Doctoral thesis

Orogenic type gold mineralization in the North Khentei gold belt, Central Northern Mongolia

（北モンゴル中央部北ケンテイ金鉱床帯における造山帯型金鉱化作用）

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July 2015

CONTENTS

Chapter I

1. INTRODUCTION

The objectives of my study are to characterize the gold mineralization processes and crystallization sequences of ore-forming minerals in representative deposits of the North Khentei orogenic gold belt of Mongolia, in an effort to construct a genetic evolution model for the gold mineralization. This study is based on mineral assemblages, petrographic textural analysis, mineral compositions, hydrothermal alteration assemblages, fluid inclusion studies and age dating analysis.

Chapter II

2. REGIONAL GEOLOGY OF THE NORTH KHENTEI GOLD BELT

Northern and eastern Mongolia is comprised of numerous terrains accreted onto the south-eastern edge of the Siberian Craton during the several Paleozoic orogenic pulses (Sengör and Natal'in 1996; Badarch et al. 2002). One of which is Haraa (Backarc/forearc basin) terrain, and it is located in the central northern part of Mongolia.

In this region, well developed structures that are north to west oriented (~N30^0 W) faults and fracture zones, intersect the Yeroogol fault and these intersections are considered favorable for gold mineralization (Cluer et al., 2005). The Gatsuurt, Boroo and Ulaanbulag deposits are situated in the part of tectonic setting along the Yeroogol fault.

Chapter III

3. LOCAL GEOLOGY

3.1 Geology of the Gatsuurt deposit

The Gatsuurt deposit is underlain by early Permian Zuunmod volcanic rocks and the early Paleozoic Boroogol granitoid complex. These basement rocks are in fault contact with late Proterozoic to early Paleozoic Kharaa Formation metasedimentary rocks (Hendry et al., 2006). The Gatsuurt ore body is geographically divided into the Central and Main zones adjacent to the sub-vertical Sujigtei fault (Hendry et al., 2006). The Central zone lies on the southeast hanging wall side of the Sujigtei fault, whereas the Main zone is on the northwest side of the fault, approximately 750 m southwest of the Central zone. The two zones initially formed as a single deposit, and were subsequently displaced by post-mineralization sinistral movement along the Sujigtei fault (Hendry et al., 2006).

3.2 Geology of the Boroo deposit

The Boroo deposit is situated along the NE-trending thrust fault structure with dips of 10 ˚NW. This structure is a branch of the Yeroogol fault (Kotlyar et al., 1999; Cluer et al., 2005), and is embedded in the metasedimentary rocks of the Kharaa Formation (Gerel et al., 1999) and granitoids of the Boroogol intrusive complex (Tumur et al., 1995). Those wall rocks are intruded by numerous late Paleozoic diorite dikes and granites (Cluer et al., 2005).

3.3 Geology of the Ulaanbulag deposit

The Ulaanbulag deposit is hosted by granite and granodiorite of the Boroogol intrusive complex (Tumur et al., 1995) and overlying metasedimentary rocks of the Kharaa Formation (Gerel et al., 1999), and these rocks are commonly separated by flat lying thrust fault.

3.4 Geology of the Khadat deposit

The Khadat copper deposit is situated in the Bayantsogt Soum of Tuv province, Central northern Mongolia. The Khadat deposit area belongs to the Kharaa forearc or backarc basin terrane (Badarch et al., 2002), and the area lies on the south extension of the North Mongolian Copper-Molybdenite and Orogenic gold belt.

Chapter IV

4. MATERIALS AND METHODS

4.1 Materials

4.1.1 Samples from the Gatsuurt deposit

Fifty-two samples were collected from drill cores taken in the Central and Main zones.

4.1.2 Samples from the Boroo deposit

Ore samples for this study were taken from open-pits in the Zones 2, 3, 5 and 6, and also from drill cores. Thirty-five disseminated and stockwork ores were hosted in granite, metasedimentary rocks and diorite dikes, and twenty-one auriferous quartz vein ores were collected at depths ranging from 1150 to 1040 m in elevation. Fifty polished thin sections were made for mineralogical study.

4.1.3 Samples from the Ulaanbulag deposit

Fifty-four samples were collected from drill cores in the deposit. The among these samples, thirty-two representative samples of the disseminated and stockwork ores and twenty-two representative samples of the siliceous ores were collected at depths ranging from 1050 to 840 m in elevation. Twenty polished thin sections were made for mineralogical study.

4.1.4 Samples from the Khadat deposit

Forty-nine samples were collected from drill cores in the Khadat copper deposit. Among the total samples, twenty-six representative ore samples were selected from surface to 100s meters in depth, and those are mostly oxidized, and show only chalcopyrite that occur as veins in fractures of metasedimentary rocks.

4.2 Methods

4.2.1 Petrological study

Fifty, fifty and twenty polished thin sections are prepared for petrological study for the Gatsuurt, Boroo and Ulaanbulag deposits, respectively. The study of ore minerals in polished section used the polarizing reflected light microscope for the identification and characterization of the ore mineral phases in a sample and the textural relationships between them. Usually ore minerals textures are recognized high magnification (400X) and it was dependent on grain size of minerals.

4.2.2 Chemical analysis of minerals

Chemical compositions of ore minerals were determined using a JEOL JXA 8530F electron microprobe analyzer (EMPA) at Shimane University.

4.2.3 X-ray powder diffraction analysis

Alteration minerals were carried out by X-ray powder diffractometer (XRD) and optical microscope.

4.2.4 Fluid inclusion analysis

Fluid inclusions in quartz were first observed using a transmitted light binocular microscope, and inclusion size, shape and distribution were recorded.

4.2.5 U-Pb age dating in zircon by LA-ICP-MS analysis

Zircon grains separated from the rock samples or thin sections carrying zircon grains were embedded in epoxy for LA-ICP-MS analyses, together with grains of standard zircon. Grains of zircon were analyzed for U–Th–Pb dating by a Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) at Hiroshima University.

Chapter V

5. RESULTS

5.1 Petrological study

5.1.1 Petrography of the Gatsuurt deposit

Pyrite and arsenopyrite are abundant in the disseminated and stockwork, quartz vein and silicified ores. These ores also contain moderate amounts of galena, tetrahedrite-tennantite, sphalerite and chalcopyrite, and minor amounts of other minerals including jamesonite, bournonite, boulangerite, geocronite, scheelite, geerite, native gold, and zircon. Abundances and grain sizes of the ore minerals vary in ores with differing host rock.

5.1.2 Petrography of the Boroo deposit

The disseminated and stockwork ores mainly contain pyrite and arsenopyrite, minor sphalerite, galena and tetrahedrite, and trace amounts of chalcopyrite, bournonite, boulangerite, alloclasite and native gold.

5.1.3 Petrography of the Ulaanbulag deposit

The main ore minerals in the deposit are pyrite and arsenopyrite, and minor minerals are chalcopyrite, galena, sphalerite and tetrahedrite. Ore mineral abundances, localities and grain sizes are variable in the disseminated and stockwork ores and siliceous ore types.

5.1.4 Petrography of the Khadat deposit

The copper mineralization occurs as vein type ores in the metasedimentary rocks and granodiorite, and the mineral assemblages in ores are varied depending on depth of the deposit. The main ore mineral in the shallow parts of deposit, which from surface to 100s meters in depth, consists of chalcopyrite and its oxidized secondary minerals as malachite and azurite, and very rarely sphalerite and pyrite are observed. However, the ores in range from 100 to 200s meters of depth commonly show assemblages of chalcopyrite, sphalerite, galena, pyrite, arsenopyrite and rarely pyrrhotite. The ores occurring from 200 to 250s meters of depth represent the disseminated and stockwork mineralization in metasedimentary rocks. It mainly consists of the assemblages of chalcopyrite, pyrite and arsenopyrite.

5.2 Mineral chemistry

5.2.1 Mineral chemistry of the Gatsuurt deposit

Pyrite-I in the disseminated and stockwork ores has almost ideal composition. In contrast, pyrite-II in the disseminated and stockwork ores exhibits strong chemical zoning due to As contents of up to 4.6 wt%, and Au up to 0.99 wt%. In the quartz vein ores, pyrite-I has ideal composition, whereas pyrite-II contains trace amounts of Au and <0.94 wt% As, but chemical zoning is not remarkable. Pyrites in the silicified ores contain 1.10-4.64 wt% As and up to 0.19 wt% Au. Arsenopyrites from the three ore types show significantly low As and high S contents relative to Fe. Arsenopyrite-I in the disseminated and stockwork ores shows no detectable chemical variation, whereas arsenopyrite-II exhibits weak chemical zonation due to varying As content. Arsenopyrite-II in the disseminated and stockwork ores and arsenopyrite in the silicified ores contain up to 0.74 wt% and 0.11 wt% Au, respectively. Chalcopyrite in the disseminated and stockwork ores and quartz vein ores contain up to 0.2 wt% Au. Tetrahedrite in the disseminated and stockwork ores has Ag, As and Te contents of up to 1.02, 3.03 and 0.25 wt%, respectively. Tetrahedrite and tennantite in the quartz vein ores contain variable amounts of Ag and As, and a small amount of Au. Native gold in the three ore types shows variable composition. That in the disseminated and stockwork ores is most auriferous, containing up to 97.97 wt% Au and 1.09 wt% Ag. Maximum Au content of native gold in the quartz vein ores is lower at 92.73 wt% Au, and 7.45 wt% Ag, and that in the silicified ores lower still at 90.88 wt% Au and 8.78 wt% Ag.

5.2.2 Mineral chemistry of the Boroo deposit

Pyrite-I contains trace amounts of Au, Pb, Bi and Co in both ore types. Pyrite-II in the disseminated and stockwork ores contains up to 4.50 wt% arsenic. Pyrite-II in both ore types contains small amounts of Au, Cu, Pb, Bi, Sb, Co, Cd and Ni. Arsenopyrite-I is relatively poor in As, whereas As content in arsenopyrite-II reaches 0.81 apfu. Arsenopyrite in the auriferous quartz vein ores does not show significant compositional difference. Galena in both the ore types contains Bi, and small amounts of Ag and Cd. Chalcopyrite in both ore types contains very small amounts of Bi, Pb and Au. Tetrahedrite in the disseminated and stockwork ores shows chemical variation caused by substitutions of Ag for Cu and of As for Sb. Tetrahedrite in the veins is considerably enriched in Ag, and also contains Bi and Cd. Tennantite rarely occurs on the rim of tetrahedrite, but only in the auriferous quartz vein ores. Native gold in the disseminated and stockwork ores has Au and Ag contents ranging between 85.22 and 92.82 wt% and from 13.47 to 7.77 wt%, respectively. In contrast, Au and Ag contents in native gold in the auriferous quartz vein ores range between 93.29 and 96.56 wt% and 7.68 and 4.88 wt%, respectively. Electrum contains 52.9 to 77.2 wt% Au, 22.93 to 42.69 wt% Ag, 0.15 to 0.76 wt% Te, and up to 2.03 wt% Cd.

5.2.3 Mineral chemistry of the Ulaanbulag deposit

Most pyrite grains exhibit chemical zoning. Early generation pyrite-I rarely contains Ni up to 0.12 wt% and Co reaches up to 3.17 wt%, whereas later generation pyrite-II contains constantly As up to 4.9 wt%, and shows concentric chemical zoning with As. Arsenopyrite has also a strong chemical zonation due to As-deficiency. Pyrite-II and arsenopyrite-II in both ore types contain Au up to 0.09 and 0.13 wt%, respectively. Galena in both the ore types consistently contains Cd, Bi and Ag. Native gold grains contain 86.67-87.97 wt% Au, 15.09-16.27 wt% Ag and 0.59-1.73 wt% Te. Au:Ag ratios of native gold in the both ore types are constant.

5.3 Wall rock alteration analysis in the Gatsuurt deposit

Sericite, quartz, albite and microcline gangue minerals were identified by X-ray powder diffraction in the disseminated and stockwork ores, whereas only quartz was identified in the quartz vein ores and silicified ores.

5.4 Fluid inclusion analysis

5.4.1 Fluid inclusion study on the Gatsuurt deposit

In the disseminated and stockwork ores, fluid inclusions occur within quartz as clusters and as two- or three-dimensional arrays. Sample from the disseminated and stockwork ores in the Main zone contains type I, II and III fluid inclusions with homogenization temperatures of 194 – 327ºC, 194 – 282ºC and 208 – 240ºC, respectively. Sample from the disseminated and stockwork ores in the Central zone contains type I and II fluid inclusions with homogenization temperatures of 289 – 355°C and 254 – 292°C, respectively.

5.4.2 Fluid inclusion study on the Boroo deposit

Two generations of quartz veins, which are narrow quartz veins and discrete quartz veins in granite have been selected for fluid inclusion study. Two types of primary fluid inclusions are identified: (I) CO_2-rich inclusions and (II) aqueous inclusions. Homogenization temperatures of type I and II were at 317 to 362ºC and 237 to 305ºC, and corresponding salinities were 3 to 6 wt% and 3.6 to 5.4 wt% (NaCl equiv.), respectively.

5.5 Age dating analysis

5.5.1 Zircon LA-ICP-MS U-Pb age dating in the Boroo deposit

Zircon grains from granite show very strong magmatic oscillatory zoning in backscattered electron (BSE) images. The weighted mean age ($^{206}Pb/^{238}U$) of all points is 467.5 ± 5.1 Ma (95% conf.). Th/U-ratios are 0.22 - 0.75 > 0.1. These ages correlate with 467.5 ± 5.1 Ma that corresponds to the timing of the igneous event of the granite.

5.5.2 Zircon LA-ICP-MS U-Pb age dating in the Khadat copper deposit

The weighted mean age ($^{206}Pb/^{238}U$) of all analyses is 274.2 ± 1.7 Ma (95% conf.), and all data are close to a Concordia of ca. 270 Ma (Fig. 31). Th/U-ratios of all data lies between 0.20 and 5.33.

Chapter VI

6 DISSCUSION

6.1 Mineralization of the Gatsuurt deposit

6.1.1 Mineralization stages and gold deposition

Three types of gold mineralization are defined in this study, based on the occurrence of the ores and their ore mineral assemblages: disseminated and stockwork ores, quartz vein ores, and silicified ores. According to their mineral assemblages and compositional changes of ore minerals and textures, each ore type can be sub-divided into several mineralization stages. The disseminated and stockwork mineralization is divided into four stages (I, II, III and IV), as defined by assemblages of pyrite-I + arsenopyrite-I; pyrite-II + arsenopyrite-II; galena + tetrahedrite + sphalerite + chalcopyrite + jamesonite +

bournonite + scheelite; and boulangerite + native gold, respectively. Four stages are also recognized in the quartz vein mineralization: stage I is characterized by pyrite-I; stage II by the assemblage pyrite-II + arsenopyrite + galena + Ag-rich tetrahedrite-tennantite + sphalerite + chalcopyrite + bournonite; stage III by geocronite + geerite + native gold; and stage IV by native gold. The mineralization of the silicified ores comprises stage I, as defined by the assemblage pyrite + arsenopyrite + tetrahedrite + chalcopyrite; and stage II, characterized by sphalerite + galena + native gold.

6.1.2 General process of ore mineralization

The textures of the ores, the mineral assemblages present, the mineralization sequences and the fluid inclusion data determined here are consistent with orogenic classification (cf. Groves et al., 1998) for the Gatsuurt deposit.

6.2 Gold mineralization of the Boroo deposit

6.2.1 Mineralization stages and gold deposition

Two distinct types of ores were defined. The disseminated and stockwork ores were produced by early stage mineralization, and the auriferous quartz vein ores by later stage mineralization. Four modes of gold occurrence are recognized in these two ore types: i) "invisible" gold in pyrite and arsenopyrite in both ore types; ii) microscopic native gold, 3 to 100 μm in diameter, that occurs as grains filling fine cavities or as an interstitial phase in sulfides in both ore types; iii) visible native gold grains, up to 1 cm in diameter, in the auriferous quartz vein ores; and iv) electrum in the auriferous quartz vein ores. In accordance of the mineral assemblages, textures and compositional changes of ore minerals of the disseminated and stockwork ores and auriferous quartz vein ores, several mineralization stages were identified.

The disseminated and stockwork mineralization is divided into four stages (I, II, III and IV), as defined by assemblages of pyrite-I + arsenopyrite-I; pyrite-II + arsenopyrite-II; sphalerite + galena + chalcopyrite + tetrahedrite + bournonite + boulangerite + alloclasite + native gold; and native gold, respectively. In the auriferous quartz vein ores, five mineralization stages are recognized: stage I is characterized by pyrite-I; stage II by pyrite-II + arsenopyrite; stage III by the assemblage sphalerite + galena + chalcopyrite; stage IV by Ag-rich tetrahedrite-tennantite + bournonite + geerite + native gold; and stage V by electrum.

6.2.2 Mineralization condition

Based on the As-Au relations observed in this study, "invisible" gold is attributed to Au^{+1} in pyrite-II and arsenopyrite, because most of the 501 EMPA analyses determined here fall below the solubility limit of gold in pyrite and arsenopyrite. Gold mineralization based on the gold remobilization mechanism was not considered for the Boroo deposit in this study. Coarse native gold grains and low sulfide contents in this ore type suggest that they were formed by a later stage gold mineralization. Electrum may also have precipitated from the gold-saturated ore fluids during gradual cooling at the latest stage.

6.3 Gold mineralization of the Ulaanbulag deposit

Two types of gold mineralization are defined in the deposit and ore mineral assemblages. The disseminated and stockwork mineralization is divided into four stages (I, II, III and IV): stage I is characterized by pyrite-I + arsenopyrite-I; stage II by pyrite-II + arsenopyrite-II; stage III consisted by assemblage of sphalerite + galena + chalcopyrite; and stage IV by native gold, respectively. Four stages are also recognized in the siliceous type ores: stage I by pyrite-I + arsenopyrite; stage II by pyrite-II + arsenopyrite; stage III by assemblage of sphalerite + galena + chalcopyrite + bournonite + boulangerite; and stage IV by native gold.

6.4 Copper mineralization of the Khadat deposit

Based on mineral assemblages, five crystallization stages (I, II, III, IV and V) are recognized for the vein-type copper mineralization: stage I is characterized by pyrite-I, stage II by pyrite-II + arsenopyrite-I, stage III by pyrite-III + arsenopyrite-II, stage IV by assemblage of pyrrhotite + sphalerite + galena, and stage V by chalcopyrite. The age of intrusive stock determined in this study is 274.2 ± 1.7 Ma.

The arsenopyrite geothermometer was also applied to estimate the temperature-f_{S_2} conditions of the copper mineralization. The estimated temperatures vary from 400 to 495°C, and logf_{S_2} falls in the range of -6.8 to -5.

6.5 Relation of ore types in the gold deposits, and tectonic significance

The auriferous quartz vein type ores developed in granite, and the volume of quartz vein or vein type ores in volcanic and metasedimentary rocks is less than that of the auriferous quartz vein type ore in granite.

The disseminated and stockwork mineralization of the deposit can be interpreted by interaction between the hydrothermal ore fluids and wall rock alteration. This interpretation is supported by the homogenization temperatures of the fluid inclusions up to 355 to 365 ºC in the Gatsuurt and Boroo deposits. However, the silicified ores in the Gatsuurt deposit are different from the disseminated and stockwork ores, the auriferous quartz vein ores and siliceous type ores in the Ulaanbulag deposit, in terms of the ore mineral assemblages and distributions, strong siliceous alteration, high Au grade, host rock that consists of fine to micron sized quartz grains, ore body shape and localization.

6.6 Classification of the gold deposits in the North Khentei gold belt

The NKGB is considered to have formed by granitoid intrusive activity during the final closure of the Mongol-Okhotsk Ocean by the collision along the Mongol-Okhotsk belt in the middle Triassic to middle Jurassic (Zorin et al., 2001; Gordienko et al., 2012; Hara et al., 2013). The NKGB is hosted in the Haraa terrane, which is interpreted as accretionary to collisional, subduction-related orogen region (Badarch et al., 2002). Thus, the NKGB has very similar geology and geotectonic settings with the model of orogenic type deposit by Groves et al. (1998). Moreover, structure controls, geochemistry of alteration, ore mineral association, and fluid inclusion of the gold deposits in the NKGB correspond to the overall features of the orogenic classification.

6.7 Implication to gold mineralization in the North Khentei gold belt

The deposits mainly consist of the disseminated and stockwork type and vein type ores, such as the auriferous quartz vein ores in the Boroo deposit, the quartz vein and silicified type ores in the Gatsuurt deposit and siliceous type ores in the Ulaanbulag deposit. They have almost identical ore mineral assemblages and mineralization stages. The occurrences of native gold in these deposits are also very similar to each other. Arsenopyrite-II in the disseminated and stockwork ores of the deposits is comparable with homogenization temperatures of up to 355ºC for fluid inclusions in quartz from the disseminated and stockwork ores in the Gatsuurt and Boroo deposits (Khishgee et al., 2014). These are considered as common features of the gold mineralization in the NKGB.

The common features of the deposits described above strongly indicate that these deposits formed from the same source of the hydrothermal activity in this region (Fig. 41). Therefore, the gold mineralization of the Gatsuurt, Boroo and Ulaanbulag deposits is classified into orogenic type, and other deposits distributing in the NKGB, such as the Baavgait, Ereen, Sujigtei, Urt and Tsagaanchuluut deposits, are also regarded to belong to the same type as that of the Gatsuurt, Boroo and Ulaanbulag deposits, because those deposits are situated in the same tectonic settings (Figs. 1, 2, 41).

Chapter VII

7. CONCLUSIONS

The Boroo, Gatsuurt and Ulaanbulag deposits consist of the disseminated and stockwork ores and the vein type ores which includes the auriferous quartz vein ores, quartz vein ores, siliceous ores and silicified ores. The disseminated and stockwork mineralization in gold deposits consists of four stages, separately. The vein type mineralization consists of four and two, five, and four mineralization stages in the quartz vein ores and silicified ores for the Gatsuurt deposit, auriferous quartz vein ores for the Boroo deposit, and siliceous type ores for the Ulaanbulag deposit, respectively.

Gold mineralization can be formed from the same source of the hydrothermal activity in this region. Thus, the gold deposits can be classified as contiguous orogenic type mineralization.

Similar features on the mineral assemblages and mineralization stages would hold for other deposits in the NKGB, and illustrate the general properties of gold mineralization in this belt.