The Origin and Tectonic Significance of the Volcanic Rocks of the Yeba Formation in the Gangdese Magmatic Belt, South Tibet

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ABSTRACT: Zircon U-Pb geochronology, Hf isotope and whole-rock geochemistry were performed on the tuffs of the Yeba Formation in the Gangdese magmatic belt, South Tibet. The results are used to detail the age, source nature and tectonic processes that led to the formation of the Gangdese belt. Dating results indicate that the rhyolitic-andesitic tuffs were formed at 174–170 Ma. Positive and variable zircon εHf(t) values of the rhyolitic tuffs reveal that the source was dominated by juvenile material, however, experienced crustal contamination. The basaltic tuffs have low HREEs, high contents of compatible elements (V and Cr) and no Eu anomaly. In contrast, the rhyolitic-andesitic tuffs show low compatible trace elements, depletion in Eu but enrichment in incompatible elements (Rb, Zr and Hf). According to the discrimination diagrams of P2O5-SiO2 and Th-Rb, the rhyolitic-andesitic tuffs show a close affinity to I-type granitoids. Moreover, these tuffs are marked by significant depletion in Nb, Ta and Ti, plotted in calc-alkaline field, and with the andesitic-rhyolitic tuffs falling into an active continental margin setting. We suggest that these tuffs of the Yeba Formation were probably generated in an active continental margin above the northward subduction of the Neo-Tethyan oceanic lithosphere.

KEY WORDS: tuff, Yeba Formation, geochemistry, U-Pb dating, Gangdese, Tibet.

0 INTRODUCTION
The Tibetan Plateau is underlain by the highest, thickest and youngest crust on the earth. Crustal thickening and growth in the region were accomplished via the emplacement of northeastern stepping transpressive wedges (Tapponnier et al., 2001). The Tibetan Plateau is composed of various exotic terranes, magmatic arcs, high-pressure metamorphic zones, ophiolitic mélanges and forearc accretionary wedges that have undergone polyphase deformation during the process of subduction, accretion and collision (Xu et al., 2007). As a huge Indosinian “orogenic collage” (Xu et al., 2015), the Tibetan Plateau is an ideal natural laboratory for us to better understand the subduction of oceanic crust, arc accretion, continent-continent collision and post-collisional events associated with ongoing uplift and crustal extrusion (Yin and Harrison, 2000). From north to south, the Tibetan Plateau can be separated into several “Tethyan” terranes, known as the Qilian-East Kunlun, Songpan-Ganze, Qiangtang, Lhasa and Himalayan (Xu et al., 2012a).

The Lhasa terrane is bounded by the Bangong-Nujiang suture zone to the north and the Indus-Yarlung suture zone to the south. The Gangdese magmatic belt (GMB) at the southern margin of the Lhasa terrane was closely related to the Indo-Asian collision. The GMB zigzags westward across the Chinese border into the Kohistan-Ladakh region in Kashmir (Burg, 2011). To the east, the GMB makes a 90° turn around the eastern Himalayan syntaxis and becomes a south-north trending belt in Burma (Chung et al., 2009; Wang et al., 2002). Voluminous volcano-magmatic rocks in the GMB are a striking feature in the Tibetan Plateau in contrast to the southern Himalayan terranes that consist of Late Proterozoic to Early Paleozoic sedimentary and metasedimentary rocks and Mesozoic sedimentary basins (Yin and Harrison, 2000; Parrish and Hodges, 1996; Burchfiel et al., 1992). Most previous work in the region focused on the collisional volcano-magmatic events in the GMB with relatively little attention paid to the pre-collisional history.

Mo et al. (2003a, b) argued that the Mesozoic-Cenozoic volcanic activity in the GMB could be subdivided into three distinct episodes. According to their model, subduction related activity persisted during the Jurassic-Cretaceous interval (from 199 to 65 Ma), represented by the Yeba Formation and Sangri...
Group. Collisional volcanism took place during the Paleocene-Middle Eocene (ca. 65–40 Ma) and was followed by post-collisional volcanism during the Late Eocene (<40 Ma), represented by rock units within the Linzizong Formation and the potassic volcanic/magmatic rocks, respectively (Chung et al., 2005; Hou et al., 2004; Nomade et al., 2004). Ji et al. (2009) suggested four discrete stages of magmatic activity, i.e., 205–152, 109–80, 65–41 (the most prominent) and 33–13 Ma, based on zircon U-Pb dating of fifty granites (see also Tafti, 2011). Magmatic activity took place at different times during the Indo-Asian collision. Some of the activity is directly related to the collision itself while other magmatism occurred well before the collision. There is a considerable body of literature pertaining to collision-related and post-collisional magmatic activity during the closure (and post closure) of the Neo-Tethyan Ocean (Li et al., 2016; Leng et al., 2016; Lee et al., 2009; Zhao et al., 2009; Zhu et al., 2009; He et al., 2007; Dong et al., 2005; Mo et al., 2003a, b, 2005; Hou et al., 2004; Nomade et al., 2004; Dong, 2002).

Studies on the subduction-related volcano-magmatism in the GMB are limited due to logistical reasons. Much of the GMB was intruded by Cenozoic plutons, in particular, the Quxu and Xietongmen batholiths (Mo et al., 2009; Wen et al., 2008; Xia et al., 2008; Dong et al., 2006a; Xu and Jin, 1984) and covered by the Linzizong volcanic rocks (Mo, 2011; Mo et al., 2003a; also seen in 1: 250,000 regional geological maps). Over the past decade, a few age determinations on subduction-related magmatic rocks have been obtained. These studies reported a ca. 178 Ma age on deformed granite in the Nymo County (Zhang et al., 2007a); a 205±1 Ma age on a two-mica granite along with a 202±1 Ma granodiorite in Nannulin County (Zhang et al., 2007b); a 188±1.4 Ma granite in the southern Gangdese batholith (Chu et al., 2006); a ca. 207 Ma (zircon SHRIMP) granite in the Menba region (He et al., 2006) and a 182.3±1.5 Ma granite porphyry pluton in the western part of the Qulong copper deposit (Yang et al., 2008). Based on the analysis of dozens of granites, Ji et al. (2009) pointed out the existence of two prominent magmatic episodes between 205–152 and 109–80 Ma prior to the Indo-Asian collision (see also Zhang et al., 2012; Tafti, 2011). These data provide some initial constraints on pre-collisional activity within the GMB; however, much of the region is understudied.

Prior to the Indo-Asian collision, northward subduction of the Neo-Tethyan oceanic lithosphere along what is now the Indus-Yarlung suture zone was the most active tectonic regime in the Lhasa terrane (Chu et al., 2006). Knowledge about pre-collisional arc-related magmatism in the GMB remains poor. Previous work indicated that the earliest subduction-related volcano-magmatism in the GMB appeared in the Early Cretaceous to Late Jurassic (Dong et al., 2006a, b; Beaudoin et al., 2005; XBGMR, 1991; Coulon et al., 1986; Debom et al., 1986). More recent studies suggest that the subduction setting on the southern margin of the GMB can be traced back to the late Triassic (Zhang et al., 2012; Ji et al., 2009). The Yeba Formation volcanic rocks are an important constituent in the pre-collisional history of the GMB. Recent studies indicate the Yeba Formation developed between 192–174 Ma in an active continental arc setting (Chen et al., 2009; Dong et al., 2006b).

During the past decade, several studies have focused on the age and petrogenesis and formation setting of the Yeba Formation (Chen et al., 2009; Zhu et al., 2008; Dong et al., 2006; Geng et al., 2005a, b; Mao et al., 2002; Gou, 1994). Although abundant data, including age dating and geochemical analysis were obtained from these studies, numerous questions remain to be addressed. Current age constraints on the Yeba Formation extend from latest Triassic to Late Cretaceous and need more dating work (Yin and Grant-Mackie, 2005; Gou, 1994).

The discovery of the Jurassic Xiongcun porphyry copper deposit has attracted more attention focusing on subduction-related magmatism in the GMB (Lang et al., 2014; Tafti, 2011; Tafti et al., 2009). The Jurassic Xiongcun Formation is the main host rock for this mineralization and recent analyses of drill core data suggest that the Xiongcun Formation is age equivalent to Yeba Formation (Lang et al., 2014; Tafti, 2011; Tang et al., 2010).

In this paper, we aim to provide tighter constraints on the timing, petrogenesis and tectonic setting of the Yeba Formation in the GMB via the acquisition of new geochronological, isotopic and geochemical data.

1 GEOLOGICAL SETTING

1.1 Tectonic Framework

The Tibetan Plateau is sandwiched in the north by the Tarim and North China cratons, by the South China craton to the east and by the Indian Block to the south (as shown in Fig. 1a; Xu et al., 2012b; Wu et al., 2010). The structure of the Tibetan Plateau is one of an orogenic collage of terranes or continental blocks accreted to the southern margin of Eurasia during sequential ocean closure since the Permian (Turner et al., 1996). From north to south, the Tibetan Plateau consists of the East Kunlun-Qaidam-Qilian (EKQQ), Songpan-Ganze (SG), Qiangtang, Lhasa and Himalayan terranes (Xu et al., 2015).

These terranes were welded to Asia along the East Kunlun-Anyemaqen, Jinsha-Litang, Bangong-Nujiang and Indus-Yarlung suture zones (Xu et al., 2012b), with broadly accepted ages for the collisions being Permo-Triassic, Late Triassic to Early Jurassic, Late Jurassic and latest Cretaceous to Middle Eocene, respectively (Zhu et al., 2013; Konstantinovskykaia et al., 2003; Turner et al., 1996). In the present tectonic regime, the Tibetan Plateau is bounded by the left-lateral Altyn fault to the north, and the Himalayan frontal thrust to the south (Tapponnier et al., 2001).

Geologically, the Tibetan Plateau is composed of the Asian continent to the north and an amalgam of rocks with Tethyan and Indian affinities to the south. The Indus-Yarlung suture zone represents the final collisional suture zone between the northern Lhasa terrane and units to the south (Yin and Harrison, 2000). The Lhasa terrane is an immense tectono-magmatic belt, bounded by the Bangong-Nujiang suture zone to the north and the Indus-Yarlung suture zone to the south, extending E-W up to 2 500 km with width of 150–300 km and occupying about 450 000 km² (Harrison et al., 2000).

Recent studies suggest that the Lhasa terrane (generally also named Gangdese, Pan et al., 2006) is not a single coherent block. The Lhasa terrane was further subdivided into northern,