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Paleomagnetic constraints on the Mesozoic drift of the Lhasa terrane (Tibet) from Gondwana to Eurasia

Zhenyu Li[1], Lin Ding[1,2]*, Peter C. Lippert[3], Peiping Song[1], Yahui Yue[1], and Douwe J.J. van Hinsbergen[4]
[1]Key Laboratory of Continental Collision and Plateau Uplift (LCPU), Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS), Beijing 100101, China
[2]Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, China
[3]Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112-9057, USA
[4]Department of Earth Sciences, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, Netherlands

ABSTRACT

The Mesozoic plate tectonic history of Gondwana-derived crustal blocks of the Tibetan Plateau is hotly debated, but so far, paleomagnetic constraints quantifying their paleolatitude drift history remain sparse. Here, we compile existing data published mainly in Chinese literature and provide a new, high-quality, well-dated paleomagnetic pole from the ca. 180 Ma Sangri Group volcanic rocks of the Lhasa terrane that yields a paleolatitude of 3.7°S ± 3.4°. This new pole confirms a trend in the data that suggests that Lhasa drifted away from Gondwana in Late Triassic time, instead of Permian time as widely perceived. A total northward drift of ~4500 km between ca. 220 and ca. 130 Ma yields an average south-north plate motion rate of 5 cm/yr. Our results are consistent with either an Indian or an Australian provenance of Lhasa.

INTRODUCTION

The Tethyan oceans surrounded by the supercontinent Pangea opened and closed as continental fragments rifted and drifted away from Gondwana in the south, opened the Meso- and Neotethyan Oceans in their wake, and closed Paleotethyan Ocean floor upon their approach toward Eurasia (Şengör, 1992; Metcalfe, 1996; Stampfli and Borel, 2002; Domeier and Torsvik, 2014). The Tibetan Plateau, sandwiched between India, South China, and North China, contains several such continental fragments (Fig. 1). From north to south, these include the Qiangtang terrane(s) that collided with northeastern Tibet in the Late Triassic (Yin and Harrison, 2000; Song et al., 2015); Lhasa, which collided with Qiangtang in the Early Cretaceous along the Bangong-Nujiang suture zone (e.g., Yin and Harrison, 2000; Kapp et al., 2007; Fan et al., 2015; Zhu et al., 2016); and the Tibetan Himalaya (the northernmost continental rocks derived from the Indian plate) that collided with Lhasa in the Eocene along the Indus-Yarlung suture zone (Yin and Harrison, 2000; Hu et al., 2015; Huang et al., 2015).

Most authors describe an ideal Wilson-cycle scenario, wherein the blocks of the Tibetan Plateau all drifted from India in Paleozoic to Mesozoic time and were reunited with India in the Cenozoic after closure of the Neotethyan and older oceans. These conclusions are commonly based on Paleozoic fossils and detrital zircon age spectra typical for the northern Gondwana margin in their stratigraphy, volcanism, and ophiolite geology (e.g., Metcalfe, 1996; Gehrels et al., 2011; Torsvik and Cocks, 2013; Zhu et al., 2011, 2013; Cai et al., 2016).

Quantifying the rift and drift history of these terranes allows us to reconstruct the opening and closure of the Tethyan oceans. Assigning ages to continental breakup events commonly relies on the interpretation of stratigraphic records of

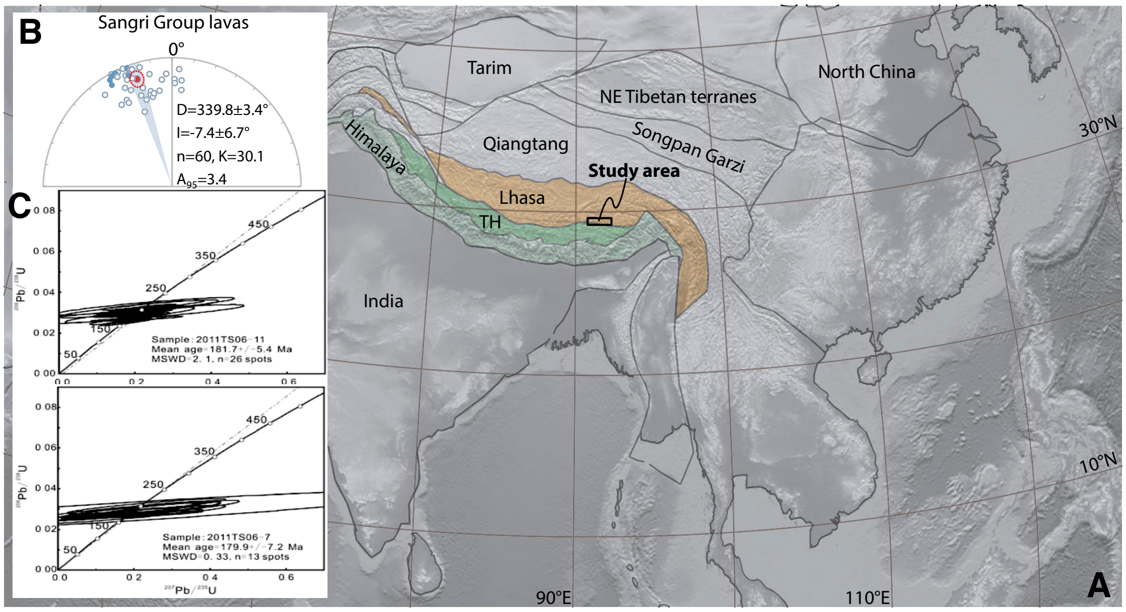

Figure 1. A: Schematic tectonic map of Tibet showing study area of Sangri Group lavas and outlines of Lhasa block and Tibetan Himalaya (TH). B: Lava site average paleomagnetic directions of Sangri Group lavas (D—declination; I—inclination; K—Fisher precision parameter). C: Zircon U-Pb ages of two samples of Sangri Group lavas (MSWD—mean square of weighted deviates).

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*E-mail: dinglin@itpcas.ac.cn

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presupposed or demonstrated once-adjacent blocks. For example, Lower Permian mafic volcanics and middle Permian overlying passive margin clastics and pelagic limestones in the Tibetan Himalaya are interpreted to reflect the departure of a continental fragment from the Indian segment of Gondwana (Garzanti, 1999). Many authors have concluded that this fragment was Lhasa (e.g., Stampfli and Borel, 2002; Torsvik and Cocks, 2013; Domeier and Torsvik, 2014); others, however, have suggested that Lhasa did not rift from Gondwana until the Middle–Late Triassic (e.g., Metcalfe, 1996; Li et al., 2004). Some have argued that Lhasa rifted from northwestern Australia rather than western Greater India in the Late Triassic (Zhu et al., 2011; 2013; Ran et al., 2012), consistent with sediment provenance of Upper Triassic turbidites interpreted to be part of the Lhasa block (Cai et al., 2016).

The transfer of continental blocks from Gondwana to Eurasia involved large south-north (i.e., latitudinal) plate motions, which can be quantitatively constrained with paleomagnetism. In this paper, we quantify the paleolatitude history of Lhasa from the late Paleozoic to present by reviewing existing paleomagnetic data and by providing a new, well-dated, high-quality paleomagnetic pole from Lower Jurassic volcanic rocks of Lhasa. We compare these constraints to the global apparent polar wander path in Eurasian and Indian/Gondwanan coordinates (Torsvik et al., 2012) and show the implications for paleogeographic reconstructions of the Mesozoic Tethyan realm.

PREVIOUS PALEOMAGNETIC CONSTRAINTS

Several high-quality paleomagnetic poles have been reported from Lower Cretaceous and Paleogene rocks of Lhasa (Lippert et al., 2014; Huang et al., 2015, and references therein; see the GSA Data Repository[1]). Paleomagnetic data from pre-Cretaceous rocks only recently became available in international literature (e.g., Zhou et al., 2016) and were mostly published in the 1980s and 1990s in Chinese literature. These data, acquired from sediments, may have inclination bias and commonly lack paleomagnetic field tests. Nevertheless, all data from Jurassic and older rocks show Southern Hemisphere latitudes for Lhasa. Here, we add a new pole from the volcanic Sangri Group of Lhasa to constrain Lhasa's northward drift in the Jurassic.

GEOLOGICAL SETTING AND SAMPLING

Lhasa is an east-west–trending continental tectonostratigraphic belt separated from the Qiangtang terrane along the Bangong-Nujiang suture zone, a >2000-km-long zone with ultramafic rocks and mélange along which the Bangong-Nujiang (or Mesotethys) ocean subducted since the Late Triassic (Yin and Harrison, 2000; Kapp et al., 2007; Zhu et al., 2011, 2013; Zeng et al., 2015). The southern margin of Lhasa is characterized by the widespread Gangdese magmatic belt of dominantly calc-alkline granitoids that were emplaced mainly from the Early Cretaceous through the Eocene (e.g., Chung et al., 2005; Zhu et al., 2011). Older Mesozoic volcanic rocks include the Jurassic–Lower Cretaceous adakite-like andesitic and basaltic rocks of the Sangri Group (Kang et al., 2014).

The Sangri Group is an ~500-m-thick suite of widely distributed volcanic and sedimentary rocks that forms a linear belt along the southern margin of Lhasa (Fig. 1; see the Data Repository); it is typically characterized by 1–3-m-thick calc-alkaline lavas and intercalated reddish-beige sandstones, and limestones. Geochemical and petrographic studies suggest that the Sangri Group lavas are the product of partial melting of subducting oceanic crust (Kang et al., 2014). Kang et al. (2014) recently reported zircon U-Pb ages of 195 ± 3.0 Ma and 189 ± 3.0 Ma from the middle part of the section at Kamadang village near Sangri County. Our own zircon U-Pb LA-ICP-MS analyses of the upper and lower parts of the section at Sangri County (Fig. 1) provide overlapping weighted mean ages of 181.7 ± 5.4 Ma (mean square of weighted deviates [MSWD] = 2.1, n = 26) and 179.9 ± 7.2 Ma (MSWD = 0.33, n = 13) (see the Data Repository for details).

For paleomagnetic studies, we collected 589 samples from 62 sites distributed across two locations: one within Sangri County (29°17.716′N, 92°02.852′E) and the other around Sangye Town along the northern bank of the Yarlung-Zangbo river (29°18.005′N, 91°34.241′E) (Fig. 1). Sampled rocks comprise basaltic andesite and andesite lavas. See the Data Repository for details about the sampling strategy and procedures, as well as descriptions of the rock magnetic and paleomagnetic measurement methods and data.

RESULTS

Rock magnetic characteristics suggest that the Sangri Group lavas contain a mixture of Ti-rich and Ti-poor titanomagnetite and Ti-rich to Ti-poor titanohematite. Most samples record two, but sometimes three, components. A low-temperature component (LT) is defined from ~80 °C to ~350 °C and has an in situ direction very similar to that of the present geomagnetic field. A high-temperature component (HT) is defined from ~350 °C to 580 or 660 °C and decays toward the origin of orthogonal vector plots. This characteristic remanent magnetization (ChRM), carried by titanomagnetite, is either shallowly upward or downward with a northerly or southerly declination. We calculated lava site averages using Fisher statistics (Fisher, 1953) on directions and applied the quality criteria explained in Lippert et al. (2014); a notable exception to this filter is that we accept site mean directions defined by three or more ChRM directions. Sixty-two (62) lava sites meet our quality criteria, of which two fall outside a 45° cutoff angle around the mean direction; these data provide an average direction (declination, D; inclination, I) of $D \pm \Delta D = 339.8° \pm 3.4°$, $I \pm \Delta I = -7.4° \pm 6.7°$, $A_{95} = 3.4°$, Fisher precision parameter $K = 30.1$, $n = 60$, corresponding to a paleolatitude of 3.7°S (uncertainty window between 7.1°S, 0.3°S). The A_{95} value falls within the n-dependent confidence envelope of Deenen et al. (2011) ($A_{95\min} = 2.3°$; $A_{95\max} = 6.2°$), indicating that the data scatter can be straightforwardly explained by paleosecular variation of the paleomagnetic field alone. The data set passes the reversal test of McFadden and McElhinny (1990) (classification C), but fails the fold test of Tauxe and Watson (1994). Maximum clustering of directions occurs between 60% and 100% unfolding, but we note that the optimal clustering at the 80% unfolding level is only marginally better than at 100% unfolding (K = 30.9 versus K = 30.1), and the paleolatitude obtained at 80% unfolding of 2.4°S [5.8°S, 0.9°N] is statistically indistinguishable from the one obtained at 100% unfolding. Therefore, we interpret the HT ChRM direction at 100% unfolding as primary and use it for the tectonic analyses discussed below.

DISCUSSION

The paleomagnetic data for Lhasa—albeit sparse—suggest that it drifted away from the northern margin of Gondwana in Late Triassic time and moved ~40° in latitude (~4500 km) northward until it collided with the Qiangtang terrane at the southern margin of Eurasia in the Early Cretaceous (Fig. 2). Our new paleolatitude estimate from the Sangri Group volcanic rocks agrees well with this trend and shows that Lhasa was close to the equator in the Southern Hemisphere in Early Jurassic time (ca. 180 Ma). These constraints suggest an average northward drift rate of ~5 cm/yr for the plate to which Lhasa belonged, which is a reasonable estimate for plate tectonic motion and subduction rates (Van Der Meer et al., 2014). We note that the rifting preceding the drift, typically accommodating a few hundreds of kilometers of extension, may have started before the Late Triassic and cannot be paleomagnetically resolved.

Paleomagnetism can constrain the paleolatitude of a kinematically independent plate but not its paleolongitude. Hence, our result is consistent with interpretations of Metcalfe (1996),

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[1] GSA Data Repository item 2016234, Figures DR1–DR13, Tables DR1–DR5, supplemental Information, and compiled (as well as processed) paleomagnetic data (Tibet.pmag, Sangri.pmag, and site-mean direction files with .dir suffix that can be uploaded and viewed on www.paleomagnetism.org), is available online at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org.

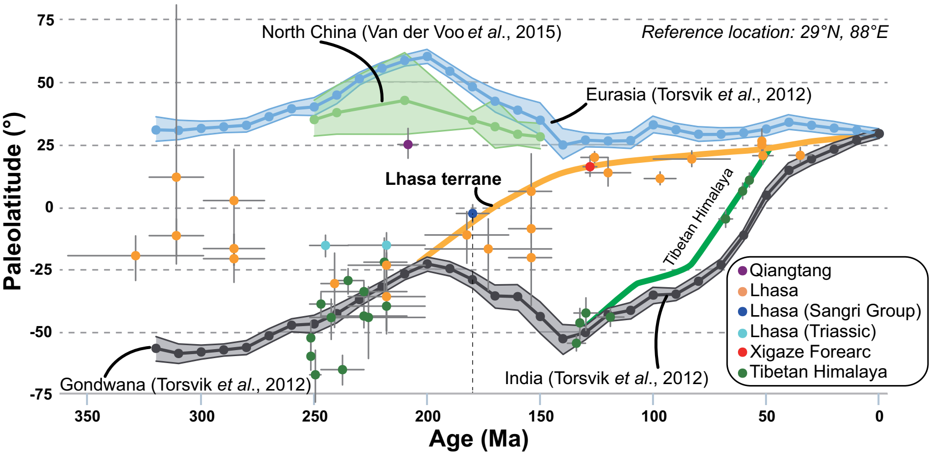

Figure 2. Paleolatitude versus time plot with paleomagnetic data of Tibetan terranes, generated using www.paleomagnetism.org (Koymans et al., 2016). All data are provided in Data Repository (see footnote 1). Eurasian and Gondwana-India paleolatitudes are from Torsvik et al. (2012); North China from Van der Voo et al. (2015); Tibetan Himalayan and Lhasa data for Early Cretaceous and younger from Ma et al. (2016) and compilation of Huang et al. (2015); pre-Cretaceous paleolatitudes of Tibetan Himalaya from compilation of van Hinsbergen et al. (2012); Triassic Qiangtang paleolatitude from Song et al. (2015); Permian to Jurassic paleolatitudes of Lhasa terrane from Zhu (1985), Ye and Li (1987), Dong et al. (1991), Guo (2009), Ran et al. (2012), and Zhou et al. (2016).

who placed Lhasa against the Tibetan Himalaya margin of Greater India, as well as with those of Zhu et al. (2011, 2013), who argued that Lhasa rifted from northwest Australia in Late Triassic time.

Our results demonstrate that Lhasa did not drift away from Gondwana together with the Qiangtang block, as widely portrayed (Stampfli and Borel, 2002; Torsvik and Cocks, 2013; Domeier and Torsvik, 2014). Recent paleomagnetic data from the Qiangtang terrane (Song et al., 2015) show that the Qiangtang terrane was already adjacent to northeast Tibet and the North China block in the Late Triassic, consistent with inferences from the geology of the Jinsha suture zone (Yin and Harrison, 2000). Therefore, the Qiangtang and Lhasa terranes must have been separated by an ocean basin thousands of kilometers wide that subducted along the Bangong-Nujiang suture zone (Fig. 3).

It is now possible to evaluate the plate tectonic history of the Paleo- and Neotethyan Oceans. From the Triassic to the Early Cretaceous, at least two major plates must have existed between Gondwana and Laurasia-Eurasia. A southern "Lhasa" plate moved northward relative to Gondwana, from which it must have been separated by a mid-ocean ridge. Lhasa converged with a plate that carried, among others, the North China block, northeast Tibet, and the Qiangtang terrane. The real plate configuration was likely more complex, with recent evidence also suggesting southward and northward subduction of the Bangong-Nujiang oceanic floor below both the Lhasa and Qiangtang terranes (e.g., Zhu et al., 2016).

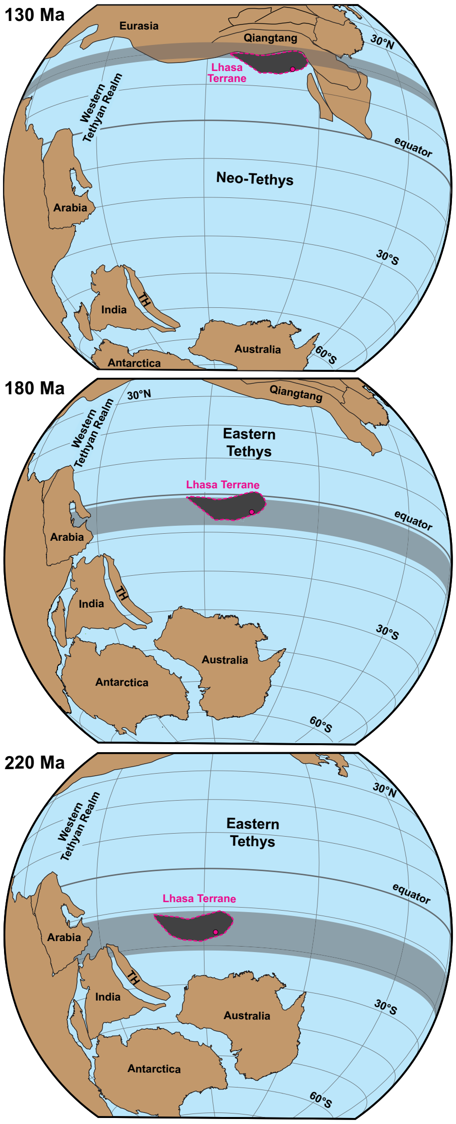

Figure 3. Paleogeography of Lhasa terrane (Tibet), using relative plate reconstruction of Seton et al. (2012) placed in paleomagnetic reference frame of Torsvik et al. (2012). Dimensions of Lhasa and Qiangtang follow from retrodeformation of van Hinsbergen et al. (2011). Note that the paleolongitudinal position of the Lhasa terrane is unconstrained by paleomagnetic data, which allow for a position adjacent to either Australia or India. TH—Tibetan Himalaya. A: 130 Ma, using paleolatitude of Lhasa provided by Ma et al. (2014). B: 180 Ma, using our new Sangri Group pole. C: 220 Ma, using paleolatitude from Dibu Co Lake locality of Zhou et al. (2016).

Our new data and synthesis of existing data show the promise of improving plate kinematic restorations of the Mesozoic Tethyan realm with the use of robust paleomagnetic data. Our new paleopole is consistent with older sediment-based data sets that lacked strong control on the age and fidelity of the magnetic remanence, but we emphasize that additional, high-quality paleopoles are required to quantitatively evaluate the Permian–Triassic drift history of Lhasa in the eastern Tethys realm.

CONCLUSION

We provide a new, high-quality, well-dated paleomagnetic pole from the Sangri Group volcanic rocks of the southern Lhasa terrane that indicates a paleolatitude of 3.7°S ± 3.4° at ca. 180 Ma. Our new pole confirms a trend shown by older and less rigorous data that suggests that Lhasa drifted from Gondwana in the Late Triassic, instead of in the Permian as widely perceived. We calculate a total northward drift of ~4500 km in ~90 m.y., yielding an average south-north plate motion rate of 5 cm/yr. Our results are consistent with Lhasa positioned adjacent to either India or Australia prior to rifting. We show that paleomagnetic data can provide a strong constraint on Mesozoic plate kinematic models of the Tethyan realm, and we urge the collection of new, high-quality, and well-dated paleomagnetic poles from upper Paleozoic and Mesozoic units of the Tibetan terranes.

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