Genesis of the Gold Deposit in the Indus-Yarlung Tsango Suture Zone, Southern Tibet: Evidence from Geological and Geochemical Data

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Abstract: The Nianzha gold deposit, located in the central section of the Indus-Yarlung Tsango suture (IYS) zone in southern Tibet, is a large gold deposit (Au reserves of 25 tons with average grade of 3.08 g/t) controlled by a E–W striking fault that developed during the main stage of Indo-Asian collision (~65–41 Ma). The main orebody is 1760 m long and 5.15 m thick, and occurs in a fracture zone bordered by Cretaceous diorite in the hanging wall to the north and the Renbu tectonic mélangé in the footwall to the south. High-grade mineralization occurs in a fracture zone between diorite and ultramafic rock in the Renbu tectonic mélangé. The wall-rock alteration is characterized by silicification in the fracture zone, serpentinization and the formation of talc and magnesite in the ultramafic unit, and chloritization and the formation of epidote and calcite in diorite.

Quartz veins associated with Au mineralization can be divided into three stages. Fluid inclusion data indicate that the deposit formed from H2O–NaCl–organic gas fluids that homogenize at temperatures of 203°C–347°C and have salinities of 0.35wt%–17.17wt% NaCl equivalent. The quartz veins yield δ34O values of 0.15‰–10.45‰, low δDvSMOW values (~173‰ to ~96‰), and the δ13C values of ~17.6‰ to ~4.7‰, indicating the ore-forming fluids were a mix of metamorphic and sedimentary organogenic fluids with the addition of some meteoric and mantle-derived fluids. The pyrite within the diorite has δ34Sv-CDT values of ~2.9‰–1.9‰ (average ~1.1‰), 206Pb/204Pb values of 18.47–18.64, 207Pb/204Pb values of 15.64–15.74, and 208Pb/204Pb values of 38.71–39.27, all of which are indicative of the derivation of S and other ore-forming elements from deep in the mantle. The presence of the Nianzha, Bangbu, and Mayum gold deposits within the IYS zone indicates that this area is highly prospective for large orogenic gold deposits. We identified three types of mineralization within the IYS, namely Bangbu-type accretionary, Mayum-type microcontinent, and Nianzha-type ophiolite-associated orogenic Au deposits. The three types formed at different depths in an accretionary orogenic tectonic setting. The Bangbu type was formed at the deepest level and the Nianzha type at the shallowest.

Key words: geology, gold mineralization, Nianzha Deposit, Indus-Yarlung Tsango suture zone, Tibet

1 Introduction

Several medium to large gold deposits have been discovered in two gold mineralization belts, which are distributed along the Ailaoshan Red-River large strike-slip shear (ARSZ) zone and the Indus-Yarlung Tsango suture (IYS) zone in the southeastern and southern Tibetan collisional orogen respectively (Fig. 1a). The gold deposits controlled by the ARSZ zone in the southeastern oblique
collision zone of Tibetan collisional orogen (Fig. 1a) were formed during the late collisional stage of Indo-Asian continental collision (40–26 Ma; Hou and Cook, 2009; Hou Zengqian et al., 2006c). These deposits, including the relatively well-studied Daping, Mojiang, Laowangzhai and Chang’an gold deposits have been confirmed to be orogenic gold deposit (Deng et al., 2014, 2015a, 2015b, 2015c, 2016; Li Hua et al., 2015, Shi Guiyong, 2010; Yuan Shisong et al., 2010; Sun Xiaoming et al., 2006, 2007, Sun et al., 2009). The gold deposits controlled by the IYS zone in southern Tibetan collisional orogen (Fig. 1a) were formed during the main collisional stage of Indo-Asian collision (65–41 Ma; Hou Zengqian et al., 2006a, 2006b). These deposits including Mayum, Bangbu and Zhemulang gold deposits have also been confirmed to be orogenic gold deposit (Jiang et al., 2009; Sun Xiaoming et al., 2010, Sun et al., 2015; Sun Qingzhong et al., 2013; Zhou Feng et al., 2011; Wen Chunqi et al., 2006a, 2006b).

The term 'orogenic gold deposit', first used by Bohlke (1982), have widely been accepted after a systematic description of the concepts and classification of this type of mineral deposit by Groves et al. (1998) and Goldfarb et al. (2001). It is one of the most important types of gold deposits (Weatherley et al., 2013; Groves et al., 2000;
Goldfarb et al., 2004, 2005) and has been widely studied (e.g., Pei et al., 2016a, 2016b; Pei Yingru et al., 2015; Niu et al., 2014; Goldfarb et al., 2013, 2014; Chen Yanjing et al., 2007; Bierlein et al., 2001, 2006; Jiang Sihong et al., 2008; Feng Chengyou et al., 2004; Zhang Dequan et al., 2001). Orogenic gold deposits were originally thought to occur only in accretionary orogenic tectonic settings (Barley and Groves, 1992; Kerrich et al., 2000) and to form at different levels within the crust, from near-surface sub-greenschist facies to deeper-level granulite facies (Groves, 1993).

The geological and geochemical studies on the gold deposits distributed along the ARSZ zone and IYS zone indicated that the mineralization characteristics of these deposits are similar to the orogenic gold deposit (Shi Guiyong et al., 2010; Yuan Shisong et al., 2010; Sun Xiaoming et al., 2006, 2007, Sun et al., 2009; Jiang et al., 2009; Sun Qingzhong et al., 2013; Zhou Feng et al., 2011; Wen Chunqi et al., 2006a, 2006b). The geochronological and tectonic studies on these gold deposits, however, showed that the ore-forming process occurred during the Indo-Asian continental collision (Deng et al., 2015; Sun Xiaoming et al., 2010, Sun et al., 2015). All of these imply that the orogenic gold deposit may also be formed at collisional orogenic tectonic settings. A large scale gold deposit naming Nianzha gold deposit, and some areas with gold prospect such as Xingxia, Dejiilan, have recently been discovered, in the central section of IYS zone (Fig. 1a), showing huge ability of gold mineralization in this suture zone. And the geological features of other mineral deposits/occurrences which distribute along IYS are listed in Table 1. The characteristics of this gold deposit and the nature of the gold metallogenic event occurred in the IYS zone during the main stage of Indo-Asian continental collision remain unclear. Given that orogenic gold deposits can form at deep to shallow crustal levels within an accretionary orogenic tectonic setting, whether the regularity exists in continental collisional orogenic environment still unknown.

The Nianzha large gold deposit (Au reserves of 25 tons with average grade of 3.08 g/t) was discovered in an ophiolitic mélangé belt of the IYS zone in 2010, and the detailed exploration of this deposit was finished in 2015. Although its characteristics are similar to those of typical orogenic gold deposits such as Bangbu and Mayum within the IYS zone, there are some differences in terms of their geological features, alteration type, and mineralization style, which may reflect differences in mineralization depth. In this paper, we provide a detailed geological overview of the Nianzha gold deposit and new isotope data of H, O, C, S and Pb to identify the geological characteristics of the deposit and to assess the sources of ore-forming fluids and metals within the deposit. These results, combining with the previous studies on the Bangbu and Mayum deposits (Jiang et al., 2009; Sun Xiaoming et al., 2010, Sun et al., 2015; Sun Qingzhong et al., 2013), are used to develop a deep–shallow metallogenic model of orogenic gold deposits in continent-collisional orogenic environments in the IYS zone.

2 Regional Geology

The Tibetan Orogen is a complex tectonic collage created by the Mesozoic accretion of four terranes onto the southern margin of the Asian continent (Allergre et al., 1984; Chang Chengfa et al., 1973; Hou et al., 2009). From north to south, these are the Songpan–Ganzi, Qiangtang, Lhasa, and Himalaya terranes (Fig. 1a), which are separated by the Jinshajiang suture, the Bangong–Nujiang suture, and the IYS, respectively, all of which represent relict sections of the Tethyan Ocean (Yin and Harrison, 2000; Hou et al., 2009).

The IYS in China is more than 2000 km long (Hou Zengjian et al., 2008), and consists of a western section along the Ga’er River that is in contact with the Indus suture zone, a central section, and an eastern section along the Yarlung Tsangpo River that turns toward Burma in the

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<td>Dejiilan</td>
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south. The IYS striking E–W separates the Mesozoic and Cenozoic acidic-intermediate intrusions and volcanic rocks of the Lhasa Terrane to the north (Mo Xuanxue et al., 2003, Mo et al., 2007) from the Triassic–Cretaceous low-grade metamorphosed marine and abyssal clastic rocks of the Himalayan Terrane to the south (Mo Xuanxue et al., 2009; Li et al., 2010). Three sub-tectonic units have been recognized in the IYS (Pan Guitang et al., 2006, Pan et al., 2012): the Yarlung Tsangpo ophiolitic mélangé belt described in detail below, the Zhongba block comprising the upper Paleozoic marine sediments with metamorphism of low-grade greenschist facies in the western section, and the Langjiexue accretionary wedge of the upper Triassic low-grade metamorphosed marine clastic rocks in the eastern section.

The Yarlung Tsangpo ophiolitic mélangé belt distributes along the IYS with a length of 2000 km and width of 5–20 km. It is divided into two branches by the Zhongba block in the western section, whereas the Langjiexue accretionary wedge in the eastern section. The belt contains clastic rock, limestone and ophiolite (composed of dunite, harzburgite, lherzolite, layered gabbro, swarm of maﬁc dike, mantle-like plagiogranite, pillow basalt, and radiolarian siliceous rock) in ﬁne-grained turbiditic matrix or strongly deformed tectonic mélange (Geng Quanru et al., 2004; Pan Guitang et al., 2006; Li et al., 2010, Li Guangwei et al., 2011; Xiong et al., 2016). Three types of ophiolites have been recognized in the central part of the belt which are supra-subduction zone (SSZ) type, mid-ocean ridge (MOR) type and rifting type (Fig. 1b). The SSZ type ophiolite of the early Cretaceous consisting of boninite and ultramafic cumulate with olivine-clinopyroxene-plagioclase order distributes in the south of Xigaze (Hu Jingren et al., 2002; Chen Genwen et al., 2003; Li Jianfeng et al., 2009; Niu Xiaolu et al., 2006; Li Wenxia et al., 2016), while the same type ophiolite of the late Jurassic to early Cretaceous distributes within the Renbu tectonic mélange belt (Hu Jingren et al., 2002). The MOR type ophiolite of the early Cretaceous composed of ultramafic cumulate with olivine-plagioclase-clinopyroxene order distributes in the north of Bailang (Hu Jingren et al., 2002; Zhao Jianan et al., 2015). The rifting type ophiolite of the late Triassic composed of intraplate basalts distributes along the Kadui-Chaba tectonic mélange belt (Hu Jingren et al., 2002).

3 Geology of Gold Deposits in the IYS

Some gold deposits such as Bangbu and Mayum in the IYS zone have been studied in detail (Duoji et al., 2003; Wen Chunqi et al., 2004, 2006b; Hou Zengqian et al., 2006b; Jiang et al., 2009; Sun Xiaoming et al., 2010; Sun Qingzhong et al., 2013; Pei et al., 2016a), whereas the Nianzha gold deposit discovered recently has not been reported in literature. Here, a detailed summary about the geology of Nianzha gold deposit and overview about the Bangbu and Mayum gold deposits are given as follows.

3.1 The Nianzha gold deposit

3.1.1 Lithological units

There are three main lithological units, which are the upper Triassic Jiangxiong Formation, the Renbu tectonic mélange belt and the Cretaceous diorite pluton, and some small lithological units of the lower Cretaceous Bima formation composed of metamorphosed silstone, sandstone, andesite and tuff, and the Quaternary in the district of Nianzha gold deposit (Fig. 2a).

The upper Triassic Jiangxiong formation belonging to the Langjiexue accretionary wedge crops out in the south of the district (Fig. 1b), and consists of metamorphosed lamellar feldspar greywacke, metasandstone, silty slate, and sericite-bearing slate (Fig. 2a; Figs. 3a, 3b). Identifying the sedimentary sequence of this formation is difficult due to strong pressed folding and intense foliation substitution. The foliation and axial plane of fold with striking E-W generally dip to the south with dip angle of 49°–57° in the southern part of the Jiangxiong formation unit, while those dip to the north in the northern margin of this lithological unit, showing folding of the foliation.

The E-W striking Renbu tectonic mélange belt with an arcuate northern margin distributes in the central part of the district (Fig. 2a), and consists of many blocks of maﬁc and ultramafic rocks, metasandstone and marble, and matrix of strongly deformed slate, phyllite and schist. The ultramafic blocks occurred as lenses with dimensions of up to 1000 m length and 100 m width mainly in the northern part of the belt, and were altered to be serpentinite with relict foliation (Figs. 3e, 3f). The maﬁc blocks with varying size occurred mainly in the central part of the belt, and consist of metamorphosed gabbro and diabase, while the metasandstone and marble blocks occurred mainly in the southwestern part of the belt. The matrix of the belt is composed of slate with intense foliation and cleavage, and minor phyllite and schist occurred locally around the blocks and in the margin of the belt. Most of the foliation, schistosity and cleavage trend with striking E–W, and dip to the south with dip angle of 40°–60°. The contacts between different blocks or between blocks and the matrix material within the belt are generally faulted, with only a few blocks remaining within their original sequences.

The Cretaceous diorite pluton belonging to the Gangdese batholith of the Lhasa terrane crops out in the north of the district (Fig. 2a), and consists of feldspar,
Fig. 2. (a), Geological map of Nianzha deposit; (b), Map of the orebody distribution of Nianzha deposit; (c), Cross-section along the prospecting line (modified from Census Investigation Report of the Nianzha Deposit, 2014).

hornblende and minor biotite and quartz with grain size of 2-6 mm (Figs. 3c, 3d). In the southern margin of the pluton, a ductile shear zone of 150 m width composed of dioritic mylonite and mylonitized diorite with mylonitic foliation striking E-W and dipping to the north at 30°–50° was developed with a motion direction of thrusting from north to south indicated by porphyroelastic and S-C fabrics in the mylonite. Intense brittle fracture zones cutting the mylonite were also developed in the southern margin of the pluton after the ductile shearing deformation.

Two main E-W striking faults were developed along the contact zones between the three lithological units (Fig. 1b). The northern one with number of F1, which is a part of the Gangdese thrust fault with deformation age of 30–24 Ma (Yin et al., 1994, 1999; Harrison et al., 1999), has a E-W striking fracture zone of 20–200 m width between the diorite pluton of Gangdese batholith and the Renbu
Fig. 3. Petrologic characteristics of rocks from the Nianzha deposit.
(a)–(b), Samples and microphotographs of sand slate; (c)–(d), Samples and microphotographs of diorite, composed mainly of plagioclase; (e)–(f), Samples and microphotographs of highly serpentinized ultrabasic rock; (g)–(h), Samples and microphotographs of vein lamprophyre.
tectonic mélangé belt. The fracture zone consisting of breccias of mylonitized diorite, metamorphosed ultramafic rock, phyllite and schist dips steeply to the north at shallow level, and turns to the south at deep level (Fig. 2c) against the north dipping mylonitic foliation in the diorite, indicating that the brittle fracture occurred after the ductile thrusting of the Gangdese thrust fault. The fracture zone and secondary order faults striking NW control the distribution of most of alteration and gold mineralization in the district. The altered tectonic breccia was broken again to form tectonic lens and breccia, and fault gouge along a fault plane in the fracture zone, indicating re-activity of the fault after gold plane mineralization. The southern main fault is between the Renbu tectonic mélangé belt and the upper Triassic Jiangxiang formation of the Langjiexue accretionary wedge, and has a fracture zone of 10–20 m width with dipping to the south. Several small faults striking NE cut the main faults, and control the intrusion of some Lamprophyre dikes with no alteration (Figs. 3g, 3h).

3.1.2 Alteration and mineralization

A very strong hydrothermal alteration belt consisting of silicification, serpentinization, carbonatization, chloritization, minor epidotization and sericitization was developed along the northern main fault and near areas in the district of Nianzha gold deposit (Fig. 2b). Different wall rocks can exhibit different alteration types as a result of particular physical and chemical properties. The silicification, which occurred mainly along the northern fault and secondary order faults in the fracture zone and adjacent mylonitized diorite, metasandstone, phyllite and slate, is the dominant alteration type with three styles.

The first is fine grained quartz aggregation with minor sericite and chlorite disseminated in diorite and metasandstone (Fig. 4a), the second is coarse grained quartz vein with minor muscovite distributed in diorite, metasandstone (Fig. 4b), phyllite and the fracture zone as breccia, whereas the third is fine grained quartz veinlets with minor sulfide penetrated into all altered rocks (Fig. 4c) and the fracture zone as cement (Fig. 4d). The serpentinization, which occurred mainly in the ultramafic rocks of the Renbu tectonic mélangé belt, formed serpentinite with relict foliation and serpentine veinlets (Fig. 4c) in the ultramafic rocks near the northern main fault, and serpentinite with relict olivine and pyroxene in the ultramafic rocks away from the northern main fault to the south, indicating that part of the serpentinization was developed by the hydrothermal alteration. The carbonatization occurred with two styles. One formed lenses of quartz-magnesite, magnesite and listwaniite between serpentinized ultramafic rocks and silicified fracture zone of the northern main fault (Figs. 4f, 4g), whereas the other formed veinlets of calcite (Fig. 4h) and ankerite distributed in the alteration belt and outside. The chloritization and epidotization occurred mainly in the diorite, especially near the northern main fault.

Gold mineralization occurred mainly with silicification in the alteration belt structurally controlled by the northern main fault and secondary order faults in this deposit (Fig. 2b). Gold orebodies with tabular, lenticular or cystiform shapes are located primarily in the fracture zone of the faults, especially the fracture zone between the serpentinized ultramafic rocks and the diorite, where high-grade ore occurred. The main orebody is tabular with striking length of 1760 m, average width of 5.15 m, and dipping length of 350 m in the fracture zone of the northern main fault (Fig. 2c). Three ore types have been recognized as follows: (1) The disseminated type ore composed of fine grained quartz, chlorite, calcite and pyrite aggregation within diorite (Fig. 5a) occurred near the fracture zone. (2) The breccia type ore composed of breccias of quartz vein, silicified diorite, metasandstone, phyllite and serpentinized ultramafic rocks, and cement consisting of fine grained quartz, ankerite, sericite, chlorite and sulfide weathered to limonite (Figs. 5b, 5d) was mainly located in the fracture zone of the fault. (3) The veinlet type ore consisting of fine grained white-gray quartz-pyrite veinlets and yellowish ankerite-quartz veinlets in silicified diorite (Fig. 5c) and metasandstone (Fig. 5f) was located adjacent to the fracture zone. The orebodies and altered wall rocks were locally fractured again and cut by NE striking fault after the alteration and mineralization.

3.1.3 Relationship between quartz veins and Au mineralization stage

The formation of orogenic gold deposits is intrinsically linked to the evolution of ore-forming fluids. Although the Au within the Nianzha area occurs throughout the diorite, areas with high Au concentrations are associated with regions of silicification. The hydrothermal activity associated with the Nianzha deposit formed a series of veins and minerals that inverted the process of fluid evolution. Three different stages of quartz veins related to Au mineralization are identified in the study area: stage 1 is characterized by the formation of quartz–feldspar and quartz–metal sulfide veins (Figs. 5a, 5b); stage 2 by the formation of grey–white quartz veinlets, and quartz–ankerite, quartz–limonite, and quartz–mica veins (Figs. 5c, 5d); and stage 3 by the formation of flat-lying quartz veins and quartz–calcite veins (Figs. 5e, 5f). Most of the gold mineralization occurred during the first two stages.

3.2 Bangbu gold deposit

The Bangbu gold deposit, located in the southern part of
Fig. 4. Photographs showing the characteristics of different types of alteration and mineralization at the Nianzha deposit. (a), Sericitization of diorite; (b), Limonite formation in diorite; (c)-(d), Silicification of vein diorite; (e), Serpentinitization of ultramafic rock; (f)-(g), Au ore body outcropping along the contact zone between sheets of ultramafic rock and diorite, the diorite is silicified and the ultramafic rock is serpentinitized; (h), Carbonization of vein diorite.
Fig. 5. Stages and types of veins in the Nianzha mining area. 
(a)–(b), Stage 1: quartz–pyrite and quartz–K-feldspar veins; (c)–(d), Stage 2: gray quartz veinlets and quartz-limonite veins; (e)–(f), Stage 3: quartz–calcite and coarse quartz veins.

Jiacha County, southern Tibet, China, occurred in the southeastern part of the Langjiexue accretionary wedge which is one of the three subunits of the IYS zone (Fig. 1a). The deposit is controlled by the regional E-W-trending Qusong-Cuong-Zhemulang brittle-ductile shear zone and the Jindi-Lunong synclinorium (Sun Xiaoming et al., 2010; Sun Qingzhong et al., 2013). In the district of the deposit, the upper Triassic Langjiexue Group composed of phyllite and metasandstone crops out, and a series of secondary order faults striking NNW and NE have also been identified (Sun Xiaoming et al., 2010; Sun Qingzhong et al., 2013). Several small granodiorite and diabase dikes intruded into the Langjiexue Group along E-W faults.

The main orebody of this deposit is a quartz vein with 500 m length and 1–2 m thickness controlled by the E-W striking brittle-ductile shear zone dipping to the south with dip angle of 20°–30°. Weakly wall rock alteration including silicification, sericitization, carbonatization and sulfidation occurred in a narrow zone near the quartz vein. The main ore minerals in all of the known ore bodies are pyrite, galena, sphalerite, chalcopyrite and native gold
occurring mostly as irregular aggregation. The gangue minerals include quartz, sericite, epidote, and carbonates. Native gold is hosted in the quartz and sulfides. Four stages of mineralization in the auriferous quartz veins have been identified: Stage 1 quartz+coarse-grained sulfides, Stage 2 gold+fine-grained sulfides, Stage 3 quartz+ carbonates, and Stage 4 quartz+greigite.

$^{40}$Ar/$^{39}$Ar age data for sericite collected from auriferous sulfide-quartz veins of the orebody in the deposit gives a plateau age of 49.52±0.52 Ma (Pei et al., 2016a). The orebody was formed during the main collisional event (~65~64 Ma; Hou Zengqian et al., 2006b) of the Tibet-Himalayan orogen created by Indo-Asian collision. Fluid inclusions indicate that the ore fluid was CO$_2$-rich, with salinities between 4.34 wt% to 7.45 wt% NaCl equiv, and homogenization temperatures predominantly ranging from 170 to 261°C. The $\delta^{18}$O fluid (3.98~7.18‰) and low $\delta^{18}$O$_{SMOW}$ (~90‰ to ~44‰) for auriferous quartz veins suggest ore-forming fluids were mainly metamorphic in origin, with some addition of organic matter (Tabal 3). The $\delta^{34}$S$_{sulfide}$ values of sulfide from auriferous quartz veins show a range from 1.2 to 3.6‰. The lead isotope compositions of sulfides from the gold ore are characterized by highly radiogenic values: 18.662 to 18.764 for $^{206}$Pb/$^{204}$Pb, 15.650 to 15.683 for $^{207}$Pb/$^{204}$Pb, and 38.901 to 39.079 for $^{208}$Pb/$^{204}$Pb (Table 4) (Pei et al., 2016a).

### 3.3 Mayum gold deposit

The Mayum gold deposit is a typical orogenic gold deposit controlled by a large-scale ductile shear zone striking E-W in the southern part of the Zhongba block which is one of the three subunits of the IYS zone (Fig. 1a) (Duoji et al., 2003; Hou Zengqian et al., 2006b; Jiang et al., 2009). The metamorphic sedimentary sequences of the late Paleozoic consisting of gray-green quartz-sericite schist and calcite-sericite-chlorite schist, yellowish-brown calcite schist, and grayish crystalline limestone crop out in the district of the deposit. The ductile shear zone and major thrust faults striking E-W and dipping to the south were developed along the bed of the sequences.

Two placer gold orebodies with Au reserves of about 20 metric ton distribute in the southern part of the district, and a gold mineralization belt in the metamorphic sedimentary sequences extends intermittently for about 4 km in the northern part of the district (Duoji et al., 2003). Sixteen gold orebodies have been delineated in the mineralization belt, with lengths of 50 to 712 m, thicknesses of 0.9 to 0.8 m, and plunge depths of 250 to 300 m. The Au grades in these orebodies range 2.23 g/t to 69.56 g/t, with an average of 31.84 g/t (Wen Chunqi et al., 2006b). The ore consists of pyrite, galena, stibnite and minor chalcopyrite, while the gangue mainly consists of quartz and calcite. Limonite, covellite and jarosite occur in the oxidation zone near the surface. Hydrothermal alteration is well developed surrounding the orebodies and fracture zone. Besides sulfidation directly associated with the gold ore, other common alteration types include sericitization, silicification, carbonatization and argillization.

$^{40}$Ar/$^{39}$Ar age data for sericite collected from auriferous sulfide-quartz veins of the orebody in the deposit gives two plateau ages of 44.08±0.39 Ma (Wen Chunqi et al., 2004) and 59.34±0.62 Ma (Jiang et al., 2009), later than the onset of the Indo-Asian collision(~65 Ma; Hou Zengqian et al., 2006b). Fluid inclusions indicate that the ore fluid was CO$_2$-rich, with salinities mainly between 1wt% and 6wt% NaCl equiv, and homogenization temperatures predominantly ranging from 260 to 280°C. The $\delta^{18}$O$_{SMOW}$ values for quartz from auriferous veins range from 13.7‰ to 16.3‰, and calculated $\delta^{18}$O$_{H_2O}$ values in equilibrium with quartz vary from 5.54 to 9.48‰, the $\delta^{18}$O$_{SMOW}$ values from ~120‰ to ~98‰ (Tabal 3). The $\delta^{34}$S$_{sulfide}$ values of sulfide from auriferous quartz veins show a variation from ~0.2 to +4.5‰. The lead isotope compositions of sulfides from the gold ore are characterized by highly radiogenic values: 18.321 to 19.603 for $^{206}$Pb/$^{204}$Pb, 15.679 to 15.811 for $^{207}$Pb/$^{204}$Pb, and 38.431 to 40.221 for $^{208}$Pb/$^{204}$Pb (Table 4) (Jiang et al., 2009).

### 4 Analytical Methods

#### 4.1 Fluid inclusion and laser Raman analyses

Microthermometric analyses were performed using a temperature-controlled microscope stage (Linkam THSMG-600) at the Chinese Academy of Geological Sciences (CAGS), Beijing, China. The temperature of the stage can be set between ~196°C and 600°C, and is controlled to within ±0.1°C at temperatures of <30°C and within ±1°C at temperatures of >30°C. Salinity (NaCl equivalent or w) was calculated using freezing temperatures, employing the formula proposed by Hall et al. (1988). Laser Raman analysis of single inclusions within quartz veins was undertaken using a laser Raman spectrometer (System-2000, Renishaw) at the Laser Raman Laboratory of the Institute of Mineral Resources, CAGS, Beijing, China, using a laser wavelength of 514 nm, a laser power of 20 mW, a minimum laser beam diameter of 1 mm, and spectral resolution of 1~2 cm$^{-1}$.

#### 4.2 Stable isotope analysis

Stable isotope analyses were undertaken using a MAT-253 EM spectrometer at the Isotopic Laboratory of the Institute of Mineral Resources, CAGS, Beijing, China. The analytical uncertainty was ±0.2‰ for oxygen, carbon, and sulfur isotopes, and ±2‰ for hydrogen isotopes.
Oxygen isotopic analysis was undertaken using the BrF₅ method (Clayton and Mayeda, 1963) where pure quartz is reacted with BrF₅ for 15 h to produce oxygen before CO₂ collection via a transformation system at a temperature of 700°C after 12 min.

Quartz carbon and hydrogen isotopes were determined using 5 g pure quartz separates that passed a 40–60 mesh, following degassing at 150°C for more than 4 h under vacuum, removing any surface water and secondary inclusion fluids. The remaining primary fluid inclusions within these samples were then decrepitated at a temperature of 400°C, yielding carbon (in the form of CO₂) and water, with the latter reacted with zinc for 30 min at a temperature of 400°C to produce hydrogen (Coleman et al., 1982). The hydrogen was then transferred to a sample bottle filled with activated carbon after freezing in liquid nitrogen.

Sulfides were prepared for analysis using Cu₂O as an oxidant (Robinson and Kusakabe, 1975), with sulfate minerals purified to pure BaSO₄ using a carbonate–zinc oxide semi-melt method, before SO₂ was extracted using V₂O₅ as an oxidant. The resulting SO₂ was used for sulfur isotope analyses.

4.3 Radiogenic isotopic analysis

Lead isotope analysis was undertaken at the Radiogenic Isotope Geochemistry Laboratory of the Science and Technology University, Hefei Province, China. Prior to analysis, 100 mg of powdered samples was added to 15 ml Teflon cups, and mixed and shaken with 8–10 drops of pure HClO₄ before heating to complete dissolution over a period of 1 week. The isolation and purification of lead isotopes were undertaken using an AG1-X8 (200–400 mesh) purification system before lead isotopic ratios were measured on a MAT-262 thermal ionization mass spectrometer. This approach used an NBS981 standard for external standardization, and the precision of this analysis is better than 0.01% (Chen et al., 2000, 2002, 2007).

5 Results

5.1 Fluid inclusion microthermometry

The fluid inclusions present in quartz veins that formed during the three stages of mineralization are rare, occur in isolation, and have no preferred orientation. They are small (generally <10 mm) and have elliptical, polygonal, or irregular shapes (Fig. 6). The fluid inclusions within the Nianzha deposit are dominated by vapor–liquid inclusions and contain <40% gas phase by volume. All of these inclusions homogenize to the liquid phase on heating.

The results of analyzes of 235 fluid inclusions are listed in Table 2. Stage 1 quartz veins contain fluid inclusions that generally homogenize between 203°C and 347°C (mainly 240°C and 280°C with a mean of 257.7°C; Fig. 7a). They have w (NaCl equivalent) salinity values of 0.35wt%–12.05wt% (Fig. 7b) with a mean value of 6.00
wt%. Fluid inclusions from stage 2 veins generally homogenize between 205.5°C and 307.1°C (mainly 220°C C–260°C with a mean of 244.3°C; Fig. 7a) and have w salinity values of 0.70wt%–11.46wt% (mean, 5.50wt%; Fig. 7b). Stage 3 quartz veins inclusions homogenize at 217.7°C–342.7°C (Fig. 7a) and have salinities of 0.35wt%–17.17wt% (Fig. 7b), yielding average values of 272.7°C and 4.64wt%, respectively. These data show no clear differences in homogenization temperature or salinity between fluid inclusions within quartz veins that formed during the different stages of mineralization, with all of these inclusions being characterized by low-temperature and low-salinity fluids.

5.2 Stable isotopes
5.2.1 H–O–C isotopes

Twenty quartz samples (four from stage 1 veins, six from stage 2 veins, and ten from stage 3 veins) were analyzed for their H, O, and C isotopic compositions. The results are listed in Table 3. The quartz have δ18O_{SMOW} values of 9.1%–19.4%, yielding δ18O_{fluid} values of 0.15%–10.45%. The δD_{SMOW} values for fluid inclusions from the quartz range from −173‰ to −96‰ and the δ13C values range from −17.6‰ to −4.7‰. Stage 1 samples yield δD_{VSMOW} values from −126‰ to −104‰, δ18O_{VSMOW} values of 9.1‰–16.6‰, δ18O_{fluid} values of 0.15‰–7.65‰, and δ13C values from −17.6‰ to −9.5‰. Stage 2 samples yield δD_{VSMOW} values from −141‰ to −96‰, δ18O_{VSMOW} values of 10.2‰–18.2‰, δ18O_{fluid} values of 1.25‰–9.25‰, and δ13C values from −14.2‰ to −8.4‰. Finally, stage 3 samples yield δD_{VSMOW} values from −173‰ to −124‰, δ18O_{VSMOW} values of 14.6‰–19.4‰, δ18O_{fluid} values of 5.65‰–10.45‰, and δ13C values from −13.9‰ to −4.7‰.

5.2.2 Sulfur isotopes

The S isotopic compositions of seven pyrite samples from the Nianzha deposit are listed in Table 4 and shown in Fig. 8. Three samples of disseminated pyrite from the diorite yield δ34S_{VCDT} values of −2.9‰–1.9‰ (average of −1.1‰), two pyrite samples from diorite-hosted quartz–sulfide veins yield δ34S_{VCDT} values of −2.7‰ and −2.4‰ (average of −2.55‰), and two chalcopyrite samples from quartz–sulfide veins yield δ34S_{VCDT} values of −2.9‰ and −2.6‰ (average of −2.75‰).
Table 3 H-O-C isotope compositions from the Nianzha, Bangbu and Mayum deposits

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<th>δ18Owater(‰)</th>
<th>δ13Cwater(‰)</th>
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Notes: T is the averaged homogenization temperature value. The fractionated translation between quartz and fluid are using 1000lnquartz-water= 3.38 × 106T-2.340 (Clayton et al., 1972).

5.3 Radiogenic isotopes
The Pb isotopic compositions of eight pyrite and chalcopyrite samples from the Nianzha deposit are given in Table 4. The respective values of 206Pb/204Pb, 205Pb/204Pb, and 208Pb/204Pb are 18.47–18.64, 15.64–15.74, and 38.71–39.27, with averages of 18.57, 15.70, and 39.01, respectively, all of which are indicative of uniform Pb isotopic compositions with small overall ranges.

6 Discussions
6.1 Structural controls on the formation of the gold deposit
The Indo-Asian orogenic event in Tibet and the related
### Table 4 Sulfur and lead isotope compositions of pyrites from Nianzha, Bangbu and Mayum gold deposit

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<th>Deposit</th>
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<td>BB-2</td>
<td>pyrite</td>
<td>3.2</td>
<td>38.947</td>
<td>15.658</td>
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<td></td>
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<td></td>
<td>BB-6</td>
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<td>1.9</td>
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<td>15.677</td>
<td>18.764</td>
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</tr>
<tr>
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<td>BB-11</td>
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<tr>
<td></td>
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<td>15.659</td>
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<td>BB-18</td>
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<td>15.655</td>
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<td></td>
<td>BB9-3-8</td>
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<td>38.923</td>
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<tr>
<td></td>
<td>BB9-3-2</td>
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<td>15.654</td>
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<td>38.925</td>
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<tr>
<td>Mayum</td>
<td>MYM06-10</td>
<td>pyrite</td>
<td>−0.2</td>
<td>38.518</td>
<td>15.708</td>
<td>18.321</td>
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<td></td>
<td>MYM04-12</td>
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</tr>
<tr>
<td></td>
<td>MYM06-10</td>
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<tr>
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<td>0.2</td>
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<td>40.101</td>
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<td>40.057</td>
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<td></td>
<td>MYM22</td>
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<td>3.8</td>
<td>40.014</td>
<td>15.749</td>
<td>19.525</td>
<td>Jiang et al., 2009</td>
</tr>
<tr>
<td></td>
<td>MYM04-29</td>
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<td></td>
<td>MYM06-30</td>
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<td>40.109</td>
<td>15.773</td>
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</tr>
<tr>
<td></td>
<td>MYM06-40</td>
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<td>4.5</td>
<td>40.147</td>
<td>15.811</td>
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<tr>
<td></td>
<td>MYM21-1</td>
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<td>40.024</td>
<td>15.776</td>
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<tr>
<td></td>
<td>MYM21-3</td>
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<td>15.740</td>
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<tr>
<td></td>
<td>MYM22</td>
<td>stibnite</td>
<td>2.6</td>
<td>39.943</td>
<td>15.745</td>
<td>19.463</td>
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</tr>
</tbody>
</table>

peak metamorphism at 65–41 Ma provided suitable conditions for the formation of orogenic gold deposits along the IYS zone (Hou et al., 2009). Trans-lithospheric structures in the IYS provided conduits for the large-scale movement of mineralizing fluids, with second- or third-order structures providing loci for gold precipitation. The Renbu tectonic mélangé zone was probably the main control on the formation of the Nianzha gold deposit. The ore-forming fluids flowed along the zone before precipitating gold in second- and third-order structures (Fig. 2a), with Au mineralization occurring in fracture zones, in both ultramafic and diorite. The hanging wall of the mineralized F1 fault contains Jiangxiong Group sandstone and slate units, whereas the footwall consists of Cretaceous diorite. The hanging wall of the F2 fault consists of the diorite intrusion and the footwall of Jiangxiong Group sediments (Fig. 2b). Hydrothermal alteration in the area is structurally controlled and the diorite located near sheets of ultramafic rock has undergone significant alteration whereas distal diorite remains fresh. A large portion of the Au mineralization within the Nianzha mining area is hosted by strongly altered diorite. While the Bangbu gold deposit is
controlled by the regional E-W-trending Qusong-Cuogu-Zhemulang brittle-ductile shear zone and the Jindi-Lunong synclinorium (Sun Xiaoming et al., 2010; Sun Qingzhong et al., 2013). And the Mayum gold deposit is controlled by a large-scale ductile shear zone which striking E-W in the southern part of the Zhongba block.

6.2 Composition and origin of ore-forming fluids

The δDvSMOW–δ18Ofluid diagram in Fig. 9 reveals that samples of quartz veins from each of the three mineralization stages do not show significant evolutionary trends, indicating a mixture of metamorphic fluid compositions towards decreasing δDvSMOW values but with relatively invariant δ18O values. This suggests that mineralization at Nianzha formed in an open system. The homogenization temperatures of 203°C–347°C and ω salinity values of 0.35wt%–17.17wt% for quartz veins indicate that the deposit formed from low-temperature and low-salinity fluids. The δDvSMOW values are generally lower than those of most orogenic gold deposits (Fig. 9), suggesting an influx of meteoric water or a fluid containing organic hydrogen (Goldfarb et al., 2004). The laser Raman spectra analysis indicates the presence of an organic gas in the fluid inclusions in quartz veins (Fig. 10). The organic matter is likely to have originated from interactions between organic-matter-bearing sedimentary units and the ore-forming fluids. Magnesite alteration (Figs. 4f, 4g) may have contributed some of the CO₂ in the fluid inclusions.

The above observations indicate that the Nianzha deposit was formed by a combination of metamorphic and sedimentary organic fluids mixed with meteoric water and a possible minor contribution from the mantle. In turn, this suggests that the deposit formed at shallow depths within an open system, a model that is consistent with the presence of small two-phase gas–liquid fluid inclusions. Samples from three of the main orogenic gold deposits within the IYS (the Nianzha, Bangbu, and Mayum deposits) all show trends towards decreasing δDvSMOW values (Fig. 9), suggesting they formed at different depths, from the deepest deposit (Bangbu) through the Mayum deposit to the shallowest (Nianzha).

The δ13C values of fluid inclusions from the study area (~17.6‰ to ~4.7‰; Table 3) are lower than typical values expected for orogenic gold deposits (~11‰ to 2‰; McCuaig and Kerrich, 1998). Carbon in hydrothermal fluids is generally derived from reservoirs that include the mantle (δ13C of ~5.0±2.0‰), sedimentary carbonates (average δ13C value of 0‰), and organic carbon (typical δ13C values around ~25‰; Zheng Yongfei et al., 2000). The δ13C values of samples from the Nianzha deposit provide evidence of a close relationship between ore-forming fluids and sedimentary organic matter, corroborating the hypothesis that the carbon in the fluids was generated by the dehydroxylation of organic matter in sedimentary rocks.

In conclusion, the fluid inclusion and H–O–C isotopes data indicate that the Nianzha gold deposit was formed by low-temperature and low-salinity H₂O–NaCl–organic gas fluids, generated by mixing metamorphic and sedimentary organic fluids with the addition of organic matter and minor amounts of mantle-derived fluids.

6.3 Metal and sulfur source of the gold deposit

Sulfur isotopes can be used to identify the source of metals within mineral deposits because S controls the precipitation of ore minerals and metals (Lv Lina et al., 2011). In addition, the Pb isotopic compositions of Pb-bearing sulfides with small amounts of U and Th (and therefore small amounts of radiogenic Pb) can be used to identify the sources of metals in mineral deposits. We used the geological data of this study and the S and Pb isotopic data to examine the factors that control the S and Pb isotopic compositions of the mineralization within the Nianzha deposit, and to provide insights into the source of metals and the processes that formed the deposit.

The S isotopic composition of sulfur-bearing hydrothermal minerals is generally controlled by the total S composition of the precipitating fluid and the temperature, oxygen fugacity, and pH at the site of precipitation (Ohmoto and Goldhaber, 1997). The total S composition is a characteristic of the source of the S within the deposits, while the temperature, oxygen fugacity, and pH relate to the environment of deposition. Under conditions of high oxygen fugacity, the dominant S species is SO₂ and the ensuing mineral assemblage comprises barite and calcite, with δ34Sbarite values approximating the δ34Ssulfate values. However, under conditions of moderate oxygen fugacity, sulfides coexist with sulfates and we have δ34Sbarite > δ34Ssulfate but δ34Ssulfate < δ34Ssulfate. Under conditions of low oxygen fugacity the assemblage is pyrite + galena + sphalerite, and δ34Ssulfate values approximate the δ34Ssulfur values (Ohmoto, 1972). The fluids that formed the Nianzha deposit were NaCl + H₂O + orogenic gas fluids, indicating that the sulfides within the deposit precipitated from reduced fluids. This in turn indicates that the δ34Svet for the sulfides in the deposit can be used to identify the source of the metals and S. However, sulfides in orogenic gold deposits generally have a wide range of S isotopic compositions, meaning that there is no definitive source for gold-transporting sulfur ligands within ore-forming fluids associated with such deposits (Goldfarb et al., 2005; McCuaig and Kerrich, 1998). For example, the δ34Svet
values of sulfides in Archean orogenic gold deposits range from 0% to 9% (Golding et al., 1990; Kerrich, 1987, 1989; McCuaig and Kerrich, 1998), whereas the δ^{34}S_{V,CDT} values of sulfides in Phanerozoic orogenic gold deposits range from ~20% to 25% (Kontak et al., 1990; Peters and Golding, 1989). In the Indus-Yarlung Tsangpo gold belt, the δ^{34}S_{V,CDT} values of sulfides at Bangbu range from 1.2% to 3.6% (Pei et al., 2016a), and at Mayum from ~0.2% to 4.5% (Fig. 8; Jang et al., 2009).

There are three main sources of S within mineral deposits: a) mantle-derived S with a small range of δ^{34}S values around 0; b) crustal S with a large range of δ^{34}S
values depending on the magmatic, sedimentary, and metamorphic history of the section of crust in question; and c) mixed S, where magmas have ascended and contaminated crustal material during emplacement, yielding material with mixed mantle and crustal S characteristics. The sulfides within auriferous quartz veins from the Nianzha deposit have a narrow range of δ34S values (−2.9% to 1.9%, with a mean of −1.1%) that are indicative of S derived from a single source, most likely the mantle (0%±3%; Chaussidon et al., 1989). The fact that the Nianzha deposit is located in a tectonic mélangé zone containing many sheets of ultramafic rock suggests that the S in the deposit was derived from deeply sourced mantle fluids.

Average growth curves of Pb in various source regions were determined by Zartman (1981) using the Pb isotopic compositions of different regions. All of the samples analyzed during this study plot close to the upper crustal and orogenic evolution lines in a 206Pb/204Pb vs. 207Pb/204Pb diagram (Fig. 11a) and close to the orogenic evolution line in a 208Pb/204Pb vs. 207Pb/204Pb diagram (Fig. 11b), with the latter being similar to samples from the Bangbu deposit.

This indicates that samples from the Nianzha deposit have mixed end-member Pb isotopic compositions that are indicative of Pb derived mainly from the mantle, with minor amounts from the crust.

Although the source of metals in the Nianzha deposit is still poorly constrained, metals in orogenic gold deposits generally come from wall rocks (Gaboury, 2013; Pitcairn et al., 2006, 2010, 2015), deep crust, or the mantle (Xue et al., 2013). Further work is required to constrain the source of ore components in orogenic gold deposit systems.

### 6.4 Timing and style of mineralization within the gold deposit

As outlined in Table 5, the Nianzha deposit has a number of features that are consistent with the orogenic gold deposit model described by Groves (1993), McCuaig and Kerrich (1998), Cox et al. (2001), and Goldfarb et al. (2001), but there are also a number of major differences between this model and the Nianzha deposit, as follows.

1. The Nianzha deposit is located in the Renbu tectonic mélangé of the IYS in an area containing a Cretaceous diorite to the north and Jiangxiong Group metasandstones.

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**Fig. 11.** (a) 206Pb/204Pb vs. 207Pb/204Pb and (b) 208Pb/204Pb vs. 207Pb/204Pb diagrams of sulfides from the Nianzha, Bangbu, and Mayum gold deposits (after Zartman and Haines, 1988).

**Table 5 Comparisons of geological characteristics of Nianzha, Bangbu and typical orogenic gold deposits**

<table>
<thead>
<tr>
<th>Geological features</th>
<th>Nianzha gold deposit</th>
<th>Bangbu gold deposit</th>
<th>Typical orogenic gold deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic background</td>
<td>Collisional orogen</td>
<td>Collisional orogen</td>
<td>Accretionary orogen</td>
</tr>
<tr>
<td>Reserve</td>
<td>251</td>
<td>∼216t</td>
<td></td>
</tr>
<tr>
<td>Grade</td>
<td>3.08g/t (average)</td>
<td>with a range of 1.35 g/t to 9.35g/t</td>
<td></td>
</tr>
<tr>
<td>Oro-controlling structures</td>
<td>Second- or third-order structures of Renbu Tectonic mélangé zone</td>
<td>Second- or third-order structures of Quxiong-Cuogu-Zhemulang</td>
<td>brittle-ductile shear zone</td>
</tr>
<tr>
<td>Host rocks</td>
<td>Cretaceous diorite</td>
<td>Upper Triassic metasedimentary rocks</td>
<td>Mafic and ultramafic volcanic rocks</td>
</tr>
<tr>
<td>Mineralization style</td>
<td>Altered rocks</td>
<td>Quartz veins</td>
<td>Veins, breccias, and disseminated</td>
</tr>
<tr>
<td>ore-forming fluid</td>
<td>0.35–17.17 eq. wt% NaCl</td>
<td>4.34–7.45 eq. wt% NaCl</td>
<td>3–10 eq. wt% NaCl</td>
</tr>
<tr>
<td>SO₂-H₂O-NaCl orogenic gas</td>
<td>CO₂-riching, CO₂-H₂O-NaCl-Ch₂N₂</td>
<td>CO₂-riching, CO₂-H₂O-NaCl-CH₄</td>
<td></td>
</tr>
<tr>
<td>Temperature conditions</td>
<td>203–347°C</td>
<td>170–261°C</td>
<td>220–500°C</td>
</tr>
<tr>
<td>Isotopes (water)</td>
<td>δD = −173% to −96%</td>
<td>δD = −80% to −44%</td>
<td>δD = −80% to −20%</td>
</tr>
<tr>
<td>Data source</td>
<td>this study</td>
<td>Pei et al., 2016a</td>
<td>Groves et al., 1998; Kerrich et al., 2000</td>
</tr>
</tbody>
</table>
and silty slates to the south. The Au orebodies in this area are located mainly within faulted contact zones between ultramafic rock sheets and the diorite, with areas of high-grade mineralization located along the margin of the diorite. The deposit is a structurally controlled orogenic gold deposit and mineralization is controlled by fault zones.

(2) The Nianzha deposit is associated with significant hydrothermal alteration that is indicative of gas–liquid activity along a tectonic shear zone. The mineralized diorite has undergone silicification, calcite and limonite alteration, all of which are typical of the alteration associated with orogenic gold deposits.

(3) The mineralization within the Nianzha deposit contains fewer sulfides than is typical for orogenic gold deposits, with the gold in the deposit occurring as native Au associated with minor pyrite.

(4) Fluid inclusion analyses indicate that the Nianzha deposit formed from H2O–NaCl–organic gas system fluids that homogenize at temperatures of 203°C–347°C and have salinities of 0.35 wt% to 17.17 wt% NaCl equivalent. However, these inclusions differ from those within typical orogenic gold deposits in that they are small and are generally two-phase gas–liquid inclusions, with the samples analyzed during this study being almost free of CO2–bearing inclusions. This is probably because the Nianzha deposit formed at shallower depths and as a result of unusual processes of mineralization when compared with typical orogenic gold deposits.

These data indicate that the Nianzha deposit is an orogenic gold deposit. In terms of the timing of formation of the deposit, although no dateable minerals were identified during this study, the timing of gold mineralizing events within this region provides evidence of the timing of the gold mineralizing event at Nianzha. The Nianzha deposit is located in an area that hosts numerous other orogenic gold deposits in the IYS (e.g., the Bangbu, Mayum, Dejilin, and Langkazi deposits). Geochronological and geochemical analyses of the Bangbu deposit (Pei et al., 2016a; Sun Qingzhong et al., 2013; Sun et al., 2015) yielded a sericite plateau ⁴⁰Ar⁻³⁹Ar age of 49.52±0.52 Ma and an isochron age of 50.3±0.31 Ma for auriferous quartz veins within the deposit. This suggests that the deposit formed during the main collisional period of the Tibet–Himalayan orogen (~65–41 Ma; Hou Zengqian et al., 2006b). ⁴⁰Ar⁻³⁹Ar dating of sericite from alteration associated with auriferous quartz veins in the Mayum orogenic gold deposit located in the southwestern part of the IYS (Jiang Sihong et al., 2008, Jiang et al., 2009) yielded a plateau age of 59.34±0.62 Ma, similar to the timing of onset of Indo-Asian collision. This result suggests that these deposits were genetically related to Indo–Asian collision and formed during the early stages of orogenesis (Jiang et al., 2009). The accurate dating of the Bangbu and Mayum gold deposits within the IYS also provides evidence that these deposits were generated as a result of collision between the Indian and Asian continents. Although it is not possible to precisely date the timing of the formation of the Nianzha deposit, it is likely that the mineralization occurred during the main stage of Indo–Asian collision (65–41 Ma). In addition, the presence of the Mayum, Bangbu, and Nianzha gold deposits within the IYS indicates that the area is highly prospective for other orogenic gold deposits associated with Indo-Asian collision.

6.5 Mineralization processes of the gold deposit

Mineralization of the Nianzha orogenic gold deposit was associated with Indo–Asian collision. The collision event started at 65 Ma, as inferred from petrological, geochemical, and paleogeographic data (Mo Xuanxue et al., 2003; Wang Chengqian et al., 2003). Mineralization in Tibet can be grouped into three major periods: (1) a main collisional convergent setting (~65–41 Ma), (2) a late collisional transform setting (~40–26 Ma), and (3) a post-collisional crustal extension setting (~25–0 Ma) (Hou Zengqian et al., 2006b, c, d, Hou et al., 2009). The main period of collisional metallogenic evolution occurred in a convergent setting characterized by collision-related crustal shortening and thickening that was coincident with peak metamorphism (Hou et al., 2009). This indicates that the Nianzha deposit formed during the main period of collisional convergence (~65–41 Ma) during India–Asia continental collision.

Deep-seated trans-lithospheric faults and ductile shear zones formed at ~65 Ma during the onset of collision between the Indian and Asian continents. The northward movement of the Himalayan Terrane caused it to converge with the Lhasa Terrane, forming the IYS, a convergent boundary between the two terranes. The IYS contains numerous sheets of ultramafic rocks that formed during the intense metamorphism and deformation that formed the tectonic mélangé in the zone. Large-scale shear zones also developed on each side of the IYS. The break-off and roll-back of the subducted Neo-Tethyan oceanic slab triggered crustal thickening and upwelling of mantle-derived fluids, contributing to the variable degrees of metamorphism of the lower crust within the collision zone. Metamorphic fluids in this area were generated by syn-peak metamorphic dehydration during lower–greenschist to upper–amphibolite facies metamorphism, and the upwelling mantle-derived fluids potentially provided metals and S to the fluids. Sulfur–bearing fluids transported gold as they migrate through a network of
complex faults, with the gold being transported as Au(HS)\textsuperscript{7–}
complex in fluids with low oxygen fugacity. These fluids were then transported to the shallower crust along
regional deep-seated faults that drove the cycling of sedimentary organic fluids that contained some meteoric
fluid. These mixed ore-forming fluids then migrated into second- or third-order structures in the Nianzha area.
Depressurization of the fluids resulted in a reduction in the concentration of organic gases and an increase in SO\textsubscript{2}/H\textsubscript{2}S
ratios (Hodkiewicz et al., 2009). The escape of H\textsubscript{2}S into the gas phase reduced the total sulfur concentration in the
fluids, and an increase in oxygen fugacity destabilized the
Au(HS)\textsuperscript{7–} complexes and resulted in the efficient precipitation of gold. The majority of gold in this area
was deposited along the margins of the Cretaceous diorite due
mainly to a drop in pressure. An outline of the genetic
model for the Nianzha gold deposit is shown in Fig. 12.

6.6 Metallocenic model of orogenic gold deposits in the
Yarlung–Tsangpo Suture zone

Orogenic gold deposits are closely related to orogenic belts, accretion, and collision (Bohleik, 1982). However,
orogenic gold deposits form in accretionary orogenic tectonic settings rather than large collisional orogenic belts
such as the Alpine–Himalayan belt (Groves et al., 1998;
Kerrick et al., 2000). The Tibetan Plateau collision
orogenic belt is prospective for orogenic gold deposits
(Hou et al., 2006a, 2006b), primarily because of the
presence of large-scale, deep-seated, and long-lived
active fault systems and a connected network of structures,
as exemplified by the Ailaoshan strike–slip shear zone and
the Yarlung–Tsangpo suture zone.

The development of orogenic gold mineralizing systems
within the IYS was closely related to the break–off and
roll–back of the Neo–Tethyan Oceanic slab during India–
Asia continental collision. The gold deposits are distributed along the IYS and formed between 59.5 and
49.5 Ma. The deposits are divided into three types based
on mineralization style. (1) Bangbu–type orogenic Au deposits, including the Bangbu and
Zhemulang deposits in the Jiacha area. (2) Mayum–type microcontinent orogenic Au deposits, including
the Mayum and Chasang deposits of the Zhongba area. The
above two types of deposits are related to metamorphic
fluids that were transported along brittle–ductile fault
systems, and gold was precipitated in open spaces within
the faults. (3) Nianzha–type ophiolite–related orogenic Au deposits, including the Nianzha and Xingxia deposits of the Renbu area and the Langkazi gold deposit in the
Langkazi area, host Au mineralization concentrated within
altered wall rocks. The three deposit types formed at different depths in the accretionary orogenic tectonic
setting: the Bangbu type formed in a deep environment,
whereas the Nianzha type is typical of shallow levels; the
Mayum type falls between the two extremes (Fig. 13).

The majority of mineralization within the IYS is hosted
by Permian–Triassic sandstone, greywacke, and ophiolite
mélange units, with gold contained in either quartz veins
or altered rocks. These deposits formed from CO\textsubscript{2}
metamorphic fluids that contain minor amounts of mantle,
sedimentary organic, and meteoric fluids. The metals in
the deposits were derived either from the deep lithosphere
or from local sediments. The orogenic gold deposits along
the IYS are structurally controlled and formed as a result
of the precipitation of gold from mineralizing fluids within
open spaces in fault zones. The orogenic gold systems
within the IYS consist of shallow deposits in altered rocks
and deep deposits with Au hosted in quartz veins. These
deposits formed contemporaneously with numerous other
Fe, Mo, and Pb–Zn deposits at different depths within the
central Lhasa Terrane (Fig. 13).

7 Conclusions

(1) The Nianzha gold deposit is a Cenozoic syn–
collisional orogenic gold deposit hosted mainly by diorite
in the IYS zone in southern Tibet. Mineralization in the
deposit is controlled by a network of faults within and
around sheets of ultramafic rocks, and occurs mainly in altered rocks. The deposit formed during the main stage of
Indo-Asian collision at about 65–41 Ma, during the Tibet–
Himalayan orogeny.

(2) Fluid inclusion and H–O–C isotope data from the
deposit indicate that mineralization was from a low–
temperature and low-salinity H₂O–NaCl–organic gas fluid. The fluid was a mixture of metamorphic and sedimentary organic fluids with minor inputs from organic matter and mantle. The S and Pb isotopic compositions of samples from the deposit suggest that both S and metals within the deposit were derived from the mantle.

(3) The geology and geochemistry of the deposit are similar to those of typical orogenic gold deposits elsewhere. However, there are some minor differences. The IYS zone is highly prospective for orogenic gold deposits, as indicated by the presence of the Nianzha, Bangbu, and Mayum deposits. Based on mineralization style, these deposits have been classified into three different types: the Bangbu-type accretionary, Mayum-type microcontinent, and Nianzha-type associated with ophiolite. These mineralization styles reflect different depths of formation within an accretionary orogenic tectonic setting: the Bangbu type formed in a deep environment whereas the Nianzha type occurs at shallow levels, and the Mayum type occurs between these two extremes.

Acknowledgments

We thank the staff of the Sichuan Institute of Metallurgical Geology and Exploration for their work in the Nianzha Mine district, and Jingtao Mao, Peiyian Xu, Changda Wu, Teng Jia, Linyuan Zhang, Xin Wang, and Ning Wen of the Institute of Geology, CAGS, for assistance during fieldwork. We are grateful to Shihong Tian and Zengjie Zhang of the Institute of Mineral Resources, CAGS, for H–O–C isotopes analyses. Funding for this research was provided by the National Key Research and Development Program of China “Deep Structure and Ore-forming Process of Main Mineralization System in Tibetan Orogen” (2016YFC0600300), the National Basic Research Program of China (2011CB403104), the China Geological Survey (12120113037901), and the National Natural Science Foundation of China (41320104004) and (41503040).

Manuscript received Nov. 7, 2016 accepted Jan. 8, 2017 edited by Liu Lian

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