Bonanza-grade accumulations of gold tellurides in the Early Cretaceous Sandaowanzi deposit, northeast China

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Abstract

The Sandaowanzi epithermal gold deposit (0.5 Moz or ca. 14 tons), located at the northern edge of the Great Xing'an range, NE China, is unique in that nearly all the gold (>95%) is contained in gold tellurides mostly in bonanza grade ore shoots (the highest grade being up to 20,000 g/t). The bonanza ores are hosted in the central parts of large-scale (> 3 m wide, 200 m long) quartz veins which crosscut Early Cretaceous andesitic trachyte and trachytic andesite, and are, in turn, crosscut by diabase dykes of similar age. There are two ore types: low-grade disseminated ores and high-grade vein ores. In the former, very fine grains of Ag-rich tellurides (mainly hessite and petzite) coexist with sulfides (pyrite, sphalerite, galena and chalcopyrite), occurring as disseminated grains or sometimes as grain aggregates. In the high-grade vein ores, coarse-grained Au–(Ag)–tellurides (calaverite, sylvanite, krennerite, and petzite) form a major part of quartz–telluride veins. Chalcopyrite forms separate monomineralic veins emplaced within the quartz–telluride veins. Spectacular textures among coarse-grained (up to 3 cm in diameter) tellurides, and micron-scale bamboo shoot-like grains are observed. Two- and three-phase telluride symplectites are common in the vein ores.

Fluid inclusion studies suggest that the mineralizing fluids are a mixture of magmatic and meteoric fluids, that homogenized in the temperature range of 260–280 °C. Sulfur isotope compositions of pyrite and chalcopyrite (δ34S = 1.64 to 1.91‰) support the origin of fluids from a deep source. It is suggested that faulting, temperature changes and variation in f2S and f2Te were major factors contributing to the two main types of mineralization and the differences between them. Early rapid cooling and subsequent slow cooling of the later fluids along fault and fracture zones were instrumental in formation of the two superposed ore types. Open-space filling and crack-sealing along fractures predominates over replacement during telluride mineralization. The Sandaowanzi deposit is a unique bonanza-grade accumulation of gold tellurides genetically related to subalkaline magmatism, which was genetically associated with Early Cretaceous regional extension.

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1. Introduction

Gold telluride minerals are common accessory components of a number of world-class epithermal gold systems (e.g., Ciobanu et al., 2008; Cook et al., 2009; Cooke and McPhail, 2001; Pals andSpry, 2003; Thompson et al., 1985; Wallier et al., 2006; Zhang and Mao, 1995). A limited number of epithermal deposits can, however, be referred to as gold telluride deposits (Cook et al., 2009) because Au and Au–Ag–tellurides contribute to an economically significant part (10–50%) of the total gold budget (e.g., Golden Sunlight, Montana, Spry et al., 1997 or Emperor, Fiji, Pals and Spry, 2003). In exceptional cases (e.g., Sacarab, Romania; Ciobanu et al., 2008), gold occurs dominantly as tellurides such as sylvanite (AuAgTe2), petzite (AuAg3Te2) and nagyagite ([Pb (Pb, Sb) S2] [(Au, Te)]) and these tellurides are generally accompanied by native gold, base metal sulfides, arsenides, and in some cases, bismuth-bearing compounds (e.g., Ciobanu et al., 2005, 2009; Kouzmanov et al., 2005; Sung et al., 2007). They generally occur as micron-scale grains, and in some of the deposits, gold also occurs as invisible gold hosted in pyrite or arsenopyrite (e.g., Kelley et al., 1998; Pals andSpry, 2003; Pals et al., 2003; Sung et al., 2009).

The majority of the deposits in which Au–(Ag)–tellurides are abundant have been related to alkaline or sub-alkaline igneous activity, generally irrespective of geological setting or age of mineralization (e.g., Jensen and Barton, 2000; Liu et al., 2011a; Mao et al., 2003a,b; Richards, 1995; Richards and Ledlie, 1993), Cook and Ciobanu (2005),
Ciobanu et al. (2006) and Cook et al. (2009) have, however, stressed that alkaline or subalkaline magmatism is not necessarily an essential prerequisite of telluride enrichment, because there are a number of significant telluride-bearing deposits associated with calc-alkaline volcanic rocks.

In contrast to almost all telluride-bearing Au deposits reported in the literature, in which both Au–(Ag)–tellurides and native gold/electrum are also present, this contribution deals with the recently discovered Sandaowanzi Te–Au–Ag deposit, N.E. China, in which Au–(Ag)–tellurides account for more than 95% of the total gold budget. Mineralogy, ore textures, fluid inclusions and sulfur isotopes were studied in order to characterize the deposit and to place constraints upon ore genesis.

2. Geological setting and ore deposit geology

2.1. Regional geology

Mesozoic subduction of the Izanagi Plate beneath the Eurasian Plate affected the eastern margin of the Eurasian continent. Large-scale loss of the lithospheric keel occurred in the North China Craton during the Early Cretaceous (Gao et al., 2004; Liu et al., 2005, 2006, 2008; Menzies et al., 1993; Wu et al., 2005; Xu, 2001). A vast area from northern China to Baikal in Russia underwent regional extension, which was characterized by widespread development of metamorphic core complexes, extensional basins (Fig. 1; Darby et al., 2004; Liu et al., 2005, 2008, 2011b; Zorin, 1999), and extensive magmatism (Wu et al., 2005).

Fig. 1. Cretaceous tectonic subdivision of the eastern part of the Eurasian continent, revised after Darby et al. (2004) and Liu et al. (2006). I — highly-extended region with metamorphic core complexes; Ia — Northeastern China (NC); Ib — Russian Chita–Baikal (BCB); II — highly-extended region with fault-bounded basins (mostly half-grabens); IIa — Northeast China–Northern Mongolia (NCNM); IIb — South China and Korean Peninsula (SCK); III — weakly-extended western North China. Red star — Beijing, Ub — Ulaanbaatar, X — Xian, Y — Yinchuan; Metamorphic Core complex names: Hh — Hohhot, Ln — Liaonan, Yg — Yagan, Ym — Yunmeng, Wz — Waziyu.
An overall Early Cretaceous tectonic configuration of the eastern Eurasian plate is shown in Fig. 1. The North China Craton (Ia in Fig. 1; Lin et al., 2008; Liu et al., 2005) and Russian Chita–Baikal provinces (Ib in Fig. 1; Donskaya et al., 2008; Zorin, 1999) are dominated by widespread Early Cretaceous metamorphic core complexes and extensive syn-kinematic granitic intrusions. The South China–Korean Peninsula (IIa in Fig. 1; Ren et al., 2002) and Northeast China–Northern Mongolia (IIb in Fig. 1, Liu et al., 2005; Liu et al., 2005, 2008, 2011b) provinces, however, are characterized by widespread occurrence of fault-bounded basins filled with Early Cretaceous volcanic and sedimentary rocks. Both the metamorphic core complexes and fault-bounded basins share many common features. The formation of half-grabens and low-angle detachment faults are possibly attributed to a geometrically asymmetric extensional stress field in the Early Cretaceous. The kinematics of the extensional structures suggests that they resulted from NW–SE extension, which provides constraints on their genetic relationship to Early Cretaceous subduction of the Izanagi Plate beneath the Eurasian continent (Liu et al., 2005, 2008, 2011b).

Magmatic rocks related to regional extension are widespread in the eastern part of the Eurasian continent. In the highly-extended regions of the North China Craton and Russian Chita–Baikal (Fig. 1), plutonic intrusions intrude the lower plates in the metamorphic core complexes (Donskaya et al., 2008; Wu et al., 2005; Zorin, 1999). Volcanic rocks were also deposited in the supra-detachment basins of the metamorphic core complexes in these zones. In the weakly-extended areas of Northeast China–Northern Mongolia, South China, and the Korean Peninsula, there are vast amounts of volcanic rocks (Fan et al., 2003; Ge et al., 1999; Lu et al., 1997; Wang et al., 2006; Zhou and Li, 2000; Zorin, 1999). In northeast China, where the Sandaowanzi gold ore deposit is located, for example, Late Jurassic and Early Cretaceous volcanic rocks cover an area of over 100,000 km² along the Great and Lesser Xing’ an Ranges (Liu et al., 2011a; Zhang et al., 2008). They have a cumulative thickness of up to 4 to 5 km (Song and Dou, 1997; Xie, 2000).

Gold, silver and base metal ore deposits are contemporaneous with the regional extension and related magmatism in northeast China (Liu et al., 2011a; Shao and Wang, 2003; Shao and Zhang, 1999; Wu and Sun, 1999). Mineralization associated with the magmatism is already well documented in both northern and southern China, where gold and base metal mineralization is coeval and genetically associated with extension and magmatism (Fan et al., 2003; Mao et al., 2003a,b; Sun et al., 2007; Yang et al., 2003).

2.2. The Sandaowanzi deposit

The Sandaowanzi gold ore deposit is located at the northeastern corner of the Great Xing’an Range (Fig. 2). The geology of the deposit is characterized by abundant Early Cretaceous volcanic rocks and a large, coarse-grained Jurassic monzogranite stock. The volcanic sequence in the mine area can be subdivided into two formations: the lower Tamulangou Formation and the upper Guanghua Formation (Fig. 3). The former is dominated by alternating trachytic andesites, andesitic basalts, and agglomerates, breccias and tuffs of andesitic composition. The lower part of the volcanic sequence is mainly composed of explosive phase rocks whereas lava flows are dominant in the upper part. The latter consists dominantly of rhyolitic and rarely of andesitic rocks. Rock types include breccias, breccia tuff, welded tuffs and agglomerates. Gold-bearing quartz veins directly intrude trachytic andesite and trachytic andesite breccias of the Tamulangou Formation. They are absent in the Guanghua Formation, although the volcanic rocks in the two formations constitute a continuous sequence. LA–ICP–MS U–Pb zircon dating revealed that volcanism took place at 135.3–124.7 Ma (Liu et al., 2011a). There are also some lacustrine carbonaceous mudstones in some
horizons, in which plant fossils, e.g., Cladophlebis of early Cretaceous age, have been identified.

The Sandaowanzi pluton, a coarse-grained monzogranite overlain by Cretaceous volcanic rocks, mostly outcrops in the southern part of the mining area. Although Lu et al. (2005), and Liu and Lu (2006) suggested that the pluton is Triassic in age, recent U–Pb zircon dating gave an age of 181.6 ± 3.4 Ma (Liu et al., 2011a). Potassium feldspar (40%), plagioclase (30%), quartz (25%), and biotite (5%) are the dominant minerals in the rock, which is massive and is medium- to coarse-grained. Fine-grained granitic dykes (124.7 ± 2.9 Ma, zircon U–Pb; Liu et al., 2011a) and syenitic dykes (135.3 ± 3.9 Ma, zircon U–Pb; Liu et al., 2011a) intruded the Sandaowanzi monzogranite. Some granodioritic and granitic dykes also intruded the Tamulangou Formation in the northern part of the area. Parallel diabase dykes crosscut the volcanic rocks of the Tamulangou Formation as well as the gold-bearing veins. Zircons from these dykes yielded ages of 116 ± 2.4 Ma (Liu et al., 2011a). Therefore, mineralization in the Sandaowanzi gold deposit can be constrained between 125.3 and 116.6 Ma, which is coeval with Early Cretaceous extension and magmatism in eastern Asia (Liu et al., 2006, 2011a,b; Wu et al., 2005).

At the regional scale, NE–NNE-oriented fault-bounded basins control the distribution of volcanic rocks along the Great Xing’an Range and in the nearby Songliao Basin (Wang et al., 2004). At the local scale, the NE-oriented brittle faults offset the mineralized fractures. In Sandaowanzi and contiguous areas, they are locally cut by NNW–oriented en echelon fractures that host Au-bearing quartz veins (Liu and Lu, 2006; Liu et al., 2006; Lu et al., 2005). The latter can are open fractures filled with Au-bearing quartz veins.

Forty gold orebodies in the Sandaowanzi deposit have a total reserve of >0.5 Moz of Au. They are irregular in shape, displaying pinch and swell along both strike and dip (Fig. 4). The orebodies are 130–560 m in length and 1–10 m thick at the surface. Several orebodies lie subparallel to one another and collectively form three ore belts within the mine area (Fig. 4). The I2 orebody is the only one that has been mined to date (Fig. 5a). The orebody strikes 300–315° and dips steeply to NE, with dip angles varying from 50 to 80° (Fig. 4b). The length of the quartz vein in the I2 orebody is over 200 m at the surface and its thickness varies from 3 to 10 m, averaging about 6 m. Present exploration from the +350 m level at surface to the +50 m level at depth reveals that the I2 orebody extends more than 300 m along the dip direction.

There are three types of quartz veins in the orebodies, based on the grain size of quartz, deformation and the mineral composition of the veins. These are: (1) mineralized veins composed mainly of very fine (μm-scale) grains of quartz; (2) coarse-grained mineralized veins; and (3) coarse-grained barren veins. The first type, which is dominant in the mining area, contains fine-grained Ag-rich tellurides and sulfo tellurides, and constitutes the relatively low-grade ores (Fig. 5a). The proportion of ore minerals veins is much greater near the centre of the veins than along their margins. Such veins form the margins (generally >2 m) of the second type of quartz vein, which hosts the high-grade ores. The former were fractured during subsequent deformation and were superimposed by the high-grade veins (Fig. 5b). The latter occurs in the central part of the former and forms the cores of the ore shoots. These are large veins, typically tens of meters along strike and dip, but generally less than a meter thick. Small or micro-scale veins are also observed along the contacts between the first type veins and the large scale high-grade veins. The third type of quartz veins are mostly small-scale and generally crosscut the first two types. Throughout all the orebodies, drusy quartz formed during post-mineralization hydrothermal activity.

Zonation, at scales from hand specimen to that of the deposit, is one of the most spectacular characteristics of the Sandaowanzi deposit and provides insights into the processes involved in mineralization. At the outcrop scale, there is a general zonation across the orebody, i.e., a central zone dominated by high-grade vein ores and outer zones of low-grade disseminated ores on either side. Zonation at sample scale is very obvious in high-grade vein ores from the +170 to +90 m levels of the I2 orebody; a representative sample from the +130 m level is
shown as Fig. 5c. Here, fractured low-grade disseminated ore is filled by later high-grade quartz veins. Coarse euhedral quartz is deposited on the walls of the fractures, with telluride-, chalcopyrite-, and quartz–tellurides veins located sequentially towards the centers of the veins (Fig. 5c). Open spaces partly filled with drusy quartz and euhedral chalcopyrite are observed in the center of the vein (Fig. 5c, corner figure). Recent exploration reveals a general variation trend among the different types of quartz–telluride veins at the deposit scale. The relative distribution of low-grade disseminated ores and high-grade vein ores changes with depth in the deposit. From the +250 m level to +190 m level, the ores are characterized by disseminated mineralization: weakly-mineralized fine-grained quartz veins above +250 m level, very low-grade, mineralized quartz veins from +230 to +190 m level, and low-grade ores from +190 to +170 m level. Between the +170 m and +90 m levels, however, low-grade disseminated ores along the margins of the orebody coexist with high-grade vein ores in the center. There are at least seven high-grade veins at the +130 m level, which display zonation patterns of the type shown in Fig. 5c. Below the +90 m level, the high-grade vein ores disappear and are replaced by low-grade disseminated ores.

Alteration is recognized in the andesites. Silicification may be particularly intense within 20 m of the quartz veins. Further away, alteration includes pyrite, adularia, chlorite and sericite, as well as calcite veining in the volcanic rocks. The type of alteration shows dependence on the composition of the rock type, in that chloritization is dominant in more basic rocks and sericitization and adularization occur in more acid rocks.

3. Analytical techniques

All the analyses were carried out at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing. More than 120 polished thin sections were examined. Microscopic observations were conducted with a reflected light optical microscope and a Hitachi Scanning Electron Microscope equipped with an Oxford IE350 energy-dispersive detector. Doubly-polished thin sections were prepared for analysis of fluid inclusions in quartz. The composition of the fluid inclusion was determined using a Renishaw Invia Reflex-type confocal Laser Raman microspectrometer (LRM). Experimental conditions were: 514.5 nm argon–ion laser; 20 mW laser power; 7 mW laser power at sample surface; 1800 grooves/mm grating; 2 cm$^{-1}$ spectral resolution; spatial resolution of 1 μm (×100 lens); 60 s scan time; and scan range of 0–4000 cm$^{-1}$. The wavenumber accuracy was ±1 cm$^{-1}$.

Geothermometric measurements were carried out with a MDSG 600 heating–freezing stage attached to a ZEISS transmitted-light microscope. Freezing and heating runs were undertaken using liquid nitrogen and a thermal resister, respectively. The lower and upper temperature limits of the stage are −196 °C and +600 °C, respectively, with an accuracy of ±0.1 °C.

Sulfur isotope analyses were performed in the same laboratory. Sulfur isotopes were measured using a gas isotope ratio mass spectrometer (IRMS). Isotopic data are reported in per mil relative to the Canyon Diablo troilite (CDT) standard for sulfur. Total uncertainties were estimated to be better than ±0.2‰ for δ$^{34}$S.

4. Mineralogy and ore textures

4.1. Gold ores

One of the most striking characteristics of the Sandaowanzi deposit is that gold is dominantly present as Au–(Ag)–tellurides. These minerals occur both within low-grade, disseminated ore (telluride–
sulfide–quartz association; Fig. 5b) and as high-grade veins, (telluride–chalcopyrite–quartz association; Fig. 5c).

Disseminated ores occur within, and constitute part of the fine-grained quartz veins (Fig. 5a, b). The grade of the disseminated ores varies from 0.37 to 84.6 g/t, with an average of 9 g/t. Mining has revealed that the disseminated ores extend through a vertical thickness of 230 m from the +280 m to +50 m levels. There is no sharp contact between mineralized and non-mineralized quartz veins. Coarse (up to 1.5 mm) blastic grains of pyrite are randomly distributed within the fine-grained quartz matrix. Tellurides occur as isolated grains, swarms of grains, or as grain aggregates. Anhedral tellurides are typically a few to tens of μm in size. They are either randomly distributed within coarse pyrite grains or occur at the grain boundaries between pyrite and quartz. In most cases, tellurides coexist with sulfides such as pyrite, sphalerite, galena and chalcopyrite. Tellurides, as well as sphalerite, galena and chalcopyrite, also occur as inclusions in pyrite or they cement brecciated pyrite grains.

Fig. 5. Field and hand specimen-scale appearance of telluride-bearing quartz vein ores. (a) Surface outcrop of the quartz vein comprising the I2 orebody; (b) contacts between disseminated and vein ores. The dark spots are coarse pyrite grains in association with other sulfides and tellurides; (c) typical zonation of a vein ore. Q – quartz, CPY – chalcopyrite.
The high-grade syntaxial or unitaxial Au–(Ag)–telluride veins, up to 15 cm wide, occur in the center of the disseminated ores (Fig. 5b, c). The ores contain quartz, chalcopyrite and Au–(Ag)–telluride minerals (Fig. 5c). Mineral grains in such ores are coarse, contrasting with the fine-grained character of the disseminated ores. Individual telluride grains can be up to 3 cm in diameter. Crystal shapes are typically euhedral or subhedral. All tellurides, as well as quartz and chalcopyrite, form drusy structures. Euhedral chalcopyrite grains characteristically grow in microlitic cavities in the centers of the veins and along grain boundaries between tellurides. The veins are locally zoned: quartz with very few tellurides in the central parts of the veins; chalcopyrite and quartz in the intermediate zone, tellurides and quartz in the marginal zone, and pure quartz in the outermost part. One example of syntactical zonation of the vein ores is shown in Fig. 5c. At the +170 m level, only one such vein is observed, but at the +130 m level, there are seven parallel veins, each wider than 12 cm. Bonanza grade veins, with grades of up to 20,000 g/t, occur at the +130 m level. The high-grade vein ores are rarely observed above the +190 m levels and disappear below the +50 m level.

4.2. Mineralogy

4.2.1. Telluride minerals

Several Au–(Ag)–tellurides, e.g., calaverite (AuTe2); krennerite ([AuAg]Te2); sylvanite (AuAgTe4); petzite (Ag3AuTe2); and hessite (Ag2Te); stützite (Ag7Te4), and empressite (AgTe), occur in both the disseminated and high-grade vein ores (Figs. 5–7). Sylvanite, petzite and krennerite are the dominant Au-bearing minerals, accounting for >60% of the total tellurides by volume. Coexisting tellurides include minor amount of coloradoite (HgTe), and altaite (PbTe), and rare tellurobismuthite (Bi2Te3).

Individual grains of petzite, sylvanite, calaverite and krennerite can be up to cm-sized in the vein ores. Gray-colored petzite primarily coexists with sylvanite, but it also coexists with other tellurides. Sylvanite is blue-gray in color and is very abundant in the ores; microanalysis shows stoichiometric compositions. Calaverite, AuTe2, is brassy yellow whereas krennerite, (Au, Ag)Te2, has a silver-white color. In most cases, calaverite and krennerite occur as isolated grains along quartz grain boundaries or along fractures that crosscut quartz grains. In some cases, however, they may coexist with petzite or sylvanite, or form symplectic intergrowths with sylvanite and empressite. Hessite is the most abundant silver telluride and occurs as single grains or grain aggregates, locally coexisting with other tellurides and sulfides in the low-grade disseminated ores.

4.2.2. Native gold

A notable feature of the gold ores from the Sandaowanzi deposit is the rarity of native gold (<5% of the total gold budget). Most native gold grains are in the form of isolated grains with a ‘bamboo shoot’-like morphology. The ‘bamboo shoot’-like grains have diameters at the base of the shoot of about 3 to 5 μm. These grains are typically of about 10 μm, up to 15 μm, in length. They grew on the surfaces of cracks within tellurides (Fig. 8a, b) or along telluride–quartz boundaries (Fig. 8c). Most grains grow from one wall of the crack to the other. Only in rare cases such as in open spaces, did they grow syntactically (Fig. 8d). Generally, less than half the spaces of the cracks are filled with native gold grains, with the rest remaining as free spaces.

A very small group of native gold grains also occur in contact with petzite–stützite symplectites or as gold–krennerite intergrowths (Fig. 8e, f), the latter of which are irregular in shape and randomly distributed within the host symplectites. Within the petzite–stützite symplectites, krennerite may also occur as isolated grains (Fig. 8f).

4.2.3. Sulfides

Pyrite is the most common sulfide in the altered volcanic rocks and in the disseminated ores, but is very scarce in high-grade ores. In the disseminated ores, isolated euhedral or subhedral grains of pyrite are commonly broken and cemented by chalcopyrite (Fig. 9a), or in most cases, by quartz (Fig. 9b). Hessite or stützite fill the fractures or occur as inclusions in pyrite grains, and sometimes occur along pyrite grain boundaries (Fig. 9b, c). In such pyrite grains, sphalerite, galena and altaite also occur as inclusions.

Second to pyrite in total sulfides abundance, chalcopyrite occurs in vein and disseminated ore. Rare isolated anhedral grains of chalcopyrite grains, up to several hundreds of μm in diameter, co-exist with pyrite, sphalerite and galena in disseminated ores (Fig. 9a). These display irregular boundaries with other minerals such as hessite or quartz and also contain inclusions of petzite, galena and quartz. Early fractured pyrite is cemented by chalcopyrite (Fig. 9a). In some vein ores, chalcopyrite occurs along grain boundaries of Au–(Ag) tellurides (Fig. 9d), or as crosscutting veins (Fig. 5c). Chalcopyrite also occurs as 2–3 μm-diameter euhedral grains along the margins of petzite (Fig. 9d). Monomineralic chalcopyrite is a conspicuous component of late, superimposed veins located within the syntaxial high-grade veins. Here, chalcopyrite and quartz are the dominant minerals; tellurides are minor. Chalcopyrite is the only sulfide species in such veins and the occurrence of euhedral, drusy chalcopyrite in the veins can be used as a visual indicator of high-grade ores (inset in Fig. 5c).

Sphalerite and galena only occur in disseminated ores where they coexist with pyrite and chalcopyrite (Fig. 9a), or occur as swarms of sphalerite–galena–hessite aggregates (Fig. 9e, f). Both sphalerite (up to 150 μm) and coexisting galena (up to 50 μm) commonly contain inclusions of hessite. Chalcocite (20 μm), are rarely observed as irregular inclusions in sylvanite grains. Chalcocite is uncommon, but is observed as a fibrous overgrowth rim along grain boundaries of stützite or sylvanite (Fig. 9g, h).

4.2.4. Gangue minerals

The gangue mineralogy of the deposit is relatively simple in comparison with other telluride-bearing Au deposits of either low-sulfidation (e.g., Pals and Spry, 2003) or high-sulfidation (e.g., Plotinskaya et al., 2006) type. Quartz is the dominant gangue phase in both disseminated and veined ores, and was precipitated throughout the duration of the mineralization event. Micron-scale chlorite and sericite are observed in the altered wall rocks adjacent to veins and in the disseminated ores. Extremely fine-grained adularia is observed only in the disseminated ores, suggesting formation during the early stage of mineralization. In
contrast, calcite veins were formed only at the latest stages of fluid activity and are generally free of sulfides or tellurides.

4.3. Paragenetic sequence

There are two major mineralization stages: an early stage of disseminated mineralization and a main vein mineralization stage. A six-stage paragenetic sequence, formulated on the basis of microscopic observations, envisages a transition from early sulfide-rich mineral associations (disseminated ores) to late low-sulfide assemblages (vein ores), coupled with a general increase in the Au content of tellurides (Fig. 10).

4.3.1. Q–S stage mineralization

In this stage, fine-grained quartz (tens of μm in diameter) is dominant. Veins containing fine-grained quartz are large, up to 10 m in width and > 100 m in length. Isolated, euhedral pyrite, up to 1.5 mm in diameter, is observed within the quartz matrix. These grains were subsequently fractured and cemented by quartz–sulfide associations during the second stage mineralization event. Hessite and galena are included within the pyrite (Fig. 9a–c). Chlorite is observed in some replaced porphyroclasts of volcanic wall rocks within the quartz veins.

4.3.2. Q–S–T stage mineralization

The Q–S–T stage is a continuation of the Q–S stage. The minerals formed during this stage enclose those formed in the Q–S stage. The typical mineral association is chalcopyrite, sphalerite, galena, petzite and hessite (Fig. 9a–c). Minor amounts of pyrite and altaite were also precipitated. Chalcopyrite is coarse (up to 1 mm) (Fig. 9a), but the other minerals are generally no more than a few tens of μm in size. They occur disseminated within the quartz matrix or as inclusions in...
sphalerite (Fig. 9a, b). Sulfides and tellurides are either associated with Q–Sp y r i t eo r a w s u l f i d e–t e l l u r i d e gr a n i s t h e nu c t o r o a t t e r s at the quartz–telluride contacts. Euhedral quartz grains are well-illustrated. (c) Bamboo-shoot like native gold grains along the quartz–telluride contacts grain boundary crack of a euhedral quartz grain; (d) Syntaxial growth of bamboo-shoot like native gold grains; (e) Native gold–krennerite mineral pair included in petzite–stützite symplectite; (f) Native gold and krennerite containing a petzite–stützite symplectite in association with sylvanite.

**Fig. 9.** Mineralogy of the telluride ores (SEM BSE (a–c, e–h) and SE (d) images). (a) Fractured pyrite grain containing telluride inclusions and cemented by chalcopyrite–galena–petzite–hessite. (b) Tellurides and galena inclusions in a fragmented pyrite grain cemented by quartz and silicates. (c) Pyrite replaced and cemented by quartz. The pyrite grain contains tellurides, galena and sphalerite as inclusions. (d) Fine-grained chalcopyrite grains along petzite–petzite grain boundaries. (e) Swarm of fine-grained sphalerite containing galena and tellurides. (f) Enlarged image of a local area in (e). (g and h) Fine aggregates of chalcocite surrounding stützite; stützite–petzite–coloradoite relationships are also shown.

**4.3.3. F–V stage vein mineralization**

The F–V stage mineral assemblage is characterized by fine veining (typically a few hundred microns in width). Some are petzite-dominant with minor sylvanite whereas others are dominated by Ag–tellurides (hessite, stützite and empressite). These veins cut across pre-existing quartz- or quartz–telluride veins.

**4.3.4. C–V stage vein mineralization**

The dominant stage of high-grade vein formation precipitated calaverite, krennerite, sylvanite, petzite and hessite within syntaxial or unitaxial veins. There are at least 7 veins at the +130 level, each...
10–15 cm in width, representing the highest grade ores (up to 20,000 g/t). Tellurides are associated with quartz and/or chalcopyrite. Microscopic-scale veins of similar compositions are also observed. Native gold, (grainsizes <30 μm) is observed in the form of krennerite–gold pairs as inclusions within stützite–petzite symplectites (Fig. 8e, f). Minor coloradoite and altaite are associated with the Au–Ag–tellurides; tellurobismutite also belongs to this stage. Chalcopyrite and chalcocite are the only sulfide species in the association. Chalcopyrite occurs within monomineralic veinlets (Fig. 5c) or along petzite–petzite grain boundaries, whereas chalcocite is characteristically present at the boundaries of stützite grains (Fig. 9g, h).

### 4.3.5. Au stage mineralization

Bamboo-shoot like grains of native gold (see above) occur within intragranular fractures in petzite–stützite symplectite, or at quartz–telluride grain boundaries (Fig. 8a–d). Native gold is the only mineral precipitated during this stage.

### 4.3.6. Q–C stage

Late-stage barren drusy quartz veins (each mm to cm in width) are typically seen as single veins or vein arrays within the central parts of pre-existing veins. Such veins may also crosscut disseminated or vein ores. Late-stage calcite-dominant veins are observed emplaced within the wall rocks but are rarely observed to penetrate the ores.

From the above, mineralization in the Sandaowanzi deposit began with infill of large veins consisting of fine-grained quartz and associated silicification, chloritization, sericitization, pyritization and adularization. Sulfide- and Au–Ag-rich mineralization (pyrite + sphalerite + chalcopyrite + galena + petzite + hessite) was formed. Coarse pyrite grains hosts sphalerite, galena and tellurides. Third-stage sulfide-rich mineralization is characterized by a coexistence of pyrite, sphalerite, galena and Au–Ag tellurides (empressite, hessite, stützite, sylvanite and petzite). Fine Ag-telluride veins (stützite, hessite and empressite) are subsequent to this stage. Au- and Au/Ag-tellurides (calaverite, krennerite, petzite and sylvanite) were mainly introduced during the fourth stage and are the dominant carriers of gold in the deposit. Monomineralic chalcopyrite veins were also formed during this stage. Native gold, in cracks in and around petzite–hessite symplectites, formed during the final stage introducing ore metals, which is succeeded by barren veins (either quartz- or calcite dominant).

#### Table 10. Paragenetic sequence of mineralization from the Sandaowanzi ore deposit.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Early (disseminated ore)</th>
<th>Main (vein ore)</th>
<th>Late (Q–C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Style</td>
<td>Q-S</td>
<td>Q-S-T</td>
<td>F-V</td>
</tr>
<tr>
<td>Pyrite</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Sphalerite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galena</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Empressite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stützite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hessite</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Petzite</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Sylvanite</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Krennerite</td>
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<tr>
<td>Calaverite</td>
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</tr>
<tr>
<td>Gold</td>
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<tr>
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<td></td>
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<tr>
<td>Coloradoite</td>
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<tr>
<td>Tellurobismuthite</td>
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<tr>
<td>Chalcocite</td>
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<tr>
<td>Quartz</td>
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</tr>
<tr>
<td>Calcite</td>
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</table>

### 4.4. Ore textures

Several characteristic microstructures provide arguments favoring open space filling and/or replacement as the main mechanism of ore formation (c.f. Taylor, 2009).

Fragmented and corroded relict pyrite is cemented by assemblages of chalcopyrite–galena–hessite–quartz. The shapes of some of these grains can be readily reconstructed (Fig. 9a, c), suggesting that brittle fracturing allowed precipitation of successive stages of mineralization. Notably, fractures within low-grade disseminated ores and early quartz veins are filled by high-grade quartz–telluride–chalcopyrite ores. Syntaxial veins have off-center median lines (Passchier and Trouw, 2005) in which early quartz crystallized along the vein margins and later tellurides in the vein centers (Figs. 8a, b, d, and 11a–c). In unitaxial veins, which lack a median line, early quartz grows on one wall and late tellurides either on top of the quartz grains or adjacent to the other wall (Figs. 8c and 11d–f). In both cases, euhedral quartz forms drusy structures whereas the tellurides fill open spaces. Euhedral chalcopyrite is also observed to have been precipitated in open spaces at the center of syntaxial quartz–telluride veins (Fig. 5c).

![Fig. 10. Paragenetic sequence of mineralization from the Sandaowanzi ore deposit. Q-S: Quartz-sulfide association; Q-S-T: Quartz-sulfide-telluride association; F-V: Fine-veining mineralization association; C-V: Coarse veining mineralization association; Au: Gold mineralization association; Q-C: Quartz-calcite association.](image-url)
Microfissures hosting the bamboo shoot-like grains of native gold are observed in individual telluride grains (Fig. 8a, b) or along telluride–quartz grain boundaries (Fig. 8b–d). These may cut across entire grains but they never enter the adjacent quartz (Fig. 8c, d). Although they may be planar or irregular in shape, the long axes of the native gold grains within them are always normal or sub-normal to the vein walls or the microfissures in which the gold grains grow. Such relationships are suggestive of native gold crystallization in open spaces.

Breccia fragments are common within low-grade or barren veins (Figs. 5b and 11d–f). These are angular in shape, commonly have straight and sharp boundaries, and are cemented by clearly later quartz which generally displays crystallographic c-axes normal to the margins of the breccia fragments.

Symplectites comprising different telluride minerals are common in the vein ores (Figs. 7d, 8e, f, and 12a, b). We observe two-phase symplectites of sylvanite–hessite, stützite–petzite, sylvanite–empressite, petzite–coloradoite, and hessite–petzite (Figs. 7d, 8e, f, and 12a), and three-phase symplectites of hessite–petzite–altaite (Fig. 12b). These textures suggest mutual exsolution from higher-temperature phases during cooling.

5. Sulfur isotope and fluid inclusion data

5.1. Sulfur isotopes

Data for 26 pyrite samples from different parts of the ore deposit and one chalcopyrite sample from high-grade vein ores were
measured in the present study, complementing data for 10 pyrite samples given by Lu et al. (2005, Table 1). The $\delta^{34}$S values for pyrite in high-grade ores, low-grade ores and altered wallrocks range from $-1.64$ to $1.91\permil$, without any obvious difference between ore types, or between ores and wall rocks. The $\delta^{34}$S value for the chalcopyrite sample is at the negative end of the values for pyrite, $\delta^{34}$S values clustering around zero are consistent with a magmatic–hydrothermal source of sulfur, probably correlating with the sub-alkaline host volcanic units.

5.2. Fluid inclusion petrography and compositions

Fluid inclusions are observed in fine- and coarse-grained quartz formed during different mineralization stages. They are mostly transparent, colorless, elliptical in shape, and have long axes of less than 20 $\mu$m. Pre-mineralization quartz grains contain a high density of randomly distributed swarms of fluid inclusions. Most syn-mineralization quartz grains contain a limited number of very small inclusions. Characteristically, quartz in the vein ores hosts fluid inclusions containing varying proportions of brown-colored matter. Relatively large, inhomogeneously distributed fluid inclusions are common in post-mineralization quartz.

There are three basic types of primary fluid inclusions (Fig. 13a–c): two-phase liquid–vapor inclusions; monophase vapor inclusions; and monophase liquid inclusions. Laser Raman spectroscopy studies reveal that the liquid inclusions are H$_2$O-dominant, with minor hydrocarbons, i.e., methane (CH$_4$), propane (C$_3$H$_8$) and butyne (C$_4$H$_6$) etc. There are also indications for the existence of CO$_3^-$ and Cl$^-$, but, notably, not of CO$_2$. The vapor inclusions are mainly composed of H$_2$O and CH$_4$ (Fig. 13d). The brown-colored inclusions in the vein ores mainly consist of hydrocarbons (CH$_6$, C$_2$H$_6$, C$_3$H$_6$, etc.), and rarely of H$_2$O and CO$_2$.

5.3. Homogenization temperatures

On heating, most of the inclusions homogenize into fluid phases, except in rare cases where decrepitation occurs before homogenization. Homogenization temperatures have a wide range (120 to 400 °C). On a histogram of homogenization temperatures for all samples (Fig. 14a), there is a single peak at 260–280 °C. Importantly, however, quartz generations belonging to discrete stages of mineralization give different temperature ranges. Some samples contain more than one generation of quartz. For example, sample 130CM23-2 (high-grade vein ore) contains at least four generations of quartz: pre-mineralization stage, a mineralization stage (including an early mineralization stage or Q–S–T stage, and a main mineralization stage or C–V stage) and a post-mineralization stage (Fig. 14b). Inclusions in quartz from the early mineralization stage give homogenization temperatures between 267 and 315 °C (peaking between 270 and 300 °C, with one outlier of 386 °C). In contrast, homogenization temperatures of the secondary inclusions in early-stage quartz mostly fall between 260 and 270 °C, albeit with several exceptions in the range of 350–372 °C. Inclusions in quartz from the main stage of mineralization show homogenization temperatures between 250 and 310 °C (peak between 260 and 280 °C). Lastly, inclusions in late-stage quartz have homogenization temperatures between 190 and 250 °C. A clear tendency is thus seen in the above data, suggesting that the initiation of mineralization took place at relatively high temperature conditions. The outlier homogenization temperatures obtained for some secondary inclusions (and for one primary inclusion), can be interpreted as recording early high-temperature mineralizations, but were mistaken as secondary inclusions. Importantly, the homogenization temperatures for the early mineralization (Q–S–T stage) and the main mineralization (C–V stage) are similar to one another, but the temperatures decreased rapidly during post-mineralization veining.

6. Discussion

6.1. Mineralizing fluids

Fluid inclusion data indicates that the primary inclusions have simple compositions thus contrasting with the hydrocarbon-rich character of inclusions in late-stage, high-grade mineralization, even if the vapor and liquid inclusions of the early mineralization both contain H$_2$O and some hydrocarbons. These data are consistent with the

**Table 1**

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<tr>
<th>Sample no.</th>
<th>Mineral</th>
<th>$\delta^{34}$S (CDT)</th>
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Note: Data for samples T21–T210 are from Lu et al. (2005).
Fig. 13. Transmitted light photomicrographs of fluid inclusions in quartz. (a) Isolated primary vapor–liquid inclusions in early-stage quartz. (b) Dark brown primary vapor inclusions close to telluride grains in main-stage quartz (from Zhao et al., 2010); (c) Small primary liquid inclusions (0.5–2 μm in size) in main-stage quartz.

Fig. 14. Homogenization temperatures of primary and secondary fluid inclusions.
pyrite, sphalerite, and galena) and Ag-rich tellurides. Crystallization of chalcopyrite occurred late during this stage. Disseminated telluride–sulfide assemblages were also precipitated in some of the altered volcanic wallrocks.

Subsequent addition of fluids with higher Fe, low S and relatively high concentrations of Au, Ag and Te cooled more slowly due to a reduced thermal contrast between fluids and their hosts (early quartz veins and low-grade disseminated ores). Fluid infiltration into fractured fine-grained quartz veins contributed to the formation of superposed high-grade ores consisting of coarse-grained quartz, tellurides and chalcopyrite. Chalcopyrite likely crystallized at a unique stage forming the monomineralic chalcopyrite veins. Syntaxial or uniaxial veining with sequential growth from quartz to tellurides and chalcopyrite imply that crack-sealing was the dominant mineralization mechanism.

The final stage of mineralization is represented by precipitation of native gold along intragranular fractures within pre-existing tellurides and along telluride–quartz grain boundaries. The filling of tensional cracks by gold at Sandaowanzi is considered to be supporting evidence for fluid throttling, as proposed by Ciobanu et al. (2004) for similar assemblages at Roșia Montană, Romania. Extraction of precious metals from fluids undergoing pressure throttling is a process recognized during vein filling (Cooke and McPhail, 2001) and has also been proposed as a critical mechanism for Au deposition at Săcărimă (Romania), a deposit which, in its abundance of Au–(Ag)–tellurides strongly resembles Sandaowanzi (Ciobanu et al., 2008; Cook et al., 2009). Cooling at this stage contributed to grain-scale brittle deformation of the tellurides.

6.3. Timing of mineralization and geodynamic setting

Field investigation suggests a close temporal and spatial relationship between gold telluride mineralization and magmatism in the mine area. Gold-bearing veins are hosted by a sequence of volcanic rocks (trachyte andesite to rhyolite), and are cut by some diabase dykes. The volcanic rocks hosting the Au-bearing quartz veins and the diabase dikes cutting the quartz veins were recently dated, using LA–ICP–MS dating, at 135.3–124.7 Ma and 116.6 Ma, respectively (Liu et al., 2011a), thus bracketing gold mineralization between 125.3 and 116.6 Ma. Moreover, two syenodiorite dykes intrude the Jurassic monzogranite and have ages of 135.3 ± 3.9 Ma and 124.7 ± 2.9 Ma. These data show that mineralization and magmatism are broadly coeval with one another. A close relationship between mineralization and magmatism is also supported by the stable isotope data (δ34S values for sulfides clustering around zero).

During the Early Cretaceous, exactly at the time of the mineralization at Sandaowanzi, the eastern Asian continent was undergoing extreme extension, generating the North China Craton, the Russian Chita–Baikal metamorphic core complexes provinces, and the South China–Korean Peninsula and Northeast China–Northern Mongolia fault-bounded basin provinces. Thick sequences of Early Cretaceous volcanic rocks were deposited in fault-bounded basins such as that hosting the Sandaowanzi deposit.

Although the geodynamic setting of volcanism is still debated, recent results indicate that magmatic activity is attributable to regional extension due to rollback of the subducting Izanagi plate beneath the Eurasian plate (Liu et al., 2011a,b). Structural analysis of Mesozoic basins (Ren et al., 2002) and dating of volcanic rocks in the Great Xing’an Range and contiguous areas (Wang et al., 2006) support this conclusion. Changes in subduction angle and subduction rollback of the subducting Izanagi plate may have triggered extension of the eastern Asian continental lithosphere (Liu et al., 2011b). A model based on the rheological analysis of the lithosphere and coupling–decoupling laws of crust–mantle evolution provides a reasonable explanation for Early Cretaceous lithospheric thinning and development of crustal extensional structures (Liu et al., 2008, 2011b). Mantle detachment may result in local delamination of the root of the mantle lithosphere, leading to upwelling of the
asthenosphere. Underplating of magma derived from the heated mantle lithosphere may induce partial melting of the lower crust. Decompression due to formation of extensional structures in the upper-middle crust may have also assisted partial melting of the lower crust. It is also probable that the extension induced an upwelling of the magma from two sources: magma generated by partial melting of the lower crust; and magma directly derived from underplating. Eruption of this magma is represented by the large volumes of volcanic rocks and related gold mineralization in the Sandoowanzi deposit and possibly in contiguous areas along the Great and Lesser Xing’An Ranges.

7. Conclusions

The Sandoowanzi deposit is a low-temperature epithermal deposit related to early Cretaceous subalkaline magmatism, triggered by regional extension during Iazanagi–Eurasian plate collision. The deposit is an unusually telluride-rich gold deposit in which Au–(Ag–)tellurides contribute >95% of the gold budget. Faulting, evolving temperature fields, and high-grade veining and crack-sealing were important emplacement processes. The study also shows that bonanza-grade accumulations of gold tellurides can be formed in sub-alkaline magmatic environments, even though the underlying reasons for the formation of such unusually rich gold–telluride ores still require additional study.

Acknowledgments

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References