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The Longmala and Mengya’a skarn Pb–Zn deposits, Gangdese region, Tibet: evidence from U–Pb and Re–Os geochronology for formation during early India–Asia collision

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The Longmala and Mengya’a deposits are two representative skarn Pb–Zn deposits of the Nyainqêntanglha Pb–Zn–(Cu–Mo–Ag) polymetallic belt in the Gangdese region, Tibet, China. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) zircon U–Pb dating of the mineralization-related biotite monzogranite from the Longmala deposit yielded a weighted mean age of 55.7 Ma, which can be interpreted as the emplacement age of the pluton. Re–Os dating of three molybdenite samples from the Longmala deposit yielded model ages of 51.8–54.3 Ma, with a weighted mean age of 53.3 Ma, which is interpreted as the mineralization age of the deposit and overlaps the age of the causative intrusion. The Re–Os dating of four molybdenite samples from the Mengya’a deposit yielded model ages of 60.4–65.8 Ma, with a weighted mean age of 63.6 Ma, which represents the mineralization age of this deposit. Our new precise age data for these two deposits are consistent with the existing ages of ca. 65–51 Ma for other skarn polymetallic deposits in the Nyainqêntanglha metallogenic belt. In addition, these new age data, combined with existing information on the geological evolution history of the Lhasa terrane, indicate that the belt of skarn deposits is closely related to initial collision between India and the Asian continents.

Keywords: geochronology; India–Asia collision; Longmala deposit; Mengya’a deposit; Nyainqêntanglha metallogenic belt; Gangdese

1. Introduction

The Gangdese orogenic belt, also called the Lhasa terrane, is bordered by the Bangong–Nujiang and the Indus–Yarlung suture zones (Figure 1a), and comprises the Gangdese porphyry Cu belt in the south (Qu et al. 2001, 2007; Hou et al. 2009; Zhu et al. 2011) and the Nyainqêntanglha skarn Pb–Zn ± Cu–Mo–Ag polymetallic belt in the north (Meng et al. 2003; Tang et al. 2012) (Figure 1b). These porphyry deposits, such as Jiama, Qulong, Bangpu, Lakang’e, Dabu, Tinggong, Gangjiang, Chongjiang, Jiru, and Zhu’nuo (Figure 1b), have already been well studied. Most of them formed during the Miocene in the post-collisional, extensional setting of the Tibetan Orogen (Qu et al. 2003; Meng et al. 2003b; Li et al. 2005; Zheng et al. 2007, 2014; Hou et al. 2009; Ying et al. 2010; Leng et al. 2010, 2013; Gao et al. 2012; Wang et al. 2012a, b). However, research on the skarn polymetallic deposits, such as Yaguila, Dongzhongla, Dongzhongsongduo, Mengya’a, Lawu, Leqingla, and Xin’gaguo (Figure 1b), are very limited. The lack of precise geochronology has hindered a thorough understanding of ore genesis and the geodynamic setting of ore formation (Zheng et al. 2002; Gao et al. 2009, 2011; Fei et al. 2010; Wei et al. 2010; Lian et al. 2010, 2011; Cui et al. 2011; Huang et al. 2012).

The Longmala and adjacent Mengya’a deposits are two representative and important skarn deposits in the Nyainqêntanglha polymetallic belt. Previous studies on Longmala and Mengya’a deposits mainly focused on ore genesis, isotope and geochemistry, and ore-forming fluid composition (Cheng et al. 2008; Wang et al. 2010, 2011, 2011c; Fu et al. 2012; Zhang et al. 2012; Ye et al. 2012). Wei et al. (2010) obtained a U–Pb age of 14 Ma for zircons from the porphyritic granite at the Mengya’a deposit, which was interpreted to its mineralization age. However, field investigations suggested that the porphyritic granite post-dated the Pb–Zn mineralization. Argon dating of phlogopite from the Longmala deposit, with the result of 56 Ma, has been interpreted as the mineralization age (Fu et al. 2014a). We have identified the ore-forming intrusive rocks at the Longmala deposit and molybdenite in both the Longmala and Mengya’a deposits, and dating of these materials should provide the first reliable metallogenic ages for these two deposits.

In this paper, we therefore report results from laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) zircon U–Pb studies of biotite monzogranite from the Longmala deposit and Re–Os dating of molybdenite from the Longmala and Mengya’a deposits. Based...
on the obtained new age data, we also discuss their ore-forming dynamic setting and skarn Pb–Zn resource potentials of Early Palaeocene–Early Eocene in the Nyainqêntanglha region.

2. Regional geology

The Longmala and Mengya’a deposits are located in the eastern part of the Nyainqêntanglha skarn polymetallic belt (Figure 1b). The Nyainqêntanglha polymetallic belt witnessed the evolution of the Neo-Tethys Ocean and experienced the process of northward subduction of the Neo-Tethys, the collision of Indian–Asian continents, and the E–W extension of the Lhasa terrane. During the Palaeocene to early Eocene, the Nyainqêntanglha region was influenced by the collision of the Indian–Asian continents, resulting in granitoids, volcanic rocks, and skarn Pb–Zn polymetallic and porphyry Mo–(Cu) mineralization (Hou et al. 2012).

The oldest unit in the Nyainqêntanglha region comprises the metamorphic basement rocks of the Proterozoic Nyainqêntanglha Group (Pan et al. 2006; Tang et al. 2009), which are covered by Carboniferous–Permian shallow marine clastic sedimentary rocks that are intercalated with continental arc volcanic rocks (Yin and Harrison 2000; Pan et al. 2006; Tang et al. 2009; Zhu et al. 2010) (Figure 2). Post-Palaeozoic rocks include the Cretaceous intrusions and the Palaeocene intrusive rocks and volcanic rocks (Tang et al. 2009; Li et al. 2010; Gao et al. 2011). The Cretaceous intrusive rocks are mainly composed of monzonitic granite, granodiorite, porphyritic granite, and dolerite, whereas the Palaeocene intrusions are primarily composed of granodiorite. The Palaeocene volcanic rocks,
consisting of tuff, rhyolite, and dacite, crop out locally and unconformably overlie the Carboniferous–Permian sedimentary rocks (Hou et al. 2012) (Figure 2). A number of faults were developed in the region, and an E–W-striking fault is the major structure controlling the distribution of the Pb–Zn polymetallic ore deposits (Li et al. 2010) (Figure 2).

3. Ore deposit geology

3.1 Longmala deposit

The Longmala deposit is a skarn Pb–Zn deposit, which also has Cu and Fe by-products. The exposed strata include Carboniferous slate and sandstone of the Pangduo Group, early Permian marble of the Wululong Formation and limestone of the Luobadui Formation, and late Permian mottled sandstone, with intercalations of siltstone and conglomerate of the Lielonggou Formation (Figure 3). There are no outcrops of intrusive rocks in the ore district. However, biotite monzogranite is discovered in a drill hole (No. ZK474) at a drill depth of 750 m and the thickness of the biotite monzogranite drilled is ~280 m. The biotite monzogranite has intruded the marble of the Wululong Formation and has caused intense skarn alteration and mineralization. Skarn alteration is located at the contact between biotite monzogranite and the surrounding marble of the Wululong Formation, and Pb–Zn–Fe orebodies occur associated with skarn alteration, and are closely spatially related to the biotite monzogranite (Figure 4).

The Longmala deposit is composed of three skarn Fe orebodies (i.e. Fe-1, Fe-2, and Fe-3) and four skarn Pb–Zn orebodies (i.e. Pb-1, Pb-2, Pb-3, and Pb-4). The skarn iron ore is dominated by magnetite. A NEE-striking fault controls the Fe-1 orebody in the northern part of the district (Figures 3 and 5a). However, the Fe orebodies are small and the ore grade is low, so they are not economic. Wall rock of the Pb–Zn orebodies and associated skarn alteration are marble of the Wululong Formation. The Pb–Zn orebodies are ENE-striking and dip steeply to the south at angles >60°. Among the four Pb–Zn orebodies, the Pb-3 orebody is fully concealed and the Pb-2 orebody is the largest one. The Pb-2 orebody, in the southern part of the deposit, with a dip of 50–80° to the southeast (Figure 4), extending for 405 m in length, has a maximum width of 140 m, with an average width of 7.5 m. The average grades of Pb, Zn, and Cu are 6.63%, 5.16%, and 1.99%, respectively (Zhongkai Mining Company Limited, unpublished report, 2009).

The ore minerals are dominantly sphalerite, galena, lesser magnetite and chalcopyrite, and minor pyrrhotite and molybdenite. Ore textures include massive, vein-like, banded, and disseminated mineral grains. The primary gangue and alteration minerals are garnet, diopside, actinolite, epidote, chlorite, phlogopite, quartz, and calcite.

Based on crosscutting relationships and mineral assemblage studies, Fu et al. (2014a) recognized five mineralization stages. (I) Prograde skarn stage: anhydrous silicate minerals are formed, such as garnet, diopside, and wollastonite. Garnet is usually red-brown or light green (Figure 5b, i), accounting for 60% of the total skarn minerals. Diopside and wollastonite usually occur together...
and they are radiated aggregation (Figure 5c). At this stage, there are few sulphides deposited. (II) Retrograde skarn stage: a large number of hydrous minerals, such as actinolite, epidote, and chlorite (Figure 5d, e), with a small amount of magnetite, are present at this stage (Figure 5e). Actinolite and epidote are the major minerals at this stage, which replace garnet and diopside of the prograde skarn stage. Actinolite usually occurs as radiated aggregation, and epidote and chlorite are fine-granular. (III) Magnetite-phlogopite stage: this stage, which is the main stage of magnetite, is characterized by the formation of magnetite and lots of phlogopite (Figure 5a, f). (IV) Sulphides stage: the economic Pb–Zn orebodies were formed at this stage, which is characterized by the formation of abundant sulphides, such as galena, sphalerite, chalcopyrite, pyrite, and pyrrhotite (Figure 5g, h). (V) Quartz-carbonate stage: sulphides are scarce at this stage. Quartz-calcite veins are well developed, crosscutting the skarn or the sulphide ores (Figure 5i).

### 3.2 Mengya’a deposit

The Mengya’a deposit was discovered by the No. 2 Geological Party of the Tibet Bureau of Geology and Mineral Exploration and Development. It is a skarn-type Pb–Zn deposit, with Cu as the by-product. The strata in the deposit include Late Carboniferous to early Permian sandstone, slate, limestone, and marble of the Laigu Formation, middle Permian bioclastic limestone at the bottom and tuff at the top of the Luobadui Formation, and late Permian mottled sandstone with intercalations of siltstone and conglomerate of the Lielonggou Formation (Figure 6). Rocks of the Laigu and Luobadui formations were intruded by porphyritic granite and dolerite, respectively (Figure 6). Field investigations demonstrate that the porphyritic granite and the dolerite have no genetic relationship with the mineralization. The porphyritic granite was dated at ca. 14 Ma by the LA-ICP-MS zircon U–Pb method (Wei et al. 2010). The NE-striking faults, as post-mineralization faults, cut through the Pb-13 orebody.

The Mengya’a Pb–Zn deposit consists of 21 orebodies. Most of them occur as concordant bodies or lenses in skarn and marble of the Laigu Formation, and a few in the skarn and marble of the Luobadui Formation or along the contacts between these two formations (Figure 6). The Pb-14 and Pb-12 orebodies are the most important and account for 85% of the total Pb +Zn reserve in the deposit. The Pb-14 orebody has characteristics of stratabound deposit, which strikes nearly E–W, dips 5–30° to the S (Figure 7), is >400 m long, and has a maximum width of 300 m and an average of 15 m. The Pb-12 orebody consists of 19 mineralization zones, generally dipping to the SW, and striking towards E–W. It has a length of 900 m and a maximum width of 282 m.
Primary ore minerals are sphalerite, galena, and pyrite, with minor chalcopyrite, pyrrhotite, magnetite, and molybdenite. Ores are mainly disseminated, with minor massive, vein-like, and banded textures. Gangue and alteration minerals are garnet, diopside, wollastonite, actinolite, tremolite, epidote, chlorite, muscovite, quartz, and calcite. The prograde skarn alteration, retrograde actinolite, epidote, chlorite assemblages, and silicification are widespread in the deposit area. The retrograde alteration and silicification are closely related to the Pb–Zn mineralization.

Four mineralization stages have been identified, based on the crosscutting relationships and mineral assemblage studies. Stage I is a prograde skarn stage that is characterized by the formation of garnet, wollastonite, and diopside. At this stage, there are nearly no ore minerals. Unlike the Longmala deposit, garnet is usually light green with a granular structure (Figure 8a, b). Wollastonite presents as radiated aggregation with white colour (Figure 8c). There is a little diopside at this stage, which is distributed in particle gaps in garnet (Figure 8b). Stage II is a retrograde stage that is marked by the formation of actinolite–epidote–chlorite assemblages (Figure 8d), with a little amount of magnetite. Stage III is a quartz-sulphide stage that is characterized by the formation of sulphide assemblages of sphalerite–galena–chalcopyrite–pyrite–pyrrhotite (Figure 8e, f) and lots of quartz (Figure 8g). Skarn minerals are always eroded by these sulphides (Figure 8h) and quartz. This stage is the main stage of sphalerite, galena, and chalcopyrite mineralization. Stage IV is a carbonate stage, with lots of calcite veins formed, crosscutting the skarn minerals and sulphides (Figure 8a, i).

4. Sampling and analytical methods

4.1 Sampling of igneous zircons and ore-related molybdenite

One biotite monzogranite core sample (ZK474-861) from the No. ZK474 drill hole (Figure 4) at the Longmala deposit was collected for zircon U–Pb dating. The biotite monzogranite sample is fresh and pink, with coarse- to medium-grained texture (Figure 9a, b),...
Figure 5. Photographs showing Fe-1 orebody and mineral assemblages in different mineralization stages of the Longmala deposit. (a) Fe-1 orebody occurs in the fault as lenticular; (b) red-brown garnet of mineralization stage I is crosscut by quartz of stage V; (c) wollastonite occurs as radiated aggregation; (d) actinolite occurs as radiated aggregation of retrograde skarn stage; (e) minor magnetite accompanied by epidote and chlorite of mineralization stage II; (f) scale-like phlogopite of mineralization stage III; (g) and (h) lots of sulphides such as sphalerite, galena, pyrite, and chalcopyrite formed in the mineralization stage IV; (i) calcite crosscut garnet of stage I and galena-sphalerite of stage IV. Grt, garnet; Qtz, quartz; Wo, wollastonite; Act, actinolite; Epi, epidote; Chl, chlorite; Cc, calcite; Phl, phlogopite; Gn, galena; Sp, sphalerite; Cp, chalcopyrite; Py, pyrite.

Figure 6. Geological sketch map of the Mengya’a deposit (modified after Wang et al. 2010). ZK2301 denotes No. ZK2301 drill hole.
containing quartz (~25%), alkali feldspar (~35%), plagioclase (~30%), biotite (~7%), and amphibole (~2%), as well as accessory minerals (~1%).

One molybdenite sample (PD5240-300) from the 5240 m level adit, two molybdenite core samples (ZK474-260.6 and ZK474-768.5) from No. ZK474 drill hole at the Longmala deposit, and four molybdenite core samples (ZK2301-10.7, ZK2301-121.6, ZK2301-230.4, and ZK2301-280.4) from No. ZK2301 drill hole at the Mengya’a deposit were collected for Re–Os dating analysis. The molybdenite sample PD5240-300 was separated from disseminated grains in the ore-bearing diopside-actinolite skarn (Figure 9c). Sample ZK474-260.6 was fine-grained molybdenite from a garnet skarn (Figure 9d). Sample ZK474-768.5 was collected from a hornfels containing a quartz-molybdenite vein. The molybdenite occurred as a large mass (Figure 9e). Samples ZK2301-10.7 and ZK2301-121.6 were molybdenite grains from quartz veins in sandstone (Figure 9f, g). Both samples ZK2301-230.4 and ZK2301-280.4 were separated from garnet-wollastonite skarns, with molybdenite occurring as film-like or scale-like grains (Figure 9h, i).

4.2 LA-ICP-MS zircon U–Pb dating
Zircon grains were first separated by conventional heavy liquids and magnetic techniques and then were purified by hand-picking under a binocular microscope. Representative zircon grains were mounted in an epoxy resin and polished down to expose the grain centre. Before isotopic analysis, their internal structures were examined under reflected and transmitted light and by cathodoluminescence (CL). Zircon U–Pb dating was conducted using a Neptune multi-collector inductively coupled plasma mass spectrometer equipped with a New Wave 193 nm laser sampler at the Tianjin Institute of Geology and Mineral Resource, China Geological Survey. Detailed analytical procedures were described in Geng et al. (2012). The data processing was conducted using ICPMSDataCal software (Liu et al. 2010) and IsoplotEx 3 software (Ludwig 2003). Common Pb was corrected by following the method of Andersen (2002).

4.3 Molybdenite Re–Os dating
The molybdenite grains were separated from finely crushed mineralized rocks by gravitational and electromagnetic methods. They were hand-picked under a binocular microscope (purity >99%) for analysis. Molybdenite Re–Os isotope analyses were conducted at the Re–Os Isotopic Laboratory, National Research Centre of Geoanalysis of the Chinese Academy of Geological Sciences, Beijing. The Re and Os concentrations and isotopic ratios were determined using a TJA X-series inductively coupled plasma mass spectrometer. Detailed sample processing procedures and mass
5. Results

5.1 Zircon U–Pb age determination

Twenty-six analyses on the zircon grains from sample ZK474-861 were obtained and the analytical data are listed in Table 1. Zircon grains are 80–165 μm in length and 40–80 μm in width, with euhedral to subhedral pyramids and prisms. The CL images reveal that the zircon grains have simple structures and oscillatory zoning (Figure 10), indicating a magmatic origin. The zircon rims have concentrations of 472–5143 ppm U, and 306–2964 ppm Th, leading to Th/U ratios of 0.20–1.46, most less than 1.0 (Table 1). $^{206}\text{Pb}/^{238}\text{U}$ ages of these zircons are mostly concordant within the error span, ranging from 54.0 ± 2.0 to 57.0 ± 2.0 Ma, with a mean age of 55.7 ± 0.3 Ma ($n = 26$, MSWD = 3.6) (Figure 11). It is interpreted as the crystallization age of the biotite monzogranite.

5.2 Re–Os ages of molybdenite

The Re and Os contents and isotopic values of molybdenite samples from the Longmala and Mengya’a deposits are listed in Table 2. Three molybdenite samples from the Longmala deposit contain Re and $^{187}\text{Os}$ concentrations, ranging from 2,848,172 to 72,414,708 ppt and from 1597.3 to 41,171.8 ppt, respectively. Their Re–Os model ages vary from 51.8 ± 0.7 to 54.3 ± 0.8 Ma, with a weighted mean age of 53.3 ± 3.7 Ma (MSWD = 2.7) (Figure 12a). The Re and $^{187}\text{Os}$ concentrations of four molybdenite samples from the Mengya’a deposit vary from 11,046 to 107,200 ppt and from 7.4 to 73.9 ppt, respectively. Their Re–Os model ages range from 60.4 ± 0.7 to...
65.8 ± 0.7 Ma, with a weighted mean age of 63.6 ± 4.2 Ma (MSWD = 10.8) (Figure 12b).

6. Discussion

6.1 Timing of magmatism and mineralization of the Longmala deposit

Mineralization-related intrusions of the Longmala deposit have not been recognized until the discovery of the biotite monzogranite dated in this study. Consequently, it is the first time to report the geochronology of mineralization-related intrusion in this paper. The new LA-ICP-MS zircon U–Pb ages indicate that the biotite monzogranite emplaced at 55.7 Ma.

Fu et al. (2014a) reported a phlogopite \(^{40}\text{Ar}–^{39}\text{Ar}\) age of ca. 56 Ma, which was interpreted as the mineralization age. Compared with measured \(^{40}\text{Ar}–^{39}\text{Ar}\) ages, the molybdenite Re–Os chronometer is typically more robust due to the high closure temperature of Re–Os isotopes in molybdenite (Suzuki et al. 1996; Stein et al. 2001). Thus, Re–Os dating of this mineral commonly provides a more reliable constraint on the timing of ore formation (Selby et al. 2002). Three molybdenite samples from the Longmala deposit yield a weighted mean age of 53.3 ± 3.7 Ma, which is consistent with the zircon U–Pb age of the biotite monzogranite. This indicates that there is likely a genetic relationship between the mineralization and the spatially related intrusion. Dating of the biotite monzogranite and molybdenite provides the first reliable constraints on the age of the Longmala deposit.

6.2 Timing of mineralization of the Mengya’a deposit

Wei et al. (2010) demonstrated that the porphyritic granite was the mineralization-related intrusion, and they interpreted the zircon U–Pb age (ca. 14 Ma) as the mineralization age. The porphyritic granite was believed to be the mineralization-related intrusion for the following reasons: (1) phyllic alteration was developed; (2) limestone was
Table 1. Isotopic data of U–Pb age determinations on zircon of the Longmala deposit.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Element (ppm)</th>
<th>Isotope ratio</th>
<th>Age (Ma)</th>
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<td>Th</td>
<td>U</td>
<td>Th/U</td>
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<td>U</td>
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</table>
metamorphosed to marble at the contact between the Luobadui Formation and the porphyritic granite; and (3) grain size of ore minerals gradually decreased away from the porphyritic granite (Wei et al. 2010). However, the porphyritic granite that we observe in the drill holes is fresh and shows no alteration. In addition, marble in the Luobadui Formation is widespread. We could not distinguish apparent changes on ore mineral grain sizes away from the porphyritic granite. Thus, the porphyritic granite may be unrelated to the Pb–Zn mineralization.

Molybdenite samples dated in this study were representative of the main episode of sulphide deposition. Two of them were developed in the skarn itself. Hence, the Re–Os dating results can be interpreted as the age of mineralization. The Re–Os model ages obtained from four molybdenite samples range from 60.4 to 65.8 Ma, with a weighted mean age of 63.6 Ma. The Re–Os model ages of molybdenite provide the first reliable constraints on the mineralization age of the Mengya’a deposit.

6.3 Implications for geodynamic setting

The Lhasa terrane (i.e. the Gangdese orogenic belt) can be divided into northern, central, and southern subterraines (Zhu et al. 2011). The skarn polymetallic deposits are located in the central Lhasa subterrane, which has undergone a complex history of northward subduction within the Neo-Tethys plate (Yin and Harrison 2000; Chu et al.)

Table 2. Re–Os isotope data for molybdenite samples from the Longmala and Mengya’a deposits.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Weight (mg)</th>
<th>Re (ppt)</th>
<th>±2σ</th>
<th>187Re (ppt)</th>
<th>±2σ</th>
<th>187Os (ppt)</th>
<th>±2σ</th>
<th>Age (Ma)</th>
<th>±2σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longmala deposit</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDS240-300</td>
<td>5.19</td>
<td>72,414,708</td>
<td>4,551,092</td>
<td>340.5</td>
<td>54.3</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK474-260.6</td>
<td>2.37</td>
<td>6,737,932</td>
<td>43,492,5</td>
<td>37.3</td>
<td>51.8</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK474-768.5</td>
<td>15.36</td>
<td>2,848,172</td>
<td>1,790,133</td>
<td>60.0</td>
<td>53.5</td>
<td>1.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mengya’a deposit</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>ZK2301-10.7</td>
<td>11.85</td>
<td>17,959</td>
<td>11,288</td>
<td>11.4</td>
<td>60.4</td>
<td>0.7</td>
<td></td>
<td></td>
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<tr>
<td>ZK2301-121.6</td>
<td>10.50</td>
<td>11,046</td>
<td>6943</td>
<td>7.4</td>
<td>64.3</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK2301-230.4</td>
<td>10.47</td>
<td>88,600</td>
<td>55662</td>
<td>60.0</td>
<td>64.7</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK2301-280.4</td>
<td>5.12</td>
<td>107,200</td>
<td>67407</td>
<td>230</td>
<td>65.8</td>
<td>0.7</td>
<td></td>
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</tr>
</tbody>
</table>
2006; Ji et al. 2009), collision-related deformation between the Indian and Asian continents (Mo et al. 2003, 2007), and the post-collisional E–W extension (Blisniuk et al. 2001; Coleman and Hodges 1995). Although the timing of initiation of the northward subduction of the Neo-Tethys slab remains controversial, more and more evidence indicates that it began in the Early Jurassic and continued through the Cretaceous (Mo et al. 2005b; Zhu et al. 2008). Final closure of the Neo-Tethys Ocean occurred in the early Cenozoic (Mo et al. 2003, 2007, 2008; Chung et al. 2005), and the India–Asia continental collision began at the early Palaeocene (~65 Ma) (Yin and Harrison 2000; Mo et al. 2003, 2007).

The India–Asia collisional event includes the main collision at 65–41 Ma, a late-collision period at 40–26 Ma, and a post-collision stage during the past 25 million years. Each of these three stages was associated with magmatism and metallogenic events (Hou and Cook 2009). The main collision and the subsequent rollback of the Neo-Tethys slab from 65 to 41 Ma had led to the shortening and thickening of the Lhasa terrane (Mo et al. 2007; Hou and Cook 2009), emplacement of the Gangdese batholiths, and the Linzizong arc volcanism (Mo et al. 2008; Ji et al. 2009), and also minor intrusions in the southern and central Lhasa terrane. Combined literature age data show that volcanism of the Linzizong took place at Palaeocene and continued to the middle of Eocene (69–39 Ma) (Figure 13a). The emplacements of magmatism during the early India–Asia collision were from 66 to 43 Ma (Figure 13b). During the widespread magmatism period of the early Cenozoic, the skarn polymetallic mineralization developed (Hou and Cook 2009). Simultaneously, in the northern part of the Lhasa terrane, minor Cenozoic plutonism and volcanism occurred (Chiu et al. 2009; Zhao et al. 2014), which were related to re-melting of the Lhasa terrane basement after collision-related thickening of the continental crust (Chiu et al. 2009).

The molybdenite Re–Os ages of the Mengya’a deposit and zircon U–Pb ages and molybdenite Re–Os ages of the Longmala deposit are coeval with the onset of India–Asia collision (Figure 14). In addition, Pb isotope studies of sulphide ore minerals from these two deposits show that ore metals were derived from the re-melted Lhasa terrane basement that formed during collision-related thickening of the Lhasa terrane (Cheng et al. 2010; Wang et al. 2010, 2014b; Fu et al. 2012).

6.4 Early Palaeocene–early Eocene skarn Pb–Zn deposits in the Nyainqêntanglha metallogenic belt and resource potential

In addition to the Mengya’a and Longmala deposits, there are several other skarn polymetallic deposits in the Nyainqêntanglha metallogenic belt (Figure 1a, b). Skarn Pb–Zn polymetallic deposits formed during the early Palaeocene, including the Yaguila Pb–Zn–Ag, Hahaigang Pb–Zn–W–Mo–Cu, and Leqingla Pb–Zn–Fe deposits. The Yaguila Pb–Zn–Ag mineralization occurred at ca. 65 Ma, with reserves of >2.7 Mt Pb+Zn, and 294.5 t Ag (Gao et al. 2011; Huang et al. 2012). The Hahaigang deposit with molybdenite Re–Os isochron age of ca. 63 Ma has reserves of 46 Mt WO₃ ore, 12 Mt Mo ore, and 1.31 Mt Cu+Pb+Zn ores, at an average grade of 0.20% WO₃, 0.07% Mo, 0.026% Cu, 0.49% Pb, and 3.1% Zn (Li et al. 2014). Molybdenite weighted mean Re–Os age of the Leqingla deposit is ca. 60 Ma (Fei 2014), and it has estimated reserves of 0.55 Mt Pb+Zn at 7.74%, and 4.55 Mt Fe at 56.27% (Zhang et al. 2008). In addition, several small occurrences (i.e. Jialong, Sadang, Lietinggang) formed during the early Palaeocene have also been reported (Huang et al. 2013; Yang et al. 2014).

Our recent study showed that Pb–Zn mineralization of the Qiema deposit occurred also in the Early Palaeocene (with the molybdenite Re–Os isochron age of ca. 61 Ma).

Skarn Pb–Zn deposits formed in the early Eocene including the Xin’gaguo, Narusongduo, and Dongzhongla deposits. Zircon U–Pb dating of the mineralization-related biotite granite shows that Pb–Zn mineralization of the Xin’gaguo deposit occurred at ca. 57 Ma.
(Cheng 2011). The proved reserve of this deposit is 0.13 Mt Pb+Zn, with average grades of 5.53% Pb and 6.92% Zn (China Nonferrous Metal Guilin Research Institute of Geology for Mineral Resources 2006). Sericite ⁴⁰Ar⁻³⁹Ar age shows that skarn Pb–Zn mineralization of the Narusongduo deposit occurred at ca. 58 Ma (Ji et al. 2014). Pb+Zn reserve of the Dongzhongla deposit is ca. 0.32 Mt. The ⁴⁰Ar⁻³⁹Ar age of the Dongzhongla deposit is ca. 42 Ma (Fei et al. 2010). Moreover, some porphyry Mo and Cu–Mo deposits formed in the Nyainqêntanglha region during the Early Eocene were discovered, such as the Sharang Mo deposit and the Jiru Cu–Mo deposit. Molybdenite Re–Os isochron ages of the Sharang and Jiru deposits are 52 Ma and 45 Ma, respectively (Zhao et al. 2014; Zheng et al. 2014). Combined ages of all the deposits formed during the Palaeocene–Early Eocene are shown in Figure 13c.

All the polymetallic deposits showed similar geological features and formed in the same tectonic setting. They were all related to Palaeocene to Eocene granitic
intrusions and hosted in the Carboniferous–Permian limestone or marble, which is overlain by carbonaceous slate, carbonaceous sandstone, or volcanic tuff. In the past two decades, exploration activities and economic geology research in the Gangdese region have focused on the extension-related Miocene porphyry copper deposits. However, recognition of the older mineralization ages at the Longmala and Mengya’a deposits, as well as other skarn deposits in the Nyainqêntanglha metallogenic belt also indicates a significant Pb–Zn mineral potential in the Gangdese region, which is related to the collision of the India–Asia continents. Thus, exploration targets at the Nyainqêntanglha region of the central Lhasa subterrane are also recommended, in which the Himalayan granites are widespread and carbonate stratigraphy is well developed.

7. Conclusions

(1) U–Pb ages of the mineralization-related biotite monzogranite and molybdenite Re–Os weighted mean model age from the Longmala deposit are 55.7 Ma and 53.3 Ma, respectively. This indicates that the Longmala deposit was formed in the early Eocene. Molybdenite Re–Os weighted mean age of the Mengya’a deposit is 63.6 Ma, which shows the Mengya’a deposit formed in the early Palaeocene. Both the Longmala and Mengya’a skarn deposits developed at the early stage of the collision between India and Asia, according to the U–Pb and Re–Os geochronology.

(2) The Lhasa terrane was in the India–Asia continental collisional convergent setting during the Palaeocene to the early Eocene, which induced thickening and re-melting of the Lhasa terrane basement and widespread magmatism and mineralization. Magmatic activity and mineralization in the Longmala and Mengya’a deposits are just formed in the compression environment after the India–Asia continental collision.

(3) The Nyainqêntanglha region is a skarn Pb–Zn polymetallic belt formed during the early phase of India–Asia collision with significant Pb–Zn mineral potential in the Gangdese region.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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