Paleomagnetic and Geochronological Results From the Zhela and Weimei Formations Lava Flows of the Eastern Tethyan Himalaya: New Insights Into the Breakup of Eastern Gondwana

Weiwei Bian1,2, Tianshui Yang1,2, Yiming Ma1,2,3, Jingjie Jin1,2, Feng Gao1,2, Suo Wang1,2, Wenxiao Peng1,2, Shihong Zhang1,2, Huaijun Wu1, Haiyan Li1, Liwan Cao1, and Yuruo Shi4

1State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing, China, 2School of Earth Sciences and Resources, China University of Geosciences, Beijing, China, 3Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China, 4Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China

Abstract The breakup of eastern Gondwana is among the hottest topics in the Earth sciences because of its effect on global climate during the Jurassic-Cretaceous, its influence on the evolution of life, and its importance to paleogeographic reconstruction. To better constrain the Jurassic and Cretaceous paleogeographic position of the Tethyan Himalaya and the breakup of eastern Gondwana, a combined paleomagnetic and geochronological study was performed on the Zhela and Weimei Formations lava flows, dated at ~138–135 Ma, in the Luozha area of the eastern Tethyan Himalaya. Both positive fold and reversal tests together with a maximum grouping at 100% unfolding indicate that the characteristic remanent magnetization directions are primary magnetizations acquired before folding. The tilt-corrected directions yielded a paleopole at 0.9°N, 293.4°E with $A_{95} = 7.0°$ and a corresponding paleolatitude of 53.5°S ± 7.0°S for the Luozha sampling area (28.9°N, 91.3°E), validating that the original erupted position of the Zhela and Weimei Formations lava flows was located in the center of the Kerguelen mantle plume. Our new results, together with the published paleomagnetic, geochronological, and geochemical results, demonstrate that the Comei-Bunbury large igneous province originated from the Kerguelen mantle plume. The temporal and spatial relationships between the Comei-Bunbury large igneous province and the Kerguelen mantle plume indicate that eastern Gondwana initially rifted at ~147 Ma and that the Indian Plate fully separated from the Australian-Antarctic Plate before ~124 Ma.

1. Introduction

The breakup of eastern Gondwana and subsequent northward drift of the Indian Plate was responsible for the formation of the eastern Indian Ocean, as well as the India-Asia collision and postcollisional convergence that produced the planet’s largest and highest plateau, the Himalayan-Tibetan Plateau. This tectonic event has had long-term impacts on the global paleoclimate, paleogeography, and the evolution of life (Besse et al., 1984; Chatterjee et al., 2013; Klootwijk et al., 1992; Ma et al., 2014, 2017; Yin & Harrison, 2000; van Hinsbergen et al., 2018; Veevers et al., 1971). A full understanding of when and how the Indian Plate separated from the Australian-Antarctic Plate is vital for modeling the evolutionary history of eastern Gondwana, the formation of the Himalayan-Tibetan Plateau, and paleoclimatic change (Ali & Aitchison, 2008; Chatterjee et al., 2013; Yin & Harrison, 2000). Although some geological and geophysical investigations have been conducted on the circum-eastern Gondwana magmatic provinces, oceanic lithosphere and surrounding basins, and the Kerguelen mantle plume over the past four decades (e.g., Chen et al., 2018; Davis et al., 2016; Gibbons et al., 2012; Hu et al., 2010; Markl, 1974; Olierook et al., 2017; Powell et al., 1988; Ramana et al., 2001; Storey, 1995; Williams et al., 2013; Zeng et al., 2017; Zhu et al., 2008, 2009), several key issues still remain to be fully resolved, such as the timing of the breakup of eastern Gondwana, ranging from ~120 to before ~140 Ma (Ali & Aitchison, 2005; Davis et al., 2016; Gaina et al., 2007; McElhinny & Embleton, 1974; Powell et al., 1988; Rao et al., 1997; Ramana et al., 2001; Williams et al., 2013), and the separation of the Indian Plate from the Australian-Antarctic Plate driven by a mantle plume (Ingle et al., 2002; Shi et al., 2017; Zhu et al., 2008, 2009) or by passive rifting (Hu et al., 2010; Zeng et al., 2017).
In this paper, we present a combined paleomagnetic and geochronological study on the Zhela and Weimei edge of the evolutionary history of eastern Gondwana. Cretaceous volcanic rocks in the Tethyan Himalaya are still urgently required to further improve the knowledge of India-Asia collision processes or the size of Greater India, rather than the breakup of eastern Gondwana. Therefore, more robust paleomagnetic data with accurate age constraints from the Jurassic and Early Cretaceous volcanic rocks in the Tethyan Himalaya are required. However, some researchers have suggested that the Bunbury basalts are too distant (~1,000 km) from the Kerguelen mantle plume (Gibbons et al., 2012; Müller et al., 1993) and cannot be attributed to its activities (Müller et al., 1993). Furthermore, Frey et al. (1996) argued that the oldest known lavas (~115–110 Ma) from the Kerguelen Plateau are considerably younger than the Bunbury basalts and proposed that the Kerguelen mantle plume was not a necessary factor in the breakup of eastern Gondwana (e.g., Olariook et al., 2016). Notably, Jurassic and Early Cretaceous igneous rocks are also widely distributed in the Tethyan Himalaya. Based on geochronological and geochemical results from the Sangxiu (~132 Ma) and Langkang (~137–143 Ma) Formations (Fms) igneous rocks of the eastern Tethyan Himalaya, some researchers have suggested that the Late Jurassic and Early Cretaceous volcanism might have originated from the Kerguelen mantle plume and concluded that this long-lived volcanic rocks would have played an important role in the breakup of eastern Gondwana (e.g., Caffin et al., 2002; Ingle et al., 2002; Shi et al., 2009, 2008). However, the geochronological and geochemical results from the Wölong volcanics (~140–119 Ma) and the Dolerites (~142 Ma) of the central Tethyan Himalaya suggested that the Early Cretaceous volcanism in the Wölong and Charong areas resulted from a regional stress field change associated with the breakup of eastern Gondwana (e.g., Hu et al., 2010; Zeng et al., 2017). Because the Late Jurassic to Early Cretaceous igneous rocks that originated from the Kerguelen mantle plume have been dispersed to different locations in the Antarctic, Australian, and Indian Plates, one key piece of evidence that must be considered in the reconstruction of eastern Gondwana is the original emplacement positions of the Late Jurassic to Early Cretaceous Kerguelen igneous rocks mentioned above and their spatial relationship with the reconstructed Kerguelen mantle plume (Caffin et al., 2002; Storey et al., 1992).

Paleomagnetism is one of the main techniques used to quantify plate paleogeography and is thus useful for constraining the history of plate evolution (Appel et al., 1998; Bian, Yang, Ma, et al., 2017; Cao et al., 2017; Chen et al., 2012, 2017; Li et al., 2016; Liebbe et al., 2010; Lippert et al., 2014; Pozzi et al., 1982; Song et al., 2015; Sun et al., 2012; Tan et al., 2010; Tong et al., 2015; van Hinsbergen et al., 2012; Yan et al., 2016 Yang, Ma, Zhang, et al., 2015). The Tethyan Himalaya was part of the northern margin of the Indian Plate during the Jurassic and Early Cretaceous (e.g., Ma et al., 2016; Yang, Ma, Bian, et al., 2015; Yin & Harrison, 2000), and reliable paleomagnetic data of the Jurassic and Early Cretaceous volcanic rocks in the Tethyan Himalaya therefore play a very important role in understanding the breakup of eastern Gondwana. Notably, although some paleomagnetic studies have been performed on Jurassic and Early Cretaceous rocks in the Tethyan Himalaya (e.g., Huang et al., 2015; Klootwijk & Bingham, 1980; Ma et al., 2016; Patzel et al., 1996; Yang, Ma, Bian, et al., 2015), only two paleomagnetic results obtained from the Lakang Fm. (Yang, Ma, Bian, et al., 2015) and the Sangxiu Fm. (Ma et al., 2016) lava flows have provided robust field tests to assure the reliability of paleomagnetic data. Furthermore, all the paleomagnetic studies have focused on the India-Asia collision processes or the size of Greater India, rather than the breakup of eastern Gondwana. Therefore, more robust paleomagnetic data with accurate age constraints from the Jurassic and Early Cretaceous volcanic rocks in the Tethyan Himalaya are still urgently required to further improve the knowledge of the evolutionary history of eastern Gondwana.

In this paper, we present a combined paleomagnetic and geochronological study on the Zhela and Weimei Fms. lava flows in the eastern Tethyan Himalaya. Our new results can significantly contribute to clarifying the magmatic origin of the Early Cretaceous Comei-Bunbury LIP, constraining the spatial relationship of the
2. Geological Background and Sampling

The Himalayas are adjacent to the Lhasa Terrane to the north and the Indian Craton to the south and contain four main units: the Tethyan Himalaya, Greater Himalaya, Lesser Himalaya, and Sub-Himalaya from north to south (Figure 2a). The main tectonic boundaries of these terranes consist of the Indus-Tsangpo suture zone, South Tibetan Detachment System, Main Central Thrust, Main Boundary Thrust, and Main Frontier Thrust from north to south (Figure 2a). The Tethyan Himalaya, which was positioned at the northern margin of the Indian Plate during the Jurassic and Early Cretaceous, is located between the Indus-Tsangpo suture zone and South Tibetan Detachment System and is composed of Proterozoic to Eocene marine sedimentary sequences interbedded with Paleozoic and Mesozoic volcanic rocks (e.g., Yin, 2006). Our study region is located in the eastern Tethyan Himalaya where Jurassic and Lower Cretaceous volcanic and sedimentary rocks are widely exposed (Figure 2b). The Zhela Fm., which is given a Middle Jurassic age in the 1:250,000
Luozha County regional geological survey report (H46C004001, 2002), primarily consists of basalt, dacite, and siltstone. The Weimei Fm. conformably overlies the Zhela Fm. and underlies the Sangxiu Fm. It mainly includes sandstone, slate, siltstone, and basalt and is assigned a Late Jurassic age (H46C004001, 2002). The Sangxiu Fm. is mainly composed of sandstone, mudstone, basalt, and andesite. Zircon U-Pb dating indicates that the Sangxiu Fm. volcanic rocks erupted during ~136–124 Ma (Ma et al., 2016; Wan et al., 2016).

Figure 2. Sketches of geology and sampling locations for this study. (a) Tectonic sketch map of the Himalayan belt and adjacent areas modified from Yang, Ma, Bian, et al. (2015). Red stars indicate sampling locations of paleomagnetic studies on Latest Jurassic to Early Cretaceous volcanic rocks from the Tethyan Himalaya and Indian Craton (for paleomagnetic sampling location abbreviations see Table 2). Abbreviations: JSZ = Jinsha suture zone; BNSZ = Bangong-Nujiang suture zone; ITSZ = Indus-Tsangpo suture zone; MFT = main frontal thrust; MBT = main boundary thrust; MCT = main Central thrust; STDS = South Tibet detachment system. (b) Simplified geological map of the paleomagnetic sampling locations in the Luoza area.
et al., 2011; Zhu et al., 2009, 2007, 2005). Notably, the Weimei and Zhela Fms. ages were defined mainly based on fossils obtained from the Comei, Gyangz, and Nagarze areas (H46C004001, 2002); no precise dates were acquired from the Weimei and Zhela Fms. igneous rocks in the Luozha area. Considering that many strata of the Tibetan Plateau have been assigned incorrect ages in the 1:250,000 scale regional geological survey report (e.g., Bian, Yang, Shi, et al., 2017; Tang et al., 2013; Yang, Ma, Zhang, et al., 2015; Yi et al., 2015), reliable isotopic ages are still necessary to accurately constrain the ages of the Weimei and Zhela Fms. volcanic rocks in the Luozha sampling area. The earliest folding of the studied Zhela and Weimei Fms. strata likely occurred at the end of the Early Cretaceous (H46C004001, 2002).

A total of 467 oriented cores from 45 paleomagnetic sites was sampled from four localities near Zhuda village (28°51.07′N to 28°52.27′N, 91°15.52′E to 91°16.6′E), ~20 km east of Yamdrok Tso (Figure 2b). Of the 45 sites, the Zhela Fm. was sampled at 11 sites, and the Weimei Fm. was sampled at the other 34 sites. The bedding attitudes could be well determined based on boundaries between adjacent lava flows or interbedded sedimentary layers (Figures 3a–3d and 3f). Some lava flows showed apparent vesicular structure (Figure 3e).

Generally, 10 core samples were collected from every paleomagnetic site and spanned several meters in stratigraphic thickness or covered at least one lava flow. All of the paleomagnetic samples were collected using a gasoline-powered drill, oriented with a magnetic compass and, where possible, a sun compass. The differences between these two oriented results were less than 3°, which indicates that local magnetic disturbance can be ignored. Two fresh samples from the Weimei Fm. (ZD17) and Zhela Fm. (ZD32) were collected for sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb dating. Furthermore, one fresh sample was collected for zircon laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) U-Pb dating from the Lakang Fm. lava flows located at the paleomagnetic site LK45 (28°8.77′N, 92°26.84′E) referred to by Yang, Ma, Bian, et al. (2015).

3. Laboratory Techniques and Measurements

Oriented cores with 2.5 cm in diameter were cut into standard 2.2-cm-long specimens for subsequent analysis. All paleomagnetic specimens underwent either stepwise thermal demagnetization up to 580 °C using an ASC-TD 48 furnace with an internal residual field less than 10 nT or stepwise alternating field demagnetization up to 120 mT using a D-2000 alternating field demagnetizer. Thermal demagnetization steps were set to 50 °C below 450 °C and shifted to 30–10 °C above 450 °C; alternating field intervals were set to 2.5–5 mT below 30 mT and changed to 10 mT above 30 mT. The paleomagnetic specimens with strong natural remanent magnetization (NRM) intensity were measured using a JR-6A spinner magnetometer, and those with weak NRM intensity were measured using a 2G-755-4K cryogenic magnetometer. Isothermal remanent magnetization (IRM), backfield demagnetization of saturation IRM, and three-axis IRM were acquired with an ASC IM10-30 pulse magnetizer and measured with a JR-6A spinner magnetometer. The three-axis IRM was imparted using an ASC IM10-30 pulse magnetizer in successively smaller fields of 2.4, 0.4, 0.12 T along three mutually orthogonal directions (Lowrie, 1990). Thermal demagnetization of the three-axis IRM was demagnetized with an Magnetic Measurements Thermal Demagnetiser Super Cooling (MMTDCS) furnace and measured with a JR-6A spinner magnetometer. Both magnetometer and demagnetizer were installed within a magnetically shielded room with a magnetic field less than 300 nT at the Paleomagnetism and Environmental Magnetism Laboratory, China University of Geosciences, Beijing. Characteristic remanent magnetization (ChRM) directions of all the specimens were gained using principal component analysis (Kirschvink, 1980) from at least four successive steps. Site mean directions were calculated using Fisherian statistics (Fisher, 1953).Paleomagnetic data were processed using the paleomagnetic software packages developed by Enkin (1990) and Cogné (2003).

To clarify the microtextures of the iron oxides, as well as elucidate whether the titanomagnetite was formed by high-temperature exsolution during initial cooling or by low-temperature transformation of primary iron oxides, microscopic observations were performed on some representative samples using a Zeiss SUPPA 55 field emission scanning electron microscope with an acceleration voltage of 20 kV and a working distance of 15.1 mm (located at the field emission scanning electron microscope Laboratory, China University of Geosciences, Beijing). The polished specimens were coated with platinum to obtain high-quality images. Energy dispersive spectrometry was carried out to obtain compositional information.

Zircons were extracted from fresh rocks using heavy liquid and magnetic and electromagnetic separation at the Langfang Laboratory of Geophysical Exploration. Cathodoluminescence images were taken to study
internal structures for subsequent U-Pb isotopic analyses. The zircon SHRIMP U-Pb dating of the two samples from the Weimei Fm. (ZD17) and Zhela (ZD32) Fm. was finished on the SHRIMP IIe at the Beijing SHRIMP Center, Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China. Analytical procedures followed Williams (1998), and data analyses were performed using the Excel-based Squid and Isoplot programs (Ludwig, 2001). Mass resolution was ~5,000 (1% definition), and the ion flow intensity of O2⁻ was 4 nA during testing. Nine mass peaks (\(^{90}Zr^{16}O^+\), \(^{204}Pb^+\), background, \(^{206}Pb^+\), \(^{207}Pb^+\), \(^{208}Pb^+\), \(^{238}U^+\), \(^{232}Th^{16}O^+\), and \(^{238}U^{18}O^+\)) were made for data signal collecting. Standard zircon M257 (561.3 Ma) was used to calibrate U content (840 ppm; Nasdala et al., 2008). The ages of the samples were corrected based on the standard zircon Qinghu (159 Ma), and the ratios between Qinghu and unknown targets were ~1.3–4. Uncertainties for individual analyses are at the 1-sigma level, whereas weighted mean ages are given at 2-sigma level.

Figure 3. (a–f) Photographs showing field outcrops in the Luoza area.
The zircon LA-ICP-MS U-Pb dating of one sample from the Lakang Fm. was finished at the Tianjin Institute of Geology and Mineral Resources. Data analyses were carried out using the Inductively Coupled Plasma Mass Spectrometry (ICPMS) DataCal (Liu et al., 2010) and Isoplot (Ludwing, 2003) programs. U-Th-Pb isotope ratios were measured using a standard material (NIST612) as an external standard (Jackson et al., 2004). Fractionation correction of the U-Pb isotope was carried out using GJ-1 as an external standard. Common lead was corrected following the method proposed by Andersen (2002). Uncertainties for individual analyses are at 1-sigma level, and weighted mean ages are given at 2-sigma level.

4. Zircon U-Pb Analytical Results

All the zircon crystals were euhedral to subhedral (50–200 μm long, 30–80 μm wide) and showed clear oscillatory zoning (Figures 4a, 4d, and 4g), which indicates that the zircons were magmatic in origin. Zircon SHRIMP U-Pb analyses yielded a variety of ages, which implies that these zircons originated from different sources (Figures 4b and 4e). We interpret the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of the youngest population as the formation time of the studied volcanic rocks. The two samples from the Zhela Fm. (ZD32) and Weimei Fm. (ZD17) lava flows yielded the youngest weighted mean $^{206}\text{Pb}/^{238}\text{U}$ ages of 135.3 ± 2.7 Ma (Figure 4c) and 137.6 ± 3.8 Ma (Figure 4f), respectively. These new zircon SHRIMP U-Pb dating results indicate that the Zhela and Weimei Fms. lava flows in the Luozha area formed during the Early Cretaceous (~135–138 Ma), rather than during the Middle and Late Jurassic as given by 1:250,000 scale Luozha regional geological survey report. The results of the LA-ICP-MS U-Pb dating for sample LK45 yielded the youngest weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 144.1 ± 3.5 Ma (Figures 4h and 4i), which shows that the Lakang Fm. lava flows in the Cuona area formed during the earliest Cretaceous. This age is consistent with the ages of ~141 Ma reported by Hou (2017) and ~147 Ma reported by Shi et al. (2017) from the Lakang Fm. lava flows in the same area. These new zircon U-Pb ages constrain the Lakang Fm. lava flows, which were sampled by Yang, Ma, Bian, et al. (2015) for a paleomagnetic study, to have an age range from ~147 to ~141 Ma.

5. Rock Magnetic and Petrographic Results

The IRM acquisition curves of the representative samples showed a rapid increase below 200 mT, and saturation was fully reached at less than 500 mT (Figures 5a and 5c). When reverse fields of the saturation IRM were applied, the remanence decreased quickly and reduced to zero between 40 and 50 mT, which indicates that low-coercivity magnetic carriers were dominant in the studied specimens. The Lowrie (1990) test showed that all the hard, medium, and soft components fully unblocked at ~530–560 °C. These rock-magnetic results reveal that low-coercivity titanomagnetite was a main magnetic carrier in the studied volcanic specimens (Figures 5b and 5d).

Backscattered electron (BSE) images and energy dispersive spectrometry (EDS) analyses showed that the studied lava flows contain abundant Ti-Fe and Ti oxides, distributed in silicates (Figure 6). These Ti-Fe and Ti oxides grains usually occur as rod-shaped and irregular shapes with a size range from several micrometers to more than 200 μm and lack obvious oxidized rims. These characteristics, combined with the rock-magnetic results mentioned above (Figures 5a–5d), indicate that these Ti-Fe and Ti oxides formed by high-temperature exsolution during initial cooling, rather than long-term low-temperature oxidation of primary iron oxides.

6. Paleomagnetic Results

Three hundred and eighty specimens were treated with stepwise thermal demagnetization, and 57 specimens were subjected to stepwise alternating field demagnetization. Typical Zijderveld diagrams are shown in Figure 7. Generally, a low-temperature component (LTC) or a low-field component (LFC) can be isolated between room temperature and 250–300 °C or between NRM and 15 mT for most specimens. The mean direction of the LTC and LFC for the 219 specimens was $D = 359.1^\circ$, $I = 51.5^\circ$, and $k = 13.1^\circ$ with $\alpha_{95} = 2.7^\circ$ in situ (Figure 8). This direction is close to the local modern geomagnetic field direction ($D = 0^\circ$ and $I = 45^\circ$) and may represent a viscous remanent magnetization of the recent magnetic field. After the LTC or LFC was removed, a stable high-temperature component between 350 and 510–580 °C or a high-coercivity component between 20 and 70–120 mT decaying toward the origin could be successfully isolated from most specimens. The high-temperature component and high-coercivity component directions, which are defined
as ChRM directions, included antipodal normal and reverse polarities (Figures 7a–7n and 7p). However, a minor portion of the specimens showed erratic demagnetization patterns after thermal demagnetization above 350 °C (Figure 7o), and reliable ChRM directions could not be isolated. Although stable directions toward the origin could be isolated at two sites of ZD19 and ZD28 (Figures 7q and 7r), their remanence directions are scattered within site (Figure 7s). On the basis of the following filtering criteria by excluding sites that (1) site mean directions obtained from less than five specimens, (2) site mean directions have

Figure 4. (a, d, g) Cathodoluminescence images of representative zircon grains from samples ZD17, ZD32, and LK45 and corresponding $^{206}$Pb/$^{238}$U ages of the individual analyzed spots. (b, e, h) U-Pb concordia diagrams of zircon grains. (c, f, i) Bar plot shows the weighted mean $^{206}$Pb/$^{238}$U ages.
precision parameters (k values) lower than 50, and (3) ChRM directions have Fisher’s precision parameter >15°, 33 out of 45 sites provided the site mean direction (overall mean A): \(D_g = 331.7^\circ, I_g = -14.1^\circ, k_g = 1.9, \) and \(a_{95} = 25.5^\circ\) in situ and \(D_s = 328.1^\circ, I_s = -68.6^\circ, k_s = 20.2, \) and \(a_{95} = 5.7^\circ\) after tilt correction (Table 1 and Figure 9a). Although the overall mean direction passes both McElhinny (1964) and McFadden (1990) fold tests at the 95% and 99% confidence levels and the reversals test (McFadden & McElhinny, 1990) at the 95% confidence level, the ChRM directions of the sites ZD26 and ZD35 fall outside of 45° angular deviations from the overall mean A, which suggests that they may record an excursional or transitional direction. Thus, these two sites were rejected from further analysis. The remaining 31 sites provide the site mean direction (overall mean B): \(D_g = 333.4^\circ, I_g = -9.0^\circ, k_g = 2.1, \) and \(a_{95} = 24.2^\circ\) in situ and \(D_s = 321.2^\circ, I_s = -68.7^\circ, k_s = 35.4, \) and \(a_{95} = 4.4^\circ\) after tilt correction, corresponding to a Fisherian site mean paleopole at 0.9°N, 293.4°E with \(A_{95} = 7.0^\circ\) (Table 1, supporting information Table S1, and Figure 9b). This overall mean B passes both McElhinny (1964) and McFadden (1990) fold tests at 95% and 99% confidence levels and yields a maximum grouping at 100% unfolding (Figure 10), which, together with the positive reversals test (McFadden & McElhinny, 1990) at 95% confidence level, supports the interpretation that the ChRM directions should be primary magnetizations acquired before folding.

We use the most widely accepted approach proposed by Deenen et al. (2011) to test whether our paleomagnetic results obtained from the Luozha area have averaged paleosecular variation or not. The \(A_{95}\) value (7.0°) deduced from the virtual geomagnetic poles of 31 lava flow sites is consistent with the N-dependent of \(A_{95\ min}/A_{95\ max}\) at 3.0°/9.4°. This result, combined with information of 31 paleomagnetic sites obtained from different lava flows spanning ~138 to 135 Ma and interbedded with many layers of sedimentary rocks (Figure 3), as well as the ChRM direction consisting of antipodal dual polarities, supports the conclusion that the paleopole (0.9°N, 293.4°E with \(A_{95} = 7.0^\circ\) obtained from the Early Cretaceous Zhela and Weimei Fms. lava flows has averaged paleosecular variation and should be a reliable Early Cretaceous (~138–135 Ma) pole for the eastern Tethyan Himalaya.

Figure 5. (a, c) IRM acquisition curves and backfield demagnetization of SIRM curves and (b, d) thermal demagnetization of three-axis IRM curves for representative samples from the Luozha area. IRM = isothermal remanent magnetization.
7. Discussion

The breakup of eastern Gondwana has principally been investigated based on marine magnetic anomalies and fracture zone data (Gaina et al., 2007; Gibbons et al., 2012; Williams et al., 2013). For example, the discrepancies of magnetic anomalies and seafloor fabric between the Mozambique and Somali Basins during M15n (135.76 Ma) suggest that the breakup of eastern Gondwana began around 135 Ma (Davis et al., 2016). The oldest oceanic crust (~140 Ma) off Western Australia that becomes younger to the west prompted McElhinny and Embleton (1974) to propose that the Indian Plate was separated from the Australia-Antarctica Plate about 140 Ma. The combination of multichannel seismic reflection, gravity, magnetic, and bathymetric results from the Bay of Bengal that indicated that the Indian Plate separated from the Antarctic Plate about M0 (120 Ma; Rao et al., 1997). The large discrepancy of the separation time can be attributed to several factors: (1) severe overprinting by plume-related magmatism or burial by large amounts of sedimentary rock influencing the magnetic and gravity data (Williams et al., 2013), (2) lack of reliable ages of the oceanic crust associated with the formation of magnetic anomaly isochrons or in the dating of the rocks (Ramana et al., 2001), and (3) complex tectonics along the continental margins of Australia and Antarctica and the surrounding basins.
Figure 7. (a–r) Demagnetization curves of representative specimens in geographic coordinates. (s) Equal area projection of scattering remanence directions within-site in stratigraphic coordinates. The solid (open) symbols represent projections onto the horizontal (vertical) planes.
Therefore, inadequate information from the conjugate margins of India, Antarctica, and Australia resulted in incomplete plate reconstruction models, especially for the fragmentation of eastern Gondwana. Because the Latest Jurassic to Early Cretaceous Comei-Bunbury igneous rocks that originated from the Kerguelen mantle plume should presently be distributed in different locations in the northeast of the Indian Plate, southwest of the Australian Plate, and northeast of the Antarctic Plate according to the reconstruction of eastern Gondwana, our reconstructions are mainly based on incorporated geochronological and paleomagnetic data from the Latest Jurassic to Early Cretaceous Comei-Bunbury igneous rocks.

7.1. The Geochronology and Magmatic Origin of the Latest Jurassic to Early Cretaceous Comei-Bunbury Igneous Rocks

Some researchers have proposed that the Early Cretaceous (~140–130 Ma) Comei-Bunbury large igneous rocks in the Tethyan Himalaya are part of the Kerguelen LIP (Zhu et al., 2009, 2007, 2005; Wang et al., 2016) and argued that the Kerguelen mantle plume originated in the Early Cretaceous (e.g., Zhu et al., 2009). However, several recent studies confirmed the presence of ~145-Ma diabase sills and ~147-Ma volcanic rocks in the eastern Tethyan Himalaya (e.g., Shi et al., 2017; Zhu et al., 2008), which suggest that the activity of the Kerguelen mantle plume may have begun in the Latest Jurassic (e.g., Shi et al., 2017). Our new zircon SHRIMP U-Pb dating results indicate that the Zhela and Weimei Fms. lava flows in the Luozha area formed during ~138–135 Ma, which shows that the widely exposed volcanic rocks erupted not during the Middle and Late Jurassic as given by the 1:250,000 scale Luozha regional geological survey report but during the Early Cretaceous. Significantly, the ages of the Zhela and Weimei Fms. lava flows in the Luozha area are consistent with the ages of the Sangxiu Fm. in the adjacent areas, such as Luozha (~135–124 Ma; Ma et al., 2016), Gyangze (~136 Ma; Wan et al., 2011), and southeastern Yamdrok Tso (~133 Ma; Zhu et al., 2005). In addition, our new LA-ICP-MS zircon U-Pb analyses, combined with SHRIMP zircon U-Pb analyses (Hou, 2017; Shi et al., 2017), indicate that the Lakang Fm. lava flows of the Cuona area erupted during ~147–141 Ma. The geochemical results show that both the Sangxiu Fm. and Lakang Fm. volcanic rocks are characterized by high contents of TiO₂, highly fractionated between light rare earth element and heavy rare earth element with no obvious Eu anomaly, which are similar to the ocean island basalts that originated from the Kerguelen mantle plume (Shi et al., 2017; Zhu et al., 2008). Moreover, the geochronological results indicate that the Comei igneous rocks in the eastern Tethyan Himalaya have an age range from ~147 to ~124 Ma (Liu et al., 2015; Ma et al., 2016; Shi et al., 2017; Zhu et al., 2009, 2008), which is close to those from the Bunbury Basalt (~137–130 Ma; Olierook et al., 2016; Olierook, Timms, et al., 2015), the Wallaby Plateau (~124 Ma; Olierook, Merle, et al., 2015), and the Naturaliste Plateau (~128 Ma; Olierook et al., 2017) in northwestern Australia. Overall, the temporal characteristics, combined with the geochemical results, suggest that the Comei-Bunbury LIP may have been associated with the Kerguelen mantle plume.

7.2. The Paleolatitudes of the Latest Jurassic to Early Cretaceous Comei-Bunbury Igneous Rocks

Reliable paleomagnetic data are an essential prerequisite for reasonable explanations. Van der Voo (1990) proposed seven quality criteria that have been widely used to evaluate the reliability of paleomagnetic data sets. Because the selection criteria are rigorous, many paleomagnetic data fail to satisfy all seven criteria. In this study, reliable paleomagnetic data must provide a robust field test such as a positive fold test, a positive reversal test, or dual-polarity ChRM directions in addition to all five other criteria to assure a primary magnetization.

Several paleomagnetic investigations of the Latest Jurassic to Early Cretaceous in the Tethyan Himalaya have been conducted (Huang et al., 2015; Ma et al., 2016; Yang, Ma, Bian, et al., 2015; Table 2). Because two poles (GB and JZ) are from a small number of specimens and obviously insufficient to meet the basic selection criteria and because the TD, WL, and GC poles lack a robust field test or dual-polarity ChRM directions, we do not...
Site Mean Directions of the Lower Cretaceous Zhela and Weimei Fms. Lava Flows From the Luozha Area in the Eastern Tethyan Himalaya

<table>
<thead>
<tr>
<th>Site</th>
<th>Strike/dip</th>
<th>n/N</th>
<th>Dg</th>
<th>Ig</th>
<th>Rs</th>
<th>Is</th>
<th>α0.95</th>
<th>Devi.</th>
<th>Plat</th>
<th>Plon</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZD1</td>
<td>299/86</td>
<td>10/10</td>
<td>6</td>
<td>10.7</td>
<td>332</td>
<td>-62.8</td>
<td>211.1</td>
<td>3.3</td>
<td>6.0</td>
<td>12.5</td>
</tr>
<tr>
<td>ZD2</td>
<td>299/86</td>
<td>8/10</td>
<td>4.3</td>
<td>10.9</td>
<td>330.4</td>
<td>-61.3</td>
<td>96.6</td>
<td>5.7</td>
<td>7.4</td>
<td>13.7</td>
</tr>
<tr>
<td>ZD3</td>
<td>299/86</td>
<td>8/9</td>
<td>3.3</td>
<td>10.7</td>
<td>329.2</td>
<td>-60.5</td>
<td>377.3</td>
<td>2.9</td>
<td>8.1</td>
<td>14.1</td>
</tr>
<tr>
<td>ZD4</td>
<td>299/86</td>
<td>9/10</td>
<td>6.3</td>
<td>11.2</td>
<td>332.3</td>
<td>-62.8</td>
<td>169.8</td>
<td>4.2</td>
<td>6.2</td>
<td>12.9</td>
</tr>
<tr>
<td>ZD5</td>
<td>299/86</td>
<td>9/10</td>
<td>3.8</td>
<td>10.3</td>
<td>328.9</td>
<td>-61.1</td>
<td>318.3</td>
<td>2.9</td>
<td>7.5</td>
<td>13.4</td>
</tr>
<tr>
<td>ZD6</td>
<td>299/86</td>
<td>7/10</td>
<td>0.4</td>
<td>4.5</td>
<td>315.3</td>
<td>-60.2</td>
<td>290.6</td>
<td>3.5</td>
<td>10.0</td>
<td>8.7</td>
</tr>
<tr>
<td>ZD7</td>
<td>299/86</td>
<td>6/11</td>
<td>355</td>
<td>203</td>
<td>336.4</td>
<td>-48.7</td>
<td>112.7</td>
<td>6.3</td>
<td>20.3</td>
<td>27.3</td>
</tr>
<tr>
<td>ZD8</td>
<td>280/80.5</td>
<td>8/8</td>
<td>354.1</td>
<td>14.1</td>
<td>336</td>
<td>-61.6</td>
<td>499.2</td>
<td>2.5</td>
<td>7.7</td>
<td>15</td>
</tr>
<tr>
<td>ZD9</td>
<td>288/84</td>
<td>5/12</td>
<td>5.7</td>
<td>6.1</td>
<td>286.8</td>
<td>-77.7</td>
<td>54.6</td>
<td>10.4</td>
<td>14.5</td>
<td>-20</td>
</tr>
<tr>
<td>ZD10</td>
<td>294/70</td>
<td>7/8</td>
<td>358.2</td>
<td>1</td>
<td>330.7</td>
<td>35.7</td>
<td>119.3</td>
<td>5.5</td>
<td>11.6</td>
<td>18</td>
</tr>
</tbody>
</table>

Note: Plat and Plon, latitude and longitude of pole; n/N, number of samples used to calculate mean and measured; Dg and Ig, declination and inclination in geographic coordinates; Rs and Is, declination and inclination in stratigraphic coordinates; k (K), the best estimate of the precision parameter; α0.95 (A95), the radius that the mean direction (pole) lies within 95% confidence; Devi, the angular difference of site directions from the site mean direction of 33 sites. (1) Overall mean A (N = 33 sites without ZD22): (a) The McElhinny (1964) fold test is positive at 95% and 99% confidence levels: ks/kg = 10.39 > F(2*(n2 - 1), (n1 - 1)) at 5% and 1% point = 1.51 and 1.80, respectively. (b) The McFadden (1990) fold test is positive at 95% and 99% confidence levels. Xi test: critical Xi at 95% = 6.68 and 99% = 9.45, respectively. Xi1 and Xi2 is = 23.01 and 30.76, Xi1 and Xi2 TC = 3.08 and 4.47, respectively. (c) The reversals test is positive at 95% confidence level. Normal polarity: D1 = 333.9°, I1 = -66.3°, k1 = 23.8, n1 = 18. Reverse polarity: D2 = 139.3°, I2 = 71.1°, k2 = 173, n2 = 15. The angle between the two mean directions is γ = 7.2° < γcritical = 11.4°; classification C. (2) Overall mean B (N = 31 sites without ZD22 and ZD26 and ZD35): (a) The McElhinny (1964) fold test is positive at 95% and 99% confidence levels: ks/kg = 16.64 > F(2*(n2 - 1), (n1 - 1)) at 5% and 1% point = 1.54 and 1.84, respectively. (b) The McFadden (1990) fold test is positive at 95% and 99% confidence levels. Xi test: critical Xi at 95% = 6.48 and at 99% = 9.16, respectively. Xi1 and Xi2 is = 17.17 and 28.98 and Xi1 and Xi2 TC = 4.94 and 3.42, respectively. (c) The reversals test is positive at 95% confidence level. Normal polarity: D1 = 320.9°, I1 = 67.8°, k1 = 40.6, n1 = 17. Reverse polarity: D2 = 130.8°, I2 = 69.3°, k2 = 32.3, n2 = 14. The angle between the two mean directions is γ = 6.7° < γcritical = 8.7°; classification B. In order to see more clearly by readers, the data that have been rejected from further analysis in this study are bold.
use these five paleopoles to constrain the paleolatitude of the Tethyan Himalaya during the Latest Jurassic to Early Cretaceous. Our new paleomagnetic data from the Zhela and Weimei Fm. lava flows, which have averaged paleosecular variation and meet all seven quality criteria proposed by Van der Voo (1990), provide a Fisherian mean paleopole at $0.9^\circ$N, $293.4^\circ$E with $A_{95} = 7.0^\circ$ and thus indicate that the Luozha sampling area ($28.9^\circ$N, $91.3^\circ$E) was located at ~53.5°S ± 7.0°S at ~138–135 Ma (Table 2). Yang, Ma, Bian, et al. (2015) obtained a high-quality paleopole ($/C0$26.8°N, 315.2°E with $A_{95} = 5.7^\circ$) from the Early Cretaceous Lakang Fm. lava flows. This pole also satisfies all seven quality criteria and provides a paleolatitude of 52.2°S ± 5.7°S for the southeastern Tethyan Himalaya (28.1°N, 92.4°E; Table 2). Notably, Yang, Ma, Bian, et al. (2015) assigned the sampled Lakang Fm. lava flows a Hauterivian (134–131 Ma) age based on bivalve fossils found in the interbedded sedimentary rocks of the Lakang Fm. (1:250,000 scale Longzi regional geological survey report (H46C004002), 2004). However, our new zircon LA-ICP-MS U-Pb results (Figure 4) and recent zircon SHRIMP U-Pb ages from the same paleomagnetic sampling locations (Hou, 2017; Shi et al., 2017) reveal that the Lakang Fm. lava flows sampled by Yang, Ma, Bian, et al. (2015) erupted at ~147–141 Ma, during

Figure 9. (a, b) Equal area projections of site mean directions of the high-temperature component from the Luozha area. The stars indicate the overall mean directions of (a) 33 and (b) 31 sites.

Figure 10. Results of stepwise unfolding of the mean directions from 31 sites.
### Table 2
Summary of the Latest Jurassic-Early Cretaceous Paleopoles From the Tethyan Himalaya, Indian Craton, and Australia

<table>
<thead>
<tr>
<th>ID</th>
<th>Lithology</th>
<th>Area</th>
<th>Slon (°E)</th>
<th>Slat (°N)</th>
<th>Age</th>
<th>Plat (°E)</th>
<th>Plon (°N)</th>
<th>$A_{95}$ (dp/dm)</th>
<th>Paleolat</th>
<th>n/N</th>
<th>Criterion (Q)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tethyan Himalaya</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>sed</td>
<td>Dzong</td>
<td>28.8</td>
<td>83.8</td>
<td>Early Aptian</td>
<td>12.0</td>
<td>289.0</td>
<td>6.0/7.5</td>
<td>−42.5 ± 6.0</td>
<td>95/—</td>
<td>123□SD7 (5)</td>
<td>1</td>
</tr>
<tr>
<td>GB</td>
<td>sed</td>
<td>Gamba</td>
<td>28.3</td>
<td>88.5</td>
<td>~98–107</td>
<td>38.4</td>
<td>277.9</td>
<td>5.7/9.5</td>
<td>−22.7 ± 5.7</td>
<td>23/—</td>
<td>123□□□□□□□□□□□</td>
<td>2</td>
</tr>
<tr>
<td>JZ</td>
<td>slate</td>
<td>Gyangze</td>
<td>28.9</td>
<td>89.8</td>
<td>$J_3$</td>
<td>7</td>
<td>329.0</td>
<td>11.0</td>
<td>−22.7 ± 11.0</td>
<td>11/—</td>
<td>123□□□□□□□□□□□</td>
<td>3</td>
</tr>
<tr>
<td>MW</td>
<td>sed</td>
<td>Nielamu</td>
<td>28.7</td>
<td>86.3</td>
<td>$J_3$</td>
<td>−38.2</td>
<td>113.1</td>
<td>1.9/3.3</td>
<td>−18.6 ± 1.9</td>
<td>316/—</td>
<td>123□□□□□□□□□□□</td>
<td>4</td>
</tr>
<tr>
<td>GC</td>
<td>sed</td>
<td>Nielamu</td>
<td>28.8</td>
<td>86.3</td>
<td>$K_1$</td>
<td>−32.7</td>
<td>115.7</td>
<td>5.1/8.4</td>
<td>−22.4 ± 5.1</td>
<td>56/—</td>
<td>123□□□□□□□□□□□</td>
<td>4</td>
</tr>
<tr>
<td>LK</td>
<td>Volc</td>
<td>Cuona</td>
<td>28.1</td>
<td>92.4</td>
<td>~147–141</td>
<td>−26.8</td>
<td>315.2</td>
<td>5.7</td>
<td>−52.2 ± 5.7</td>
<td>225/31</td>
<td>123□□□□□□□□□□□</td>
<td>4</td>
</tr>
<tr>
<td>aWL</td>
<td>Volc</td>
<td>Wölking</td>
<td>28.5</td>
<td>87.0</td>
<td>~138–130</td>
<td>4.4</td>
<td>256.0</td>
<td>4.6/5.2</td>
<td>−55.4 ± 4.6</td>
<td>201/—</td>
<td>123□□□□□□□□□□□</td>
<td>7</td>
</tr>
<tr>
<td>SX</td>
<td>Volc</td>
<td>Langkazi</td>
<td>28.8</td>
<td>91.3</td>
<td>~135–124</td>
<td>−5.9</td>
<td>308.0</td>
<td>6.1</td>
<td>−48.5 ± 6.1</td>
<td>216/26</td>
<td>123□□□□□□□□□□□</td>
<td>9</td>
</tr>
<tr>
<td>ZD</td>
<td>Volc</td>
<td>Zhuode</td>
<td>28.9</td>
<td>91.3</td>
<td>~138–135</td>
<td>0.9</td>
<td>293.4</td>
<td>7.0</td>
<td>−53.5 ± 7.0</td>
<td>219/31</td>
<td>123□□□□□□□□□□□</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Indian Craton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ab</td>
<td>Volc</td>
<td>Siang valley</td>
<td>28.3</td>
<td>95.1</td>
<td>$J_3$–$K_1$</td>
<td>−24.6</td>
<td>313.6</td>
<td>8.6/10.2</td>
<td>−55.5 ± 8.6</td>
<td>174/34</td>
<td>123□□□□□□□□□□□</td>
<td>10 and 11</td>
</tr>
<tr>
<td>RT1</td>
<td>Volc</td>
<td>Rajmahal Traps</td>
<td>24.2–25.3</td>
<td>87.4–87.8</td>
<td>~118</td>
<td>7</td>
<td>297.0</td>
<td>4.5/6</td>
<td>−47.2 ± 3.0</td>
<td>158/25</td>
<td>123□□□□□□□□□□□</td>
<td>12</td>
</tr>
<tr>
<td>RT2</td>
<td>Volc</td>
<td>Rajmahal Traps</td>
<td>24.2–25.3</td>
<td>87.4–87.8</td>
<td>~117</td>
<td>9.4</td>
<td>296.6</td>
<td>3.0/3.7</td>
<td>−45.6 ± 3.0</td>
<td>120/34</td>
<td>123□□□□□□□□□□□</td>
<td>13</td>
</tr>
<tr>
<td>SH3</td>
<td>Volc</td>
<td>Rajmahal Traps</td>
<td>24.2–25.3</td>
<td>87.4–87.8</td>
<td>~117</td>
<td>10.4</td>
<td>296.8</td>
<td>4.3/5.3</td>
<td>−44.8 ± 4.3</td>
<td>112/19</td>
<td>123□□□□□□□□□□□</td>
<td>14</td>
</tr>
<tr>
<td>RT</td>
<td>Volc</td>
<td>Rajmahal Traps</td>
<td>24.2–25.3</td>
<td>87.4–87.8</td>
<td>~117–118</td>
<td>9.8</td>
<td>296.4</td>
<td>2.8</td>
<td>−45.4 ± 2.8</td>
<td>293/78</td>
<td>123□□□□□□□□□□□</td>
<td>15 and 16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BB</td>
<td>Volc</td>
<td>Bunbury</td>
<td>−33.3</td>
<td>115.5</td>
<td>~137–130</td>
<td>−50</td>
<td>163.4</td>
<td>−5.20 ± 4.0</td>
<td>54/5</td>
<td></td>
<td>123□□□□□□□□□□□</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>−34.3</td>
<td>115.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: ID, palaeopoles abbreviation used in the plot and text; volc, volcanic rocks; sed, sedimentary rocks; $J_3$, Late Jurassic; $K_1$, Early Cretaceous; $K_2$, Late Cretaceous; Slat (Slon), latitude (longitude) of sites; Plat (Plon), latitude (longitude) of poles; $A_{95}$, the radius that the mean pole lies within 95% confidence; dp/dm, semiaxes of elliptical error of the pole at a probability of 95%; Paleolat, palaeolatitude calculated for the reference point located at their studied area; mean reference point (33.8°N, 115.6°E) located at the studied area for Australia and the Rajmahal Traps, respectively; n/N, number of samples or sites used to calculate Fisher mean; Criteria (Q), data quality criteria (number of criteria met) after Van der Voo (1990) (1, well determined rock age; 2, sufficient sample number [N > 24, $k > 10$, and $a_{95} ≤ 16.0$]; 3, proper demagnetization techniques; 4, field tests; 5, structural control and tectonic coherence with the craton or block involved; 6, the presence of reversals; 7, no resemblance to paleopoles of younger ages [by more than a period]; $F_+$, positive fold test; $F_-$, positive fold test with additional data from the adjacent sampling area; $R_+$, positive reversal test; $D_+$, dual-polarity; "□", failed to meet this criterion). References 1, 4, 5, 6, and 8 provide the palaeomagnetic results; References 2, 3, 7, and 9 provide the geochronological results. References: 1 Klootwijk and Bingham (1980). 2 Patzelt et al. (1996). 3 Zhu et al. (1981). 4 Li et al. (2006). 5 Yang, Ma, Bian, et al. (2015). 6 Shi et al. (2017). 7 Hou (2017). 8 Huang et al. (2015). 9 Ma et al. (2016). 10 Ali et al. (2012). 11 Aitchison et al. (2014). 12 Kloomvijkt (1971). 13 Poomachandra Rao and Mallikharjuna Rao (1996). 14 Sherwood and Mallik (1996). 15 Schmidt (1976). 16 Olierook et al. (2016). In order to see more clearly by readers, the data calculated in this study are bold.
the Latest Jurassic to Earliest Cretaceous. Furthermore, Ma et al. (2016) also reported a high-quality paleopole (5.9°N, 308.0°E with $A_{95} = 6.1°$) that fulfills all seven quality criteria, from the Early Cretaceous (~135–124 Ma) Sangxiu Fm. lava flows. This high-quality pole yielded a paleolatitude of 48.5°S ± 6.1°S for the Langkazi area of that study (28.8°N, 91.3°E; Table 2). The three high-quality paleopoles mentioned above, which are from a large number of lava flows and exclude compaction-induced inclination shallowing, indicate that the Comei igneous rocks, which are presently located at ~28–29°N in the eastern Tethyan Himalaya, actually erupted at ~48.5–53.5°S during ~147–124 Ma (Figures 1 and 11).

For the volcanic rocks of the northeastern Indian Craton, Ali et al. (2012) reported paleomagnetic data from the Abor volcanics in the lower Siang valley ($D_s = 86.4°$, $I_s = 68.8°$, $k_s = 18.1$, and $A_{95} = 6.0°$) that satisfy six quality criteria and include dual-polarity ChRM directions and thus should be reliable based on our selection criteria (Table 2). This reliable paleomagnetic data set provides a paleolatitude of 55.5°S ± 8.6°S for the Siang area (28.3°N, 95.1°E). It should be noted that the Abor volcanics were assigned an Early Permian age by Ali et al. (2012). However, their later LA-ICP-MS and SHRIMP U-Pb results indicated that these Abor volcanic rocks should actually be part of the Early Cretaceous Comei-Bunbury LIP (Aitchison et al., 2014). Although the Early Cretaceous Abor volcanic rocks lie at ~28.3°N, their original eruption positions were at ~55.5°S. Therefore, the high-quality volcanic paleomagnetic data observed from the eastern Tethyan Himalaya and the northeastern Indian Craton prove that the widely distributed Latest Jurassic to Early Cretaceous volcanic rocks, which are presently located at ~28–29°N, originally erupted at ~48.5–55.5°S (Figures 1, 11b, and 11c).

For the Australian Plate, only one paleopole (50°N, 163°E with $A_{95} = 4°$) from the Bunbury basalt is available (Table 2). This paleopole contains 54 samples of dual polarities and also satisfies the selection criteria mentioned above. Although Schmidt (1976) considered the sampled Bunbury basalt as Late Cretaceous in age...
based on K/Ar dating by McDougall and Wellman (1976), recent 40Ar/39Ar geochronological results revealed that the Bunbury basalt actually erupted at ~137–130 Ma (Olierook et al., 2016). Therefore, these paleomagnetic and geochronological results confirm that the studied Early Cretaceous Bunbury basalts in the southwestern Australian Plate, presently located at ~33.8°S, originally erupted at ~52.0°S for the mean reference point (~33.8°N, 115.6°E) located at the Bunbury area (Figures 1 and 11). In addition, paleomagnetic data from the Rajmahal Traps (117–118 Ma) in Northeast India are summarized in Table 2. These three paleopoles include dual polarities and meet our selection criteria. Considering that the age ranges of the Rajmahal Traps and these three paleopoles are almost consistent with each other, their site mean directions are combined together. The site mean direction from 78 sites is $D = 316.0^\circ, I = -65.1^\circ$ with $A_{95} = 2.4^\circ$, corresponding to a paleopole at 9.8°N, 296.4°E with $A_{95} = 2.8^\circ$ and yielded a paleolatitude of 45.4°S ± 2.8°S for a local reference point (24.8°N, 87.6°E).

For the Antarctic Plate, most paleomagnetic data from Late Jurassic to Early Cretaceous igneous rocks are from western Antarctica (DiVenere et al., 1995; Grunow, 1993; Grunow et al., 1987, 1991). These igneous rocks are primarily from Mesozoic and Cenozoic subduction associated with intrusive and extrusive rocks (Grunow et al., 1987). Because no paleomagnetic data have been reported from igneous rocks related to the Kerguelen mantle plume in eastern Antarctica (Grunow et al., 1991) and because Australia and eastern Antarctica were a continuous continent during the Late Jurassic to Early Cretaceous (Grunow et al., 1991; Williams et al., 2013), in this study we consider the paleopole of Australia as the united entity of the Australian-Antarctic Plate.

### 7.3. The Breakup of Eastern Gondwana

Although the Comei-Bunbury igneous rocks related to the Kerguelen mantle plume have drifted to distant locations distributed widely in the Antarctic, Australian, and Indian Plates (Chen et al., 2018; Frey et al., 1996; Ingle et al., 2003; Kent et al., 2002; Müller et al., 1993; Storey et al., 1989; Zhu et al., 2009), paleomagnetic results show that their original positions upon eruption were within a paleolatitude range of ~48.5–55.5°S (Table 2), fully consistent with the eruption center of the reconstructed Kerguelen mantle plume LIP (~45.4–52.3°S) based on the hybrid reference frames described by Torsvik et al. (2008). These results undoubtedly validate that the Latest Jurassic to Early Cretaceous Comei-Bunbury igneous rocks originated from the Kerguelen mantle plume. The geochronological results of the Lakang Fm. lava flows from the eastern Tethyan Himalaya indicate that the activity of the Kerguelen mantle plume started at ~147 Ma, revealing that eastern Gondwana initially rifted at ~147 Ma. The paleomagnetic results demonstrate that the Latest Jurassic to Early Cretaceous Comei-Bunbury igneous rocks erupted entirely within a similar paleolatitude of ~48.5–55.5°S during ~147–124 Ma (e.g., Shi et al., 2017; Zhu et al., 2008), which, combined with the fact that (1) no younger basalts associated with the breakup of eastern Gondwana have been found from after 124 Ma in the Tethyan Himalaya, (2) the Indian Plate started to move northward after 140 Ma (Besse & Courtillot, 2002; Torsvik et al., 2012), (3) the paleolatitude observed from the Rajmahal Traps suggests that the Indian Plate had moved to a more northerly location at ~118 Ma (Figure 11c), and (4) the Australian-Antarctic Plate maintained a relatively stable paleolatitude during 140–120 Ma based on the Australia and East Antarctica apparent polar wander paths (Torsvik et al., 2012), suggests that the Indian Plate fully separated from the Australian-Antarctic plate before ~124 Ma.

### 8. Conclusions

We have presented a combined paleomagnetic and geochronological study from the Zhela and Weimei Fms. lava flows in the Luozha area of the eastern Tethyan Himalaya. Our new and well-dated paleomagnetic results have been averaged for paleosecular variation and meet all seven quality criteria proposed by Van der Voo (1990) for evaluating the reliability of paleomagnetic data. Our results, combined with the Late Jurassic to Early Cretaceous paleomagnetic and geochronological data from the Tethyan Himalaya, India, and Australia, led us to come to the following conclusions:

1. Our new zircon SHRIMP U-Pb dating indicates that the Zhela and Weimei Fms lava flows in the Luozha area of the eastern Tethyan Himalaya formed during ~138–135 Ma, rather than during the Middle and Late Jurassic as given by 1:250,000 scale Luozha regional geological survey report.

2. Our geochronological results, combined with published geochronological and geochemical results from the Comei-Bunbury large igneous rocks, suggest that the Comei-Bunbury LIP may have been associated with the Kerguelen mantle plume.
3. The Luozha area of the eastern Tethyan Himalaya was located at 53.5°S ± 7.0°S during ~138–135 Ma, just located in the center of the Kerguelen mantle plume.
4. The temporal and spatial relationships of the Comei-Bunbury LIP and the Kerguelen mantle plume indicate that eastern Gondwana initially rifted at ~147 Ma and that the Indian Plate fully separated from the Australian-Antarctic Plate before ~124 Ma.

References


Bian, W., Yang, T., Ma, Y., Jin, J., Gao, F., et al. (2017). New Early Cretaceous paleomagnetic and geochronological results from the western Lhasa terrane: Contributions to the Lhasa-Qiangtang collision. Scientific Reports, 7(1), 16216. https://doi.org/10.1038/s41598-017-16482-3


