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ORIGINAL ARTICLE

Major Miocene geological events in southern Tibet and eastern Asia induced by the subduction of the Ninetyeast Ridge

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Abstract Cenozoic adakitic rocks in the Gangdese changed from barren continental melts to ore-forming slab melts at ∼ 23 Ma. The distribution and chemical characteristics of the ore-forming adakites point to an association with the Ninetyeast Ridge. The subduction of the thick, rigid Ninetyeast Ridge changed the geometry and rheology of the eastern Tibetan Plateau lithosphere and asthenosphere, restrained the eastward escape of asthenospheric mantle as well as continental fragments, and promoted the uplift and building of the Tibetan Plateau, which consequently changed the tectonic and climatic regimes in eastern Asia.

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1 Introduction

The interaction between the Indian and Eurasian plates is an ongoing example of continent–continent collision and continental subduction, the details of which are of critical importance to better understand the formation of the Himalaya and Tibetan Plateau, and plate tectonics in general.

The Tibetan Plateau is the highest and largest orogenic belt on Earth's surface, standing ∼ 5000 m above sea level with an area of ∼ 3 million km^2. It appears to have mainly formed through crustal shortening and thickening after collision of the Indian and Eurasian continents commenced at ∼ 34 to 55 Ma (Tapponnier et al. 2001; Aitchison et al. 2007; Royden et al. 2008; Meng et al. 2012; Ding et al. 2017). In contrast to the dramatic crustal shortening in western and central Tibet immediately following the collision, eastern Tibet is characterized by the escape of large fragments of lithosphere that started at 40–35 Ma (Tapponnier et al. 2001; Royden et al. 2008). Meanwhile, major geologic events occurred around the Tibetan Plateau: southward extrusion of the Indochina Peninsula (Tapponnier et al. 1982), large-scale dextral movement of the Red River–Ailaoshan shear zone (Leloup et al. 1995), rapid trench retreat along much of the west Pacific, Philippine, and Indonesian oceanic subduction boundaries as indicated by widespread Early Cenozoic extension (Hall and Morley 2004), Eocene–Oligocene extension in the South and East China Seas (Taylor and Hayes 1980; Sibuet et al. 2004), and formation of other extensional basins along the continental margins of Asia

(Maruyama et al. 2009). These have been attributed to geometric accommodation associated with oblique collision/subduction (Tapponnier et al. 2001) and partially to trench retreat in the western Pacific and Indonesian arcs (Royden et al. 2008).

Major tectonic changes occurred in the Miocene. The tectonic regime of the Tibetan Plateau changed to rapid uplift and crustal thickening in southern Tibet ~ 20 Ma (Harrison et al. 1992) and the Plateau likely reached its current height at ~ 15 Ma (Spicer et al. 2003), initiating the present-day Asian monsoons (Licht et al. 2014). The escape of lithospheric fragments to the east of the Plateau and trench retreats along the eastern margin of Eurasia appear to stop at about the same time, implying close connections between these events (Royden et al. 2008). Meanwhile, Cenozoic porphyry copper mineralization has been documented in the Gangdese belt, southern Tibet (Hou et al. 2009; Xiao et al. 2012). The geochemistry of these porphyry deposits provides clues to the mechanism that controlled/coordinated these major collision-associated tectonic events. Here we show that all these events were associated with the subduction of the Ninetyeast Ridge.

2 Results

The Gangdese porphyry-copper-deposit belt is the largest of its type in China, being ~ 400 km in length and ~ 100 km in width. It is in the southeastern Tibetan Plateau, next to the eastern Himalayan syntaxis (Figs. 1 and 2). Adakitic porphyries associated with ores formed at 23–15 Ma (Hou et al. 2009; Xiao et al. 2012), about 10–35 Ma younger than the collision between the Indian and Eurasian continents (Aitchison et al. 2007; Meng et al. 2012). Based mainly on these ages, the deposits were assumed to be typical post-collisional orogenic copper porphyries (Hou et al. 2009). Consequently, the formation of these ore-forming adakites was attributed to partial melting of underplated mafic lower crust or relicts of previously subducted oceanic slabs induced either by slab breakoff or mantle thinning in an extensional setting (Hou et al. 2004, 2009, 2015).

Geochemically, post-collisional ore deposits are usually sulfur-poor and gold-rich (Richards 2009). In contrast, the Gangdese porphyries are sulfur-rich and gold-poor, and are associated with highly oxidized adakite with abundant magnetite-hematite and anhydrite (Hu et al. 2015; Sun et al. 2015). For example, the Qulong porphyry, the largest copper deposit in China, has anhydrite contents ranging from 5 vol% to 90 vol% in veins, and 1 vol% to 5 vol% in altered rocks (Xiao et al. 2012). Such high sulfur contents are seen mostly in arc environments, not in post-collisional settings (Richards 2009).

Remarkably, there was a major transition in the geochemistry of the adakites in the Gangdese at ~ 23 Ma. Adakite was originally defined as being associated with partial melting of subducted oceanic slabs, with close spatial relationship with young (< 25 Ma), hot subducting oceanic plates (Defant and Drummond 1990). Later studies have suggested that some adakitic rocks may have formed through partial melting of thickened/delaminated lower continental crust (Chung et al. 2003; Gao et al. 2004; Wang et al. 2005; He et al. 2011). These two types of adakite may be differentiated using geochemical characteristics (Liu et al. 2010; Sun et al. 2012). Cenozoic adakites formed at 30–9 Ma in the Gangdese belt and are taken as post-collisional intrusions based on their ages relative to the collision. Adakites younger than ~ 23 Ma are of slab melting origin (Fig. 3) and are associated with porphyry deposits. In contrast, slightly older adakites plot in the field defined by partial melting of continental crust. These adakites are barren and are attributed to foundering of thickened lower crust (Chung et al. 2009). Such transition implies major tectonic changes in the Gangdese. The most straightforward explanation is the commencement of the subduction of the Ninetyeast Ridge.

The ore-forming adakites are distributed near the eastern Himalayan syntaxis. Moreover, ~ 90% of the Cu reserves are located in the east end of the belt, along a north–south axis about 100 km long, next to the eastern Himalayan syntaxis, with the two largest porphyry copper deposits in the belt, the Qulong and Jiama ($>$ 10 million tonnes of Cu metal reserves each) occurring here. These major porphyry copper deposits in the Gangdese belt have much higher ε_{Hf}, ε_{Nd}, and oxygen fugacity than other contemporaneous adakitic porphyries in the belt (Fig. 4). Their higher ε_{Hf} and ε_{Nd} values have been attributed to partial melting of either juvenile crust derived from the mantle (Hou et al. 2009) or relicts of previously subducted Jurassic oceanic crust (Hou et al. 2015) during post-collisional extension in the Tibetan Orogen. However, this is not supported by Sr/Y–La/Yb data (Fig. 3), which do not show the high La/Yb expected for continental adakite. Instead, it may be better explained by slab melting. Continental crust has consistently lower Cu content than oceanic crust, so slab melts are far more favorable for Cu deposits than continental crust melts (Sun et al. 2011, 2012).

More importantly, the oxygen fugacities of these adakites are very high, consistent with subduction-related magmas (Ballhaus 1993; Kelley and Cottrell 2009) but much higher than post-collisional magmas. The oxygen fugacity of adakites from Qulong, for example, reached the hematite-magnetite oxygen buffer, which is about four orders of magnitude higher than the fayalite-magnetite-

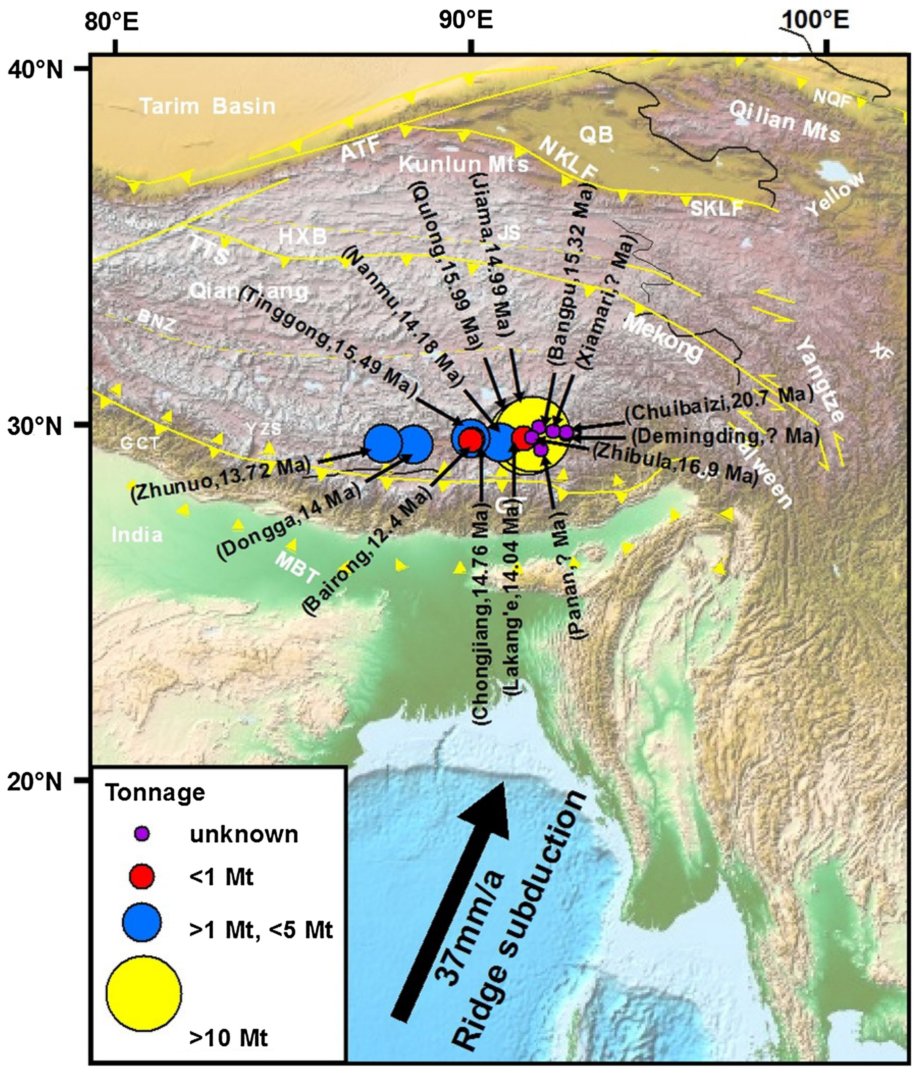

Fig. 1 Schematic of the Tibetan Plateau, showing the eastern Himalayan syntaxis, the Gangdese porphyry copper deposits, and subduction direction of the Ninetyeast Ridge. Most of the copper reserves are concentrated in the east end of the belt, close to the eastern Himalayan syntaxis

quartz buffer (Sun et al. 2013). Given that sulfate solubility in magma is up to about 1%, whereas that of sulfide is around 1000 parts per million (Jugo 2009), the extremely high sulfur contents in these adakites suggest that the high oxygen fugacity was a primary feature.

Normal mantle has quite uniform oxygen fugacity near the fayalite-magnetite-quartz oxygen buffer, as indicated by mid-ocean ridge basalts and abyssal peridotites (Stagno et al. 2013). Convergent margin magmas have systematically higher oxygen fugacities compared to intraplate settings (Ballhaus 1993; Parkinson and Arculus 1999; Kelley and Cottrell 2009), which is likely due to subduction-released fluids (Sun et al. 2007). Relicts of previously subducted Jurassic oceanic crust (Hou et al. 2015) presumably should have been dehydrated long ago. Partial melting of such oceanic crust cannot form magmas with high oxygen fugacity either. In fact, even mafic arc magmas have oxygen fugacity close to that of mid-ocean ridge basalts (Lee et al. 2010), likely due to the lack of additional fluids. Moreover, the Gangdese batholith (slightly earlier than the porphyries) was also much more reducing as indicated by tin deposits that predate the porphyries (Hou and Cook 2009). Therefore, it is unlikely that highly oxidizing magmas could form through direct partial melting of mafic lower crust or previously subducted Jurassic oceanic crust in the Miocene in the Gangdese belt.

The coupling between high oxygen fugacity, higher ε_{Hf} and ε_{Nd}, and large Cu reserves can best be explained by ridge subduction, with the Ninetyeast Ridge as the likely player. At 6000 km long, ~ 300 km wide, and several hundred to more than 2000 m higher than the surrounding Indian Ocean floor, the Ninetyeast Ridge is the largest aseismic ridge in the world. Spatially, the Ninetyeast Ridge is co-terminal with the eastern Himalayan syntaxis of the Tibetan Plateau (Fig. 1), suggesting that a significant fraction of the Ninetyeast Ridge may have already been subducted. The subduction of such a large ridge inevitably results in major deformation of the overriding plate, and

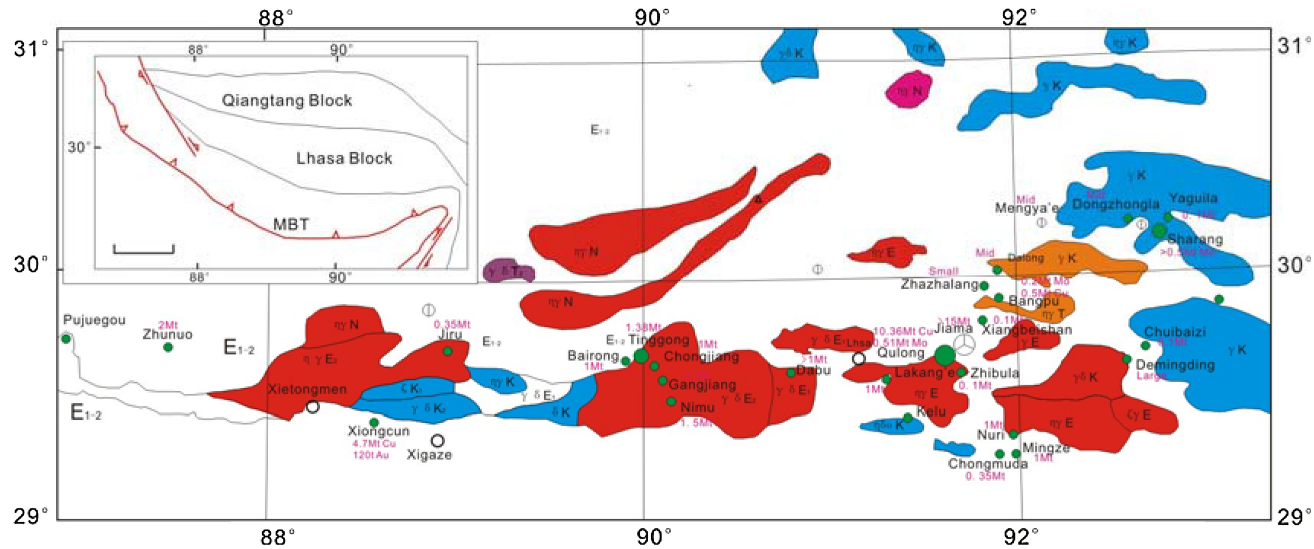

Fig. 2 Distribution of the Gangdese porphyry copper-molybdenum deposits. The Gangdese deposit belt is generally known as roughly east–west extending. About 90% of the reserves, however, are concentrated along a north–south trending belt in the east end, with two super large deposits, the Jiama and Qulong

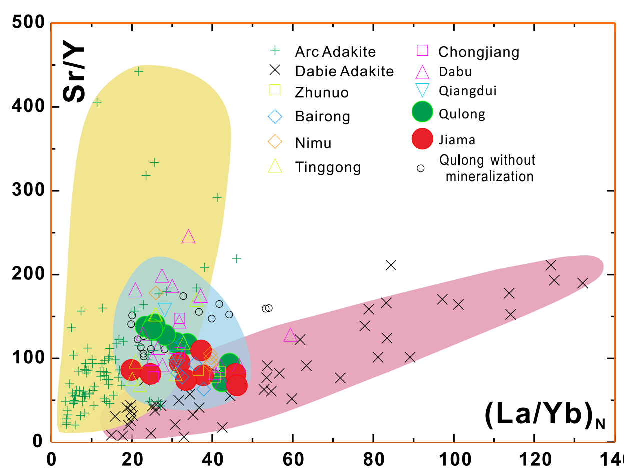

Fig. 3 A Sr/Y versus La/Yb diagram for Cenozoic Gangdese adakites associated with the Gangdese porphyry copper deposit. Adakites from circum-Pacific and the Dabie Mountains represent slab and continental crust melts, respectively (Liu et al. 2010; Sun et al. 2012). Adakites older than 23 Ma are barren and plot in the Dabie field. Ore-forming adakites are younger than 23 Ma and show closer affinities to the circum-Pacific adakites, indicating major components from slab melts, essential to copper mineralization (Sun et al. 2011). Some of the adakites from porphyry deposits also plot in the Dabie field likely because of the thick continental crust in the Plateau. The transition is coincident with major tectonic changes in the Tibetan Plateau

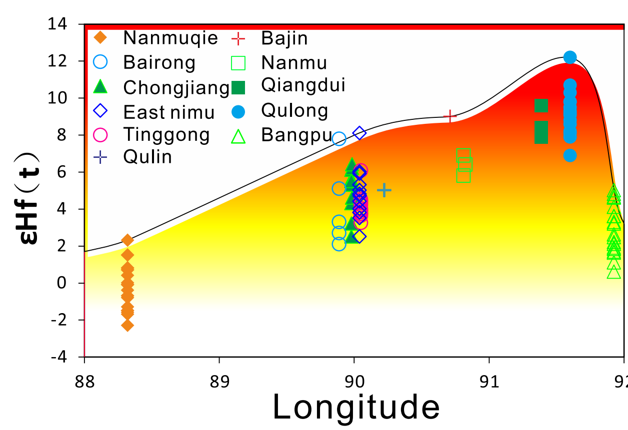

Fig. 4 Variations of εHf in zircon from the Gangdese porphyry belt from west toeast. The two largest porphyry deposits, the Qulong and Jiama, have the highest εHf, which is consistent with higher proportions of "mantle" derived components

correspondingly deeper earthquakes with higher magnitude.

The Ninetyeast Ridge is currently at ~ 25°N, moving and subducting northeastward at a speed of ~ 37 mm/year (Subrahmanyam et al. 2008). Based on plate reconstruction, the drifting direction and rate have not changed significantly during the last 23 Ma (van Hinsbergen et al. 2011). Therefore, the Ninetyeast Ridge has drifted more than 300 km eastward and 650 km northward during the last 23 Ma, i.e., subduction was likely occurring directly beneath the Gangdese porphyry copper belt at 23 Ma.

Earthquakes deeper than 120 km in the eastern Tibetan Plateau are concentrated along the northward extension of the Ninetyeast Ridge, pointing towards the eastern Himalayan syntaxis (Fig. 5). Consistently, using seismic ambient noise (Sun et al. 2010), two high-shear-velocity anomalies have been identified near the eastern Himalayan syntaxis: a shallower one in the south at 40–70 km depth and a deeper (> 70 km) one of > 50-km thickness with irregular shape. The deeper high anomaly extends from 22°N to 32°N, several hundred kilometers to the north of

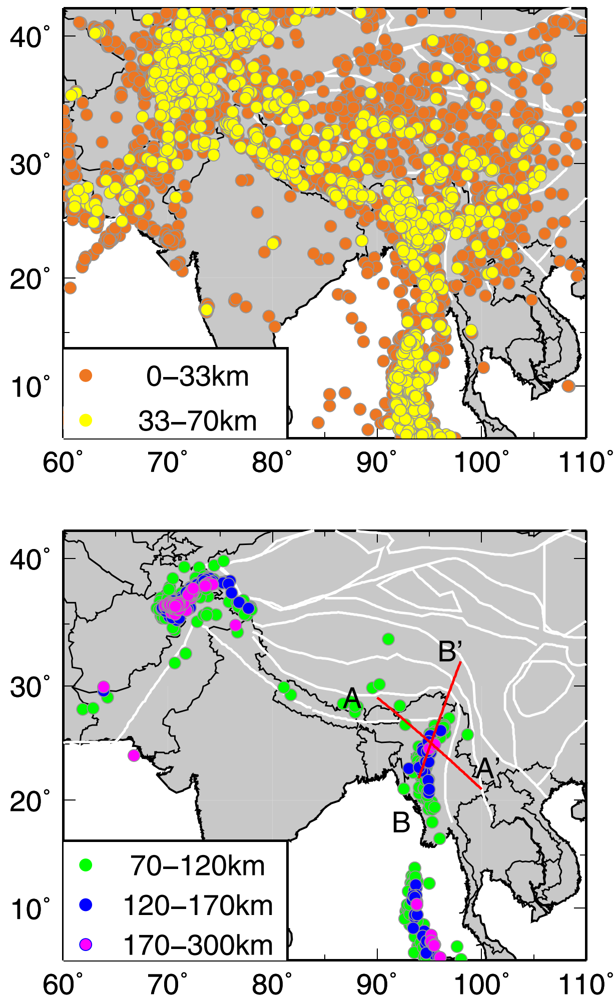

Fig. 5 Earthquake distribution in Tibet and nearby regions. Data are from the National Earthquake Information Center catalog and include all events from 1964 to 2010 of magnitude greater than 4.6. Earthquakes are divided into groups according to depth. Also the positions of the cross sections (red lines) are shown in Fig. 6. White lines are major faults and blocks in China. Earthquakes deeper than 120 km are concentrated in the eastern and western Himalayan syntaxes. Those in the eastern Himalayan syntaxis are attributed to the subduction of the Ninetyeast Ridge

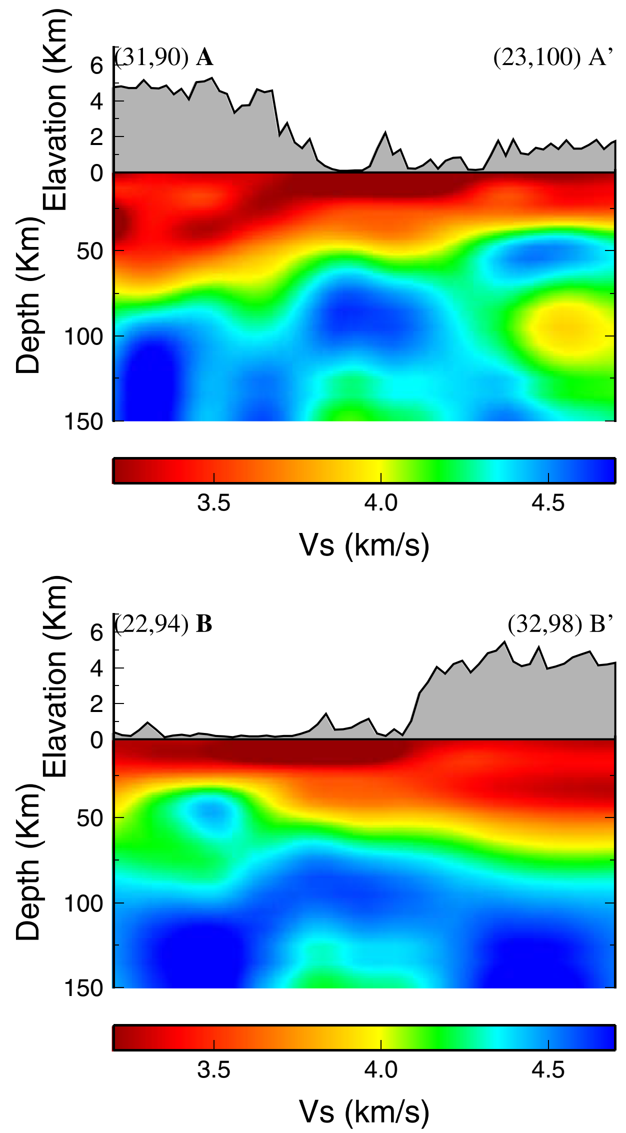

Fig. 6 Cross sections of shear velocity (positions are shown in Fig. 5). Also shown on top is the topography along the eastern Himalayan syntaxis. AA' is along great circle from (31°N, 90°E) to (23°N, 100°E). A ~ 30-km thick high velocity anomaly region is clearly shown at about 40–70 km at the eastern end of AA'. Another high velocity region > 50-km thick with an irregular shape extends from 22°N to 32°N or even further. These anomalies are likely the subducted Ninetyeast Ridge. Note the Gangdese porphyry deposit belt is located at ~ 29°N, and the deeper anomaly goes beyond 32°N

the Gangdese porphyry deposit belt (Fig. 6). These high velocity anomaly regions are interpreted here as the subducted Ninetyeast Ridge. Similarly, previous studies find high P-wave velocity anomalies: a narrow shallow one, and a wider and deeper one in the Burma subduction, to the south of the eastern Himalayan syntaxis (Li et al. 2008). Our results show that the anomalies extend to the Gangdese. These, together with the northeastward drifting direction of the Indian Plate indicate that the Ninetyeast Ridge was, and is still, subducting beneath the eastern Tibetan Plateau.

3 Discussion and conclusion

The asymmetric distributions of Cu reserves and chemical characteristics of the Gangdese porphyry belt are partially due to different erosion styles/rates induced by subduction of the Ninetyeast Ridge. Porphyry Cu deposits formed at paleodepths of < 4 km (Sillitoe 2010), and are likely controlled by the solubility of ore-bearing fluids in magmas. The widespread preservation of porphyry deposits in the Gangdese porphyry belt indicates denudation of < 4 km since their formation at 23–15 Ma. In contrast, the lack of Miocene porphyry further east is likely due to intensive erosion (i.e., erosion to depths of > 40 km) as indicated by the wide exposure of granulite (Zhang et al. 2010).

The oldest ore-forming adakite formed at $\sim$ 23 Ma. Partial melting of subducted oceanic crust occurs at depths > 100 km and the drifting rate of the Indian Ocean was $\sim$ 30 mm/year in the Miocene, so it would take $\sim$ 3 Ma for the ridge to be subducted deep enough to form adakite, i.e. the initiation of ridge subduction is $\sim$ 3 Ma earlier than the oldest adakite. Therefore, the subduction of the Ninetyeast Ridge must have started at $\sim$ 26 Ma, promoting the uplift of the Tibetan Plateau and major consequent changes in tectonic and climatic regimes.

Based on these observations, we propose that initiation of subduction of the Ninetyeast Ridge changed the geometry and rheology of the eastern Tibetan Plateau significantly at $\sim$ 23 Ma. Subsequently, subduction of the ridge restrained the asthenosphere and blocked the eastward escape of mantle and continental fragments. Meanwhile, crustal shortening induced by collision was mainly accommodated by uplift, and thus promoted the raising of the Tibetan Plateau. Partial melting of the subducted Ninetyeast Ridge produced adakites with high oxygen fugacity, and high Cu and sulfur contents—the Gangdese porphyry Cu deposit belt. Meanwhile, uplift of the Tibetan Plateau triggered the onset of the modern Asian monsoonal system between 22 and 25 Ma (Clift et al. 2008; Licht et al. 2014; Prell and Kutzbach 1992) and east–west crustal extension generated ultrapotassium volcanic rocks at $\sim$ 23 Ma (Liu et al. 2014).

The Miocene east–west crustal extensions in southern Tibet has previously been interpreted as gravitational collapse resulting from the extreme elevation (Coleman and Hodges 1995; Williams et al. 2001). Remarkably, such extension is associated with the cessation of the southeastward fragmentation, i.e., the Plateau grew high enough, but most of this motion did not extend beyond the plateau. These conclusions strongly support that both the rapid uplift and oroclinal structure of the eastern Himalayan syntaxis are due to the roughly perpendicular subduction of the Ninetyeast Ridge. Such a geometry dramatically changed the boundary conditions in the eastern Tibetan Plateau, which controls the large-scale lateral variations of the tectonic regime within Tibet (Copley et al. 2011), i.e. eastward motion within the Plateau due to gravitational collapse.

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