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An early bird from Gondwana: Paleomagnetism of Lower Permian lavas from northern Qiangtang (Tibet) and the geography of the Paleo-Tethys

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A B S T R A C T

The origin of the northern Qiangtang block and its Late Paleozoic–Early Mesozoic drift history remain controversial, largely because paleomagnetic constraints from pre-Mesozoic units are sparse and of poor quality. In this paper, we provide a robust and well-dated paleomagnetic pole from the Lower Permian Kaixinling Group lavas on the northern Qiangtang block. This pole suggests that the northern Qiangtang block had a paleolatitude of $21.9 \pm 4.7°$S at *ca*. 296.9 ± 1.9 Ma. These are the first volcanic-based paleomagnetic results from pre-Mesozoic rocks of the Qiangtang block that appear to average secular variation accurately enough to yield a well-determined paleolatitude estimate. This new pole corroborates the hypothesis, first noted on the basis of less rigorous paleomagnetic data, the presence of diamictites, detrital zircon provenance records, and faunal assemblages, that the northern Qiangtang block rifted away from Gondwana prior to the Permian. Previous studies have documented that the northern Qiangtang block accreted to the Tarim-North China continent by Norian time. We calculate a total northward drift of *ca*. 7000 km over *ca*. 100 myr, which corresponds to an average south-north plate velocities of ∼7.0 cm/yr. Our results do not support the conclusion that northern Qiangtang has a Laurasian affinity, nor that the central Qiangtang metamorphic belt is an *in situ* Paleo-Tethys suture. Our analysis, however, does not preclude paleogeographies that interpret the central Qiangtang metamorphic belt as an intra-Qiangtang suture that developed at southernly latitudes outboard of the Gondwanan margin. We emphasize that rigorous paleomagnetic data from Carboniferous units of northern Qiangtang and especially upper Paleozoic units from southern Qiangtang can test and further refine these paleogeographic interpretations.

1. Introduction

The Paleozoic–Mesozoic tectonic evolution of what is now the crust of the Tibetan Plateau affected not only the pre-Cenozoic distribution of land and sea, ocean currents, and climate and ecological dynamics, but also set the stage for strain partitioning, regional climate patterns, and biogeography during the Cenozoic India–Asia collision (Dewey and Burke, 1973; Metcalfe, 2011). Thus, a more complete understanding of the geology, climate, and biology of the modern Tibetan plateau requires a thorough understanding of its complicated pre-Cenozoic history. For example, a series of continental fragments from the Tibetan Plateau have rifted and drifted northwards from Gondwana to Eurasia since the Late Paleozoic, opening the Meso- and Neo-Tethys oceans behind them and closing the ocean floor of Paleo-Tethys on their approach (Metcalfe, 2011; Yin and Harrison, 2000).

From south-to-north, these fragments include the Tethyan Himalaya (the northernmost continental rocks derived from the Indian plate) that collided with the Lhasa block between the Latest Cretaceous and Eocene (Cai et al., 2012; DeCelles et al., 2014; Ding et al., 2005); the Lhasa block (delineated by the Indus-Yarlung suture in the south and the Bangong-Nujiang suture (BNS) in the north) that sutured to the Qiangtang block in the Late Jurassic-Early Cretaceous (Kapp et al., 2007; Yan et al., 2016); and the Qiangtang block (delineated by the BNS in the south and the Jinsha suture in the north) that accreted to an amalgamated North

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China-Tarim block (NCB) during the Late Triassic (Ding et al., 2013; Roger et al., 2010; Song et al., 2015).

Quantifying the rift and drift history of these blocks allows us to reconstruct the opening and closing of the Tethys oceans and estimate ancient plate velocities in the absence of marine magnetic anomalies. To achieve this, the past positions of continents can be determined using paleomagnetism, anomalies, paleobiogeography, paleoclimate records, and stratigraphic and magmatic records. For example, the presence of Carboniferous glaciomarine diamicites associated with a cool-water biotic assemblage of Gondwana-affinities suggests that Qiangtang was part of Gondwana at that time (Golonka and Ford, 2000; Smith and Xu, 1988). The presence, however, of the Cathaysian fossil plant *Gigantopteris* in Permian limestones, as well as Permian subaerial and submarine lava flows consistent with rifting, imply that the Qiangtang block had separated from Gondwana sometime between the Carboniferous and Early Permian (Chang et al., 1986; Pearce and Mei, 1988). Some authors, however, have argued that Qiangtang rifted away from Laurasia (Pan et al., 2004; Xiao et al., 1986), and other authors have suggested that the Qiangtang block is comprised of separate northern and southern sub-blocks delineated by the Longmucuo-Shuanghu suture (Chen and Xie, 1994; Li, 1987). In this latter paleogeographic reconstruction, the northern Qiangtang block has Cathaysian or Laurasian affinities, whereas the southern block rifted from Gondwana (Leeder et al., 1988; Li, 1987; Zhang et al., 2013).

Because the transit of continental blocks from Gondwana to Eurasia resulted in large latitudinal motions, the magnitude and rate of this plate motion can be calculated using paleomagnetism (e.g., Li et al., 2016). Thus, in this study, we quantify the paleolatitudal history of the northern Qiangtang block from the Late Paleozoic to the present by reviewing existing paleomagnetic data to produce an apparent polar wander path (APWP). We test these reviewed data with a new, well-dated, statistically robust paleomagnetic pole that is based on Lower Permian Kaixinling Group lavas from the Tuotuohe region of the northern Qiangtang block. We compare our data to global APWPs (Torsvik et al., 2012) to test the geographic affinity (e.g., Gondwana *vs*. Laurasia) of the northern Qiangtang block and to provide quantitative reconstructions of the Late Paleozoic to Early Mesozoic Tethyan region in a paleomagnetic reference frame.

2. Geological setting and paleomagnetic sampling

The Qiangtang block lies between the Jinsha suture to the north and the Bangong-Nujiang suture to the south (Fig. 1a). Within Tibet, the Qiangtang block stretches from the Karakorum fault in the west to the Longmen Shan and Red River Shear Zone in the east. A large east–west-trending belt of Mesozoic metamorphic rocks, bounded by Late Triassic–Early Jurassic dome-shaped low-angle normal faults in the center of the Qiangtang block (Kapp et al., 2000; Pullen and Kapp, 2014), is referred to as the Longmucuo-Shuanghu suture (LSS) (Fig. 1a). Some authors distinguish a northern and southern Qiangtang block based on this suture (Li, 1987; Zhang et al., 2006).

Our study area lies along the northern edge of the northern Qiangtang block, some tens of kilometers south of the town of Tuotuohe and adjacent to the Lhasa–Golmud highway. Paleozoic to Cenozoic strata are widely exposed in this area, including the Upper Carboniferous to Middle Permian Kaixinling Group, which includes the Zarigen, Nuoribagaribao, and Jiushidaoban formations that consist of sandstones and mudstones, bi-modal volcanic rocks, and carbonates (Fig. A1; Li et al., 2012a). In contrast, the conformably overlying Upper Permian Wuli Group, which includes the Nayixiong and Lapochari formations, is mainly composed of carbonates and sandstones (Qinghai BGMR, 2005). The Upper Triassic Jieza Group, comprised of the Jiapila, Bolila, and Bagong formations, is predominantly composed of clastic and carbonate sediments but includes some intermediate-basic volcanic rocks (Qinghai BGMR, 2005); it is in angular unconformity with the underlying strata. Thus, field relationships distinguish a distinct phase of folding of the Late Carboniferous to Middle Permian Kaixinling Group and require that this folding occurred between the Late Permian and Late Triassic.

We selected two sections with distinctly different bedding orientations for paleomagnetic sampling of the volcanic rocks of the Lower Permian Nuoribagaribao formation (the middle part of Kaixinling Group) (Fig. 1b). In both of these sections, sedimentary strata, which range in thickness from a few meters to several tens of meters, are interbedded with volcanic rocks (Fig. A2). These volcanic rocks mainly consist of basalts and basaltic andesites that have amygdaloidal structures; interbedded sedimentary units in our field area are mostly comprised of sandstones and micritic limestones. We collected a total of 202 paleomagnetic samples from 22 volcanic sites within the two sections. Thirteen of these sites were collected at Section A (34°05.4′N, 92°21.9′E), where bedding dips ∼49° toward the southwest. Nine sites were sampled at Section B (34°03.6′N, 92°21.6′E), ∼5 km south of Section A, where the bedding dips ∼53° toward the northeast. Each sample site consists of at least eight core samples collected across several meters of lateral outcrop and across the height of each distinctive flow. All paleomagnetic samples were collected with a portable petrol-powered drill, oriented using both the sun and a magnetic compass to evaluate differences between local declinations and the current International Geomagnetic Reference Field of the study area. Because our data show that the average absolute difference between magnetic and solar compass readings across all sections was $0.8 \pm 0.4°$ ($n = 126$ of 202 samples), we are confident including samples that have no solar compass orientations in our results. Bedding attitudes were also measured from intercalated sediments using a magnetic compass.

3. U–Pb zircon ages of volcanic rocks

We extracted zircons from our bulk sample using routine crushing and heavy mineral separation techniques. Zircons were visually inspected with cathodoluminescence (CL) to characterize internal structures. We used laser-ablation-multicollector inductively coupled plasma mass spectrometry (LA-ICP-MS) to collect U and Pb isotopes on single zircons at the Key Laboratory of Continental Collision and Plateau Uplift (KLCCPU), Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS), Beijing, China. We report $^{206}Pb/^{238}U$ ages for grains less than *ca*. 1.0 Ga and $^{207}Pb/^{206}Pb$ ages for grains with ages greater than 1.0 Ga. Age estimates with >10% uncertainty are not used in our interpretations. Additional details of our analytical procedures, as well as the configuration of the LA-ICP-MS system, are described by Cai et al. (2012). We interpret the mean age of the youngest population ($n \geq 3$) of zircons with overlapping ages from a single sample as the crystallization age. All age calculations were made using Isoplot software (Ludwig, 2007).

CL images of 16 zircon grains from one basaltic andesite sample 12Qpc01 (Fig. 2a) show that individual crystals are anhedral or subeuhedral, with small or no xenocrystic cores. Four spots exhibit variable Th contents between 32 ppm and 408 ppm, U contents between 63 ppm and 321 ppm, and Th/U ratios between 0.4 and 1.4. These measurements correspond to slightly discordant apparent ages of 2262 ± 6 Ma, 346 ± 7 Ma, 340 ± 4 Ma, and 339 ± 3 Ma (see Fig. 2b and Table A1 for more information). We speculate that these zircons may have been incorporated from the basement during magma emplacement. The youngest population exhibits a range of Th concentrations between 18 ppm and 986 ppm, U con-