Rifting of the northern margin of the Indian craton in the Early Cretaceous: Insight from the Aulis Trachyte of the Lesser Himalaya (Nepal)

Saunak Bhandari, Wenjiao Xiao, Songjian Ao, Brian F. Windley, Rixiang Zhu, Rui Li, Hao Y.C. Wang, and Rasoul Esmaeili

ABSTRACT

To reconstruct the early tectonic history of the Himalayan orogen before final India-Asia collision, we carried out geochemical and geochronological studies on the Early Cretaceous Aulis Trachyte of the Lesser Himalaya. The trace-element geochemistry of the trachytic lava flows suggests formation in a rift setting, and zircon U-Pb ages indicate that volcanism occurred in Early Cretaceous time. The felsic volcanics show enrichment of more incompatible elements and rare earth elements, a pattern that is identical to the trachyte from the Late Jurassic to Early Cretaceous juxtaposed suspect terranes (Robinson and Pearson, 2013). Near its southern border (Fig. 1B), at an elevation of ~1500 m, the 250-m-thick Cretaceous Taltung Formation comprises a Cenozoic foreland basin with synorogenic sediments, whereas the other units are pre-Himalayan. Therefore, there is still insufficient geological evidence to substantiate any of the extension necessary to enable rifting of the terranes.

INTRODUCTION

The tectonic evolution of the Himalayan orogen was the result of the closure of the Neo-Tethys Ocean and the terminal collision of India with Eurasia (Searle et al., 1987; DeCelles et al., 2000; Yin, 2006; van Hinsbergen et al., 2012). It has long been considered that an integral Indian plate drifted northward and collided with Tibet (Searle et al., 1987), but recent advances have reported that the northern margin of India was separated as microcontinents that moved northwards to collide with Tibet (van Hinsbergen et al., 2012). This has created controversy about the nature of amalgamation between India and Eurasia and, thus, their final collision time.

The northern margin of the Indian craton has been variously considered to consist of a passive margin south of the Yarlung-Tsangpo suture (Myrow et al., 2003), or early Paleozoic accreted terranes (DeCelles et al., 2000), or Late Jurassic to Early Cretaceous juxtaposed suspect terranes (Martin, 2017). However, van Hinsbergen et al. (2012) controversially considered that the Tibetan Himalaya was separated from the northern margin of the Indian craton in the Early Cretaceous. Recently, further data have accrued that suggest there were several rifted terranes in the Tethys that collided with Asia before the terminal collision (Aitchison et al., 2007; Li et al., 2013; Xiao, 2015; Yang et al., 2015a, 2015b; Ma et al., 2016; Xiao et al., 2017; Ao et al., 2018; Chen et al., 2018). However, there is still insufficient geological evidence to substantiate any of the extension necessary to enable rifting of the terranes.

To help resolve these problems, we present new data on trachytic alkaline rocks from the Gondwana sequence of the Lesser Himalaya in central Nepal in order to help constrain the Cretaceous history of the northern part of the Indian craton, and we discuss their significance for the tectonic evolution of the Himalayan orogen.

GEOLOGICAL SETTING

Traditionally, the Himalaya is divisible into four major lithotectonic units (Figs. 1A and 1B): the Sub-Himalaya, Lesser Himalaya, Greater Himalaya, and Tethys Himalaya (Gansser, 1964; Yin, 2006). The Sub-Himalaya comprises a Cenozoic foreland basin with synorogenic sediments, whereas the other units are pre-Himalayan.

The Lesser Himalaya, which is the oldest and stratigraphically lowest unit, contains Proterozoic gneisses and Paleozoic and Mesozoic sediments (Robinson and Pearson, 2013). Near its southern border (Fig. 1B), at an elevation of ~1500 m, the 250-m-thick Cretaceous Taltung Formation (Fig. 1C) consists of fining-upward fluvial cycles of alternating cross-bedded sandstones and mudstones interbedded with 100-m-thick alkaline trachytic lava flows that belong to the 200-m-thick pillow lava-bearing, vesicular Aulis volcanic rocks. These volcanic rocks are interbedded with fluvial, imbricated pebble conglomerates and carbonateous black
Figure 1. (A) Position of Nepal in South Asia after DeCelles et al. (2001). (B) Position of Nepal within the Himalaya modified from Robinson and Pearson (2013). (C) Detailed geological map of the Aulis-Marmera area with sample locations modified after Sakai et al. (1992).
shales with silicified wood up to 40 cm in diameter and silicide wood fragments (Sakai, 1983). Sakai et al. (1992) reported three lava flows, each 5–100 m thick, which are interbedded with conglomerates, sandstones, tuffs, tuffaceous shales, and sediments that include considerable volcanic detritus derived from the Aulis volcanics. Figure 2 shows a representative columnar section with three distinct lava flows from the Marmara area (Fig. 1C). The Taltung Formation formed in a shallow-water, coastal, fluvial, volcaniclastic environment with episodic marine transgressions that was very similar to the shallow-marine, volcaniclastic, continental shelf–type environment of the Rajmahal sediments in eastern India. Early Cretaceous rift- and plume-related alkaline and basaltic lavas were then erupted into both of these successions (Sakai, 1983). The Early Cretaceous breakup of Gondwana was assisted by several mantle plumes, such as the Kerguelen Plume (Chatterjee et al., 2013). Such plume-related magmatic products typically occur along continental margins of continents that have been separated from another continent.

**METHODOLOGIES**

We collected five samples of the Aulis Trachyte (NA6, NA8, NA12, NA18, and NA23) for geochemical and geochronological studies, as shown in Figure 1C. As Sakai (1983) reported, all lava flows in the Aulis-Marmara belt have identical lithologies, textures, and petrographic assemblages. Hence, our five collected samples are representative of the lava sequence; among them, we selected two for zircon data analysis (NA18 and NA23).

Geological mapping around the volcanic lava flows was expected to encounter evidence for an extensional event, but we did not document any such structures. The area has been investigated regionally by Sakai (1983), who defined many lithostratigraphic strata and reported several local and regional structures. However, he did not demonstrate any regional extensional structure either. Since the area was intensely deformed during the Himalayan orogenic events (Fig. 1C), older tectonic imprints might have been concealed by succeeding deformation events.

Representative trachyte samples from the Aulis Trachyte were crushed using a tungsten carbide mill, and the powder was passed through a 200 mesh. Glass beads were made by fusing this powder at 1050–1100 °C. Major- and trace-element concentrations for the sample were determined by X-ray fluorescence (XRF; Rikagu RIX 2100) and PerkinElmer Elan 9000 inductively coupled plasma–mass spectrometry (ICP-MS), respectively, at the Mineral Division of ALS Chemex, Co., Ltd., Guangzhou, China. For the XRF analysis, analytical procedures were as described by Goto and Tatsumi (1996) with analytical precision within 1%, whereas...
trace-element compositions were measured by the method described by Wu et al. (2015), and analysis precision was well within 5%.

We collected two samples (each >5 kg) of the Aulis Trachyte for zircon dating. Zircon grains were separated from rock samples using conventional heavy liquid and magnetic separation methods. Zircons were handpicked and mounted in epoxy resin. They were polished and cathodoluminescence images were acquired, which helped to check internal structures and potential target sites. U-Pb geochronological analyses of zircon were conducted using laser-ablation (LA)–multicollector (MC) ICP-MS at the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources of Changchun, China. The instrument was used with the automatic positioning system. It couples a quadrupole ICP-MS (Agilent 7900) and 193 nm ArF Excimer laser (COMPexPro 102, Coherent). The analysis involved a laser spot size of 32 μm for all analyses, laser energy density at 10 J/cm², and repetition rate at 8 Hz. The procedure of laser sampling was 30 s blank, 30 s sampling ablation, and 2 min sample-chamber flushing after the ablation. The ablated material was carried into the ICP-MS by a high-purity helium gas stream with a flux of 1.15 L/min. In order to increase energy stability, the whole laser path was fluxed with Ar (600 mL/min). The counting time was set as 20 ms for 209Pb, 208Pb, 207Pb, and 206Pb, 15 ms for 232Th and 238U, 20 ms for 49Ti, and 6 ms for other elements. Zircon grains were separated from rock samples using handpicked and mounted in epoxy resin. They were polished and cath-

RESULTS

The lava flows are of different thicknesses, chemically homogeneous, and variably weathered (Fig. 3A). Our chosen fresh samples were plagioclase-phric and had typical trachytic textures with euhedral phenocrysts of plagioclase, sanidine, kaersutite, and anorthoclase in a matrix of minute lath-shaped plagioclase microlites (Figs. 3B and 3C); the feldspar phenocrysts were up to 5 mm long and had oscillatory zones. Some trachytes also included small rock fragments that might have been the source for old zircons in trachyte (Fig. 3D).

Geochemistry

Major- and trace-element data from the Aulis Trachyte are listed in Table 1. The major-element abundances confirm the acidic alkalinity of the lavas. On plots of (Na₂O + K₂O) versus SiO₂ (Fig. 4A) and Nb/Y versus Zr/TiO₂ (Fig. 4B), the samples cluster in the trachyte field (Le Bas et al., 1986; Winchester and Floyd, 1977, respectively). A chondrite-normalized rare earth element (REE) plot (Nakamura, 1974) depicts enrichment of light (L) REEs relative to heavy (H) REEs (Fig. 4C), and a mid-ocean-ridge basalt (MORB)–normalized spider diagram (Fig. 4D; Pearce, 1983) shows distinct positive anomalies of K, Rb, and Th, and pronounced negative anomalies of Sr, Ba, P, and Ti. In general, the volcanic rocks are enriched in the more incompatible elements. Pronounced negative anomalies of Nb, P, and Ti and enrichments in more incompatible elements are well-established characteristics of lavas in continental rifts (Storey et al., 1992; Singh and Bikramaditya Singh, 2012). The REE patterns of the Aulis Trachyte and a trachyte from an extensional rift at Karaburhan in Turkey (Sarftaikoğlu et al., 2009) are almost identical (Fig. 4C), as also are trachytes from the East African Rift (Kenya rift) (White et al., 2012) in a chondrite-normalized multi-element spider diagram (Fig. 4E; Thompson, 1982). The Zr-Ti diagram (Pearce, 1982) demonstrates that the Aulis Trachyte is a within-plate lava (Fig. 3F).

Ages

Even after careful examination of the zircons, we were unable to obtain a precise age of eruption. Most of the determined ages have a discordance that is due to Pb loss and/or inheritance. A major Pb-loss event might be associated with movement on the once-overlying Main Central Thrust. Sakai et al. (1992) found a K-Ar whole-rock age of 17.4 ± 0.9 Ma in this

### TABLE 1. MAJOR ELEMENTS (WT%) AND TRACE ELEMENTS (PPM) FROM THE AULIS TRACHYTE OF THE LESSER HIMALAYA (NEPAL)

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**Note:** LOI—loss on ignition.

*Total iron.*
Figure 4. (A) Total alkali-silica (TAS) diagram plotting (Na$_2$O + K$_2$O) vs. SiO$_2$ (in wt%: Le Bas et al., 1986). (B) Nb/Y vs. Zr/TiO$_2$ diagram (Winchester and Floyd, 1977). (C) Chondrite-normalized rare earth element (REE) plot (Nakamura, 1974), where the pattern is compared with the field for trachyte of the extensional setting from Karaburhan, Turkey (Sarıfakıoğlu et al., 2009). (D) Mid-ocean-ridge basalt (MORB)–normalized multi-element spider diagram (Pearce, 1983). (E) Chondrite-normalized multi-element variation diagram (Thompson, 1982) compared with the trachyte from the Kenya rift (White et al., 2012). (F) Tectonic setting discrimination Zr-Ti plot (in ppm) showing within-plate lava character (Pearce, 1982).
The spread in age is from ca. 110 Ma to ca. 125 Ma. Two clusters at ca. 119 Ma (Fig. 6; GSA Data Repository Item1). LA-ICP-MS zircon U-Pb age data (as described in the Geological Setting section). The range of ages might with each other) might be due to slight Pb loss and/or inheritance of other grains were either old inherited zircons or were highly discordant. Sample NA23 from Marmera village (Fig. 1C) produced 40 zircons, of which only 35 grains were useful for LA-ICP-MS dating, with the other zircons being too small (Fig. 5). Among the 35 analyses, only 13 grains were considered to be close to the age of eruption, because other grains were either very old and xenocrystic, or highly discordant, similar to sample NA18 (Fig. 5). Since most of the ages obtained from the trachyte samples ND18 and ND23 were discordant, we carried out U-Pb geochronological analysis of 37 zircons from the specimen NA06 by LA-ICP-MS at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing for independent confirmation of the suggested age. The configuration of the LA-ICP-MS and the method for age determination are very similar to those of the Key Laboratory of Mineral Resources Evaluation in Northeast Asia, Ministry of Land and Resources of China. Among 37 zircons, 6 grains resemble the Cretaceous events, but most of them are highly discordant, like the other samples (Fig. 6; GSA Data Repository Item). LA-ICP-MS zircon U-Pb age data are given in the Data Repository Item.

Among 13 zircons from sample NA18, six zircons were obviously discordant, and seven zircons were internally concordant but externally discordant (they fall on concordia but do not overlap with each other). The spread in age is from ca. 110 Ma to ca. 125 Ma. Two clusters at ca. 110 Ma and ca. 125 Ma, each with three zircons, are separated by 120 Ma zircon. A similar spread and two concentrations at ca. 115 Ma and ca. 125 Ma (with two and four internally concordant zircons, respectively) were demonstrated by sample NA23. Among six zircons of sample NA06, three were obviously discordant, and three were internally discordant. Two of them fall at ca. 112 Ma, and one falls at ca. 125 Ma on a concordia line. Some external discordance (points fall on concordia but do not overlap with each other) might be due to slight Pb loss and/or inheritance of slightly older (but still Early Cretaceous) igneous zircon. Although most ages were discordant, all three samples gave the same Early Cretaceous age, which is consistent with the fossil occurrence of intravolcanic strata (as described in the Geological Setting section). The range of ages might point to inheritance of zircon from protracted magmatism. Sakai (1983) reported extensive alternating volcanism and sedimentation. Intravolcanic siltstones of the Taltung Formation contain fossil plants (Sakai, 1983; Kimura et al., 1985) of four genera belonging to *Ptilophyllum*, *Pterophyllum*, *Cladopherebis*, and *Elatochlaus*, which have been assigned a Late Jurassic to Early Cretaceous age, and which are well known in sediments within the Rajmahal Traps. The wide fissiliferous age range does not provide a precise date of the alkaline magmatism. Sakai et al. (1992) obtained a Rb-Sr mineral isochron age of 96.7 ± 2.8 Ma on a phonotephrite; however, this Rb-Sr isotopic technique still requires a more precise confirmation if we are to understand the timing of the alkaline material. Furthermore, the age was obtained from a single phonotephrite gravel “probably eroded out from the Taltung Formation” (Sakai et al., 1992, p. 65), and the mean square of weighted deviates (MSWD) was not reported.

Our zircon dates strongly suggest an Early Cretaceous age for Aulis Trachyte volcanism, which is consistent with previous radiometric dates as well as biostratigraphic ages from interbedded sedimentary rock.

**TECTONIC IMPLICATIONS**

The Late Cretaceous and Paleocene history of the Neo-Tethys Ocean has long been well defined because of paleomagnetically determined, Early Cretaceous positions of the Lhasa terrane, the Himalayan sequences, and India (Besse et al., 1984; Patzelt et al., 1996; Tong et al., 2008; Lippe et al., 2011; Yi et al., 2011; Chen et al., 2012; Torsvik et al., 2012; Liebke et al., 2013; Ma et al., 2014; Huang et al., 2015; Xiao, 2015; Yang et al., 2015a, 2015b). The argument about the Early Cretaceous rifting of the northern Indian craton was already hypothesized with the study of Early Cretaceous volcaniclastics in the Tethys Himalaya of southern Tibet and central Nepal (Jadoul et al., 1998; Hu et al., 2010). However, the idea has come under debate after recent paleomagnetic studies (van Hinsbergen et al., 2012; Yang et al., 2015a, 2015b). Recently, van Hinsbergen et al. (2012) suggested that there was an ocean, called the Greater India Basin, between the Tibetan Himalaya and the Lesser Himalaya and India to the south. However, no geological evidence has since been recorded from the Lesser Himalaya to confirm rifting and extension of the predicted Tibetan-Himalayan microcontinent (van Hinsbergen et al., 2012).

The Aulis Trachyte in the current work provides the first evidence that supports the start of rifting and extension in the Early Cretaceous in the present-day Lesser Himalaya. Reconstruction of Late Cretaceous and Paleocene paleolatitudes of the Tibet Himalaya and the calculated apparent polar wander paths (APWPs) of India (Torsvik et al., 2012; van Hinsbergen et al., 2012) clearly imply considerable extension and rifting, because the amount of crustal shortening during the Himalayan orogeny is far less than the 2675 ± 700 km allowed by the Late Cretaceous latitude difference.

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![Figure 5. Representative cathodoluminescence (CL) images of zircons used for volcanic eruption age determination; red circles indicate positions of laser spot.](image-url)
Figure 6. U-Pb concordia diagrams for the Aulis Trachyte zircon samples from rock specimens NA18, NA23, and NA06.
between India and the Tibet Himalaya (Schelling, 1992; DeCelles et al., 2001). The paleolatitude of the Tibet Himalaya in the Early Cretaceous is significantly different from that in the Late Cretaceous, and that difference increased with time, supporting the idea of van Hinsbergen et al. (2012) that the Tethys Himalaya and Indian craton were a single body during the Early Cretaceous. Van Hinsbergen et al. (2012) demonstrated that before and until the Early Cretaceous (120 Ma), the Tethys Himalaya and India were separated by 2.1° ± 5.5° of latitude, whereas in the Late Cretaceous to Paleocene, the separation was 24.1° ± 3° relative to India. Ma et al. (2016) predicted that the extension and separation of the Tibet Himalaya from the Indian craton occurred after 130 Ma, which is similar to the interpretation of Yang et al. (2015a), who, from a paleomagnetic study of Cretaceous lava flows in the Tethys Himalaya, demonstrated an ~2.1° paleolatitude difference and separation after 134–130 Ma between the Tethys Himalaya and the Indian craton.

Because the eruption time of the Aulis Trachyte was broadly synchronous with the paleomagnetically determined time of separation of the Tibetan-Himalayan microcontinent, we present a tectonic model for the Early Cretaceous separation of the Tibetan-Himalayan microcontinent including geological evidence from the present-day Lesser Himalaya (Fig. 7). We agree with the data of van Hinsbergen et al. (2012), which indicate that the Tibet Himalaya started to drift at ca. 117 Ma, and by ca. 68 Ma, it had drifted northwards by 2675 ± 700 km from the Indian craton (Fig. 7). The presence of this wide oceanic basin (the Greater India Basin) is consistent with the two-phase collision of India and Eurasia (Xiao, 2015). The first “soft” collision of a Tibet-Himalaya microcontinent with Asia was at ca. 55 Ma, and it was followed by subduction of the oceanic plate of the Greater India Basin under Tibet, enabling the final “hard” collision of the main Indian craton with Asia at ca. 25–20 Ma (van Hinsbergen et al., 2012).

Recently, Early Cretaceous mafic rocks generated in a continental rift setting were reported from the Tethys Himalaya, and they imply the separation of the Tethyan Himalaya from the Indian craton and a two-stage India-Asia collision (Chen et al., 2018). The model of Chen et al. (2018) considers the extension in the Tethys Himalaya. Hence, part of the Tethys Himalaya and Greater Himalaya should have been part of the Indian craton during the final collision. However, this assumption is unable to address the middle Eocene metamorphism and exhumation of the Greater Himalaya (Carosi et al., 2016). An early Eocene (54 Ma) metamorphic event has been documented from north Himalayan gneiss domes (Smit et al., 2014), which are considered to be the upper part of the Greater Himalaya (Ding et al., 2016). Hence, rifting of the Indian craton along the southern part of the present-day Greater Himalaya is more convincing with respect to Himalayan metamorphic and deformational history. Furthermore, multiple rifting and subsequent accretion events have occurred before final collision.

Chatterjee et al. (2013) identified five volcanic events around the Indian Shield that were related to different plumes. Among them, similarities in fossil content of intravolcanic siltstone show that the Aulis Trachyte was coeval with the Rajmahal flood basalt (118–115 Ma) related to the Kerguelen plume (118 Ma; Baksi, 1995; Ray et al., 2005; Ghatak and Basu, 2013; Ghose et al., 2017). The two most favored environments for rifting and continental extension are an old collisional suture zone and a mantle plume or hotspot (Vink et al., 1984; Chatterjee et al., 2013). Both of these conditions were attained during the separation of the Tibetan-Himalayan microcontinent because the rifted portion of the Indian craton was comparable to the early Paleozoic accreted terranes (DeCelles et al., 2000) and the Kerguelen plume was coeval with the extension event.

**CONCLUSION**

By comparing our age and geochemical data from the Aulis Trachyte with recent paleomagnetic data, we conclude that the Aulis Trachyte erupted in an extensional tectonic setting, probably in a plume-generated, rifted continental margin, when the Tibetan-Himalayan microcontinent began to drift to the north in the Early Cretaceous. Our evidence of extension, along with recent documentation of Cretaceous rift-related volcanism from the Tethys Himalaya, supports the concept that there might have been several different terranes in the Neo-Tethys Ocean before the terminal collision between India and Eurasia.

**ACKNOWLEDGMENTS**

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