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Graphic abstract

Contemporaneous east–west extension and north–south compression at 43 Ma in the Himalayan orogen

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Abstract

It was previously proposed that the onset of east–west extension in the Himalayan orogen occurred after ca. 19 Ma. Here we present a Re–Os isochron age of ca. 43 Ma for sulfides from the Zhaxikang Zn–Pb–Sb–Ag polymetallic deposits, which occur within N–S–striking normal faults that reflect E–W extension in the Tethyan Himalayan orogen. This age is consistent with previously reported ages for regional metamorphism (ca. 48–42 Ma), granitoids (ca. 47–40 Ma) and gabbros (ca. 45 Ma) occurring along the Indus–Yarlung suture. In addition, this type of structure also broadly occurs in the Lhasa terrane, and plays a critical role in the Eocene porphyry–(skarn) copper polymetallic mineralization there. By ca. 45–43 Ma, the north–south–directed horizontal deviatoric stresses had peaked and subducted Neo–Tethyan slab breakoff had occurred at great depth, leading to abrupt slowdown of Indo–Asia convergence (ca. 45 Ma). E–W extension initially developed at shallow depths, resulting in formation of the north–south trending normal faults in the plateau. This type of extension would lead to collapse of the Tibetan plateau and decrease in altitude, subsequently resulted in Central Asian and the global climate changes. Our study places new constraints on the timing and nature of early Cenozoic tectonics and metallogenesis in the Himalayan orogen and climate changes in Central Asia.

Keywords

N–S trending faults; E–W extension; Re–Os dating; Zhaxikang Pb–Zn–Sb deposits; Himalayan orogen; Climate changes

1. Introduction

Numerous N–S (including NE and NW) trending strike–slip or normal faults have been reported in the Himalayan orogen (Blisniuk et al., 2001) (Fig. 1A). They have been proposed as active during the period 19–13 Ma (e.g. Blisniuk et al., 2001; Edwards and Harrison, 1997; Thiede et al., 2006; Williams et al., 2001; Yin, 2000; Mitsuishi et al., 2012) or even as young as 8–4 Ma (Coleman and Hodges, 1995; Mahéo et al., 2007). In the same region, another phase of extension also has been identified as a series of E–W trending, north–dipping, normal faults and shear zones known as the Southern Tibetan Detachment System (STDS) (Fig. 1A; Burchfiel et al., 1992; Burg and Chen, 1984). Previous studies

demonstrated that the STDS was active at ca. 24–12 Ma (Guillot et al., 1994; Coleman and Hodges, 1995; Noble and Searle, 1995; Edwards and Harrison, 1997; Murphy and Harrison, 1999; Yin and Harrison, 2000; Yin, 2006). The STDS occurs widely within the Himalayan Orogen and was generally crosscut by the N–S trending normal faults, suggesting the north–south directed extension occurred prior to the east–west extension (Edwards and Harrison, 1997; Yin, 2000). Distinct kinematics as well as different age ranges for the two types of extensional structures have been taken to indicate that they are caused by two distinct tectonic events (e.g. Blisniuk et al., 2001). However, Mitsuishi et al. (2012) demonstrated that the two phases are at least in part contemporaneous. Anczkiew et al. (2001) even proposed that the E–W extension was initiated at ca. 28 Ma, indicating that it could be locally earlier than the N–S extension.

Compared to STDS, N–S trending faults are closely correlated with the Pb–Zn–Sb–Au mineralization in the Himalayan orogen (Hou et al., 2004). This type of faults also broadly occurred in the Lhasa terrane (Fig. 1B). As recorded by previous documents, they locally constrained the distributions and occurrences of orebodies of the porphyry–(skarn) deposits such as the Jiru porphyry copper deposit (Zheng et al., 2014), Shalang molybdenum porphyry deposit (Zhao et al., 2014) and Jiaduobule skarn Fe–Cu deposit (Yu et al., 2011). This feature indicates that they should play a critical role in porphyry–(skarn) copper polymetallic mineralization. In addition, the E–W extension is associated with surface uplift history of the Tibetan–Himalayan plateau (e.g. Coleman and Hodges, 1995), which is among the most interesting topics in geosciences because of its significances on geomorphology, environment, tectonics, geological dynamics and climate changes in the region and globe during Cenozoic time (e.g. Wang et al., 2008). It is well known that uplift of the Tibetan Plateau and Himalaya changes geomorphology and environment (Liu and Dong, 2013) as well as distributions and current directions of the main rivers in Asia (Brookfield, 1998; Zeitler et al., 2001; Clark et al., 2004). The uplift was also considered as critical reflection of the dynamics of continental plateaus (Wang et al., 2008) and Asian–global climate changes, including the derivations and evolutions of monsoon, intra–continental arid environment, and westerly circulation (Raymo and Ruddiman, 1992; Molnar et al., 1993; An et al., 2001; Liu and Dong, 2013). Accordingly, it is a critical issue to study the E–W extension, in order to well constrain the Cenozoic tectonic evolution, metallogenesis and climate changes. The Pb–Zn–Sb mineralized N–S trending faults are broadly exposed in the Zhaxikang area,

south Tibet (Fig. 1B), but their characteristics and implications have not been well reported, making this area ideal for studying this type of structure.

Here we carried out an extensive field mapping program in the Zhaxikang area. On the basis of detailed field observations and structural investigations, this paper presents new tectono-stratigraphic data that reveal the structural style of the faults at Zhaxikang. Re–Os geochronological studies were undertaken on sulfide mineralization that was hosted by the N–S trending normal faults. The results suggest that the E–W extension and related normal fault-hosted Pb–Zn–Sb–Ag–(Au) mineralization occurred synchronously with syncollisional felsic magmatism at ca. 43 Ma. In light of the data, we further discuss its tectonic and metallogenic implications as well as correlation with growth of the Tibetan–Himalayan plateau and Asian climate changes.

2. Geological background

The Himalayan orogen separates the Indian Plate from the Asian Plate (Fig. 1A). The Lhasa terrane in the Asian plate, north to the Himalayas, contains widespread volcanic and intrusive rocks along its southern margin, which were associated with northward subduction of Neo–Tethyan oceanic slab prior to 65 Ma and subsequent continental collision between the Indian and the Asian blocks (e.g. Mo and Pan 2006; Hou and Cook, 2009). There were two main stages of magmatism in the Lhasa terrane: an early Tertiary stage represented by the Linzizong volcanic rocks and coeval Gangdese batholith, and a late Oligocene–Miocene stage that formed potassic–ultrapotassic and calc–alkaline rocks (Chung et al., 2005).

Several major north-dipping thrust systems that occur in the Himalayan orogen, the most prominent of which are the Main Central Thrust (MCT) and Main Boundary Thrust (MBT) (Fig. 1A). These thrust systems indicate that the main part of the Indian continent has been thrust beneath the Himalayas. In the same region, a phase of (north–south) extension has been identified as a series of E–W trending, north-dipping normal faults and shear zones known as the southern Tibetan detachment system (STDS) (Burg and Chen, 1984; Burchfiel et al., 1992).

The Himalayan orogen mainly consists of three tectonic blocks from north to south (e.g. Yin, 2006; Fig. 1A): a) The Tethyan Himalayan sequence (THS), bounded by the IYS and STDS, consists of

Proterozoic–Eocene carbonate and siliciclastic sedimentary and volcanic rocks; b) The Higher Himalayan Crystallines (HHC), the footwall of the STDS, has a lower boundary defined by the MCT, and mainly consists of Precambrian to Paleozoic high–grade metamorphic rocks of amphibolite facies to lower granulite facies, calc–silicate gneiss and augen orthogneiss (e.g. Searle et al., 2003; Goscombe et al., 2006); c) The Lesser Himalayan sequence (LHS), composed of Proterozoic–Cambrian low–grade metasediments (Richards et al., 2005), adjoins the MCT to the north and the MBT to the south. Both the THS in the hanging wall of the STDS and the HHC mainly consist of rocks that make up the pre–collisional Indian continental margin (e.g. Hodges, 2000).

There are generally interpreted as two phases of metamorphism at different times (Hodges, 2000, and references therein), with peak metamorphism at 38–32 Ma (Eohimalayan, M1 stage) and a later high–temperature thermal event resulting in widespread anatexis at 26–18 Ma (Neohimalayan, M2 stage). The later Neohimalayan event was mostly correlated with the leucogranite generation (e.g., Searle et al., 2003).

Cenozoic igneous rocks in the Himalayas mainly include: a) the Eocene (ca. 47–40 Ma) anatectic (two–mica) granites and gabbros (Fig. 1A) that distribute in the Tethyan Himalaya, along the IYS (Yin, 2006; Hou et al., 2012; Ji et al., 2016); b) the Oligocene–Miocene leucogranites that occur in two sub–parallel belts in the Tethyan and High Himalayas, along the STDS (e.g. Hou et al., 2004; Wu et al., 2015). In addition, extensive bimodal igneous rocks include basalt, diabase, gabbro, felsic lavas and minor granite (Zhu et al. 2009; Liu et al. 2015; Zhou et al. 2018). They are onset in Mesozoic and widespread in the Jurassic–Cretaceous passive continental sequences (Fig. 1B) such as the Lakang Formation and Sangxiu Formation, which consist of sandstone, sandy shale, slate and muddy limestone (Zhu et al. 2007, 2008).

As proposed by Hou and Cook (2009): the Himalayan orogen underwent a complex history of tectono–magmatic evolution from continental collision and subsequent underthrusting in the main–collisional period (65–41 Ma), through intra–continental under–thrusting and large scale horizontal block movements in the late–collisional period (40 to–26 Ma), to E–W crustal extension in the post–collisional period (≤ 25 Ma) (Blisniuk et al., 2001; Hou et al., 2004). Geological events, stress regimes, and plausible deep lithospheric geodynamic processes for each collisional stage were also summarized by Hou and Cook (2009) (Table 1).

A three-stage model has been further proposed for the tectonic-magmatic evolution during the main-collisional period in Tibet (Mo et al., 2007; Hou and Cook, 2009). At ca. 70–60 Ma, roll-back of a flatly-subducted Neo-Tethyan oceanic-slab (Chung et al., 2005) facilitated the early dragging down of the attached Indian continental lithosphere and collision with the Asian continent, resulted in initial shortening of the Asian continental crust and related crustal anatexis. Paleocene granitoids occurred at 66–58 Ma; and then the thermal structure of the mantle wedge was changed, leading to generation of early Linzizong volcanic magmas between 65 and 60 Ma. At ca. 60–54 Ma, the slab roll-back mechanism was replaced by deep subduction of the Indian continental lithosphere, which most likely caused a sudden decrease in the convergent rate from 170 mm/a (at ca. 70–60 Ma) to 105 (at ca. 60–54 Ma; Lee and Lawver, 1995). This accounted for generation of crust-derived calc-alkaline granitoids in the eastern Gangdese range at 54–52 Ma. At ca. 53–42 Ma, break-off of the Neo-Tethyan slab happened at depth and upwelling of the asthenosphere through the “window” triggered partial melting of the lithospheric mantle, in turn generating numerous small gabbro intrusions (52 to 45 Ma; Hou and Cook, 2009; Ji et al., 2016) and tholeiitic subvolcanic rocks (42 Ma) along the Gangdese belt. Another direct consequence of slab break-off was the sudden decrease in rate of convergence from about 90 to about 60 mm/a at ca. 40 Ma (Lee and Lawver, 1995), as well as stress relaxation of the Lhasa terrane, during which abundant polymetallic mineralization was deposited.

Extensive E–W extension led to the formation of numerous N–S trending normal fault systems across the Tethyan Himalaya (Blisniuk et al., 2001; Hou et al., 2004), locally forming rifts, such as the Gulu–Yaodong and Sangri–Cona rifts (Yang et al., 2009). These N–S faults occur along with Pb–Zn–Sb–Au mineralization in the Himalayan orogen (e.g. Hou et al., 2004). Tens of deposits such as the Shalagang, Zhaxikang, Mazhala, Zhegu and Langkazi ore deposit occur in the Tethyan Himalaya, forming an E–W-striking metallogenic belt (Yang et al., 2009). Three styles of Pb–Zn–Sb–Au mineralization has been recognized, i.e., Sb–, Sb–Au–, and Au–styles, which was onset in the Miocene, coeval with the N–S faults at a post-collisional stage (Yang et al., 2009). As the most prominent Pb–Zn–Sb–Ag–(Cu–Au) metallogenic zone in south Tibet, the Zhaxikang area comprises a group of ore/mineral deposits including the Mazhala, Zhaxikang, Soye, Keye, Zedang, Segang, Jiangzhula, Kada, Tamyota, Changzha and Jisong deposits (Fig. 1B). These deposits contain more than 300 million tonnes (Mt) Pb–Zn–Sb metals, including 1.146 Mt lead at an average grade of 1.92–4.20%, 1.407 Mt

zinc at an average grade of 2.18–3.82%, 0.345 Mt antimony at an average grade of 0.95–2.04% and 3000 tonnes silver at an average grade of 14.78–96.91 g/t. In addition, the mineralized N–S trending faults are also broadly exposed at Zhaxikang (Fig. 1B), making this area ideal for studying the E–W extension and related hydrothermal events.

3. The Zhaxikang faults

Our detailed field investigations indicate that the main structures exposed in the Zhaxikang area are N–S (including NNE and NW) trending faults and E–W trending thrust and detachment (Fig. 1B). These structures occurred between the Upper Triassic and the Lower Cretaceous strata, including the Nieru Formation (T_3), Ridang Formation (J_1), Zhela Formation (J_2), Sangxiu Formation (J_3K_1) and Lakang Formation (K_1). These strata consist of sandstone, mudstone, sandy shale, muddy limestone and volcanic rocks, plus minor slate and sericite schist that reflect lower greenschist facies metamorphism (Fig. 1B).

The N–S trending faults broadly occurred in or around the Zhaxikang area. Most of them show a western dip, with partly dipping to east. Pb–Zn–Sb–Fe–Cu sulfide at Zhaxikang is generally hosted by those N–S faults that show an overall trend of 0° – 30° or 315° – 360° with a dip of 55° – 80° W (Fig. 1B and 2). These sulfide-bearing N–S faults crosscut the wall rocks of the Upper Triassic to the Lower Cretaceous strata (Fig. 2, 3 and 4A). Geomorphological indicate a normal component of movement on the N–S trending faults (Fig. 3). Collectively, these features indicate that the N–S trending faults in the Zhaxikang area are affiliated with the regional E–W extension in southeastern Tibet.

Ore sulfides that occur in the N–S normal faults mainly include pyrite, arsenopyrite, sphalerite, galena, stibnite, boulangerite and chalcopyrite (Fig. 4). Ores generally show vein (Fig. 4A), massive (Fig. 4B) or vuggy cavity filling texture (Fig. 4C). The disseminated mineralization is also present. Vein type of sulfide ores generally crosscut foliation planes in country rocks (Fig. 4A).

The E–W trending thrust system continuously occurs south to the Zhaxikang area (Fig. 1B). This type of fault usually shows a relatively small dip of $<40^\circ$ N (Fig. 5). The latter stratum obviously thrusts beneath the earlier stratum (Fig. 5). Fracture zone and fold commonly occur along with those thrust faults (Fig. 5). The flexible rocks (e.g. muddy slate and schist) were strongly deformed whereas

the brittle rocks (e.g. quartzarenite) were broken off. These broken fragments of quartzarenite locally occur as dominos within the relatively flexible rocks, which is a typical field evidence for the thrust system (Fig. 5).

The E–W trending detachment system is not well developed at Zhaxikang (Fig. 6). This type of faults were only observed in the Segang and Zedang hills and commonly occur in small-scale, thus it is difficult to show them in the geological map. Greisenization occurs as meniscus vein (width: 10–30 centimeters) within the faults, whereas mylonite occurs around the faults. Geomorphological features also indicate a normal component of detachment on the E–W faults (Fig. 6) with a northern dip, reflecting the STDS in the region.

Although the regional STDS was previously proposed that they locally occurred prior to the E–W extension that represented by the N–S trending formal fault system (Edwards and Harrison, 1997; Yin, 2000), there is no direct evidence to constrain the sequence between the N–S and E–W fault systems at Zhaxikang. In this paper, we mainly focus on the geochronological study of the sulfide-bearing N–S formal faults in this area.

4. Analytical methods

Nine sulfide samples (eight pyrites and one chalcopyrite) of the Fe–Cu sulfide stage were collected from the adits of the Zhaxikang and Keye ore deposits for Re–Os dating by a thermal ionization mass spectrometry (TIMS). The sampling locations are shown in Fig. 1B.

Sulfide Re–Os isotope analyses were performed at the Re–Os Laboratory, National Research Center of Geoanalyses, Chinese Academy of Geological Sciences. The Carius tube method was used for the dissolution of sulfides and equilibration of samples and tracers ^{185}Re and ^{190}Os at 200°C for 24 h (Li et al., 2009; Qu et al., 2009; Du et al., 2012). Os was recovered by distilling directly from the sample solution in the Carius tube and was subsequently purified by micro-distillation. Acetone was used to extract Re from the sample matrix (Li et al., 2009). Re and Os concentrations and isotopic compositions were determined using negative thermal ionization mass spectrometry (N-TIMS). The standard GBW04477/JCBY of copper–nickel sulfide (Re = 38.61 ± 0.54 ppb, total Os = 16.23 ± 0.17 ppb and $^{187}\text{Os}/^{188}\text{Os}$ = 0.3363 ± 0.0029 ; Du et al., 2012) was used in this study to monitor

reproducibility and instrument stability. Blank Re and Os levels were less than 3 and 0.02 pg, respectively, and negligible in all cases. Chalcopyrite standard GBW04477/JCBY yielded a Re content of 38.65 ± 0.12 ppb and a total Os content of 16.09 ± 0.05 ppb, with an $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.3361 ± 0.0017 . These values are very consistent with the recommended values (Du et al., 2012). Data presented in Table 2 are blank corrected.

5. Results

Detailed Re–Os data for the analysed sulfides are presented in Table 2 and illustrated in Fig. 7. The results define a Re–Os isochron age of 43.3 ± 3.5 Ma (MSWD = 6.3), with an initial $^{187}\text{Os}/^{188}\text{Os}$ intercept of 0.564 ± 0.033 (Fig. 7). It looks like the slightly large MSWD value is attributable to P2 and P4 that relatively scatter from the isochron (Fig. 7). However, even excluding the two samples, the other seven separates also yield similar ^{187}Re – ^{187}Os isochron age of 43.1 Ma and initial $^{187}\text{Os}/^{188}\text{Os}$ of 0.561 ± 0.013 , with smaller error of 2.5 and MSWD of 3.4 (Fig. 7). The identical ages indicate that the analytical procedure used in this study is reliable, and the isochron age of ca. 43.3 Ma ($n = 9$) could be taken as the Re–Os dating result for all the sulfide samples. The slightly large MSWD of our plotted data is possibly due to variation in the initial $^{187}\text{Os}/^{188}\text{Os}$ ratio or differential diffusion of Os between samples, however, the Re–Os age is nevertheless considered useful (Stein and Hannah, 2014; van Acken et al., 2014). In fact, Re–Os isochron ages with large MSWD (4–17) for pyrite, chalcopyrite and sphalerite have been previously reported (e.g. Selby et al., 2009; Lawley et al., 2013; Akbulut et al., 2016).

6. Discussion

6.1. Age of Fe–Cu sulfide and E–W extension

It is difficult to directly obtain evidence of the exact timing of movement on a fault. In some sulfide minerals, the Re–Os isotopic system has a relatively high closure temperature, and remains stable during thermal metamorphism and deformation events; accordingly, it can be applied to place timing constraints on sulfide-bearing faults and ore deposits (Stein et al., 1998; van Acken et al., 2014). For

example, a closure temperature of roughly 500°C was previously reported for molybdenite Re–Os isotopic system (e.g. Suzuki et al., 1996). Stein and Bingen (2002) and Bingen and Stein (2003) even proposed that the Re–Os system in molybdenite can not be affected by high-temperature (~800°C) granulite-facies metamorphism. More than 500°C was also calculated for the closure temperature of pyrite ($\pm$ chalcopyrite), based on the experimental diffusion results (e.g. Brenan et al., 2000). Selby et al. (2009) reported Re–Os data for chalcopyrite, pyrite and bornite from the Ruby Creek carbonate-hosted copper deposit, and then proposed that the Re–Os systems of these sulfides can remain robust through greenschist metamorphism. Zhu and Sun (2013) reported the chalcopyrite Re–Os age from the Lala copper deposit in southwestern China, and then suggested that chalcopyrite Re–Os system is almost unaffected by upper greenschist facies metamorphism with temperature up to 500°C.

In the Himalayan orogen, high-grade metamorphism of amphibolite facies to lower granulite facies, calc-silicate gneiss and augen orthogneiss only occurred in the HHC (e.g. Searle et al., 2003; Goscombe et al., 2006). The Zhaxikang area is located in the THS that mainly consists of Proterozoic–Eocene carbonate and siliciclastic sedimentary and volcanic rocks, and there only occurs lower greenschist facies metamorphism that is represented by slate plus minor sericite schist in the Ridang Formation (Fig. 1B). Hence the pyrite–chalcopyrite Re–Os isotope system in this study can not be reset during the metamorphism. In addition, our data yielded by all the nine sulfide samples plott on or near the Re–Os isochron with a much higher age than those of the Oligocene–Miocene leucogranites, also precluding that the Re–Os isotopic system was affected by the local metamorphism or the latter tectono-thermal events. In fact, the pyrite and chalcopyrite in our study are separated from the pyrite–chalcopyrite–galena–sphalerite assemblage, which indicates a relatively high closure temperature for the Re–Os isotope system (~730 °C; Stevens et al., 2005). In all these cases, the Re–Os isochron age of ca. 43.3 Ma determined in this study can provide a directly geochronologic evidence for the Fe–Cu sulfide at Zhaxikang in the Himalayan orogen. As mentioned above, pyrite and chalcopyrite are hosted by the N–S trending normal faults. Accordingly, the Re–Os age of Fe–Cu sulfide can be also taken as the onset time of the N–S trending fault system.

The Re–Os age also suggests that the Eocene E–W extension at Zhaxikang were coeval with magmatism (Fig. 1A), metamorphism and gold metallogenesis in the region. Previous U–Pb dating of metamorphic zircons also indicated multiphase metamorphic ages of ca. 47–37 Ma (Zeng et al., 2011).

In addition, a series of (two-mica) granitoids were dated at 47–40 Ma (Aikman et al., 2008; Hou et al., 2012; Zeng et al., 2011), and gabbros were dated at 45.0 ± 1.4 Ma (Ji et al., 2016) occur along the IYS (Fig. 1A). The Banbu large gold deposit, located along the southern part of the IYS in southern Tibet, was also dated at 43.6 ± 3.2 and 44.8 ± 0.96 Ma by Ar–Ar dating of sericite (Sun et al. 2016).

Although Re–Os dating is commonly used to constrain the age of mineralization in Tibet, there is rare report that this isotopic system was used to directly date the onset time of the N–S fault system. The age of ca. 43.3 Ma recorded by the Re–Os system obviously predates previous determinations of the age of both the E–W extension (≤ 19 Ma, Mitsuishi et al., 2012) and the STDS (≤ 24 Ma; Edwards and Harrison, 1997; Murphy and Harrison, 1999; Yin, 2006), reflecting an earlier thermo–tectonic event in the Himalayan orogen. This age (Fig. 7) is also significantly different from the previously published mica Ar–Ar ages. Although mica K–Ar and Ar–Ar isotopic systems have a relatively low closure temperature ($< 350^\circ\text{C}$, Cliff, 1985) and can be easily disturbed by later deformation, metamorphism or hydrothermal events, a Miocene ^{40}Ar – ^{39}Ar plateau age of 17.9 ± 0.5 Ma for biotite and sericite in the Zhaxikang ore deposit (e.g. Sun et al., 2018), suggesting a possibility that the N–S trending faults in this area moved in another episode. In fact, multistage tectono–thermal events that occur in the same ore deposit are very common. Previous studies also reported two periods of copper mineralization for the Dexing and Jiru porphyry copper deposits, both of which are related to two periods of tectono–thermal system (Zhou et al., 2012; Zheng et al., 2014). In all these cases, the N–S trending faults in the Himalayan orogen possibly activated in several times.

The Eocene Fe–Cu mineralization at Zhaxikang in the Himalayan orogen is also coeval with the porphyry–(skarn) Cu–Mo–Fe metallogenesis in the Lhasa terrane. Zheng et al. (2014) and Zhao et al. (2014) presented good Re–Os isochron ages of 44.9 ± 2.6 Ma (MSWD = 2.7, $n = 5$) and 52.3 ± 0.3 Ma (MSWD = 0.6, $n = 13$) for the Jiru and Shalang porphyry Cu–Mo deposits, respectively. In addition, Yu et al. (2011) also reported a U–Pb age of 50.9 ± 1.8 Ma (MSWD = 2.3, $n = 9$) for ore-bearing monzogranite from the Jiaduobule skarn Fe–Cu deposit. (e.g. Yu et al., 2011; Zhao et al., 2014; Zheng et al., 2014). The N–S trending normal faults, reflecting the E–W extension, broadly occur both in the Himalayas and in the Lhasa terrane (Fig. 1B). These faults also well occur in the porphyry–(skarn) deposits above, and locally constrain the distributions and occurrences of their orebodies. Therefore, the Eocene E–W extension plays a critical role both in hydrothermal Fe–Cu–(Pb–Zn) mineralization from

the Himalayas and in porphyry–(skarn) copper polymetallic mineralization from the Lhasa terrane.

6.2. Source of Fe–Cu sulfide

The initial $^{187}\text{Os}/^{188}\text{Os}$ ratio (0.56 ± 0.01 – 0.03) yielded by the Re–Os dating of sulfides is much higher than that of oceanic mantle (0.108 – 0.165 ; Pearson et al., 1995) or primitive upper mantle (0.126 – 0.129 ; Meisel, et al., 1996), but is compatible with typical values of the inhomogeneous continental crust (0.31 – 11 , even lower for crustal mafic rocks: ~ 0.17 ; Esser and Turekian, 1993; Pearson et al., 1995; Saal et al., 1998). In addition, the ratio is very identical to those of the Sudbury nickel ore deposit in Canada ($^{187}\text{Os}/^{188}\text{Os}$ ratio: 0.55 – 0.91) and the Kipushi base metal deposit in DR Congo ($^{187}\text{Os}/^{188}\text{Os}$ ratio: 0.74 ± 0.23), which show a crustal origin for their metal sources (Dickin et al., 1992; Schneider et al., 2007). We thus infer that the Os contained in the Zhaxikang Cu–Fe sulfides is of crustal origin. This is consistent with the crustal origin of the syncollisional two–mica granites in the region. As proposed by previous scholars (e.g. Mo and Pan 2006; Hou et al., 2012; Yin, 2006), the Indian continent was subducting beneath the Himalaya mountains along the Himalayan thrust during India–Asia collision at 65 – 40 Ma, and the lithosphere was strongly thickened; and then the voluminous Eocene felsic magmas were derived by partial melting from a thickened Indian lower crust and were subsequently mixed with amphibolite–derived granite melts, or were contaminated by the middle crust under southern Tibet. In summary, Fe–Cu sulfide at Zhaxikang possibly had a crustal source that associated with coeval syn–collisional felsic magmatism in the region.

6.3. Tectonic and climatic implications

The surface uplift history of the Tibetan Plateau and Himalaya is one of the most interesting topics in geosciences because of its effect on regional and global climate changes, its influence on monsoon intensity, and its reflection of the dynamics of continental plateaus in the Cenozoic (Wang et al., 2008). Models of plateau growth vary in time, from pre–India–Asia collision (e.g. ca. 100 Ma ago) to gradual uplift after the India–Asia collision (e.g. ca. 55 Ma ago) and to more recent abrupt uplift (<7 Ma ago), and vary in space, from northward stepwise growth of topography to simultaneous surface uplift across the plateau (Wang et al., 2008).

It is recognized that the Himalayan–Tibetan orogen underwent several periods of uplift–erosion

events (e.g. Sorkhabi et al., 1994; Zhong and Ding, 1996; Tapponnier et al., 2001; Chung et al., 2005; Wu et al., 2008), the earliest one of which occurred in the Eocene. Based on studies of the Cenozoic K-rich volcanic rocks that broadly occur in the Tibetan plateau, previous researchers held that uplift of the whole plateau happened prior to 50 Ma (e.g. Turner et al., 1993, 1996; Chung et al., 2005; Wu et al., 2008). Wang et al. (2008) presented geologic and geophysical data from north-central Tibet, including magnetostratigraphy, sedimentology, paleocurrent measurements, and $^{40}\text{Ar}/^{39}\text{Ar}$ and fission-track studies, and then proposed that the central plateau was elevated in large scale by ca. 40 Ma ago. This time (ca. 40 Ma) of uplift was very identical to the studies in northern Tibet (Fang et al., 2003; Dupont-Nivet et al., 2007). Rowley et al. (2008) reported oxygen isotope of the Lunpola basin, central Tibet, and suggested that the Eocene (40–35 Ma) central Tibetan plateau arrived at the same altitude as today. This was further supported by the recalculation of new geomagnetic polarity data on basis of numeric model of the plateau elevation (Tang and Liu, 2001). As suggested by Tang and Liu (2001), the strongly positive geomagnetic pole during 40–35.7 Ma reflected the uplift time of the plateau. The south Himalayas and the Sanjiang region, located in the eastern margin of the Himalayas, were both proved to be elevated at 45–38 Ma (Zhong and Ding, 1996; Tapponnier et al., 2001). In all these cases, the earliest uplift of the Tibetan plateau most likely occur at ca. 50–36 Ma, and the northern boundary of the protoplateau was in the region of the Tanggula Shan (Wang et al., 2008).

The Eocene uplift of the plateau was also coeval with the derivation of Asian monsoons. Liu et al. (2017) reported that South Asian monsoons had been formed in early Eocene, based on their numerical simulation. Shukla and Mehrotra (2016) studied quantities of fossils of broad-leaf plants in early Eocene (ca. 50 Ma) coal-bearing strata that reflect humid climate, and then suggested that South Asian monsoons should arrived at Central Asia by 50 Ma ago. Recently, more and more studies also proved that Central Asia was emplaced in a (semi-) humid climate environment from early to late Eocene (e.g. Tapponnier et al., 1979; Zhang et al., 2015; Sun et al., 2015; 2017). However, the Eocene uplift of Himalayas could prevent the South Asian monsoons into Central Asia (e.g. Wu et al., 2008; Molnar et al., 2010); subsequently the climate within Asian continent would change to be cool (Raymo and Ruddiman, 1992) and arid (Manabe and Broccoli, 1990; Broccoli and Manabe, 1992; Kutzbach et al., 1993; Sato and Kimura, 2005). This apparently contradicts the uplift of the Himalayan–Tibetan plateau in the Eocene, as mentioned above. A reasonable interpretation should be that, collapse or extension

occurred synchronously with the uplift. Our Re–Os age indicates that the regional E–W extension initiated in the Eocene (ca. 43.3 Ma), which could result in collapse of the plateau and decrease in altitude. This interpretation is further supported by previous studies. Actually, Eocene collapse of the Himalayan orogen or extension of the lithosphere occurred at 50–40 Ma, reflecting uplift of Himalayas (Turner et al., 1993, 1996; Chung et al., 2005; Wu et al., 2008). Chung et al. (1998, 2005) and Ji et al. (2016) even proposed that the lithosphere delamination and thinning or Neo–Tethyan slab breakoff possibly occurred at depth prior to 40 Ma.

In conclusion, Asian paleoclimate was significantly influenced by the Eocene extension, which was possibly resulted from lithosphere delamination–thinning or slab breakoff at great depth (mantle level) and E–W extension at relatively shallow depth (crustal level) in the Himalayan–Tibetan plateau.

6.4. Tectono–thermal evolution

The Himalayan orogeny, associated with large scale of orogenic gold mineralization, has been suggested to occur in a syn–collisional setting at ca. 65–40 Ma, due to the N–S trending compression caused by the India–Asia collision (e.g. Mo and Pan 2006; Yin, 2006; Hou et al., 2012; Sun et al. 2016). Our new Re–Os data suggests that the E–W extension reflected by the N–S trending faults and related Fe–Cu sulfide also occurred at ca. 43 Ma. This indicates that the E–W extension at Zhaxikang was significantly coeval with N–S compression at the main collisional stage in northern Himalaya.

Here we propose a new model to explain the early Cenozoic tectono–thermal evolution in this area. Prior to ca. 65 Ma (Mo and Pan 2006), the Neo–tethyan oceanic slab was northward subducting beneath the Asian continental block (Fig. 8A), and then collision between the Indian and Asian blocks initiated, resulting in the Himalayan orogeny (Fig. 8B). With ongoing collision between the two blocks, high–grade metamorphism occurred along with widespread syn–collisional anatectic magmatism (ca. 50–40 Ma; e.g. Ratschbacher et al., 1994; Yin, 2006; Hou et al., 2012) and intense deformation. At ca. 45–43 Ma, the N–S trending horizontal deviatoric stresses peaked (Cook and Royden, 2008), and subsequently N–S stress was released during lithosphere delamination (Chung et al., 1998, 2005) or Neo–Tethyan slab breakoff (Kohn and Parkinson, 2002; Ji et al., 2016) at great depth (asthenospheric mantle level). This possibly resulted in the deceleration of convergence between India and Asia, from 8–10 to 4–6 cm/yr at ca. 45 Ma (Patriat and Achache, 1984; van Hinsbergen et al., 2011). It was at this

time that we suggest E–W extension initially developed at shallow depth (crustal level), reflected by the formation of a series of N–S trending normal faults in the Zhaxikang area, even in the whole Tibetan plateau (Fig. 8C). Given that magmatism and related (e.g. Fe, Cu and Au) mineralization were broadly coeval, the metals were carried into the N–S trending faults, possibly from the coeval felsic magmas. However, a large number of previously reported ages of ≤ 19 Ma for E–W extension suggest this structural system was extensively reactivated in the Miocene, even forming large scale of N–S trending rifts (e.g. Yin, 2000; Yin and Harrison, 2000; Williams et al., 2001; Mitsuishi et al., 2012).

7. Conclusions

Our structural study and Re–Os isotopic results suggest that E–W extension at Zhaxikang initially occurred in the Eocene, coeval with N–S compression and syn–collisional magmatism–metamorphism. The result predates previous determinations of the timing of emplacement of both the E–W extension and the STDS that reflects the N–S extension in the region. This study provides new constraints on early Cenozoic tectonics and metallogensis in the Himalayan orogen as well as climate changes in Central Asia.

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Figures and captions

Fig. 1. A: Tectonic map of southern Tibet, showing the location of the main fault systems and terranes; map modified after Hou et al. (2012) and Zhang et al. (2012). B: Stereonet plots showing orientations of N–S trending faults measured in the outcrop and adits of the Pb–Zn–Sb polymetallic deposits in the Zhaxikang area; geological map is based on field observations supported by our field mapping and drilling projects. IYS: Indus Yarlung–Zangbo suture, MCT: main Central Thrust; MBT: main Boundary Thrust; STDS: southern Tibetan Detachment System; TH: Tethyan Himalayan sequence, HH: high Himalayan crystallines, LH: lesser Himalayan sequence; Eocene granitoids were from Hou et al., 2012; Eocene gabbros (ca. 45 Ma) were from Ji et al., 2016.

Fig. 2. Cross sections showing a three-dimensional distribution for the sulfide ore-bearing N–S normal faults at Zhaxikang. Location of Zhaxikang is shown in Fig. 1B.

Fig. 3. Geological features showing the N–S trending normal faults at Zhaxikang.

Fig. 4. Representative photographs showing ore types (A–C) and mineral assemblages (D–F) of the Zhaxikang ore deposit. A. Vein ore crosscutting the foliation planes in country rocks. B. Massive ore. C. Ore with vuggy cavity filling texture. D. Pyrite and quartz are filled, crosscut or replaced by galena, boulangerite and stibnite; galena is also crosscut and replaced by boulangerite. E. Chalcopyrite in sphalerite or at the boundary between sphalerite and galena. F. Quartz and arsenopyrite are crosscut and replaced by sphalerites. Py: pyrite, Gn: galena, Sp: sphalerite, Ccp: chalcopyrite, Blr: boulangerite, Qz: quartz.

Fig. 5. Sketch (A) and field photographs (B) showing E–W trending thrust in Jisong village from the Zhaxikang area.

Fig. 6. Sketches showing E–W trending detachments in Zedang and Segang hills from the Zhaxikang area.

Fig. 7. TIMS Re–Os dating for pyrite and chalcopyrite from the Zhaxikang Pb–Zn–Sb polymetallic deposits occurred in the N–S trending faults.

Fig. 8. A new tectonic model showing the generation of the E–W extension, coeval syn-collisional granitoids and Cu–Au–Fe mineralization at ca. 43 Ma in the Himalayan orogen. HOB: Himalayan

678 orogen belt; IYS: Indus Yarlung–Zangbo suture; circle represents Cu–Au–Fe mineralization; Dashed
679 represents N–S trending fault; Red field represents Eocene granitoid. A. Prior to ca. 55 Ma (Yin 2006)
680 and perhaps even earlier (65 Ma; Mo and Pan 2006), the palaeo–Tethyan plate was northward
681 subducting beneath the Asian continent. B. Collision between the Indian and the Asian blocks occurred
682 at 65 or 55 Ma (Yin 2006; Mo and Pan 2006). C. With ongoing collision between the two blocks, the
683 N–S trending horizontal deviatoric stresses peaked (Cook and Royden, 2008), and by ca. 43 Ma, the
684 N–S trending normal faults initially developed at a crustal level in the Zhaxikang area (even in the
685 whole Tibetan plateau), subsequently felsic magmatism and related (e.g. Fe, Cu and Au) mineralization
686 occurred.

Table 1 Brief description of the tectono–magmatic events in different evolution stages of the Himalayan orogen (Hou and Cook, 2009).

Pre–collision	Main–collision	Late–collision	Post–collision
120–70 Ma	65–41 Ma	40–26 Ma	25–0 Ma
Andean–type arc along Gangdese mountain range	Tethyan Himalayan thrust belt in south Tibet; Narrow mountain range in Lhasa terrane; Qimen–Tagh thrust system and early Tertiary basins in central Tibet	Contraction system in central Tibet strikeslip faulting and shearing systems in east Tibet thrusting system and nappe structure in east Tibet	South Tibetan detachment system NS–striking normal fault system across orogen; East–west extension
Calc–alkaline arc granitoids (120–70 Ma), intruded along the Gangdese arc	Magmatism occurring along the Gangdese arc in Lhasa terrane Linzizong volcanic rocks (65–40 Ma) Muscovite–granites (66–58 Ma) calc–alkaline granitoids (65–41 Ma) Bimodal bimodal granitoid and gabbro (52–47 Ma) mafic intrusions (42–38 Ma)	Magmatism mainly occurring in the transform zone in east Tibet High–K calc–alkaline rocks (40–30 Ma) Potassic potassic intrusion rocks (40–30 Ma) REE–bearing carbonatite–alkalic complex (40–27 Ma) Cu–bearing stocks (40–32 Ma) Lamprophyre (35–26 Ma)	Magmatism widely occurring in the Tibetan plateau ultrapotassic rocks (26–13 Ma) Potassic rocks (25–0 Ma) Cu–bearing adakitic stocks (19–13 Ma) Leucogranites (23–16 Ma)
Convergence and continuous compression	Early: compressional; late: stress relaxation	Early: transpressional; late: transform to transtensional	Early: lower–crust flow; late: E–W extension
Subduction of the Neo–Tethyan oceanic slab; melting of wedge mantle metasomatized by subduction zone components	Indo–Asian impact (70–65 Ma)→rolling back of subducted Neo–Tethyan oceanic slab→subduction of Indian continent→breakoff of oceanic slab→flat subduction of Indian continental–slab (<40 Ma)	Intra–continental subduction or terrane underthrusting caused by flat subduction of Indian continent in central Tibet; Asthenospheric upwelling in east Tibet	Break–off and delamination of Indian continental slab; Asthenospheric upwelling and mantle lithospheric thinning

Table 2 TIMS Re–Os isotopic analytical data of the Fe–Cu sulfide from the Zhaxikang Pb–Zn–Sb polymetallic deposits occurred in the N–S trending faults.

Sample	Mineral assemblage	Mineral separate	Weight (g)	Re (ppb)	±	Common Os (ppb)	±	$^{187}\text{Re}/^{188}\text{Os}$	±	$^{187}\text{Os}/^{188}\text{Os}$	±
P1	Py–Gn–Sp–Sbn–Qz	Py	0.70134	0.0790	0.0003	0.00511	0.00002	74.51	0.77	0.62	0.01
P2	Py–Gn–Sp–Sbn–Qz	Py	0.70161	0.0400	0.0003	0.00081	0.00001	237.85	2.53	0.71	0.01
P3	Py–Gn–Sp–Sbn–Qz	Py	0.70025	0.0175	0.0001	0.00090	0.00001	94.20	1.09	0.64	0.01
P4	Py–Gn–Sp–Sbn–Qz	Py	0.70625	0.0775	0.0018	0.00050	0.00001	750.58	27.34	1.21	0.06
P5	Py–Gn–Sp–Sbn–Qz	Py	0.70126	0.3406	0.0016	0.00079	0.00001	2064.08	34.95	2.01	0.07
P6	Py–Gn–Sp–Sbn–Qz	Py	0.70676	0.0873	0.0003	0.00091	0.00001	459.98	3.44	0.90	0.01
P7	Py–Gn–Sp–Sbn–Qz	Py	0.70140	0.1491	0.0005	0.01898	0.00009	37.84	0.23	0.58	0.01
P8–1	Py–Gn–Sp–Ccp–Qz	Py	0.70254	0.1540	0.0008	0.01927	0.00008	38.46	0.26	0.58	0.01
P8–2	Py–Gn–Sp–Ccp–Qz	Ccp	0.70094	0.0228	0.0002	0.01899	0.00029	5.79	0.10	0.56	0.01

Uncertainties are absolute at 2σ with error. Sbn: stibnite, Py: pyrite, Gn: galena, Sp: sphalerite, Ccp: chalcopyrite, Qz: quartz.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Highlights

E-W extension initially occurred in the Eocene (ca. 43 Ma).

E-W extension was coeval with N-S compression in SE Tibet.

E-W extension plays a critical role in regional tectonics and metallogenesis and Asian climate changes.