-pearceite, py = pyrite, pyrr = pyrrhotite, pyro = pyrophyllite, qz = quartz, rho = rhodochrosite, ser = sericite, st = stannite, sp = sphalerite, tet-ten = tetrahedrite-tennantite, yo = yohannsenite, wt = wurtzite

References : 1, Hasegawa et al. (1987); 2, Isobe, 1990; 3, Kanbara and Kumita 1990; 4, Kuwahara et al. (1983); 5, Kurosawa and Suga (1991); 6, Matsuhisa et al. (1986); 7, Ohta (2004); 8, Ohta (1995); 9, Ohta (1989); 10, Ono and Sato (1994); 11, Sanga et al. (1992); 12, Sato et al. (2004); 13, Sawai et al. (1989); 14, Shimizu and Aoki in prep. (2005); 15, Shimizu and Aoki (2001a); 16, Shimizu and Aoki (2001b); 17, Shimizu et al. (1998); 18, This study; 19, Toyoha Mining Co., Ltd. (2003); 20, Yajima and Ohta (1979); 21, Watanabe (1990a); 22, Watanabe (1990b); 23, Yoshie pers.com. (2001)

Hydrothermal alteration

The hydrothermal alterations at Koryu and Toyoha are summarized in Table 1. The hydrothermal alteration at Koryu is generally weak and restricted to the vein margin while those at Toyoha are intense and pervasive around ore veins.

Physical dimensions, mineralogy and metal zonings

The physical dimensions (numbers of productive veins, area of vein swarm, vein orientation, vein thickness and elevation of exploitation) of each deposit are summarized in Table 1.

The physical characteristics suggest that Koryu has an extremely small mineralizing system compared to that of Toyoha. The mineralization episode, mineral assemblage, mineralogy and metal zoning in each deposit are also summarized in Table 1.

Vein textures

Shimizu et al. (1998) defined the terms of "structure" and "texture" for Koryu quartz features described in hand specimens and under the microscope, respectively. "Structure" and "texture" correspond to "texture" and "subsidiary texture", respectively, by extending to their use to sulfide-dominant vein features of Toyoha in this study. The vein textures and subsidiary textures in each deposit are summarized in Table 1. Variable vein textures and subsidiary textures are seen throughout ore veins, especially at bonanza zones in each deposit. Some interpretations of these textures are also summarized in Table 1.

Age of mineralization

The K-Ar ages for adularia in Koryu Au-Ag veins and those for sericite in host rocks proximal to Toyoha base metal veins are summarized in Table 1. These ages have been interpreted as the age of metal deposition for each deposit (Sawai et al., 1989; Shimizu et al., 1998). The data suggest that the Koryu mineralizing system is rather short and monotonous while that of Toyoha is long and overprinted on old (chronologically distinct) mineralizing systems as shown in Table 1. The range of mineralization ages at Koryu (1.4-0.85Ma) is partly overlapped with the Plio-Pleistocene mineralization ages of Toyoha (2.93-0.49Ma). Each range of the mineralization ages at Koryu and Toyoha are contemporaneous with the nearby volcanisms as shown in Table 1.

Fluid inclusion studies

The fluid inclusions studies were conducted on quartz at Koryu and quartz and sphalerite at Toyoha (e.g., Yajima and Ohta, 1979; Shimizu et al., 1998). Evidence of boiling hydrothermal fluids is summarized in Table 1. Homogenization temperature and salinity data, and their interpretations at both deposits are also summarized in Table 1.

Depth of emplacement

Paleodepth of mineralization for each deposit is shown in Table 1. At Koryu, hydrothermal mineralogy and fluid inclusion study (Shimizu et al., 1998) showed that a bonanza gold mineralization at the 30 m mine level (480 m above sea level), Vein 3 developed at a shallow depth (< 1000m). At Toyoha, the shallowest and the deepest mineable level of epithermal veins are estimated as 450m and 850m from the paleosurface, respectively, using the fluid inclusion data by Shimizu and Aoki (2001a). Although the paleodepth of the Toyoha xenothermal mineralization has not been specified, the mineable xenothermal veins extend to a depth at least 150 m longer than mineable epithermal veins (Toyoha Mines Co., Ltd. 2003). This study shows that the paleodepths of the epithermal mineralization zone of Koryu and Toyoha were partly overlapped.

Stable isotope studies

Stable isotope data are summarized in Table 1. Oxygen and hydrogen isotopic analyses were conducted on quartz samples from Koryu (Shimizu et al., 1998). Oxygen isotopic study has also been performed on quartz samples from Toyoha (Matsuhisa et al., 1986; Shimizu and Aoki, 2001a; this study). The stable isotope data combined with fluid inclusion data have been interpreted as shown in Table 1.

Mechanism of metal precipitation

Vein texture, fluid inclusion and stable isotopic studies suggest different causes of ore precipitation between Koryu and Toyoha (Table 1).

Discussion

Although Koryu and Toyoha mineralization shows some similarities (vein textures, partly overlapping formation ages and paleodepths, d^{18}Ofluids values and vein formations contemporaneous with the nearby andesitic volcanisms), the characteristics of ore formation (wall-rock alteration, physical dimensions, mineralogy and mechanism of metal precipitation) were different between the two deposits as described in the previous sections.

The magmatic-hydrothermal system at Koryu is rather small and short-lived without intense hydrothermal alteration. There is no nearby old hydrothermal system related to precious or base metal mineralization overprinted on the Pleistocene (1.4-0.85Ma) mineralization. Compared to the ore fluids at Toyoha, those at Koryu were poor in chlorine. The H2S/Cl ratio in ore fluids might be higher than those of Toyoha, leading to precious metal transportation to the ore site as bisulfide complexes (e.g., Seward, 1989) possibly from magma superior to base metal transportation as chloride complexes (e.g., Helgeson, 1969).

In contrast, the Plio-Plesitocene magmatic-hydrothermal system at Toyoha is large and long-lived, and overprinted on the old hydrothermal systems associated with base metal mineralizations. The large magmatic-hydrothermal systems could generate large amounts of chlorine-enriched fluids from magma and possibly from deep host rocks as a result of intense hydrothermal alteration. The base metals transportation to the ore site as chloride complexes could be superior to precious-metal transportation as bisulfide complexes possibly from magma during the epithermal and xenothermal mineralizations. The overprinting hydrothermal systems indicate that base metals could also be remobilized from old ores by deep saline fluids during the Plio-Pleistocene mineralization. The rare -metals such as indium and tin could be mainly carried by rejuvenated deep-circulated fluids from reduced magma interacted with basement rocks during the xenothermal mineralization (Ohta, 1995).

Watanabe (2002) and Yahata (2002) compiled the data of geology, formation ages and types of metal deposits at Sapporo-Iwanai district: A large number of Au-Ag deposits occurred in subaerial andesitic terrains in Plio-Pleistocene whereas many Pb-Zn-Cu deposits occurred related to volcanisms during the upheaval from submarine to subaerial environments in middle-to-late Miocene. Toyoha deposit is one of the exceptions formed by Plio-Pleistocene subaerial-magmatic hydrothermal systems. My study suggests that the size, life span of magmatic-hydrothermal system and overprinting on the different mineralizing systems could constrain the type of metal deposits (precious and polymetallic deposits) nearby subaerial andesitic volcanoes in Plio-Pleistocene. A large polymetallic deposit could be formed by a large and long-lived magmatic-hydrothermal system overprinted on the old base metal mineralizing system.

Conclusions

The Koryu Au-Ag epithermal deposit was formed by a small and short-lived subaerial magmatic-hydrothermal system in Pleistocene, while the Toyoha epithermal and xenothermal deposits were formed by large and long-lived subaerial magmatic-hydrothermal systems in Plio-Pleistocene, overprinting on the old base metal mineralizing systems.

The size, life span of magmatic-hydrothermal system, and overprinting on the different mineralizing systems could constrain the type of metal deposits (precious and polymetallic deposits) nearby subaerial andesitic volcanoes in Plio-Pleistocene.

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