Original Article

Zircon U–Pb Age and Deformation Characteristics of the Jiama Porphyry Copper Deposit, Tibet: Implications for Relationships between Mineralization, Structure and Alteration

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Abstract

The Jiama copper deposit is one of the largest deposits recently found in Tibet and is composed of three types of mineralization including skarn, hornfels and porphyry. To investigate the relationship between mineralization, structure and alteration, we report new zircon U–Pb age and present field observations on the deformation characteristics associated with the copper mineralization in Jiama. Two main periods of deformation were identified, represented by D₁ and D₂ in Jiama. The first deformation (D₁) occurred around 50 Ma, whereas the second deformation (D₂) that was closely related to mineralization occurred later. Previous zircon U–Pb and molybnite Re–Os dating results indicate that the mineralization occurred at ∼15 Ma and thus the D₁ regional deformation significantly occurred before the mineralization time, although the D₁ deformation probably provided important space for the development of significant copper deposition. Our new mapping and observations on the D₂ deformation demonstrate that the mineralization was closely coeval with or slightly later than the time of D₂ deformation. The new U–Pb zircon age further indicates that the aplite formed in ∼17.0 Ma and thus the D₂ deformation happened later than this time because the D₂ deformation cut across the aplite, which is proposed to be the key control for copper mineralization. Altered laminated hornfels including three types of alteration (A-, K- and S-type) were found spatially associated with the D₂ deformation. The type-A is mainly silicification, with fine sericite or chlorite, as well as abundant disseminated sulphides on fracture surfaces; the type-S is mainly fine-grained silicification with patches of chlorite, epidote and common sulphides; the type-K (potassic alteration) appears to be fine-grained biotite. Such types of alteration indicate the presence of skarns at depth where ore shoots are located. Taken together, the multiple structural-magmatic-mineralization events contributed to the formation of the supergiant Jiama porphyry copper deposit in Tibet. The results have general implication for regional exploration.

Keywords: deformation, Jiama, mineralization, structure, Tibet.
1. Introduction

Studies on porphyry copper mineralization potentially include aspects such as mineralization age, petrological and geochemical features of ore-host rocks, mineralization-related alteration, tectonic settings of mineralization as well as structural control on mineralization. Each of them plays an important role in exploration at mine scale or regionally. The giant porphyry copper mineralization that formed during the Late Cenozoic in Tibet has been a focus in recent decades (Schärer et al., 1984; Aitchison et al., 2000; Meng et al., 2003; Qu et al., 2004b, 2007, 2009; He et al., 2007; Yang et al., 2009; Gao et al., 2010; Hou et al., 2011, 2012a; Searle et al., 2011). To date, a lot of studies have focused on the age, geochemistry and tectonic settings of large porphyry copper deposits such as Jiama in Tibet (Qu et al., 2004a; Tang et al., 2010, 2011; Zheng et al., 2010; Qin et al., 2011, 2012; Hou et al., 2013; Zhong et al., 2013; Ying et al., 2014). These studies have shown that the copper deposits in Tibet mainly formed during the Late Cenozoic and their origin seems to be related to the input of mantle-derived basaltic magmas into the thick crust at post-collisional setting after the Asia-India collision at the Cenozoic (Hou et al., 2011). The host rocks associated with copper mineralization in Tibet are mainly intermediate-felsic rocks derived from partial melting of the newly formed, thick lower continental crust (Hou et al., 2004, 2011). The source of copper was therefore probably located in the newly formed, water-rich arc-like lower crust. Although the general age, petrogenesis and tectonic settings for copper deposits in Tibet have been well studied, little work has concentrated on figuring out the relationship between structure, alteration and mineralization on a relative small scale, e.g., in the scope of a deposit (Burg & Chen, 1984; Yin et al., 1999).

The Jiama porphyry copper deposit in Tibet is one of the largest deposits recently found in Tibet, which contains approx. 750 Mt Cu and approx. 170 t Au as well as other metals (e.g., Pb, Zn, Ag, etc.). The ore-bearing rocks were emplaced at approx. 14 Ma and are mainly composed of dioritic porphyry and granitic porphyry containing mafic enclaves (Tang et al., 2010; Qin et al., 2012). The rocks are high-K and calc-alkaline with low MgO content. The genesis of the ore-host rocks in the Jiama copper deposit and the tectonic settings under which the magmas formed have attracted extensive attention in recent studies (Tang et al., 2010, 2011; Zheng et al., 2010; Qin et al., 2011). Similar to most porphyry copper deposits in South Tibet, previous studies have shown that the Jiama copper deposit was formed in a post-collisional setting, and was derived from newly formed lower crust (Hou et al., 2009, 2012b; Tang et al., 2010; Zheng et al., 2010; Qin et al., 2011). The key structural controls on the mineralization process and ore shoots after the magma formation, however, remain unclear.

Two main structural events have affected rocks that host the Jiama giant copper deposit, including the first deformation (D1) and the second deformation (D2). The first deformation is correlated with a regional structural event timed at around 50 Ma and has been well studied in previous work (Kapp et al., 2007; Tang et al., 2010; Zhong et al., 2012, 2013). This structural event occurred significantly prior to the copper mineralization and it probably provided important space for the development of copper deposition (Zhong et al., 2012). The D2 deformation was named as the Jiama-kajunguo thrust-gliding nappe tectonic system and it might have been tectonically caused by the continental-continental collision between the Indo-Asia plates during the Cenozoic (Zhong et al., 2012, 2013). The D2 deformation is interpreted as the most important control for the final development of mineralization because it was temporally associated with the main time of mineralization in Jiama and is spatially associated with alteration. The detailed nature and characteristics of the D2 deformation have not been studied yet.

In this study, we present district structural studies for the Jiama copper deposit in order to investigate the major structural control (e.g., the D2 deformation) on the copper mineralization. Given that the D2 deformation occurred significantly prior to the main time of mineralization, we have focused mainly on the D2 deformation that is interpreted to be closely associated with copper mineralization. In addition, to precisely confirm the age of the D2 deformation in the Jiama deposit, we report zircon U-Pb age for aplite from the Jiama deposit. We propose that D2 deformation in the Jiama porphyry copper deposit is synchronous or slightly post-dates the mineralization. The results have crucial implications for further regional prospecting.

2. Geological background

2.1 Region and district geology

The Jiama copper deposit is a porphyry-skarn type copper polymetallic deposit (Fig. 1). It is located in the south part of the Gangdese-Nyenchen Tanglha terrain. The strata that host Jiama are mostly composed
of island arc volcanic rocks and passive margin sediments. The strata hosting mineralization are mainly composed of the rocks belonging to the Duodigou Group (J3d) (pale white marble, crystalline limestone, marl, gray black calcirudite and debris micrite) and the Linbuzong Group (K1l). The upper part of the Linbuzong Group is interbedded with lithic sandstone, quartz sandstone, lithic quartz siltstone and argillite; the lower part consists of argillite, carbonaceous shales with fine-siltstone and fine sandstone with bioclastic micrite.

Many small dykes are exposed at Jiama, whereas the mineralized porphyry stocks were emplaced at depth (not exposed on the surface). The sequence of emplacement of mineralized intrusive rocks from oldest to youngest is: quartz dioritic porphyry, granitic porphyry, monzogranitic porphyry and granodioritic porphyry. The formation age of these magmatic rocks is mainly at 16.3 to 14.8 Ma with a peak at 15 Ma based on zircon U–Pb dating (Qin et al., 2011). The Re–Os isochron ages of molybdenites in mineralized porphyry, skarn and hornfels range from 15.5 to 14.0 Ma (Ying et al., 2010, 2014), which are consistent with the formation time of the host magmatic rocks.

The structural trend at Jiama is due to the collision between the Indian and Eurasian plates at the southern edge of the Gangdese-Nyenchen Tanglha terrane. As a result of long-term regional strike-slip, sub-structures mostly trend to WNW and thus result in development of many WNW directed nappes. The Jiama deposit is mainly controlled by nappe structures that are vergent from north to south and have a transform direction from south to north (Zhong et al., 2012). Nappe structures in the mining area consist of a series of overturned folds, including the Hongta and Niumatang anticlines and the Xiaogongpu syncline. A detached nappe-gliding body extends from the Copper Mountain throughout Bulang ditch to the Mogulang ditch. This slide-nappe is divided into three parts from south to north: the front, central and rear (Fig. 2) sections (Zhong et al., 2012) and the outcrop of the gliding area is approximately 4 km² (Fig. 1).

2.2 Geological features of skarn-type copper-rich orebody

At Jiama, there are three types of copper orebody: skarn, porphyry and hornfels. The skarn copper orebody is shaped like a thick layer parallel plate. The Linbuzong Group overlying the skarn consists of sandstone slate and hornfels, whereas the Duodigou Group limestone and marble underlie the skarn orebody. The skarn orebody appears to occupy a structural zone between the two groups. The orebody strikes NW–SE (300°) extending 2.85 km and dips NE (30°) extending about 2.5 km, although the margin is not well defined.

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The tendency of the orebody clearly varies from steep to slow, and then changes to steep again as a result of the nappe structures (Fig. 2). Steep dips of the upper part, which are located in Qianshan region, range from 50 to 70°. The central zone is the main orebody and dips generally less than 20°, becoming slightly steeper around the marginal area of Niumatang. This marginal area in Niumatang is exactly located between Xiagongpu and Zegulang and covers nearly 5 km². The steeper orebody at depth is located in the north of Zegulang typically dipping 30 to 40°. On the basis of the latest drillhole data, multiple high-grade (copper) blocks occur in this skarn-type orebody. The geological characteristics of the high-grade blocks are presented in the following sections (Fig. 3).

The typically horizontal skarn orebody is shown in Figure 3. The main trend of high-grade mineralization is 120°. However, apparent ore shoots trending 30° might be an artificial effect due to drilling layout and may not be representative of the alteration of the original ore body. The 030° direction represents a regional structure from Jiama to Qulong. The 120° orientation parallels to the axial plane of D2. The 120° faults are small displacement faults that are mapped in the pit and are clearly part of D2. The 030° structures (and an apparent jog in that structure that locates the intrusive porphyry) appear to be reactivation of an inferred basement fault and many different intrusive centres lie on this trend (Qulong, Xiangbaishan, etc). The main anticline that hosts the highest grade skarn terminates against this zone, implying differential movement on the 030° structure during D2 deformation. From the cross-section seven in Figure 3a, the distribution of multiple high-grade orebody blocks appears to be in close spatial relationship with folds or faults. It can be clearly seen in the cross-section (Fig. 3) that high-grade copper-rich orebodies have been intersected by drill holes of ZK702, ZK710, ZK714, and ZK722 (Fig. 3a). Some smaller orebodies around drill hole ZK701 and ZK707 have unknown structural relationships.

3. Field observations

3.1 Lithologies, alteration and structures in Niumatang Pit

Several lithologies are found in the Niumatang pit. The upper part of the pit comprises two main metasedimentary units: a well-bedded, mostly fine-grained carbonaceous unit with interbedded mudstone and thin fine-grained sandstone, and a massive coarse-grained unit comprising fine to medium grained sandstone with uncommon interbedded mudstone. Towards the bottom of the pit, closer to the mineralized zone, a number of skarn lithologies are exposed. Strong skarnification of the metasedimentary rocks has resulted in a massive to banded, generally pale green rock unit composed of green garnet and diopside with common small patches and zones of carbonate and gypsum. A less altered sedimentary precursor is indicated by the scale, thicknesses and morphology of banding in altered areas and are similar to those observed in the hornfels sediments. The strong development of skarn resulted in the formation of massive rocks composed of green garnet, ±brown garnet, ±diopside, and ±wollastonite. The transition zone from skarn to hornfels is composed of skarn with gradational variation and is in irregular contact with marble. It is difficult to determine the precursor of this
type of skarn in the Niumatang pit and therefore, all types of skarn lithologies have been mapped as a single unit.

Three types of alteration have been mapped in the Niumatang pit in this study. The most common type of alteration occurs on higher berms and is developed in hornfels sediments that are associated with quartz-sulphide veins and appears most obviously as a light grey or light green-grey colour and overprinting the sediments and contrasts with the usual dark grey colour. This is defined as type-A alteration and is mainly silicification, particularly proximal to veins with fine sericite and/or chlorite, as well as abundant disseminated sulphides together with sulphides occurring on fracture surfaces (see Fig. 4a). The second alteration type (type-S) occurs on lower berms of the Niumatang pit and is readily distinguished based on the white to pale green colour of the rocks. In detail, this alteration type is mainly fine-grained silicification with patches of chlorite, epidote and common sulphides. This alteration (type-S) appears to cross-cut bedding in the sediments (Fig. 4b). A third type, mapped in only a tiny area of the pit proximal to skarn mineralization is characterised by red-brown colour of

![Image](image_url)

**Fig. 4** (a) Alteration associated with quartz-sulphide veins comprising silicification with sericite and/or chlorite with sulphides. Lead mountain. (b) Alteration type-A. Alteration of hornfels sediments. This alteration comprises mostly strong, fine-grained silicification with chlorite, epidote and sulphides. Copper Mountain. (c) Alteration type-S. Dark patches are remnant hornfels and the cross-cutting nature of bedding planes and foliation in the Niumatang pit. Where observed the same angular relationships prevailed. A regional anticline occurs to the SSW of the Niumatang pit.
the hornfels sediments. It appears to be the fine-grained biotite and therefore interpreted as potassic alteration (type-K).

A number of structures have been mapped in the Niumatang pit. Foliation is intermittently developed in the fine-grained hornfels sediment lithologies. This appears to be a regionally developed foliation and may be associated with thrusting and folding in this area. Bedding and foliation are commonly oriented such that fold vergence towards the anticline is always directed to the north or northeast (Fig. 4c), indicating that the Niumatang pit is located on the northeast limb of a regional anticline. Although a number of clay gouge filled faults have been mapped and measured, only one fault contains some kinematic indicators that suggest a normal fault. Some faults have quartz-sulphide veins suggesting that these faults significantly post-date mineralization. Other faults persist across several berms and high walls, although it is anticipated that their displacement is small.

Three types of veins have been discriminated in the Niumatang pit, but only two of them have been mapped because the unmapped type is steeply dipping, commonly parallel with each other, and comprises a thin (several micrometre) calcite infill and are considered as late-stage structures commonly parallel joints in the area. Quartz veins within the skarn commonly contain open space which is filled by textures with sulphides or secondary copper minerals. These veins are commonly steeply dipping in an approximately north–south direction and are only observed within skarn. The most striking veins in the Niumatang pit are those that the structures therein contain altered zones with many quartz-sulphide veins that are variably deformed. These zones are discrete and contain veins that display a range of deformation geometries. These include boudinaged, folded, and strongly flattened veins with intrafolial folds. No lineation or rodding type structure was observed. The wall rocks are strongly silicified and fine-grained and all veins contain sulphides. These structures are shown in Figure 5.

3.2 Lead Mountain/Copper Mountain’s lithologies, alteration and structures

Marble is more widely exposed in Lead Mountain and Copper Mountain pits than in the Niumatang pit area, but their lithologies are generally similar. The transition from unaltered marble, having a prevailing fabric developed in coarse-grained carbonate, to well-developed skarn is observed. Skarn-type alteration of the limestone is well exposed in the Lead Mountain area. The rocks in this transition zone are pale to dark grey and contain carbonate which partially originated as carbonate veining with fine-grained green garnets. In some areas substantial carbonates grade into well-developed coarse-grained skarn.

In the Lead Mountain area, folds are well developed in the marble and in the hornfels sediments (Fig. 6a). The folded layering comprises bedding, 

(S1) foliation and sulphide-bearing quartz veins. Crenulation cleavage is observed especially in the hinge regions of F2 folds (Fig. 6b). An aplitic dyke in the Lead Mountain pit is folded (see Fig. 6c). A recumbent fold within the marble is exposed in the southern part of the Lead Mountain pit. The ubiquitous fabric developed in marble is interpreted as S1, which is axial planar to this fold. The fabric in the marble (Fig. 6d) has been clearly deformed, but in part it resembles bedding and shows some variations in grain size between layers. In the marble exposed in the Lead Mountain pit, 

(S0) and bedding (S0) are mostly parallel to each other. Folding of bedding (decimetric scale layering) is exposed in cliffs above the Lead Mountain pit and is consistent with the F2 folding. This supports the interpretation that S1 and S0 are sub-parallel in this area and that both are folded by F2 folds. Measurements of bedding, S1 and S0 (composite foliation comprising S1, veins and S0) have been combined because they are sub-parallel in both the Copper Mountain and Lead Mountain pit areas. Together, these folded fabrics help to specify the F2 fold orientation and define D2 deformation zones.

4. Methods

Geological mapping was carried out in Niumatang, Lead Mountain, and Copper Mountain pits of the Jiama deposit. Field observation formed the basis for map and cross-section interpretation. The process included: construction of geological maps, structural data recording, map interpretation, cross-section construction, and an interpreted deformation/mineralization/alteration history.

Zircons were separated from the studied aplite in Lead mountain (Fig. 6c) using magnetic and heavy liquid separation methods, and then hand-picked under a binocular microscope. Approximately 100–200 grains for the sample were mounted into an epoxy resin disc. Prior to isotope analysis, all grains were photographed under both transmitted and reflected light, and subsequently examined using the
cathodoluminescence (CL) image technique. Isotopic ratios were analyzed using a Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS) at the University of Science and Technology of China (USTC). During the analyses, the standard zircon 91500 was used as the external standard for U–Pb isotopic analysis. Generally, 32-micrometer diameter spots were used, with 44- or 60-micrometer

Fig. 5 (a-b) Folded quartz-sulphide veins with apparent folded foliation $S_1$ such that an incipient crenulation foliation $S_2$ is developed. Lead mountain. (c) Boudinaged quartz-sulphide veins. (d) Strongly folded quartz-sulphide veins. Lead mountain. (e) Fold limbs are commonly “sheared out”. Niumatang pit. (f) Folded quartz-sulphide veins. Strongly flattened quartz veins indicated by the presence of highly lenticular veins, intrafolial folds and strong wall-rock fabric development. Lead mountain.
diameters sometimes, depending on the size of the analyzed zircons. Final isotopic ratios and ages of the zircons were processed using the CommPbCorr# program (Andersen, 2002). The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age calculated using the ISOPLOT program (Ludwig, 2001) was used to represent the age of the aplite.

5. Zircon U–Pb dating results

The zircon U–Pb dating results are reported in Table 1. Zircons from the aplite sample (A3467) collected from the Lead mountain area are generally prismatic, colorless, transparent, and euhedral. Most zircon grains display oscillatory zoning as shown in the CL images (Fig. 7), which are typical of magmatic zircons. Analyses of thirteen spots yielded generally concordant U–Pb ages, with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 16.93 ± 0.4 Ma (Fig. 7), which is considered as the crystallization time of aplite intrusion in the Lead mountain area.

6. Discussion

6.1 Characteristics of deformation $D_2$

Structures attributed to the second deformation ($D_2$) have been interpreted on cross-section and in 3D models of Figure 8a. $D_2$ folds trend 120° sub-parallel to $D_2$ high strain zones. The model in Figure 8a represents the top of skarn orebody (green) whereas yellow part denotes the base. Porphyry rocks are shown as purple in this figure. A cross-section which cuts across the Niumatang pit shows high-grade skarn orebodies and $D_2$ deformation zones interpreted to depth. The mapping results and observations from drilling cores are used to mark bedding, foliation and $D_2$ deformation zone in the cross-section 23 (Fig. 8c). The deformation region of $D_2$ parallels to the fold axis in 120° direction. The drilling line is designed nearly 30° which is vertical to the direction of 120° such that $D_2$ occurs as a narrow area in the cross-section.

The mapping of the Niumatang pit is shown in Figure 9c. The Niumatang pit is mostly occupied by hornfels siliciclastic sediments with various skarn
bodies in the lower, western part of the pit. The contact between the skarn and siliciclastic sediments is irregular and transitional with strongly altered hornfels. Several types of alteration have been mapped, which vary with proximity to the skarn. For example, the most distal alteration zones are the A-type alteration (silicification, sericite, chlorite), whereas more intense and widespread S- and K-type alteration occurred closer to the skarn (Fig. 10). A-type alteration is spatially associated with many deformed veins, and S2 foliation is locally developed in this alteration zone. The alteration type changes from A-type into S- and K-type with distance closer to the skarn.

The geological mapping for the berms in the Lead Mountain pit is shown in Figure 9a. Hornfels siliciclastic sediments generally occur in the northern part, whereas marbles occur in the south. A garnet-bearing skarn is well-developed along the contact. Alteration becomes stronger closer to the skarn with various alteration types in both the marble and hornfels sediments. Skarn-type alteration zones containing garnets within marble occur further to the south. Three intrusive dykes have been mapped in this area. Two of them are typical of the porphyry dykes containing abundant quartz and feldspar phenocrysts with rare mafic minerals (hornblende). The third dyke is mainly fine-grained aplite and is in temporal association with the porphyry dykes and D2 deformation. The mapping results demonstrate that a porphyry dyke cuts across (and therefore post-dates) both skarn and the fine-grained aplitic dyke (see Fig. 9). The aplite dyke was deformed by D2 deformation whereas the porphyry dyke was not. The age of this porphyry dyke is dated at approx. 15 Ma (Qin et al., 2011; Ying et al., 2014). The aplite dyke therefore pre-dated the D2 deformation, and the age of approx. 17 Ma we obtained should represent a maximum age for the D2 deformation.

The hornfels sediments in the Copper Mountain pit have been strongly altered and generally lack internal structure such as bedding and foliation. The massive nature of these sediments indicates that they belong to a massive fine-grained sandstone unit similar to that mapped in the upper part of the Niumatang pit. The contact zone between the hornfels sediments and the marble is composed of skarn and altered rocks surrounding skarn. Like that encountered in the Lead Mountain pit, the layering in skarn and in the adjacent marble and hornfels sediments is steep to vertical, and in some cases, possibly overturned. Large porphyry dykes cut the sequence in the Copper Mountain pit, are generally steeply dipping and strike in an
Fig. 8 (a) Interpreted folds in the skarn are also likely to be $D_2$ deformation zones that can be modelled as surfaces. (b) Spatial distribution characteristics of skarn $D_2$ deformation zone. (c) The observation of $D_2$ phenomenon in drill cores of line 23.
Jiama porphyry copper deposit, Tibet

**Rock Types**

- **Sedimentary rocks**
  - SLH
  - SAH
  - SCM
- **Skarn rocks**
  - AKG

- **Intrusive rocks**
  - IFQ
  - IPF
  - IPQ

- **Alteration types**
  - A
  - S
  - K
  - G

**Bedding and Foliations**

- $S_b$: Sedimentary layering-bedding
- $S_1$: Fine, slaty foliation, interpreted $S_1$
- $S_2$: Crenulation foliation (of $S_1$) interpreted $S_2$
- $S_3$: Composite fabric comprising $S_2, S_3$, and veins all sub-parallel.
- $S_{3/1}$: Bedding parallel to $S_1$ foliation. Strong deformation fabric in marble (SCM)

**Faults and veins**

- Fault with common fault gouge.
- Veins
  - $V_{sb}$: Deformed quartz sulphide veins. Common in D2 deformed zones.
  - $V_{qs}$: Quartz and sulphide (or secondary Cu minerals) with open saphe textures. Developed in skarn.
  - $V_c$: Carbonate veins. Common as deformed veins in marble. Occur as subparallel planar thin veins in hornfels.
approximately NNE direction. These dykes in the Copper Mountain area contain more quartz phenocrysts and particularly abundant xenoliths (usually less than 100 mm) than those in the Lead Mountain area. Clay gouge filled in fault zones, cut the hornfels sediments and indicate a late stage deformation with little significant displacement.

An interpretation of the D2 deformation zones and alteration is shown in Figure 10. It can be seen that the alteration becomes more intense closer to skarn. The lowest berm includes large areas of altered hornfels sediment outcrop suggesting that significant areas of skarn may have developed on hornfels sediments. West of the mapped area, skarn outcrops in contact
with marble occur, so that at least some of the skarn was developed on marble as well. The location of the original contact between hornfels sediments and marble is uncertain because it has been replaced by skarn. A possible interpretation is that the skarn is well developed in the Niumatang pit area due to the presence of altered D₂ deformation zones. In other words, D₂ deformation zones which developed during alteration and mineralization (as evidenced by mineralised Vₘₖ veins in D₂ zones) provided additional fluid access to the contact between marble and hornfels sediment, and ultimately enhanced the fluid trap.

### 6.2 The forming mechanism of high-grade orebody—the effect of D₂

The formation of D₂ deformation, which controls skarn orebody development, is divided into four stages (Fig. 10): Stage 1, σ stress caused conjugate veins showing feature of an acute bisector; Stage 2, veins begun to fold when the initial foliation started to develop; Stage 3, veins strongly deformed into folds with foliation developed; and Stage 4, veins were completely flattened and only early fold hinges remain and foliation developed extremely strongly during this stage.

Based on the observations from pit mapping (Figs 5, 9, 10), we infer that the strong deformation zone of quartz sulfide veins occur within the high strain zone. The D₂ deformation typically deformed S₁, which regional foliation D₂ was formed later than the regional folds and overthrust (Zhong et al., 2012). In addition, the occurrence of sulfides indicates that this deformation may be formed simultaneously or slightly later than with mineralization. No linear fabric was observed in the D₂ deformation zone, indicating their formation was due to flattening. Structural phenomena related to this deformation zone display different extents of stress change within the entire region. As observed in Figure 10, we find that the deformation in the center (high stress) is stronger than that at the edge. However, systematic stress gradient has not been widely observed in the deformation zone. In the D₂ deformation zone, the main deformation characteristics are like those commonly observed in the third and fourth stages, although the deformation features of the second stage have also been observed.

As shown in Figure 6, an interpreted F₁ fold has been folded by F₂ (D₂ deformation) in the south part of the Lead Mountain area. This suggests that a D₂ deformation structure was previously developed in this region.

The gliding-nappe attributed to D₁ deformation and named the Jiama-Kajunguo thrust system, formed at approx. 50 Ma (Zhong et al., 2013). The D₁ is actually a passive far field event and the D₂ is formed during the main collisional orogeny (including the formation of nappes). D₂ mainly provided the space for the development of deposits, and thus contributed significantly to the metallogensis of the deposit. It might represent the main regional deformation event response to the India–Asia collision during the Cenozoic (Kapp et al., 2007; Hou et al., 2009; Zhong et al., 2012, 2013). Aplite veins in Lead Mountain were formed earlier than the D₂ deformation because the veins were subject to D₂ deformation. Therefore, the D₂ deformation should occur slightly after 17 Ma. Mineralization was later or synchronized with D₂ deformation. Mineralized veins (quartz sulfide veins) were prior to the development of skarn alteration. The porphyry emplacement was later than D₂ deformation around approx. 15 Ma. Then there are some other small-scale structure activities resulting in micro-structures such as fault gouge, which are typically even later.

### 6.3 The relationship between alteration, structure and mineralization

Three types of alteration (A-, S- and K-type) have been mapped in different locations in the Jiama area. The type-A alteration occurs in the distal to the Jiama deposit. Type-S occurs intermittently and is recognized by the appearance of white to pale green colour of the rocks. In detail, this alteration type is mainly fine-grained silicification with patches of chlorite, epidote and common sulphides (pyrite, chalcopyrite, bornite and tetrahedrite). Type-K alteration was mapped in only a tiny area and is recognised by red-brown colour of the hornfels sediments. The deformation in the D₂ deformed zones initially resulted in vein development, thus improving fluid access to those zones, as evidenced by development of alteration in wall rocks. Skarn was located below the D₂ deformed zones, and D₂ developed a series of altered rocks which were gradually transformed into skarn, the major deposit orebody.

### 6.4 Exploration implications

The results from the regional structural mapping and the observation of rock alteration in this study may have important significance for exploration. First, although there were at least two periods of
deformation in the Jiama district and perhaps more in other regions, only the second deformation (i.e., D₂) was found to be associated with alteration and copper mineralization. The D₂ deformation can be identified, dated and described in detail. The zircon U–Pb age obtained from the aplite in the Jiama area has constrained the time of the D₂ deformation. In addition, high-grade ore shoots appear frequently in the D₂ deformation zones. Secondly, the K, S and A alteration types are also associated with in the D₂ deformation. Further exploration of the deeper areas or those peripheral to the Jiama deposit should fully take into account the key control of the D₂ deformation which was generally closely related to copper mineralization as demonstrated in this present study. In addition, the rock and alteration types closely related to the D₂ deformation might be useful pathfinders to mineralization.

7. Conclusion

In this paper, we presented detailed deformation characteristics associated with copper mineralization in the Jiama deposit district, Tibet, and reported new zircon U–Pb age for the aplite from this area to confirm the precise time of the structural deformation that is associated with and may have controlled the copper mineralization. Two periods of deformation were discerned in this area. Both deformation events are important for the development of copper mineralization, and in the following we summarize several key points:

1 Based on structural mapping and observations of rock alteration in the Niumatang, Copper Mountain and Lead Mountain areas of Jiama, Tibet, we demonstrate that there was a close relationship between structure, mineralization and alteration. The relationship is gradually variable. Mineralization developed widely in the alteration area accompanying deformation, with more veins being related to stronger deformation.

2 The progressive deformation characteristics observed in the field at the Lead Mountain and Niumatang pits indicate the similar strain intensity. The results therefore indicate that the intensity of mineralization is also variable at different areas. This has general implications for regional exploration.

3 Field-based observations indicate that mineralization was coeval or slightly later than D₂ deformation in the Jiama area. Our new zircon U–Pb dating indicates that aplite in the Lead mountain area formed in 16.9 Ma and therefore the D₂ deformation occurred slightly later than this time. Together with previous molybdenite Re–Os dating which revealed that the major copper mineralization occurred at approx. 14 Ma, we propose that the copper mineralization in Jiama was temporally related to the D₂ deformation.

4 Our observations suggest that the copper mineralization was closely related to the D₂ deformation which can be efficiently confirmed with thorough detailed mapping and observation of alteration features. For example, the observations that the D₂ deformation controlled ore shoots can be interpreted on several cross-sections through the Jiama deposit. This result could provide a good indication for future exploration of high-grade copper orebodies.

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