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118–115 Ma magmatism in the Tethyan Himalaya igneous province: Constraints on Early Cretaceous rifting of the northern margin of Greater India

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ABSTRACT

Understanding the dynamics of Large Igneous Provinces (LIPs) is critical to deciphering processes associated with rupturing continental lithosphere. Microcontinental calving, the rifting of microcontinents from mature continental rifted margins, is particularly poorly understood. Here we present new insights into these processes from geochronological and geochemical analyses of igneous rocks from the Tethyan Himalaya. Early Cretaceous mafic dikes are widely exposed in the eastern and western Tethyan Himalaya, but no such rocks have been reported from the central Tethyan Himalaya. Here we present an analysis of petrological, geochronological, geochemical, and Sr–Nd–Hf–Os isotopic data for bimodal magmatic rocks from the center-east Tethyan Himalaya. Zircon U–Pb dating yields six weighted-mean concordant $^{206}Pb/^{238}U$ ages of 118 ± 1.2 to 115 ± 1.3 Ma. Mafic rocks display MORB-like compositions with flat to depleted LREE trends, and positive $\varepsilon_{Nd}(t)$ (+2.76 to +5.39) and $\varepsilon_{Hf}(t)$ (+8.0 to +11.9) values. The negative Nb anomalies and relatively high $^{187}Os/^{188}Os$ ratios (0.15–0.19) of these rocks are related to variable degrees (up to 10%) of crustal contamination. Geochemical characteristics indicate that mafic rocks were generated by variable degrees (2–20%) of partial melting of spinel lherzolites in shallow depleted mantle. Felsic rocks are enriched in Th and LREE, with negative Nb anomalies and decoupling of Nd ($\varepsilon_{Nd}(t) = -13.39$ to -12.78) and Hf ($\varepsilon_{Hf}(t) = -4.8$ to -2.0), suggesting that they were derived mainly from garnet-bearing lower continental crust. The geochemical characteristics of the bimodal magmatic associations are comparable to those of associations that form in a continental rift setting. Results indicate that Early Cretaceous magmatism occurred across the whole Tethyan Himalaya, named here as the "Tethyan Himalaya igneous province". Separation of the Tethyan Himalaya from the Indian craton may have occurred during ongoing Early Cretaceous extension related to the Kerguelen mantle plume during the nascent stages of a global plate-reorganization event. If this is the case, our findings provide clues to the nature of the Tethyan Himalaya, challenging traditional view of the India–Asia single-stage collision model.

1. Introduction

The Cenozoic India–Asia collision contributed to the uplift of the Himalayan–Tibetan orogen, influencing the global climate and continental dynamics. Geological, geochemical, and geophysical studies have improved our understanding of this orogen (Jadoul et al., 1998; Yin and Harrison, 2000; van Hinsbergen et al., 2012), but several issues remain debated. One of the most important questions is the India–Asia collision process. Three models have been proposed for the collision between Asia (including the Lhasa Terrane) and Greater India: a single-stage collision at *ca*. 70 Ma along the Indus–Yarlung suture zone (IYSZ; Yin and Harrison, 2000); a two-stage collision process, first between Greater India and an island arc at *ca*. 50 Ma, followed by collision of the combined Greater India arc with Asia (*ca*. 40 Ma; Bouilhol et al., 2013); and two-stage collision between Asia and a Tethyan Himalaya microcontinent that separated from Greater India at *ca*. 50 Ma, followed

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by collision of Greater India with the combined Tethyan Himalaya–Asia at 25–20 Ma (van Hinsbergen et al., 2012; Lippert et al., 2014; Yang et al., 2015). Studies of the pre-Cenozoic tectonic evolution of the Tethyan Himalaya are therefore crucial in constraining the India–Asia collision process.

Paleomagnetic data indicate that the Tethyan Himalaya and cratonic Greater India were together at *ca*. 120 Ma but separated at *ca*. 70 Ma (van Hinsbergen et al., 2012). The timing of the separation is poorly constrained but is likely to have occurred at *ca*. 105–100 Ma, during the global plate-reorganization event (Whittaker et al., 2016) or at *ca*. 120–110 Ma based on the paleomagnetic data (van Hinsbergen et al., 2012). The rifting of continents and the tectonic transition from a continental rift to an ocean basin are generally considered to result from extensional processes (McKenzie and Bickle, 1988) accompanied by different stages of magmatism, from the initiation of continental rifting and break-up to incipient ocean spreading (Hegner and Pallister, 1989). Magmatic rocks that form in a continental-rift setting are commonly characterized by bimodal compositions, with mafic rocks displaying a MORB-type affinity associated with the melting of depleted mantle, and felsic rocks being derived from partial melting of continental crust (Pin and Paquette, 1997; Li et al., 2005; Chen et al., 2017a).

Previous studies have suggested an extensional environment in the western and eastern Tethyan Himalaya during the Early Cretaceous, based on studies of magmatic rocks and volcaniclastic sediments (Zhu et al., 2007, 2009; Hu et al., 2010; Liu et al., 2015; Wei et al., 2017). The ages of Early Cretaceous magmatic rocks in the eastern and western Tethyan Himalaya are mainly 140–130 Ma, and considered to be part of the Kerguelen large igneous province (LIP) (Zhu et al., 2007; Wei et al., 2017). In general, the Early Cretaceous magmatic rocks in northern Greater India are spatially and temporally separated (Olierook et al., 2017). However, no such rocks have been reported from the middle of the Tethyan Himalaya. This hinders reconstructions of the tectonic–magmatic evolution of the whole Tethyan Himalaya prior to India–Asia collision. In this contribution, we present an analysis of petrological, geochronological, geochemical, and Sr–Nd–Hf–Os isotopic data for bimodal magmatic rocks from the center-east Tethyan Himalaya. The results, together with regional data from the eastern and western Tethyan Himalaya, suggest that Early Cretaceous magmatism occurred across the whole Tethyan Himalaya from east to west, which we name here the "Tethyan Himalaya igneous province". Zircon U–Pb dating results suggest that the ages of magmatic rocks from the center-east Tethyan Himalaya are 118–115 Ma, different from another phase of magmatic rocks (140–130 Ma) in the eastern and western Tethyan Himalaya. This difference can provide new insights into the Early Cretaceous tectonic–magmatic evolution of the Tethyan Himalaya.

2. Geological setting, samples and analysis

The IYSZ represents the deformed remnant of the Neotethys Ocean and is traditionally considered to mark the collision zone between India and Asia (Fig. 1a). The Himalaya is located south of the IYSZ and is composed of upper continental crust derived from northern Greater India, subducted beneath the Lhasa Terrane in southernmost Asia (Yin and Harrison, 2000). The collision between the Lhasa Terrane and Asia took place mainly in the Early Cretaceous (Chen et al., 2017b). The Himalaya can be divided into three tectono-stratigraphic zones, namely the Tethyan Himalaya, the Greater Himalaya, and the Lesser Himalaya, separated by the South Tibetan Detachment System (STDS) and the Main Central Thrust (MCT), respectively (Fig. 1a).

The Tethyan Himalaya marks the northern extent of Greater India (Yin and Harrison, 2000). Roy (1976) proposed the presence of a possible Himalayan micro-continent, located between India and Tibet, that rifted off from Greater India, as inferred from its crystalline core. Detailed tectono-sedimentary studies indicate that the Tethyan Himalaya was an isolated terrane during the Mesozoic (Liu et al., 2012), and it displays typical block-in-matrix structures and contains mélange (Xiao et al., 2017). The Tethyan Himalaya generally comprises Paleozoic–Cenozoic carbonates, clastic sedimentary rocks, and Paleozoic–Mesozoic magmatic rocks (Yin and Harrison, 2000), with Early Cretaceous igneous rocks being an important component of the central Tethyan Himalaya. Previous work focused mainly on magmatic rocks from the eastern Tethyan Himalayan sequence (Zhu et al., 2009; Liu et al., 2015), but work in the western portion has also been done (Wei et al., 2017). Consequently, there are no zircon U–Pb age data or geochemical data for rocks from the central Tethyan Himalaya.

Here, we focus mainly on the center-east Tethyan Himalaya, from the Lazi to Kangmar areas (Fig. 1b), which is dominated by Lower Triassic to Early Cretaceous sedimentary strata. The Upper Triassic Nieru Formation displays contrasting lithologies in these areas. In the Lazi area, it comprises slate and sandstone, whereas slate is the dominant rock type in the Kangmar area. Bivalve and ammonite fossils in the Nieru Formation suggest that deposition occurred mainly during the Carnian–Norian.

In the Lazi area, a bimodal suite of mafic and felsic volcanic rocks intrudes the Upper Triassic Nierue Formation (Fig. 1c). Field observations indicate a close temporal relationship between these rocks, and the outcrop is 40–50 m thick (Fig. 1c). South of Lazi City, two mafic dikes intrude the Nieru Formation (Fig. 2a). In the Kangmar area, Upper Triassic strata are also intruded by mafic rocks near Lu village (Fig. 2b). This intrusion covers an area of $\sim$44 km^2 and is roughly oval in outcrop area with an irregular boundary.

The mafic rocks display porphyritic textures, and phenocrysts are mainly olivine (3–6 vol.% of the rock mass), augite (3–5 vol.%), and plagioclase (2–4 vol.%) (Fig. S1). The matrix is mainly altered needle-like plagioclase, augite, magnetite, and glassy cryptocrystalline material. The felsic rocks display typical felsitic textures and comprise mainly micro-crystals of feldspars and quartzs.

In this paper, we present the comprehensive analysis of geochronological, geochemical, and Sr–Nd–Hf–Os isotopic data for bimodal magmatic rocks from the center-east Tethyan Himalaya. Detailed analytical methods are described in the Supplementary Information.

3. Results

3.1. Zircon LA–ICP–MS U–Pb dating

Results of zircon U–Pb geochronology for the sampled magmatic rocks of the Tethyan Himalaya are given in Table S1. Six intrusive rock samples (five mafic and one felsic) from the Lazi–Kangmar area were selected for zircon LA–ICP–MS U–Pb dating. Mafic-rock zircons display oscillatory zoning in cathodoluminescence (CL) images and have Th/U ratios of 0.21–2.92, indicating a magmatic origin (Corfu et al., 2003). Felsic-rock zircons have long prismatic forms (100–150 µm long), are homogeneous with weak, broad zoning, and have Th/U ratios of 0.26–2.99, again indicating a magmatic origin.

Mafic-rock zircons from the Lazi area yield three $^{206}Pb/^{238}U$ weighted mean ages of 118.1 ± 1.2 Ma ($n = 10$; MSWD $= 1.14$; probability of fit $= 0.59$; 2 sigma here and throughout), 117.7 ± 1.2 Ma ($n = 11$; MSWD $= 0.97$; probability of fit $= 0.72$), and 116.9 ± 1.1 Ma ($n = 14$; MSWD $= 0.98$; probability of fit $= 0.73$); while felsic-rock zircons yield a mean age of 115.7 ± 1.3 Ma ($n = 16$; MSWD $= 1.6$; probability of fit $= 0.30$) (Fig. 3a–d). For samples from the Kangmar area, 18 zircons yield weighted-mean