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Hot Paleocene-Eocene Gangdese arc: Growth of continental crust in southern Tibet

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ABSTRACT

The 1600 km-long Gangdese magmatic belt features extensive Paleocene–Eocene I-type intrusive rocks and coeval volcanic successions, which can be divided into Group I (~69–53 Ma), Group II (~53–49 Ma), and Group III (~49–43 Ma), corresponding to Neo-Tethyan slab rollback, Neo-Tethyan slab breakoff, and ongoing Indian-Asian collision, respectively. The magmas from these three groups show significant variations in geochemical and isotopic compositions, which provide the information of the growth of continental crust in southern Tibet. The most voluminous magmatism in the Gangdese belt occurred during ~53–49 Ma. High zircon saturation temperature (up to 800 °C) and Ti in zircon temperature (up to 980 °C) estimations suggest there is a period of thermal anomaly during ~53–49 Ma. Starting from ~53 Ma, magmas have increased K_2O contents, and their zircons have decreased Th/U ratios, and Y and Yb contents. Zircons from Group II have the most heterogeneous Hf isotopic compositions ($\varepsilon Hf_{(t)} = -5.3$ to 15.1). These are evident of ingress of asthenosphere mantle in the arc, extensive crustal melting, and magma mixing. Magma underplating during this time is the main mechanism for the growth of continental crust. With the Indian-Asian collision going on, the magmas in Group III show high Th/Y and La/Yb ratios and K_2O contents, but significantly low Tzr and T(ti-zr) values (mostly below 750 °C). These features suggest the water-fluxed melting of early arc residues occurred in the late stage of growth of continental crust. The crust has been thickened and nearly mature at this stage. This study has great implication on understanding of growth of continental crust in orogenic belts.

1. Introduction

The Gangdese magmatic belt is about 1600 km long, and located along the southern margin of the Tibetan plateau. This magmatic belt records a series of magmatic events starting with Late Triassic–Early Jurassic subduction of the Neo-Tethyan ocean (Chu et al., 2006; Ji et al., 2009; Kang et al., 2014; Meng et al., 2016; Ma et al., 2017; C. Wang et al., 2016; Wang et al., 2017a), followed by Indian-Asian collision at ~55–50 Ma (Allégre et al., 1984; de Sigoyer et al., 2000; Gao et al., 2008; Van der Voo et al., 1999; Wang et al., 2015a, 2015b; Hu et al., 2016). From the subduction to collision, the Tibetan crust was thickened significantly, with the present thickness up to ~80 km in southern Tibet (Murphy et al., 1997; Kapp et al., 2005; Zhu et al., 2017). The compositions of this thickened crust have been revealed by the reported crustal xenoliths entrained by Miocene ultrapotassic volcanic dykes from southern Tibet. They are intermediate to felsic with SiO_2 contents between 55.93 and 74.1 wt% (Chan et al., 2009; R. Wang et al., 2016; Wang et al., 2017b). This raises a question of when and how such intermediate-felsic continental crust forms in the Gangdese belt. The crustal xenoliths show abundant inherited zircons with Paleocene-Eocene ages (R. Wang et al., 2016). The La/Yb and Sr/Y ratios of Gangdese arc magmas show an abrupt increase at Eocene, suggesting the growth of continental crust mainly occurred in the Paleocene-Eocene (Ji et al., 2012; Wang et al., 2015a, 2015b; Zhu et al., 2015, 2017). This is in broad agreement with the paleoelevation of 3800 ± 700 m from clumped isotope paleothermometer (Rowley et al., 2015) and paleoelevation of 4500 ± 400 m from C–O isotopic data (Ding et al., 2014; Zhu et al., 2015) at Eocene. However, the mechanism of growth of continental crust in the Gangdese belt is not clear.

Previous researchers proposed the formation of continental crust via island arcs (Taylor and McLennan, 1985). However, the main magmatic products of island arcs are more or less basalts. In contrast with oceanic crust with basaltic composition, the average continental crust is andesitic in composition (Taylor and McLennan, 1995; Rudnick and Gao, 2003), similar to that of Tibetan crustal xenoliths. We think the Gangdese belt is an ideal location for study of the growth of continental crust, because of good preservation of igneous rocks, and a lifespan from subduction to collision (Mo et al., 2003; Zhu et al., 2015).

Here, we review major aspects of the geodynamic of the Himalayan-Tibetan orogen and the evolution of the Gangdese magmatic arc in the

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Paleocene-Eocene. We then use a compilation of 17 new samples with published geochemical and isotopic analyses to distinguish three Paleocene-Eocene igneous suites (Group I, Group II, and Group III) well preserved in the Gangdese belt. We add high-precision LA-MC-ICPMS U-Pb dating, new zircon trace element data, and Hf isotopic data to constrain the magma emplacement ages, and magmatic conditions and evolution. These features are combined with geodynamic reconstructions to derive an integrated petrogenetic model for growth of continental crust in the Gangdese belt.

2. Tectonic setting

2.1. Tectonics

The Himalayan-Tibetan orogen is composed of the Himalayas, Lhasa terrane, Qiangtang terrane, and Songpan-Ganze complex, from south to north, separated from each other by the Indus-Yarlung Zangbu, Bangong-Nujiang, and Jinsha River sutures (Yin and Harrison, 2000; Fig. 1). The geological setting of the Lhasa terrane has been described in detail by several authors (e.g., Mo et al., 2005; Pan et al., 2004; Wen, 2007; Zhang et al., 2013; Zhu et al., 2011, 2013, 2015, 2017; Wang et al., 2015a, 2015b), and is only briefly summarized here. The core of the Lhasa terrane consists of Archean and Proterozoic crystalline basement that is considered to have rifted from the Gondwana margin in the Carboniferous–Middle Permian or earlier (Zhu et al., 2010). The Lhasa terrane is thought to have collided with the Qiangtang terrane to the north in the Early Cretaceous (Yin and Harrison, 2000; Kapp et al., 2005; Zhang et al., 2017), and northward subduction of Neo-Tethyan oceanic lithosphere beneath its new northern margin (represented by the accreted Lhasa terrane) began in the Late Triassic or Early Jurassic (Chu et al., 2006; Wang et al., 2017a). Whole rock Nd and zircon Hf isotopic compositions of the granitoid rocks in the Lhasa terrane suggest an old and isotopically evolved central Lhasa subterrane with juvenile northern and southern subterranes (Zhu et al., 2011; Hou et al., 2015; Wang et al., 2015a).

The India–Asia convergence rate increased from ~12 cm/yr to ~17 cm/yr at ~69 Ma, then dropped back to ~10 cm/yr at ~58 Ma (Lee and Lawver, 1995). During this time, the arc magmatism migrated towards south (Mo et al., 2003; Zhu et al., 2015). These lines of evidence together with geodynamic reconstruction (Replumaz et al., 2010) suggest that rollback of the subducted Neo-Tethyan slab occurred at ~69–58 Ma, and triggered the extensive Paleocene–Eocene magmatism (Chung et al., 2005; Ding et al., 2003; Wen et al., 2008; Ji et al., 2009, 2012). Consequently, the Neo-Tethyan oceanic slab is thought to have broken off at ~53–49 Ma based on the intensification and heterogeneous geochemical compositions of Linzizong volcanic rocks and coeval plutons (Chung et al., 2005; Lee et al., 2009, 2011; Wen et al., 2008; Wang et al., 2015b; Zhu et al., 2015).

The India–Asia collision started at ~55–50 Ma when the Greater India plate (Indian continental margin; Ali and Aitchison, 2005) first collided with the Lhasa terrane (Meng et al., 2012; van Hinsbergen et al., 2012; Zhu et al., 2015; Ding et al., 2016; Hu et al., 2016). The thicker and more rigid Indian craton continues to subduct beneath the Lhasa terrane to the present day (Kind and Yuan, 2010; Replumaz et al., 2010; Zhao et al., 2010). Seismic tomographic studies indicate that the Indian continental lithosphere (100 to 200 km thick) extends northward below the Tibetan plateau, where it directly contacts the base of the Tibetan crust (Nábělek et al., 2009; Gao et al., 2013; R. Wang et al., 2016; Wang et al., 2017b).

2.2. Magmatism

North-directed Neo-Tethyan subduction beneath southern Tibet produced voluminous Jurassic–Cretaceous calc-alkaline magmatism in the Lhasa terrane (Harris et al., 1986; Wen, 2007; Mo et al., 2008; Lee et al., 2011; Wang et al., 2017a). In contrast to most Jurassic-Cretaceous igneous rocks that show typical continental arc features, a suite of ~90–85 Ma charnockites with adakite-like features were reported from the eastern Gangdese belt (Wen et al., 2008; Guan et al., 2010; Zhang et al., 2010). These adakite-like rocks have been interpreted to have been derived from partial melting of the lower crust during "flat-slab"

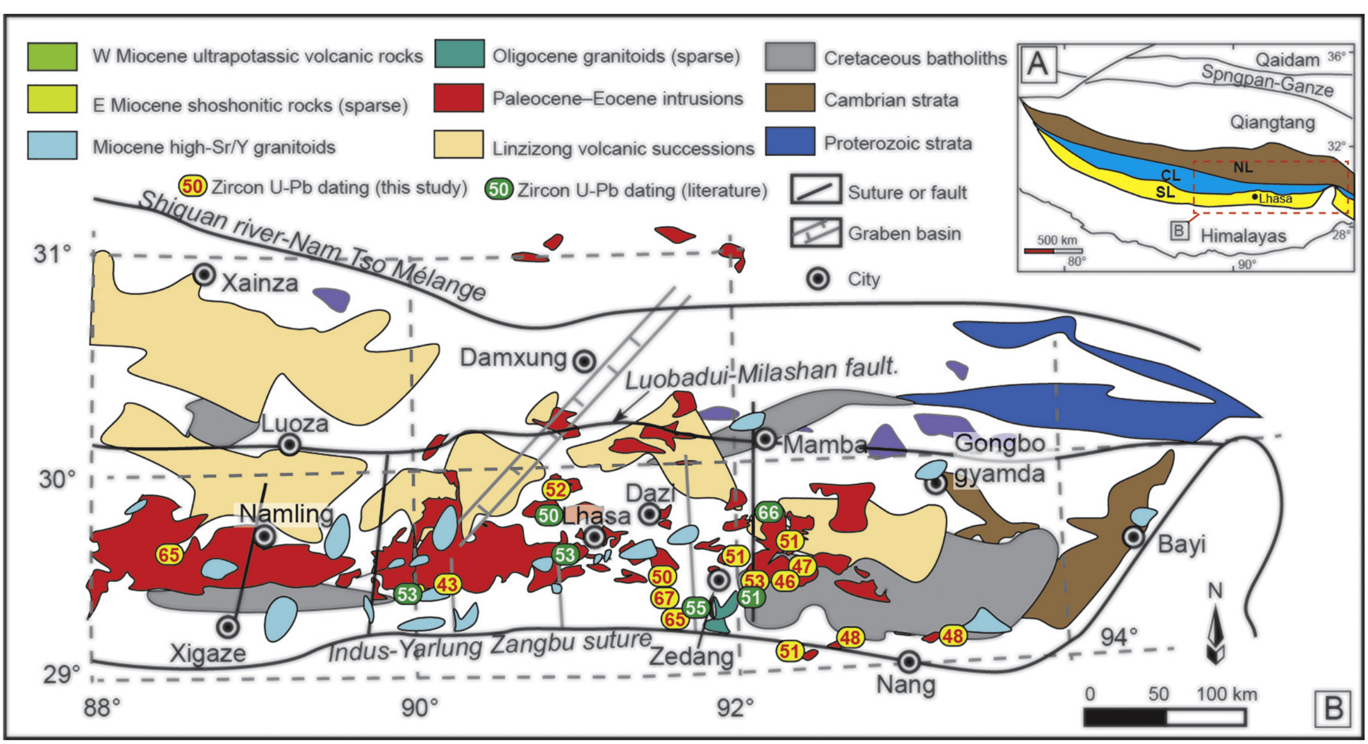

Fig. 1. Geology of the eastern Gangdese magmatic belt in the Lhasa terrane, showing the locations of samples described in this paper (modified from Zhu et al., 2013; Wang et al., 2015a). Ovals with numerals mark the locations and ages (in Ma) of samples dated by zircon U-Pb from this study (Table 1) and the literature (Wang et al., 2015b, and references therein).

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