Fluid inclusions from the Jinchang Cu–Au deposit, Heilongjiang Province, NE China: Genetic style and magmatic-hydrothermal evolution

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ABSTRACT

The Jinchang Cu–Au deposit is located in the easternmost part of the Central Asian Orogenic Belt (CAOB). The mineralization here is associated with Cretaceous porphyritic intrusions of ca. 120–110 Ma and is mainly hosted within intensely altered Mesozoic granites, breccia pipes, ringed and radial faults. The gold ores are disseminated in the wall rock, and also occur as massive auriferous quartz-sulfide veins in fractures and breccias. Fluid inclusion data from breccias, chalcopyrite–quartz vein, and pyrite–quartz vein display homogenization temperatures in the range of 200 to >550 °C and the fluids show variable salinity in the range of 0–58 wt.% (NaCl equiv.). The halite absent fluid inclusions shows a slight increase in salinity with a sharp decrease in temperature. We interpret that the high-salinity brine and low salinity vapor or aqueous-rich fluids from ores represent fluid unmixing from magma. The fluid inclusion data from Jinchang demonstrate that the main mineralization took place at temperatures from 480 °C to 200 °C, and evolved from high to low salinities. Geology and fluid inclusion data suggest that the Jinchang deposit is an oxidized intrusion-related Cu–Au deposit. The voluminous hydrothermal magnetite formed during high temperature potassic alteration of wall rocks in this ore deposit can be used as a potential prospecting tool.

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1. Introduction

The Jinchang Cu–Au deposit, in NE China was discovered and explored since the 1990s (Mu et al., 2000; Chen et al., 2002). Hitherto, more than 40 tons of gold have been mined with an average gold grade of 8 g/t. Previous studies were mainly focused on the geology, ore-controlling structures, geochemistry of fluid inclusions (e.g., Jia et al., 2005; Wang et al., 2007, 2011; Men et al., 2008; Zhang et al., 2008), and geochronology of the gold mineralization and magmatism (Lu et al., 2009; Zhao et al., 2012; Zhang et al., 2013). Fluid-inclusion data derived from the different orebodies have been used to propose various genetic models which include: (1) epithermal gold deposit in auriferous quartz-sulfide veins formed from low temperature fluids with low concentrations of CO2 (Zhu et al., 2003); (2) porphyry type deposit attributed to high formation temperatures and salinities (30–60%, NaCl) from intrusive-style orebodies (Jia et al., 2005); (3) overprinting of porphyry-epithermal type (Wang et al., 2007); and (4) orogenic gold deposit as inferred from CO2-enriched fluids in breccias (Zhang et al., 2008). Recently, Zhang et al. (2013) documented the hydrothermal features of No. 18 orebodies from the Jinchang mine, similar to the alteration zones in intrusion-related porphyry deposit (e.g., Lowell and Guibert, 1970; Guibert and Lowell, 1974), though the zone of alteration in the Jinchang mine is relatively minor in comparison with those typical of large porphyry deposits worldwide. Thus, the genetic style of the Jinchang gold deposit remains elusive, hindering the formulation of effective exploration strategies. In previous studies, the fluid inclusion data were mainly derived from quartz within cements of the breccias-type ores and alteration ores. However, no detailed investigations have been carried out the quartz–chalcopyrite, quartz–pyrite veins. Also, the previous fluid inclusion data from this deposit published Chinese literature are of preliminary nature and do not address the evolution history and ore genesis. In a recent study, Zhang et al. (2013) presented results from a detailed study on the geology and geochronology of gold-hosting granites in the Jinchang mine, and discussed the genesis of those granites and gold metallogeny, although no fluid inclusion data and the genetic style of the ore deposit were presented. In this paper, we provide new data on fluid inclusions trapped in breccias and chalcopyrite–quartz and quartz–pyrite veins, and integrate these with previous fluid inclusion data (Wang et al., 2007, 2011; Men et al., 2008). We also evaluate the zircon alteration features to investigate the genetic style, fluids evolution processes and associated metallogeny. The importance of hydrothermal magnetite grains as a potential tool for...
tracing the evolution of ore-bearing fluids evolution and for ore prospecting is also addressed.

2. Geological setting

The Jinchang gold deposit is located in the easternmost portion of the Central Asian Orogenic Belt (CAOB), the largest Phanerozoic accretionary orogen on the globe bound by the Siberian Craton to the north and by the North China Craton (NCC) to the south (Fig. 1a) (Jahn et al., 2000; Kovalenko et al., 2004; Safonova, 2009; Xiao et al., 2013; Kröner et al., 2013; Goldfarb et al., 2014 and references therein). The study area belongs to the Songnen block (Wu et al., 2011), abutting against the western margin of the Khanka block (e.g., Xu et al., 2009; Wu et al., 2011; Zhou and Wilde, 2013), and to south of the Jiamusi block. The gold district is located at the junction of the Laoheshan Depression and Taipingling Uplift (Chen et al., 2002; Jia et al., 2005; Zhang et al., 2013). The two units are separated by the NNE trending transcurrent Suiyang fault (Fig. 1b), which controls the distribution of subsidiary faults in the Jinchang area. The Taipingling Uplift (as the southern collage of the Zhangguangcai Rang) is characterized mainly by Mesozoic granites with minor Mesozoic–Cenozoic volcano–sedimentary rocks (e.g., Zhang et al., 2004; Jia et al., 2004; Li, 2006; Liu et al., 2010; Wu et al., 2011; Zhou and Wilde, 2013). The Laoheshan Depression is located at the junction of the Laoheishan Depression and Taipingling Uplift (Chen et al., 2002; Jia et al., 2005; Zhang et al., 2013). The volcano-sedimentary rocks with U–Pb ages around of 220–200 Ma (Xu et al., 2009). Granitoids in the ‘uplift’ are mainly composed of diorite, granophyric granite, monzogranite, syenogranite and alkali–feldspar granite, with minor volume of diorite and gabbro (Fig. 1b). Recently, Wu et al. (2011) synthesized the available geochronological data on granitoids in NE China, which reveal a peak age of 200 Ma for granitoids exposed regionally around the Jinchang Cu–Au deposit, consistent with the ages of gold-hosting granitoids in the Jinchang mine (e.g., Lu et al., 2009; Zhang et al., 2013).

3. Ore geology

3.1. Deposit geology

Mesozoic granitoids are dominant with minor volcano–sedimentary rocks and mafic to felsic dikes in the mine (Fig. 2). The granitoids mainly comprise diorite, granophyric granite, monzogranite, and granite porphyry. Previous isotopic data revealed that the felsic intrusions were mainly emplaced at ~200 Ma, with mafic to felsic dikes intruding at ca. 120–110 Ma (Lu et al., 2009; Zhao et al., 2012; Zhang et al., 2013). The volcano-sedimentary rocks show U–Pb ages of 220–200 Ma (Xu et al., 2009).

The timing of metallogeny has been investigated using Ar–Ar dating on quartz from cements of breccias and the results show a reasonable plateau age of 122 ± 1 Ma (Jia et al., 2005), consistent with the age of the gold-hosted dioritic porphyry (Zhao et al., 2012). Rb–Sr dating on sericite from the gold-hosted granite and diorite porphyry in the No. 18 orebodies show mineralization ages of ~110 Ma, similar to the zircon U–Pb ages of granite porphyry and diorite porphyry (Zhang et al., 2013; Lu et al., 2009). The geochronological data indicate that gold mineralization at Jinchang is temporally related to the Cretaceous porphyries and formed at ~120–110 Ma (e.g., Jia et al., 2005; Zhang et al., 2013). A summary of the geochronological data on magmatism and metallogeny in this area is given in Table 1.

The major gold-hosting structures in the mine, are breccia pipes, and ringed, radial and linear faults (Fig. 2). Several breccia pipes occur mainly in E–W-trending faults to the west of ringed faults, and are important gold-hosting structures in the Jinchang mine (Figs. 2 and 3). Breccia pipes mainly occur at the intersection of two sets of faults striking in different directions.

Orebodies in the Jinchang mine can be divided into breccias, veins and alteration types (stockworks in hydrothermally altered granitic wall rocks), accounting for 41%, 39%, and 20% of the total gold production, respectively. Several tens of orebodies have been recognized (Fig. 2), including 6 breccias-style orebodies, 26 quartz-sulfide veins (filling fractures), and several alteration-style orebodies (Fig. 4; collectively termed as No. 18 orebodies). The vein type of orebodies cutting across breccia- and alteration-styles can also be observed in some places.

3.2. Mineralization and alteration

The ores are divisible into auriferous quartz-sulfide veins (Fig. 5a and b), breccias (Fig. 5c), and disseminated mineralization types (Fig. 5d). The first type ores occur in fractures and cements of breccia pipes, with an inhomogeneous gold grade of 10 to several thousands g/t and native gold grains or veinlets can be observed by naked eyes. The second type of ores is distributed in the breccia pipes, with variable gold grade of 8–88 g/t. The third type occurs within extensively altered granitoids of the No. 18 orebodies and in breccia pipes, which are characterized by disseminated sulfides.
and fine quartz-sulfide stockworks or veinlets (Fig. 5d–f), with average gold grade of 5.31 g/t.

The ore mineral compositions are similar in different ore types, characterized by enrichment in sulfides that locally occur as aggregate clots or veins. The sulfides in quartz-sulfide vein generally account for 30–50 vol.% (even up to 80–90 vol.%), whereas those in breccias and disseminated types are about 5–20 vol.%. The metallic minerals are complex but dominated by pyrite, with minor chalcopyrite, pyrrhotite, galena, sphalerite, molybdenite, stibnite, magnetite, native gold and silver occurring unevenly throughout the deposit. The gangue minerals are mainly composed of quartz, sericite, feldspar, epidote, kaolinite, biotite, chlorite and calcite.

Potassic alteration is extensive and is dominant in the mine, resulting in the formation of voluminous hydrothermal magnetite or chlorite + quartz (Fig. 6a and b). The potassic alteration is overprinted by other types of alterations, similar to porphyry deposit systems elsewhere (e.g., Titley, 1982). Taking into consideration the nature of intrusion-related porphyry deposit, the potassic alteration is presumed to be caused by fluids of magmatic origin (e.g., Gustafson and Hunt, 1975; Rusk et al., 2004; Seedorff et al., 2005), whereas the alterations of later stages (e.g., phyllic), superimposed on the earlier alteration zones, were caused principally by meteoric fluids, although the precise mechanism is debated (e.g., Sheppard and Taylor, 1974; Dilles et al., 1992; Zaluski et al., 1994; Taylor, 1997). Alternate models suggest origin from cooling magmatic fluids (e.g., Hedenquist et al., 1998; Watanabe and Hedenquist, 2001; Harris and Golding, 2002; Calagari, 2003; Rusk et al., 2004; Khashgerel et al., 2009). Thus, a complex overprint of hydrothermal alteration selvages occurs commonly in the wall rocks of porphyry deposits or some intrusion-related gold deposits. This is the case in the central part of the Jinchang mine where complex overprinted alteration selvages can be observed around the No. 18 orebodies, leading to controversies surrounding the genesis of ore deposit. The pervasive high temperature potassic alteration with voluminous magnetite at Jinchang is distinctive, in contrast with epithermal deposits. The alteration sequences are recognized in terms of mineral assemblage and crosscutting relationship, such as potassic, silicic, propylitic, quartz + sericite + pyrite, and advanced argillic stages (locally fracture controlled).

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The reported quartz δ18O (SMOW) values from Jinchang mine are mainly from quartz breccias with phyllic alteration, and show a range of 2.4–10.1‰, whereas those from quartz-sulfide veins show a range of 0.71‰ to 4.2‰ (Zhang et al., 2013). The hydrogen isotope data (δD) of breccias show a variation from −99‰ to −70‰, whereas the quartz-sulfide veins show a constant value of −70‰. These isotopic compositions not only indicate that fluids were mainly derived from magmatic sources, but also suggest that fluids in the later stage of phyllic alteration mainly belong to the cooling stage, with mixing of minor meteoric water (e.g., Hedenquist et al., 1998; Harris and Golding, 2002; Khashgerel et al., 2009), as

<table>
<thead>
<tr>
<th>Rock</th>
<th>Method</th>
<th>Mineral</th>
<th>Age (Ma)</th>
<th>εHf</th>
<th>T2Hf (Ma)</th>
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<tr>
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<td>201 ± 3</td>
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<tr>
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<td>Zircon</td>
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<td>−4.7</td>
<td>+6.6</td>
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<td>+1.1</td>
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<td>Sericite</td>
<td>110 ± 4</td>
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<td>110 ± 3</td>
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<td>110 ± 3</td>
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<td>Zircon</td>
<td>118 ± 5</td>
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<td>Ar–Ar</td>
<td>Quartz</td>
<td>122 ± 1</td>
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revealed by the relatively high 
$d^{18}O$ and constant values of $\delta D$ of the late stage quartz-sulfide veins. The economic grade of ores in the No. 18 orebodies mainly occur in phyllic alteration zones (Fig. 4b), and can be attributed to that magmatic fluids superimposed on the wall rocks and metal deposition during the cooling processes.

Some of the zircon grains in the ores of phyllic altered granites (mineral assemblage dominated by sericite + quartz + pyrite) in drill holes are cracked and display wormy shape (Fig. 7), suggesting cracking and alteration post-dating the major tectono-thermal event. The details of these samples including geochemistry and U–Pb ages were reported in a recent study (Zhang et al., 2013), and their U–Pb ages of ~200 Ma and sericite Rb–Sr age of ~110 Ma have been obtained (Table 1). In this study, we examined the textures in more detail through BSE images and EDS spectra of hydrothermal minerals in and around the grains to carefully evaluate the signature of zircon alteration in the Jinchang mine and provide further evidence for high temperature alteration. We find that the hydrothermal minerals in and around the altered zircon grains are dominated by rutile, sericite and quartz, which are consistent with phyllic alteration of the host rocks. Rutile is a common mineral in the alteration zones of porphyry deposit systems (Williams and Cesbron, 1977; Czamanske et al., 1981; Scott, 2005), which is coeval with hydrothermal alteration and results from the breakdown of Ti-rich minerals (e.g., Williams and Cesbron, 1977; Czamanske et al., 1981; Beane and Titly, 1981; Force, 1991; Rabbia et al., 2009). The magmatic Ti-rich minerals are strongly affected by high-temperature, SO$_2$–rich oxidizing fluids (e.g., Udubasa, 1982; Force, 1991; Haggerty, 1991), which promote oxidation-induced breakdown of titanite, biotite or ilmenite during potassic alteration and generate hydrothermal rutile. Furthermore, magmatic Ti-magnetite also re-equilibrates to hydrothermal Ti-poor magnetite during potassic alteration, releasing Ti for rutile formation. Mineral assemblage of rutile + sericite + quartz in and around altered zircon grains suggest that hydrothermal rutile crystallized at the stage of phyllic alteration, but postdated high temperature potassic alteration of wall rocks and zircon alteration. These observations are highly consistent with the previous report of hydrothermal rutile deposited in phyllic alteration zones (Scott, 2005). The rutile formation in phyllic altered rocks
Fig. 5. Characteristics of ores; (a) auriferous chalcopyrite–quartz vein; (b) pyrite–quartz vein; (c) breccias with Cu mineralization; (d) quartz-sulfides veins crosscut alteration minerals of sericite + pyrite + quartz in granite; (e) sulfide veins crosscut breccias ores; (f) Potassic altered granite was cut by quartz-sulfides veinlets; K – potassic alteration, and P – propylitic alteration.

Fig. 6. Characteristics of the wall rock alterations at Jinchang mine; (a) biotite + magnetite as mineral assemblage of potassic alteration; (b) mineral assemblage of chlorite + Q + Mag + Chal in chalcopyrite–quartz vein; (c) disseminated chalcopyrite in chalcopyrite–quartz vein; (d) sulfidation in granites with sericitization and chloritization (propylitic alteration zone) in granites; (a) and (d) after Zhang et al. (2013); Q – quartz, Bi – biotite, Mag – magnetite, Pl – plagioclase, Ser – sericite, Py – pyrite, Chl – chlorite, Chal – Chalcopyrite.
also indicates that Zr and Ti in rocks were mobile during the interaction between high temperature ore-forming fluid and wall rocks. Though the chemical compositions of rutile can be used as indicator for ore prospecting (e.g., Clark and Williams-Jones, 2004; Scott, 2005; Rabbia et al., 2009; Meinhold, 2010 and references therein), the hydrothermal rutile grains in our samples are too small for geochemical analysis.

In terms of the paragenetic sequences and the crosscutting relationships, gold mineralization in the Jinchang district can be divided into four hypogene stages: (1) chalcopyrite–quartz; (2) quartz–sericite pyrite; (3) pyrite quartz; (4) quartz polymetallic sulfide; and (5) pyrite calcite. Among these, only stage (5) does not have any economic significance.

4. Sampling and analytical method

Quartz crystals within cements of breccias and all types of quartz veinlets at Jinchang are fluid inclusion-rich. We selected samples from J0 ores of chalcopyrite–quartz and pyrite quartz veins, and cements of breccias for fluid inclusions study. The cements of breccias show an assemblage of quartz + sericite + pyrite (Fig. 5c and Fig. 6d). The chalcopyrite–quartz vein exhibits dominant mineral assemblage of chalcopyrite + quartz + chlorite (Fig. 5a), and the pyrite–quartz vein in ore body is dominated by quartz + pyrite, with minor sericite (Fig. 5b). Petrographic studies and inclusion analyses focused on fluid inclusion assemblages, bearing in mind the general principle that a group of inclusions trapped synchronously represent a fluid inclusion assemblage provided that these were trapped along the same primary growth zone in the mineral, or along the same healed fracture (Bodnar et al., 1985; Bodnar, 2003).

In the Jinchang mine, the vast majority of fluid inclusions occurs in scattered groups and clusters without unambiguous evidence for contemporaneous trapping. Different types of fluid inclusions clustered in the same quartz grain are difficult for discriminating the various generations. Their shapes vary from rounded to sub-rounded, irregular, spheroidal, ellipsoidal, elongate, and negative quartz crystals.

The microthermometric study of fluid inclusions was carried out with a Leitz microscope and a Linkam THMS 600 programmable heating–freezing stage (Shepherd et al., 1985) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). Most measurements were made at a heating rate of 0.2–0.4 °C/ min. Accuracy of the measurements was ensured by calibration against the triple-point of pure CO₂ (~56.6 °C), the freezing point

![Fig. 7. BSE images of zircon and EDS spectra of hydrothermal minerals from Jinchang mine. (A) and (B) are hydrothermal sericite; (C) and (D) are rutile.](image-url)
of water (0.0 °C) and the critical point of water (374.1 °C) using synthetic fluid inclusions supplied by FLUID INC. Detailed analytical procedures follow those of Fan et al. (2003).

5. Results

5.1. Previous data

Previously, fluid inclusion studies were focused on breccias (Li et al., 2003; Jia et al., 2005; Zhang et al., 2008; Men et al., 2008), and alteration-style ores (Wang et al., 2007), but no data were reported from the quartz-sulfide veins. Fluid inclusion petrography from Jinchang ores (Wang et al., 2007, 2011; Men et al., 2008), allow a classification into three types: (1) pure vapor mono-phase; (2) two-phase vapor-rich or liquid-rich inclusions, with the vapor phase characterized by H₂O, with minor CO₂; and (3) high salinity polyphase inclusions with halite and metallic sulfide daughter minerals.

The first type of fluid inclusions is mainly trapped in breccias and No. 18 orebodies and show homogenization temperatures higher than 570 °C. The second type is widespread in all types of ores. Those from the alteration-style ores have wide homogenization temperatures varying from 189 to >600 °C and relatively low salinities (2–10 wt.% NaCl equiv.) (Wang et al., 2007). The inclusions data derived from breccia-style ores show homogenization temperatures in the range of 230–510 °C and salinities of 2.5–20 wt.% NaCl equiv. (e.g., Men et al., 2008).

The high salinity polyphase inclusions (third type) with halite and metallic sulfide daughter minerals occur widespread in all types of the Jinchang orebodies (e.g., Zhang et al., 2006; Wang et al., 2007, 2011; Men et al., 2008). Daughter minerals are mainly salt, sulfate and sulfide (e.g., Wang et al., 2007; Men et al., 2008), and are represented by chalcopyrite, anhydrite, barite, arsenopyrite, malachite, and libethenite. Those in the alteration-style ores of No. 18 orebodies have homogenization temperature and salinity ranging from 260 to 450 °C (Fig. 9, average of 315 °C in pyrite–quartz veins and 359 °C in chalcopyrite–quartz veins). Those trapped in quartz from breccias show homogenization in the range of 250–480 °C. Most of these occur in chalcopyrite–quartz and pyrite–quartz veins and breccias are characterized by low salinity (Fig. 10a, 5–20% NaCl equiv.).

The second type inclusions yielded homogenization temperature ranging from 260 to 450 °C (Fig. 9, average of 315 °C in pyrite–quartz veins and 359 °C in chalcopyrite–quartz veins). Those trapped in quartz from breccias show homogenization in the range of 250–480 °C. Most of these occur in chalcopyrite–quartz and pyrite–quartz veins and breccias are characterized by low salinity (Fig. 10a, 5–20% NaCl equiv.).

The high salinity multi-phase inclusions with halite and metallic sulfide daughter minerals occur widespread in Jinchang orebodies (e.g., Wang et al., 2007; Men et al., 2008). Those in ores of the

5.2. Results from present study

Three populations of fluid inclusions were identified on the basis of their phase composition at room temperature (Fig. 8): (1) vapor-rich aqueous 2 phase, mainly characterized by vapor of H₂O with minor CO₂ (Fig. 8a and b); (2) liquid-rich aqueous 2 phase (Fig. 8c); and (3) multi-phase inclusions with daughter minerals of halite or metallic sulfide minerals (Fig. 8b and d). No pure mono-phase inclusions were observed. The daughter mineral halite crystals are larger than the other solid phases and can be readily distinguished by their cubic shape. The opaques are mainly sulfides. There are also micro-populations of inclusions with different phase types coexisting, although these cannot be investigated due to their very small size (Fig. 8a and b).

Inclusions of the first type are dominantly trapped in cements of breccias, and even after heating up to 550 °C, their final homogenization (disappearance of the aqueous phase) is difficult to precisely observe and we infer this temperature to be around 600 °C. They generally coexist with multi-phase inclusions with daughter minerals or liquid-rich aqueous 2 phase fluids. This type of fluid inclusions is also observed from altered granites in the No. 18 orebodies (Wang et al., 2007). Few of such inclusions are trapped in the chalcopyrite quartz vein.

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chalcopyrite–quartz and pyrite quartz veins yielded homogeneous temperature and salinity of 300–500 °C (average 433 °C) and average 51 wt.% NaCl equiv. and 200–400 °C (average 316 °C) and average 33 wt.% NaCl equiv. (Figs. 9 and 10), respectively. In contrast, those in cements of breccias cannot obtain the homogenization temperatures even heating to 550 °C with average salinity of 43 wt.% NaCl equiv.

In summary, the trapping temperatures and salinities of fluid inclusions are in the range of 250 to >550 °C and 0–58 wt.% (NaCl equiv.) in chalcopyrite quartz veins, 200–400 °C and 0–55 wt.% (NaCl equiv.) in pyrite–quartz veins, and 250 to >550 °C and 7–55 wt.% (NaCl equiv.) in cements of breccias (Fig. 10a). Mono-phase vapor and vapor-rich fluid inclusions are widespread and dominant in breccias and show high trapping temperatures of over 550 °C (or even above 600 °C) with relatively high salinities (see Table 2).

6. Discussion

6.1. Genetic style of intrusion-related Cu–Au deposit

The fluid inclusion data gathered from different styles of orebodies in the Jinchang Cu–Au deposit have been interpreted in various ways and the mechanism of ore genesis has remained controversial (e.g., Mu et al., 2000; Li et al., 2003; Jia et al., 2005; Wang et al., 2007; Zhang et al., 2008). The potassic alteration assemblage here is represented by K-feldspar (orthoclase), biotite, chlorite, quartz, and magnetite (Fig. 6a), developed locally around of No. 18 orebodies and generally overprinted by phyllic alteration, which suggests a widespread high temperature alteration, and hence is markedly different from the lower temperature (100–200 °C) epithermal deposits (e.g., Hedenquist and Lowenstern, 1994; Marini et al., 2011). The intense zircon alteration and formation of hydrothermal rutile also suggest the existence of high temperature alteration by ore-forming fluids in the Jinchang mine, similar to those reported from oxidized intrusion-related porphyry deposits (Scott, 2005; Rabbia et al., 2009). Zhang et al. (2013) documented the general characteristics of hydrothermal alteration, although they did not pay attention to zircon alteration and formation of hydrothermal minerals of rutile and magnetite. Hence, we point out that the abundance of hydrothermal magnetite in the Jinchang mine is similar to gold-rich or gold only intrusion-related porphyry deposits (e.g., Vila and Sillitoe, 1991; Sillitoe, 2000) and is distinctive from reduced intrusion-related deposits (e.g., Thompson and Newberry, 2000; Lang and Baker, 2001; Hart, 2005).

With regard to the compiled stable isotope values of $\delta^{34}$S, $\delta^{18}$O, and $\delta^D$ obtained from mineral separates (Zhang et al., 2013), the
ores in Jinchang are similar to many intrusion-related gold systems (e.g., McCoy et al., 1997; Sillitoe and Thompson, 1998; Duuring et al., 2007), but markedly different from epithermal type. Furthermore, the magmatic-hydrothermal temperatures and salinity of trapped fluid inclusions also provide robust evidence to distinguish intrusion-related deposit from other types (e.g., Roedder, 1984; Eastoe, 1978; Sillitoe, 1991; Ulrich et al., 2001; Redmond et al., 2004). Taking into consideration the ore geology, the alteration scale in the Jinchang mine is to a much lesser degree than that of typical porphyry deposits, whereas, in the present case, the A- and B-types of veins which are typical metal-carrying veins in porphyry deposits are absent.

In summary, the various features discussed above indicate that the genetic style of the Jinchang deposit represents intrusion-related Cu–Au deposit, associated with highly oxidized porphyry magmas, distinctive from reduced intrusion-related gold deposits (e.g., Thompson and Newberry, 2000; Lang and Baker, 2001; Hart, 2005).

6.2. Genesis of fluid inclusions

The fluid inclusions trapped in the ores from Jinchang reveal that the magmatic-hydrothermal fluids exsolved from high temperature magmas are of two distinct categories in terms of temperature and salinity: (1) high temperature with high salinity vapor-rich polymorph and (2) high temperatures and low salinity vapor- or aqueous-rich fluid inclusions. The origin and evolution of these fluid inclusions are still elusive, though co-existence of vapor and high-salinity melt inclusions has already been observed in granites (Kamenetsky et al., 2004). Such fluids might be generated by phase separation from a high temperature and low-salinity fluid by precipitation of 250–450°C (e.g., Harris and Golding, 2002; Rusk et al., 2008) or direct exsolution from the magma through unmixing of fluids (e.g., Kamenetsky et al., 1999, 2004; Campos et al., 2002; Veklser, 2004; Webster and Mandeville, 2007). Alternately, the high temperature vapor with low salinity fluid might have separated from brine and evolved to vapor-rich or aqueous-rich low salinity fluid (Heinrich et al., 1999; Heinrich, 2005). After the initial exsolution from magma, the high-T vapor with low salinity evolve to low temperature vapor-rich and liquid-rich aqueous fluids with low salinity, whereas, the high-T and high-salinity fluids (brine) evolve to halite-bearing multi-phase fluids through boiling and cooling (Fig. 10a). Many of the vapor-aqueous fluid inclusions trapped from high to low temperatures exhibit very low salinity, and display a clear salinity gap within the range of 20–30 wt.% at 200–350°C (Fig. 10a) which separates them from the halite-bearing inclusions. Roedder (1984) and Shepherd et al. (1985) interpreted this gap to be caused by halite meta-stability (failure to nucleate very small daughter crystals of halite). In addition, these fluids evolved with a different trend with the temperatures of the non-halite-bearing fluids decreasing sharply with slight increase in salinity around 200–300°C. The phenomena can be attributed to be the result of fluid re-boiling at temperatures around 200–300°C. In contrast, the halite-bearing fluids show a positive relationship between temperature and salinity (Fig. 10a), suggesting that these fluids are saturated with salinity along their cooling paths.

6.3. Implications for fluid evolution and metallogeny

The fluid inclusions from Jinchang are markedly similar to those from other porphyry deposits, where the trapping temperatures vary from close to the water-saturated granite solidus (homogenization temperatures up to >600°C), to coincident with metal precipitation of 250–450°C (e.g., Eastoe, 1978; Henley and McNabb, 1978; Roedder, 1984; Hedenquist and Lowenstern, 1994; Calagari, 2004; Redmond et al., 2004; Candela and Piccoli, 2005; Rusk et al., 2008; Landtwing et al., 2010). The initial exsolved fluids interacted with wall rocks, leading to potassic alteration at temperatures generally from <500 to 650°C (e.g., Harris and Golding, 2002; Rusk et al., 2008). During potassic alteration phase, abundant hydrothermal magnetite and biotite are widely developed in the potassic alteration zone, as revealed by our observations in the Jinchang...
As the magmatic fluid cooled, HCl dissociated and SO2 proportioned into H2SO4 and H2S (e.g., Seedorff et al., 2005). The fluid became acidic, and acid (sericitic) alteration was superimposed on the earlier potassium silicate alteration as observed in the ore field. The feldspar dissolution with gray sericite or sericite-chlorite halos produced by acidic reactions generally formed at temperatures of 400–450 °C (Ruske et al., 2004, 2008). These temperatures largely overlap with those of fluid inclusions trapped in the chalcopyrite–quartz veins at Jinchang (300–500 °C, mainly 350–450 °C) and are similar to those of aqueous-rich fluids trapped in cements of breccias (Fig. 9) and pyrite–quartz veins (250–350 °C), indicating that the chalcopyrite–quartz veins formed after potassic alteration, but earlier than the hypogene stage of sericite + quartz + pyrite at Jinchang.

Stability of chlorite at low pressure is a direct function of Fe/Mg ratio and temperature, and according to the experimental data of James et al. (1976), chlorite + quartz + magnetite can be stable at temperatures lower than 500 °C with Log fO2 approximately at –30 to –20, if pressure is lower than 1 kbar. Nonetheless, magnetite + chalcopyrite at pressure of 1.5 kbar can be stable at temperatures of approximately 400–500 °C with Log fO2 at –30 to –20 (Simon et al., 2000). Therefore, in the chalcopyrite vein, mineral assemblages of magnetite + chlorite + chalcopyrite + quartz (Fig. 6b and c) indicate formation temperatures of 400–500 °C with Log fO2 at –30 to –20, which are consistent with the homogenization temperatures of trapped fluids in quartz.

During acidic alteration, the increased H2S concentration raised the concentration of HS– which caused voluminous sulfide precipitation, and ore minerals such as chalcopyrite and pyrite, became important vein minerals (300–500 °C). This was followed by the formation of sulfide (pyrite–quartz) veins (250–350 °C) or quartz-sulfide veins which is the main stage of gold mineralization. At the main stage of gold mineralization, the magnetite or bornite formed at high temperature potassic alteration with relatively insufficient sulfur content would be replaced by pyrite and chalcopyrite, respectively due to the increased sulfur contents of phyllic alteration. The replacement might re-concentrate gold contents due to the high solution of gold in magnetite and bornite at high temperature (Simon et al., 2000). However, chalcopyrite and magnetite at Jinchang mine were formed at relatively low temperature of 500 °C, and their solubility of gold is much lower (e.g., Simon et al., 2000). Thus, significant amounts of gold in ore-forming fluids will migrate with pyrite into the tail as pointed out by Simon et al. (2000), such as phyllic alteration halos, breccia pipes and quartz-sulfide veins.

Our data confirm the view that the potassium silicate alteration is only the early stage of an evolving fluid expulsion event (Cathles and Shannon, 2007), as also supported by our ore-field geological observation that the pervasive potassic alteration in the absence of phyllic alteration in the No. 18 orebodies, has no economic mineralization. In addition, deposition of abundant hydrothermal magnetite during the period of potassic alteration would decrease the oxygen fugacity of residual fluids rapidly to reducing condition (e.g., Sun et al., 2004; Liang et al., 2009), and lead to voluminous sulfide minerals accumulation with copper and gold deposition in the main mineralization stage which postdated the potassic alteration. Daughter minerals of sulfate and sulfide coexisting in primary fluid inclusions hosted by mineralized quartz-veins in potassic alteration zones is a strong evidence in support of this interpretation (e.g., Men et al., 2008; Liang et al., 2009).

6.4. Implications of the hydrothermal magnetite formation

The occurrence of voluminous magnetite in the potassic alteration zones of the Jinchang gold mine deserves special mention, as it indicates high oxygen fugacity of the ore-forming fluids, adequate to inhibit sulfide mineral deposition (e.g., Sun et al., 2004). The deposition of voluminous hydrothermal magnetite would lead to a decrease in the oxygen fugacity of fluids leading to reducing conditions (e.g., Liang et al., 2009), triggering the precipitation of sulfide minerals. If the hydrothermal magnetite formed until relatively low temperatures (<450 °C), a large amount of Cu element might disperse into the wall rocks, and a substantial volume of Au would migrate upwards to higher levels of the crust transported in relatively low temperature fluids (vapor or brine). The Au would then precipitate to form an intrusion-related gold deposit, but would lack associated Cu ores, as shown by experimental results (Kesler et al., 2002). As to the Jinchang mine, the mineral assemblages of the outer part of chalcopyrite–quartz vein from deep breccias pipe (Fig. 5a) are dominated by (1) chalcopyrite + quartz + magnetite with minor chalcopyrite (Fig. 6b), and (2) chalcopyrite + quartz inboard (Fig. 6c). The hydrothermal magnetite minerals occur in the core or margin of hydrothermal chlorites (Fig. 6b), followed by chalcopyrite, reflecting a crystallized sequence of hydrothermal magnetite, chlorite, and chalcopyrite. This phenomenon suggests that crystallization of magnetite from high temperature fluids can transform the ore-forming fluids from an oxidized to a reduced state. Consequently, voluminous sulfides are precipitated in the wall rocks or quartz veins, at relatively lower temperatures. Several studies (e.g., Sillitoe, 2000 and references therein) have shown that intrusion-related gold deposits do not require any special tectonic settings, but the role of magnetite has been noted in many examples. Therefore, the formation temperatures and the amount of hydrothermal magnetite probably function as deciding factors on the formation of intrusion-related gold-rich or -poor deposits. Thus, magnetic techniques can be applied for ore prospecting to detect such kind of intrusion-related Cu–Au deposits in that voluminous hydrothermal magnetite grains were formed during high temperature alteration processes.

6.5. Implications for ore prospecting

In previous studies, the depth of ore formation as computed from pressures derived from fluid inclusions in breccias is of the order of ~2–3 km (Jia et al., 2005), whereas the quartz-diorite stock as studied in drill holes were emplaced at a depth of ~3 km, calculated with mineral thermo-barometers (Luo et al., 2012). The estimated pressure of fluid inclusions from sulfide-quartz veins varies in the range of 3–1 km (Fig. 10b, computed following Bodnar et al., 1985). These estimates are remarkably consistent with each other. Experimental results show that Cu would preferentially participate into high temperature brine or vapor and Au into low temperature ones (Kesler et al., 2002). Therefore, we predict that there is great potential for gold and copper prospecting in and around the No. 18 orebodies at Jinchang. Also, skarn-type Cu–Au deposits can be expected in depth on a regional scale, since voluminous carbonate sediments (Huangsong group) might have been incorporated within the Triassic continental collision zone during the final ocean closure.

7. Conclusions

Fluid inclusion data from the breccias, chalcopyrite–quartz veins, and pyrite–quartz veins in the Jinchang mine, display homogenization temperatures in the range of 200 to >550 °C and the fluids show variable salinity in the range of 0–58 wt.% (NaCl
The halite absent fluid inclusions shows a slight increase in salinity with a sharp decrease in temperature, suggesting that the high-salinity brine and low salinity vapor- or aqueous-rich fluids represent fluid mixing from magma. The fluid inclusion data demonstrate that the major metallogeny took place at temperatures from 480 °C to 200 °C, and evolved from high to low salinities. The potassium silicate alteration is only the early stage of an evolving fluid expulsion event, and voluminous hydrothermal magnetite formed during high temperature potassic alteration of the wall rocks in this ore deposit can be used as a potential prospecting tool.

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Appendix A. Supplementary data
Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2013.12.017.

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