Late Triassic paleolatitude of the Qiangtang block: Implications for the closure of the Paleo-Tethys Ocean

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Abstract

To better constrain the Late Triassic paleolatitude of the Qiangtang block and the closure of the Paleo-Tethys Ocean, a combined paleomagnetic and zircon U/Pb geochronological study has been conducted on the Upper Triassic Jiapila Formation volcanic rocks on the northern edge of the Qiangtang block of Central Tibet (34.1°N, 92.4°E). These rocks are dated to 204-213 Ma. Progressive thermal or alternating field demagnetization successfully isolated stable characteristic remanent magnetizations (ChRM) that pass both the fold and reversal tests, consistent with a primary magnetization. These are the first volcanic-based paleomagnetic results from pre-Cretaceous rocks of the Qiangtang block that appear to average secular variation well enough to yield a reliable paleolatitude estimate. Based on our new paleomagnetic data from Upper Triassic lavas, we conclude that the Late Triassic pole of the Qiangtang block was located at 64.0°N, 174.7°E, with $A_{95}=6.6^{\circ}$ ($N=29$). We compile published paleomagnetic data from the Qiangtang block to calculate a Late Triassic latitude for the Qiangtang block at $31.7\pm3.0^{\circ}\text{N}$. The central Paleo-Tethys Ocean basin was located between the North China (NCB) and Tarim blocks to the north and the Qiangtang block to the south during Late Paleozoic-Early Mesozoic. A comparison of published Early Triassic paleopole from the Qiangtang block with the coeval paleopoles from the NCB and Tarim indicates that the

43 Paleo-Tethys Ocean could not have closed during the Early Triassic and
44 that its width was approximately $\sim 32\text{-}38^\circ$ latitude ($\sim 3500\text{-}4200$ km).
45 However, the comparison of our new combined Late Triassic
46 paleomagnetic result with the Late Triassic poles of the NCB and Tarim,
47 as well as numerous geological observations, indicates that the closure of
48 the Paleo-Tethys Ocean at the longitude of the Qiangtang block most
49 likely occurred during the Late Triassic.

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51 Key words: paleomagnetism; U/Pb geochronology; Upper Triassic
52 volcanic rock; paleolatitude; Qiangtang; Paleo-Tethys

1. Introduction

The formation and uplift of the Tibetan Plateau resulted from the convergence of a series of Gondwana-origin blocks towards the southern margin of the Eurasia plate since the Late Paleozoic, accompanied by the closing of three successive oceans (Paleo-Tethys, Meso-Tethys, and Neo-Tethys) (Ding et al., 2014; Metcalfe, 1996). The Paleo-Tethys Ocean basin was between the North China block (NCB) and Tarim blocks to the north and the Qiangtang block to the south (Ding et al., 2013; Pullen and Kapp, 2014). Knowing the age and kinematics of the closure of the Paleo-Tethys Ocean is critical to deciphering the evolution of Eurasia and Tethys, as well as the tectonic history of the Tibetan Plateau, particularly for understanding the paleogeography and collision history that preconditioned Tibetan lithosphere for subsequent collisional events and eventual surface uplift. However, large uncertainties remain in the timing of the closure of the Paleo-Tethys Ocean, and estimates include the Late Permian to Early-Middle Triassic (Jiang, et al., 2013; Sha and Fursich, 1999), the Late Triassic to Early Jurassic (Ding et al., 2013; Roger et al., 2010), and the Middle Jurassic to Middle Cretaceous (Yin and Harrison, 2000). One reason for these disparate age estimates is that different studies have utilized different methods to define collision, such as palaeontological data, magmatic activity, the onset of extensive contractile deformation, and the end of marine sedimentation.

Paleomagnetic data from Late Triassic rocks of the Qiangtang block are limited, such that paleomagnetism has not been used with rigor to address the timing of the closure of the Paleo-Tethys Ocean; these data could, however, provide independent

constraints on this collision history. For example, published paleomagnetic data from Late Triassic volcanic and sedimentary rocks yield paleolatitude estimates that range from 24°S to 30°N (Cheng, 2012; Lin and Watts, 1988; Song et al., 2012; Ye and Li, 1987). Song et al. (2012) obtained two Late Triassic paleopoles from the Late Triassic sedimentary rocks in the central Qiangtang block: one at 59.2°N, 179.2°E, with $A_{95}=4.1^\circ$, and the other at 65.1°N, 184.4°E, with $A_{95}=3.7^\circ$; data for both poles pass fold and reversal tests. We note, however, that paleomagnetic results from Cenozoic sediments in Asia record inclinations that are 10-30° more shallow than coeval volcanic rocks or predicted from the coeval Eurasia reference poles (e.g., Dupont-Nivet et al. 2010; Lippert et al., 2011), probably due to deposition and compaction of sediments (Kodama, 2012) or non-dipole field effects (Si and Voo, 2001). Although volcanic rocks should be immune from these forms of inclination shallowing, the only published Late Triassic volcanic data set (Lin and Watts, 1988) from the Qiangtang Block is comprised of too few paleomagnetic sites to characterize secular variation and these data lack field tests. In this paper, we describe new paleomagnetic and U/Pb geochronologic data of the Upper Triassic Jiapila Formation volcanic rocks from the northern edge of the Qiangtang block to address the limitations in previous data sets. Our goal is to better constrain the paleolatitude of the Qiangtang block, which will allow us to independently test the range of permissible Qiangtang and Tarim-NCB collision ages.

2. Geological setting and paleomagnetic sampling

From north to south, the interior of the Tibetan plateau comprises the approximately east-west-trending Kunlun-Qaidam, Songpan-Ganzi/Hoh Xil, Qiangtang, and Lhasa blocks; these blocks are separated by approximately east-striking suture zones of Late Paleozoic to Mesozoic ages (Fig. 1a) (Chang et al., 1986; Ding et al., 2013). The Qiangtang block, which lies between the Jinsha suture (Paleo-Tethys) to the north and the Bangong-Nujiang suture (Meso-Tethys) to the south, is approximately 400-500 km wide in the central part, and it narrows to <150 km in the western and eastern parts (Fig. 1a; Yin and Harrison, 2000). A large E-W-trending belt of Mesozoic high-pressure metasedimentary-matrix tectonic mélange in the core of a crustal-scale antiformal culmination is bounded by Late Triassic-Early Jurassic domal low-angle normal faults in the central Qiangtang (Pullen and Kapp, 2014) (Fig. 1a). Volcanic and volcanic-sedimentary rocks of Late Triassic age are found throughout the Qiangtang region (Wang et al., 2008a).

The sampled area lies along the northern edge of the Qiangtang block tens of kilometers south of the town of Tuotuohe along the Lhasa-Golmud Highway. Paleozoic to Cenozoic strata are widely exposed in outcrop in this area. The Carboniferous Zaduo Group is mainly composed of clastic and carbonate rocks of passive continental-margin shelf to continental rise depositional environments, and the Permian Kaixinling Group consists of sandstones and mudstones, bi-modal volcanics, and carbonates (Li et al., 2012). The Upper Triassic Jieza Group (comprising the Jiapila, Bolila, and Bagong Formations), which is predominantly composed of clastic and carbonate sediments, as well as intermediate-basic volcanic

rocks, unconformably overlies the Carboniferous-Permian strata (Ding et al., 2013). The Jieza Group is unconformably overlain by Middle-Upper Jurassic Yanshiping Group and Cretaceous-Cenozoic rocks (Li et al., 2012; Pearce and Mei, 1988). The Middle-Upper Jurassic Yanshiping Group is overlain in angular unconformity by Cretaceous strata (Qinghai BGMR, 2005). Hence, the time of the deformation of the Yangshiping Group is inferred to be Late Jurassic-Early Cretaceous, which is coeval with the Qiangtang-Lhasa collision (Dewey et al., 1988; Kapp et al. 2007). Similar deformation observed in the Jieza Group should not have occurred after that of the Yanshiping Group. Therefore, we conclude that the folding of the Upper Triassic Jieza Group occurred should not occur after the Late Jurassic-Early Cretaceous, when the Lhasa block accreted onto the Qiangtang block (Kapp et al., 2007).

Initially, Pearce and Mei (1988) [ENREF 49](#) assumed the volcanic series outcropping south of Tuotuohe were entirely of Late Permian age, based on the observation that the volcanic sequence conformably overlies lower Upper Permian limestone in certain places and is overlain by coal-bearing Upper Permian clastic rocks observed elsewhere. However, paleontological data show that both Permian and Triassic fauna occur in the sedimentary rocks in this area (Sha, 1998). Moreover, field studies and radiometric age studies (Wang et al., 2008b) showed that the Permian volcanic suites are entirely composed of basalts; in contrast, the Triassic suites are mostly comprised of basalt-andesite (or rhyolite). Thus, geochronological data confirm that Triassic volcanic rocks occur south of the Tuotuohe area. We collected one basaltic andesite and one sandstone sample from our sampled sections for zircon U-Pb

geochronological dating to compare with the results of Wang et al. (2008b).

We selected three sections with different bedding orientations for paleomagnetic sampling of the Upper Triassic Jiapila Formation volcanic rocks to the south of the town Tuotuohe (Fig. 1b). At all three sections, the volcanic rocks are interbedded with sedimentary rocks with thicknesses ranging from a few decimeters to a few tens of meters (Figs 2c, d). The volcanic rocks mainly consist of basalts, trachybasalts, and basaltic andesites with partially doleritic texture and amygdaloidal structure (Fig. 2). The sedimentary rocks mostly comprise laterally continuous, tabular mudstones, fine sandstone and micritic limestone. Therefore, we assume that, on first order, the sedimentary and volcanic layers were originally horizontal, although we acknowledge that the rocks may have been deposited on a small tilt. Forty-two volcanic paleomagnetic sites, involving 355 samples, were collected from the three sections. Nineteen of these sites were drilled at Section A (34°06.3'N, 92°22.4'E), situated ~30 km south of Tuotuohe; here bedding dips 47-57° towards the northeast. Fifteen sites were sampled at Section B (34°06.03'N, 92°22.8'E), ~1 km from Section A, where the bedding dips 51-56° towards the northeast. Eight sites were sampled at Section C (34°07.8'N, 92°22.4'E); this section lies approximately 3 km north of Section A, and the dip is ~51° towards the west (Fig. 1b). Generally, each site comprises of at least 7 core samples and spans several meters in stratigraphic thickness, or at least one distinctive lava flow. All paleomagnetic samples were collected with a portable petrol-powered drill and oriented by both sun and magnetic compasses in order to evaluate any differences between local declinations and the present International

Geomagnetic Reference Field in the study area. The average absolute difference between the magnetic and solar compass readings was $3.3 \pm 1.3^\circ$ ($n=242$) at all sections; therefore, we feel confident including samples with no solar compass corrections in the results. Bedding attitudes were measured from intercalated sediments using a magnetic compass.

3. Zircon U-Pb analytical methods and results

Zircons were separated from bulk samples using routine crushing and heavy mineral separation techniques. The zircons were visually characterized with cathodoluminescence (CL) images to reveal any internal structures. U-Pb spot analyses were performed on single zircons separated from the volcanic and sandstone samples using laser-ablation-multicollector inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Key Laboratory of Continental Collision and Plateau Uplift (KLCCPU), Institute of Tibetan Plateau Research, Chinese Academy of Sciences (ITPCAS), Beijing, China. The ages reported in the text are $^{206}\text{Pb}/^{238}\text{U}$ ages for grains less than ~ 1000 Ma and $^{207}\text{Pb}/^{206}\text{Pb}$ ages for grains with ages > 1000 Ma. Ages with $> 10\%$ uncertainty ($^{206}\text{Pb}/^{238}\text{U}$) were not included in the interpretation. More detailed analytical procedures and the configuration of the LA-ICP-MS system are described in [Cai et al. \(2012\)](#) [ENREF 3](#) [ENREF 2](#). We analyzed 24 zircon grains to date the volcanic rock, and we interpret the mean age of the youngest population (not less than three ages) of zircon ages to be the crystallization age. For the sandstone sample, the youngest population of zircon ages is used to provide constraints on the

maximum permissible depositional age.

The CL images of 24 zircon grains from the basaltic andesite sample (12Qtc01; [Fig. 3a](#)) show that individual crystals are anhedral or subeuhedral, with no or few xenocrystic cores. Four spots have variable Th contents of 53-390 ppm, U contents of 171-1299 ppm, and Th/U ratios from 0.9 to 3.9 and yield slightly discordant apparent ages of 2151 ± 5 Ma, 1152 ± 12 Ma, 879 ± 5 Ma, and 794 ± 6 Ma, respectively ([Fig. 3b](#); for more information on the age range, please see [Table A.1](#) in the Supplementary material). These zircons may have been incorporated from the basement during the upwelling of the lava. The remaining youngest population exhibits a range of Th concentrations from 74 to 4211 ppm, U concentrations from 45 to 1127 ppm, and Th/U ratios mostly from 0.5 to 1.6. The twenty youngest results produce a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 203.6 ± 0.62 Ma (2σ , MSWD=0.43; [Fig. 3b](#)), calculated using the Isoplot program ([Ludwig, 2007](#)). These zircons have Th/U ratios consistent with a magmatic origin, and we interpret this age to be the crystallization age of this volcanic rock.

The sandstone sample, 12Qtc02, was collected from the lower part of the Upper Triassic volcanic series in section B. Individual zircon crystals are subeuhedral or euhedral and yield Th/U ratios of 0.06-2.24; we measured 91 usable ages (see some representative zircon CL images in [Fig. 3c](#); for more information on the age range, please see [Table A.2](#) in the Supplementary material). There are two main age populations: 200 to 1000 Ma and 1800 to 2500 Ma, as well as one significantly older age of 3481 ± 4 Ma. The three youngest ages are 210 ± 3 Ma, 212 ± 2 Ma, and 214 ± 1 Ma,

with a mean age of 213.3 ± 1.7 Ma (2σ) (MSWD=1.06; Fig. 3d). Our new U-Pb results are relatively consistent with the previously published $^{206}\text{Pb}/^{238}\text{U}$ age of $\sim 229 \pm 7$ Ma and whole-rock ^{40}Ar - ^{39}Ar plateau age of $\sim 219 \pm 5$ Ma for rock in our sampling area (Fig. 1; Wang et al., 2008b). Furthermore, the limestone in the Jiapila Formation around the Tuotuohe area contains the brachiopoda *Zhidothyris yulongensis*, *Septamphiclina qinhaiensis*, *Timorhynchia sulcata* (Qinghai BGMR, 2005), suggesting a Late Triassic age, which is consistent with our new U-Pb results. In conclusion, we are confident in the Late Triassic (204-213 Ma) ages of these volcanic sequences in this study. Our slightly younger ages probably reflect a difference in sampling locality from Wang et al. (2008b) and suggest that volcanism in this area was prolonged throughout the Late Triassic.

4. Rock magnetism

To identify magnetic carriers and select appropriate demagnetization steps, the isothermal remanent magnetization (IRM), back-field demagnetization of saturation IRM, and hysteresis parameters were measured in one powdered sample from each site using a variable field translation balance (VFTB) and a Princeton Measurements Corporation Model 3900 vibrating sample magnetometer. We measured the temperature dependence of magnetic susceptibility for one pilot sample from each site, with heating-cooling runs from room temperature to 700°C in an air-based atmosphere. This procedure used a CS-3 heating device coupled to a Kappabridge KLY-3 (AGICO). These instruments are located at the Paleomagnetism and

Geochronology Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences. The magnetic properties of some samples were measured at the Paleomagnetic Laboratory at UC Santa Cruz (UCSC, see [Table 1](#)). There, magnetic hysteresis properties were measured on a Princeton Measurement Corporation Model 2900 alternating gradient magnetometer and the temperature dependence of magnetic susceptibility was measured using a Kappabridge KLY-2 (AGICO).

Based on the rock magnetic experiments, all specimens can be divided into two general groups ([Fig. 4](#)). In the first group (sites Qt01-05, Qt11-12, Qt16-17, Qt19-26, Qt30-32, and Qt35-42), the IRM curves ([Fig. 4a](#)) exhibit a gradual increase, and saturation is not completely reached even at 1.5 T; these observations indicate that high-coercivity magnetic carriers dominate the magnetic remanence. The wasp-waisted hysteresis loops suggest the presence of both low- and high-coercivity magnetic carriers ([Fig. 4b](#)) ([Tauxe et al., 1996](#)). The thermomagnetic curves show distinct changes in magnetic susceptibility near 580°C and near 680°C ([Fig. 4c](#)). Collectively, these results suggest that both low-Ti titanomagnetite and hematite are the main carriers of remanence in the first group of samples. Therefore, samples from this group were demagnetized using only progressive thermal methods.

In the second group (sites Qt06-10, Qt13-15, Qt18, Qt27-29, and Qt33-34), the IRM usually reaches saturation at less than 200 mT ([Fig. 4d](#)). Magnetic hysteresis loops are typically upright and slightly pot-bellied ([Fig. 4e](#)). Thermomagnetic curves show a distinct change in magnetic susceptibility near 580°C. Take together, these results indicate a simple magnetic mineralogy dominated by low-Ti titanomagnetite

(Fig. 4f). Magnetic squareness (M_{rs}/M_s) and coercivity (H_{cr}/H_c) ratios range from 0.04 to 0.3 and from 2.0 to 5.0, respectively, and plot within the pseudo-single domain range of a Day plot (Dunlop, 2002; Fig. A.1 in the Supplementary material). Samples from this group were demagnetized using both progressive thermal and alternating field (AF) demagnetization methods.

To check whether the hematite in the first group was produced by low-temperature oxidation (LTO) of original Ti-rich titanomagnetite, a thorough microscope examination of several representative specimens from sites Qt04 and Qt38 was performed. We used an electron probe microanalyzer (EMPA) (JXA-8230, JEOL, Japan) in back-scattered electron (BSE) imaging mode with an acceleration voltage of 15 kV and a working distance of 11.0 mm at the KLCCPU of ITPCAS. The polished specimens were carbon-coated before analysis to improve the quality of the images. Energy dispersive spectrometer (EDS) analyses were conducted using an EMPA equipped with an X-Max 50 EDS analyzer (Oxford Instruments PLC, Abingdon, Oxfordshire, UK).

The specimens from Sites Qt04 and Qt38 show doleritic textures, and consist of strip-shaped microcrystalline plagioclase and interstitial fine-grained Fe-oxide and pyroxene grains. The BSE images reveal that most Fe oxide grains in the studied volcanic specimens have irregular shapes and a variety of sizes that range from 10 μm to 50 μm ; we did not observe obviously oxidized rims (Figs 5a,b). The EDS analyses indicate that all the Fe oxides have only small amounts of titanium (Figs 5c-f). These results, combined with the IRM, hysteresis, and thermomagnetic results, suggest that

both low-Ti titanomagnetite and hematite were produced by exsolution during initial cooling (Geissman and Van der Voo 1980), rather than by a LTO process of primary Ti-rich titanomagnetite long after cooling. This hypothesis is consistent with demagnetization results described below that indicate low-Ti titanomagnetite and hematite carry the same remanence direction (Fig. 6).

5. Paleomagnetic results

All specimens were subjected to either progressive thermal or AF demagnetization. The majority of the specimens were treated with progressive thermal demagnetization, which was conducted in either an ASC-TD 48 thermal demagnetizer (China University of Geosciences, Beijing (CUGB)) or a custom-built furnace (UCSC), both with a residual magnetic field of less than 10 nT in the center of the ovens. Thermal demagnetization intervals were 50-100°C at lower temperatures and as small as 5-10°C at higher temperatures near the Curie point. Progressive AF demagnetization was conducted using a D-Tech D-2000 AF demagnetizer with AF current field intervals that were generally smaller (2-3 mT) at lower fields and larger (5-10 mT) at higher fields. Most remanent magnetization measurements were measured with an AGICO JR-6A spinner magnetometer and a 2G-755-4K cryogenic magnetometer, installed at the Paleomagnetic and Environmental Magnetism Laboratory at the CUGB, where the magnetometers and demagnetizers have been installed in a shielded room with residual fields less than 300 nT; for samples at UCSC, remanent magnetization was measured using an AGICO JR-5 spinner magnetometer.

The demagnetization results were plotted on orthogonal vector diagrams, and directions were calculated by principal component analysis. Well-defined ChRMs isolated by the two treatment types are generally indistinguishable from each other (Fig. 6). Site-mean directions were determined using standard Fisher statistics. Following Huang et al. (2005a), Johnson et al. (2008), and Lippert et al. (2011), site mean directions defined by fewer than five samples, by 95% confidence cones (α_{95}) larger than 15° , or by precision parameters (κ) less than 50 were excluded from further analysis. This ensured site mean directions at comparable scatter and quality.

Several (e.g. >10) independent spot readings (i.e. distinct mean directions) are required to accurately represent the time-averaged behavior of the geomagnetic field. Because the length of time between the eruption of successive lava flows is often much less than the typical timescale of geomagnetic secular variation, each site at a specific sampling locality may not represent an independent sampling of the geomagnetic field. Indeed, visual inspection shows that site mean directions cluster into a few groups (Fig. 7b). Therefore, we have grouped site mean directions to reduce redundant sampling: stratigraphically successive site mean directions are compared using a standard F-test for a common true mean direction (McFadden and Lowes, 1981). Group mean directions for successive sites found to share a common direction were then calculated by taking the Fisher mean direction of all samples in the grouped sites.

Paleomagnetic studies of the present and ancient magnetic field show that virtual geomagnetic poles (VGPs) fit a Fisherian distribution better than site mean directions

(e.g., [Johnson et al., 2008](#)). Therefore, we transform site and group mean directions into VGPs, calculate the Fisher mean VGP, and then calculate the mean direction following ([Butler, 1992](#)). Uncertainties on the mean inclination and declination follow [Demarest \(1983\)](#).

The intensity of the natural remanent magnetization (NRM) varies from 0.02 A/m to 10 A/m, with a predominant range of 0.1 A/m to 2 A/m. In general, both thermal and AF demagnetization can successfully isolate a stable ChRM. A low-temperature component (LTC) was generally removed at temperatures less than 400°C ([Fig. 6](#)). The mean direction of the LTC is $D=1.7^\circ$, $I=51.8^\circ$, with $\kappa=6.6$, and $\alpha_{95}=6.5^\circ$ ($n=83$, *in situ* coordinates), which is indistinguishable from the present geocentric axial field direction ($D=0^\circ$ and $I=53.6^\circ$) in this region ([Fig. 7a](#)). These results, combined with a negative fold test ([Watson and Enkin, 1993](#)) for the LTC, suggest that it is probably a viscous remanent magnetization acquired recently. The high-temperature component (HTC) decays toward the origin at temperatures from $\sim 400^\circ$ to 580-680°C or to peak alternating fields of 80-120 mT ([Fig. 6](#); for more information on the HTC directions, please see [Table A.3](#) in the Supplementary material). Most sites yield a normal-polarity HTC ([Figs 6a-l](#)), but six sites record a reversed polarity HTC that is antipodal to the normal-polarity HTC ([Figs 6m-p](#)).

[Table 1](#) and [Fig. 7](#) show the site/group mean directions of the volcanic sites/groups and their VGPs. All 42 sites yield a Fisher mean VGP at 63.8°N , 179.7°E , ($A_{95}=6.2^\circ$, $K=13.5$, $S=22.3^\circ$) in tilt-corrected coordinates; the corresponding tilt-corrected mean direction is $50.6\pm 5.5^\circ$ inclination and $31.1\pm 5.8^\circ$ declination (Mean-A). However, a

few of these sites do not meet our data quality criteria and the mean direction of Sites Qt11 and Qt19 were discarded from further analysis due to too few samples and Sites Qt29 and Qt39 are excluded because they are defined by large 95% confidence cones (α_{95}) or low precision (κ) of their mean directions. The thirty-eight remaining sites yield a Fisher mean VGP at 63.9°N, 177.7°E, ($A_{95}=6.2^\circ$, $K=15.1$, $S=21.0^\circ$) in tilt-corrected coordinates; the corresponding tilt-corrected mean direction is $51.6\pm5.4^\circ$ inclination and $31.2\pm5.9^\circ$ declination (Mean-B). We note that some of the stratigraphically adjacent site-mean directions are indistinguishable from each other, and that the 38 sites can be binned into thirty-one independent group mean directions. These 31 group mean directions yield a Fisher mean VGP at 65.0°N, 179.8°E, ($A_{95}=7.0^\circ$, $K=14.6$, $S=21.5^\circ$) in tilt-corrected coordinates; the corresponding tilt-corrected mean direction is $50.9\pm6.1^\circ$ inclination and $29.7\pm6.6^\circ$ declination (Mean-C).

The tilt-corrected group-mean directions of groups T09 and T26 are located $>30^\circ$ from the group mean direction of 31 direction groups (Mean-C), suggesting that these two group-mean directions may record transitional or excursions geomagnetic field behavior (Huang et al., 2005a). Group T09 is stratigraphically located between Group T08 (reversed polarity) and Group T10 (normal polarity) (Table 1), and the T09 and T26 directions are similar. Therefore, we suggest that these two group-mean directions record a transitional geomagnetic field direction and should not be used to characterize the time-averaged position of the geomagnetic pole. After excluding these two anomalous directions, the remaining 29 groups yield a Fisher mean VGP at

0.7°N, 252.4°E, ($A_{95}=14.0^\circ$, $K=4.6$, $S=37.8^\circ$) in *in situ* coordinates; the corresponding *in situ* mean direction is $-67.6\pm 8.0^\circ$ inclination and $32.5\pm 17.9^\circ$ declination. The Fisher mean VGP of tilt-corrected Fisher mean VGP at 64.0°N , 174.7°E ($A_{95}=6.6^\circ$, $K=17.2$, $S=19.5^\circ$), resulting in a tilt-corrected mean direction of $53.0\pm 5.5^\circ$ inclination and $31.4\pm 6.3^\circ$ declination (Mean-D).

The 29 tilt-corrected group-mean directions (Mean-D) show significant improvement in the grouping compared to the *in situ* directions ($\kappa_s/\kappa_g=4.34$, critical value of 1.87 at 99% confidence and 1.56 at 95% confidence, (McElhinny, 1964)) and pass the fold test at high confidence ($\xi_2=21.30$ before, and $\xi_2=0.83$ after tilt correction, critical value $\xi=8.86$ at 99% and $\xi=6.26$ at 95% confidence level) (McFadden, 1990). A progressive unfolding correction shows that the site-mean direction has the highest precision parameter at 103.6% unfolding (with 95% uncertainties ranging from 100.4% to 107.3%) (Watson and Enkin, 1993). Furthermore, the reversal test is positive at the 95% confidence level (McFadden and McElhinny, 1990) (Fig. 7, Table 1). Therefore, we conclude that the group Mean-D direction indicates a pre-folding origin; we attribute this folding to the Lhasa-Qiangtang collision, which occurred in Late Jurassic-Early Cretaceous time (Kapp et al., 2007).

We conclude that the ChRM directions of the 29 groups that define Mean-D record a primary thermoremanence. We do not observe any paleomagnetic, rock magnetic, or petrographic evidence that suggests the ChRM directions are biased by unremoved overprints. Based on the paleomagnetic analysis discussed above, we report a new Late Triassic paleopole for the Qiangtang block at 64.0°N , 174.7°E ($A_{95}=6.6^\circ$,

K=17.2, S=19.5°) ([Table 1](#)), corresponding to a paleolatitude of $\sim 33.5 \pm 6.6^\circ\text{N}$ for the Qiangtang block in the Late Triassic (reference point: 34.1°N , 92.4°E).

6. Paleosecular variation

To obtain accurate paleolatitudes, we not only have to measure structural corrections accurately but also characterize secular variation sufficiently. A generally accepted approach to evaluate averaging of secular variation is to examine the angular dispersion (S) of VGPs in a sample set, assuming that each VGP (or virtual paleolatitude) is an independent and instantaneous record of the geomagnetic pole position. We compare the VGP dispersion of our paleomagnetic pole to the dispersion observed in ancient lava sequences (e.g., [Johnson et al., 2008](#)) that do yield good estimates of the GAD field when averaged; we also compare our results to the scatter calculated from secular variation models based on these time-averaged field data (e.g., [Tauxe and Kent, 2004](#)). Our assumption is that the Triassic geomagnetic field behaved on first-order similar to the recent geomagnetic field.

The S parameter of the Qiangtang lava data set can be calculated from the Fisher's precision parameter (K) of the VGPs using $S=(2/K)^{0.5}$, where S is in radians ([Cox, 1970](#)). The direction groups represent independent samples of the ancient geomagnetic field and, we argue, are hence most suitable for calculating S parameter. We use an arbitrary and liberal precision uncertainty of $\pm 5^\circ$ following [Lippert et al. \(2011\)](#); in truth, this value may be higher or lower. The Upper Triassic volcanic rocks yield a VGP dispersion of 19.5° (95 percent confidence interval of $18.6\text{--}20.5$) at

~33.5°N, which is consistent with the $S_\lambda=21.3$ (with the limits 18.3-24.2) for the ~200 Ma Central Atlantic Magmatic Province flood basalts (Knight et al., 2004) and $S_\lambda=15.6$ (with the limits 12.5-18.8) of dispersion observed in VGP populations from 0-5 Ma lavas at a similar latitude (Johnson et al., 2008). We also note that the radius of the cone of confidence around the mean VGP position (A_{95}) is 6.6°, which is well within the value consistent with a pole population that averages paleosecular variation (4.4-9.8°, Deenen et al., 2011). In conclusion, these observations, combined with the fact that the HTC directions include dual polarities and pass the positive reversal test at 95% confidence, strongly suggest that the group mean directions of the Upper Triassic volcanic rocks have a primary origin and have adequately characterized geomagnetic secular variation, and are therefore suitable for paleogeographic reconstructions.

7. Discussion

7.1 Late Triassic position of the northern Qiangtang Block

Several paleomagnetic investigations of Upper Triassic rocks from the Qiangtang block have been completed; however, significant discrepancies exist between them, with estimates for upper Triassic latitudes ranging from 24°S to 30°N. We summarized all the available Late Triassic data of the Qiangtang block (ENREF 31 ENREF 44Fig. 8; please see Table A.4 in the Supplementary material for more information) and apply the seven reliability criteria of Van der Voo (1990) to appraise them. These reliability criteria include (1) well-determined rock ages and the

assumption that the magnetization age is the same as the actual rock age, (2) a ‘sufficient’ number of samples, (3) proper demagnetization techniques and documentation, (4) field tests to constrain the age of the magnetization, (5) structural control and tectonic coherence with the craton or block involved, (6) the presence of reversals, and (7) no resemblance to paleopoles of younger ages. For example, a quality factor of $Q=5$ (with 7 being the best) means that five of these quality criteria are satisfied. Certain criteria (such as criteria 4 and 6), which indicate whether the magnetization is primary, are obviously more important than others when calculating an accurate paleolatitude. In all of the paleolatitude calculations that follow, we assume a geocentric axial dipole (GAD) geomagnetic field and calculate the paleolatitude of a reference site located at 34.1°N , 92.4°E in present coordinates.

[Lin and Watts \(1988\)](#) reported a Late Triassic paleopole from Batang Group volcanic rocks to the north of the Tuotuohe area (approximately 80 km north of our study area). This paleopole is based on only five sites (34 specimens) and yields a paleolatitude of $\sim 27.9 \pm 17.1^{\circ}\text{N}$ for the reference site. Although the paleolatitude within the 95% confidence level is also consistent with that of our volcanic rocks ([Fig. 8](#)), we do not include this volcanic paleopole in further discussions because it is based on only 5 sites, has a large latitude error, and lacks any robust field tests for the relative age of the magnetization. A paleopole (31°N , 279.5°E , with $A_{95}=21.9^{\circ}$) based on Upper Triassic sedimentary rocks was reported by [Ye et al. \(1987\)](#) and corresponds to a paleolatitude of $\sim 24.5 \pm 21.9^{\circ}\text{S}$ for the reference site. We also excluded this paleomagnetic result from further discussions because it has no robust field test or

detailed sampling and demagnetization information. Another paleomagnetic result was obtained from four sedimentary sites (26 specimens) in the Upper Triassic Jieza Group (Cheng, 2012). This result, which yields a paleolatitude of $\sim 17.9 \pm 13.5^\circ \text{N}$ for the reference site, was discarded because it has too few paleomagnetic sites and no field tests.

In contrast, our paleomagnetic data from the volcanic Upper Triassic Jiapila Formation fulfills all seven quality criteria of Van der Voo (1990), and paleosecular variation appears to have been characterized. The tilt-corrected direction of 29 volcanic groups (Mean-D) yields a paleolatitude of $\sim 33.5 \pm 6.6^\circ \text{N}$ for the northern Qiangtang block for the reference site. Furthermore, Song et al. (2012) obtained two Late Triassic paleopoles from the Tumengela Formation and Zala Formation in the central Qiangtang block: one at 59.2°N , 179.2°E , with $A_{95} = 4.1^\circ$ and the other at 65.1°N , 184.4°E , with $A_{95} = 3.7^\circ$. These paleopoles correspond to paleolatitudes of $30.3 \pm 4.1^\circ \text{N}$ and $29.7 \pm 3.7^\circ \text{N}$ for the reference site. These two paleomagnetic results also fulfill all seven of the quality criteria. When compared our new results reported here, these data suggest that inclination shallowing may have been negligible in the Tumengela and Zala Formations. Because both our volcanic and the sedimentary results from Song et al. (2012) fulfill all seven criteria and are statistically indistinguishable (Fig. 8), we have combined the site-mean or group-mean directions from both studies to calculate the paleolatitude for the Qiangtang block.

To calculate the mean paleolatitude of the Qiangtang block, we first transform each site/group mean direction to its corresponding VGP. The inclination (corresponding to

paleolatitude-only) for a common site in the Qiangtang (34.1°N, 92.4°E) is then calculated for each VGP. The corresponding paleolatitude is calculated assuming a GAD field: $\lambda = \tan^{-1}[\tan(I)/2]$, where λ is the virtual paleolatitude of the sampling site or group and I is the calculated site or group inclination at the reference site from each VGP. Finally, the maximum likelihood paleolatitude of these virtual paleolatitudes is calculated following the method of [Arason and Levi \(2010\)](#). Uncertainties in paleolatitudes are calculated following [Demarest \(1983\)](#) and the procedure of [Arason and Levi \(2010\)](#). Except for the three sedimentary sites (sites x4, x7, and x8) with larger directional uncertainties ($\alpha_{95} > 15$) in the Xiaochaka area ([Song et al., 2012](#)), the forty-nine Late Triassic paleomagnetic sites and groups observed in the Qiangtang block yield a paleolatitude of $31.7 \pm 3.0^\circ\text{N}$ (Supplementary material, [Table A.5](#)). In this study, we use $31.7 \pm 3.0^\circ\text{N}$, which was calculated from the 29 volcanic groups and 18 sedimentary sites on the Qiangtang block, as the Late Triassic position of the northern margin of Qiangtang Block (specifically, the reference point at 34.1°N, 92.4°E).

7.2 Constraints on the evolution of the Paleo-Tethys Ocean

Similarities in detrital zircon age populations suggest that the accretion of the Songpan-Ganzi ‘basement’ and Kunlun-Qaidam blocks to the NCB was complete by Silurian-Permian time (e.g., [Gehrels et al., 2003](#)). Therefore, in this paper we associate the Songpan-Ganzi and Kunlun-Qaidam blocks with the NCB. The east-central Paleo-Tethys Ocean basin was located between the NCB and Tarim blocks to the north and the Qiangtang block to the south ([Metcalf, 1996](#); [Ding et al.,](#)

2013; Pullen and Kapp, 2014); farther east, the Paleo-Tethys separated the NCB from the South China block (SCB) (Metcalf, 1996). Thus, to analyze the evolution of the Paleo-Tethys Ocean, the calculated paleolatitudes of the Qiangtang block should be compared to the expected paleolatitudes of the southern margin of the NCB and Tarim blocks during the Triassic. Our new paleomagnetic results from Upper Triassic volcanic rocks from the northern Qiangtang block provide a key constraint on the evolution of the Paleo-Tethys Ocean.

In the following discussion, a common reference point located at 34.1°N, 92.4°E in the north-central Qiangtang terrane is used for all paleolatitude comparisons. Zhao et al. (1996) reviewed Early Triassic poles of the NCB and calculated an average pole using data from eight studies. The mean Early Triassic pole for NCB lies at 57.9°N, 357.4°E, with $A_{95}=4.8^\circ$, which corresponds to a paleolatitude of $25.9\pm4.8^\circ\text{N}$ for our reference point. The Early Triassic pole of the Tarim block obtained from six sedimentary sites (41 specimens) reported by McFadden et al. (1988) is located at 69.3°N, 182.9°E, with $A_{95}=12.8^\circ$, and yields a paleolatitude of $31.5\pm12.8^\circ\text{N}$. We use this paleopole to calculate the Early Triassic paleolatitude of the Tarim block, because the underlying paleomagnetic data record dual-polarity directions and fulfill six of Van der Voo's (1990) criteria. In contrast, the paleomagnetic results from the Lower Triassic Kanglu Formation sedimentary rocks from the Qiangtang block yield a paleopole at 16.9°N, 202.5°E, with $A_{95}=6.7^\circ$, corresponding to a paleolatitude of $-6.3\pm6.7^\circ\text{S}$ for the reference point (Cheng et al., 2012). Although this paleomagnetic result has 2 sites (15 specimens), we use it nonetheless to calculate the Early Triassic

position of the Qiangtang block because the rocks have: (1) a well-determined age; (2) adequate demagnetization; (3) coherence with the Qiangtang block; and (4) no resemblance to paleopoles of younger age. We fully acknowledge that more paleomagnetic data from Early Triassic rocks of Qiangtang are needed. The comparison between this Early Triassic Qiangtang paleopole and the coeval NCB and Tarim results indicates that the Paleo-Tethys Ocean was not closed during the Early Triassic and that its width was approximately $\sim 32\text{--}38^\circ$ of latitude ($\sim 3,500\text{--}4200$ km) (Fig. 9). Even if these sediments are biased toward low paleolatitudes by sedimentary inclination shallowing, the magnitude of shallowing observed in other rocks of similar facies still requires that the Qiangtang terrane was positioned at a latitude far south of the southern Tarim and NCB margin in the Early Triassic.

Ma et al. (1993), Wu et al. (1990), and Yang et al. (1991) measured three Late Triassic paleopoles from the Tongchuan area of the NCB: 61.6°N , 6.6°E , with $A_{95}=4.4^\circ$; 70.1°N , 9.4°E , with $A_{95}=5.8^\circ$; and 62.3°N , 7.7°E , with $A_{95}=3.8^\circ$, respectively. These three results are quite consistent with each other, so we calculated a mean paleopole of 64.7°N , 7.7°E , with $A_{95}=7.2^\circ$ by averaging these three poles; this pole predicts a paleolatitude of $32.7\pm 7.2^\circ\text{N}$ for the NCB during the Late Triassic for the reference point. The Late Triassic pole of the Tarim block obtained from 8 sedimentary sites (55 specimens) reported by Fang et al. (1990) is at 52.1°N , 166.8°E , with $A_{95}=5.8^\circ$, and yields a paleolatitude of $35.4\pm 5.8^\circ\text{N}$. The combined mean direction of our new data and the results from Song et al. (2012) yields a Late Triassic latitude of $31.7\pm 3.0^\circ\text{N}$ for the northern Qiangtang block for the reference point. These

results clearly indicate that the Late Triassic position of the reference point of the Qiangtang block ($31.7\pm3.0^{\circ}\text{N}$) is indistinguishable from the Late Triassic latitude of the NCB ($32.7\pm7.2^{\circ}\text{N}$) and Tarim ($35.4\pm5.8^{\circ}\text{N}$) (Fig. 9). This paleolatitude overlap suggests that the Qiangtang block was already accreted to the southern margin of Tarim and the NCB by Late Triassic time, although the data are also consistent with a paleogeography in which Qiangtang is latitudinally close but not yet sutured to the Tarim-NCB margin. We infer that the likely age for the closure of the central Paleo-Tethys Ocean is Middle Triassic to Late Triassic (Fig. 9).

Our analysis indicates that the Paleo-Tethys Ocean was still ~3,500-4200 km wide during the Early Triassic. On the assumption that the Qiangtang block could have moved northwards at a speed as fast as ~15-20 cm/yr during the Early Triassic to Late Triassic (similar to calculated velocities for the Indian plate in Late Cretaceous time (van Hinsbergen et al. 2011)), the consumption of ~3,500-4200 km oceanic lithosphere would have taken at least ~18-28 Myr. Because the duration of the Middle Triassic era is only 10 Myr (Gradstein et al., 2012), we suggest that the most likely closure time of the central Paleo-Tethys Ocean is during the Late Triassic. To further test this, reliable paleomagnetic data from Middle Triassic rocks from the Qiangtang block are critical.

The conclusion that the closure of the central Paleo-Tethys Ocean between Qiangtang and Tarim and NCB occurred during the Late Triassic is supported by numerous geological observations (e.g., Dewey et al., 1988; Ding et al., 2013; Liu et al., 2015). The Jinsha suture is characterized by ophiolitic rocks and associated

deep-marine sedimentary rocks, including an Upper Triassic *mélange* with Devonian, Carboniferous, and Permian exotic blocks in an Upper Triassic matrix (Metcalf, 1996). The ages of the ophiolites are regarded as Late Permian to Early Triassic, and the age of the suture is regarded as Late Triassic-Early Jurassic (Dewey et al., 1988). The Late Triassic-Early Jurassic deformation of the Hoh-Xil/Songpan-Ganzi turbidites and initiation of nonmarine deposition mark the demise of the Paleo-Tethys Ocean basin and the accretion of the Qiangtang block to Tarim and the NCB (Ding et al., 2013; Pearce and Mei, 1988; Liu et al., 2015). Igneous rocks with ages spanning 225-190 Ma are extensively distributed in Hoh-Xil/Songpan-Ganzi and eastern Kunlun regions, also suggesting the closure of the Paleo-Tethys Ocean occurred during Late Triassic (Zhang et al., 2014).

Moreover, the NCB is separated from the SCB by the east trending Qinling (Dabie) suture of Late Paleozoic-Early Mesozoic age; this suture marks the remains of the eastern Paleo-Tethys. Zhao and Coe (1987) suggested that the SCB and NCB first collided near the eastern part of the suture zone (in modern coordinates), and then sutured progressively westwards in a scissor-like pattern with associated relative rotation during the Mesozoic (see also Yin and Nie, 1993). Paleomagnetic data constrain this collision to post-Permian to pre-upper Middle to Late Jurassic (Fig. 9) (Zhao and Coe, 1987; Gilder and Courtillot, 1997; Gilder et al., 2008). Field relationships (Liu et al. 2015), sedimentary provenance and facies (Zhou and Graham, 1996; Weislogel et al. 2010; Liu et al. 2015), fold-and-thrust belt deformation (Yin and Nie, 1993; Liu et al. 2015), and regional metamorphism (Hacker et al. 2006), however,

are most consistent with accretion of the SCB to the NCB in Late Triassic. Thus, although they are distinct continental units, the northward motion of the SCB and Qiangtang block and the timing of their amalgamation to the Tarim and NCB continental margins are broadly similar. However, the exact kinematic differences (or similarities) between the accretion process for these continental units cannot be distinguished with existing paleomagnetic data.

8. Conclusion

We have reported new geochronologic and paleomagnetic results from 42 sites in Upper Triassic volcanic rocks to the south of the town of Tuotuohe on the Qiangtang block. Our zircon U-Pb geochronologic results for volcanic rocks indicate that these lavas were erupted during the Late Triassic (204-213 Ma). The new paleomagnetic data satisfy all seven reliability criteria described by [Van der Voo \(1990\)](#). Furthermore, the data pass the reversal test and appear to characterize secular variation, suggesting that the data accurately represent the position of the geomagnetic pole at the time the lavas were erupted. Our paleomagnetic data from Upper Triassic volcanic rocks, combined with previous paleomagnetic data from coeval rocks elsewhere in the region, position the northern margin of the central Qiangtang block at $31.7 \pm 3.0^\circ\text{N}$. Our review of the paleomagnetic data from Triassic rocks on now-adjacent blocks (NCB and Tarim) to the Qiangtang block suggests that the Paleo-Tethys Ocean was ~3,500-4200 km wide during the Early Triassic and most likely closed during the Late Triassic, consistent with several geological observations within this suture zone. Thus,

the Qiangtang block became the southern margin of the amalgamated Tarim-NCB
continent in the Late Triassic.

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Figure captions

Figure 1: a. Tectonic map showing the major blocks and suture zones. From south to north, the sutures are the Yarlung-Zangpo suture (IYS), Bangong-Nujiang suture (BNS), Jinsha suture (JS), Ayimaqin-Kunlun-Muttagh suture (AKMS), south Qilian suture (SQS), Danghe Nan Shan suture (DHS), and the north Qilian suture (NQS). Modified from [Yin and Harrison \(2000\)](#) and [Ding et al. \(2013\)](#). b. Geologic maps of the sampling area showing distributions of paleomagnetic sampling sections (white squares), and geochronological samples (black solid circles are samples of [Wang et al. \(2008\)](#); black solid squares are this study).

Figure 2: Photographs showing the Late Triassic volcanic sequence south of the Tuotuohe area. a. The distribution of the three sections. b. Volcanic sequences. c-d. Relationship between volcanic sequences and sedimentary sequences in section A. e. Amygdaloidal structure. f. Contacts between adjacent lava flows.

Figure 3: Some representative Cathodoluminescence images of zircons from (a) basaltic andesite sample (12Qtc01) and (c) sandstone sample (12Qtc02), spots (circle) and their U-Pb ages. U-Pb isotopic dating diagram showing the U-Pb ages and data for (b) 12Qtc01 and (d) 12Qtc02. All errors are shown at the 2σ level.

Figure 4: Magnetic properties of the volcanic rocks: a and d, acquisition of isothermal remanent magnetization (IRM) and back-field demagnetization of saturation IRM. b

and e, hysteresis loops. c and f, thermomagnetic curves.

Figure 5: BSE and EDS images of the representative specimen from the site Qt04. Red solid circles in graphs a and b indicate the spots analyzed by EDS, and the corresponding results are shown in graphs (c-f).

Figure 6: Orthogonal vector plots of thermal and AF demagnetization behavior of typical volcanic specimens in tilt-corrected coordinates. Solid and open circles represent vector endpoints projected onto the horizontal and vertical planes, respectively. Thermal (AF) demagnetization steps are in °C (mT) in all plots.

Figure 7: Equal-area projections of paleomagnetic directions: (left) in geographic coordinates; (right) in stratigraphic coordinates. Solid/open symbols represent downward/upward inclinations. a. Low-temperature components. b. All 42 site-mean ChRM directions with 95 per cent confidence intervals (Mean-A). c. All accepted 29 group-mean ChRM directions with 95 per cent confidence intervals (Mean-D). See text for details.

Figure 8: Paleomagnetic poles from Triassic units of the NCB, Tarim, SCB and Qiangtang (reference point: 34.1°N, 92.4°E). Small-circle with its 95% confidence area (gray region) passing through 31.7±3.0°N calculated from the combination of our data and data from [Song et al. \(2012\)](#)'s paleomagnetic results for the Late Triassic

from the Qiangtang block and centered on the reference point (solid red star). Gray circles are discarded in the discussion. For more information on the pole information, please see [Table A.4](#) in the Supplementary material.

Figure 9: Paleolatitudinal comparison between NCB, Tarim, SCB, and Qiangtang during the Triassic; all paleolatitudes calculated for a common reference point in north-central Qiangtang (34.1°N, 92.4°E). 1: paleolatitude of Qiangtang in the Early Triassic ([Cheng et al., 2012b](#)); 2: the average paleolatitude of Qiangtang estimated from paleomagnetic results from this study and [Song et al. \(2012\)](#); 3: the paleolatitude of NCB in the Early Triassic ([Zhao et al., 1996](#)); 4: the paleolatitude of NCB during the Middle Triassic ([Huang et al., 2005b](#)); 5: the average paleolatitude of NCB during the Late Triassic ([Yang et al., 1991](#); [Ma et al., 1993](#); [Wu et al., 1990](#)); 6: the paleolatitude of Tarim in the Early Triassic ([McFadden et al., 1988](#)); 7: the paleolatitude of Tarim in the Late Triassic ([Fang et al., 1990](#)); 8: the paleolatitude of SCB in the Early-Middle Triassic ([Gilder et al., 2008](#)); 9: the paleolatitude of SCB in Early Jurassic ([Gilder and Courtillot, 1997](#)). Age abbreviations: P₃-Late Permian, T₁-Early Triassic, T₂-Middle Triassic, T₃-Late Triassic, J₁-Early Triassic. For more information for individual poles, please see [Table A.4](#) in the Supplementary material.

Figure A.1: Day plot of hysteresis data, showing the magnetic grain size of bulk samples. Thin straight dark lines delineate magnetic grain size fields: PSD (pseudo-single domain), SP (superparamagnetic), SD (single domain) and MD

(multidomain).

Tables

[Table 1](#): Site and group mean directions of the Upper Triassic Qiangtang Jiapila Formation volcanic rocks.

[Table A.1](#): U-Pb isotopic data for volcanic rock 12Qtc01 from the northern Qiangtang block.

[Table A.2](#): U-Pb isotopic data for sedimentary rock 12Qtc02 from the northern Qiangtang block.

[Table A.3](#): Characteristic remanent magnetization (ChRM) directions for Tuotuohe lavas.

[Table A.4](#): Triassic paleomagnetic results from Qiangtang, North China, Tarim and South China blocks (reference point: 34.1°N/92.4°E).

[Table A.5](#): Summary of Late Triassic palaeomagnetic results from the Qiangtang block.

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Table 1 Site and group mean directions of the Upper Triassic Jiapila Formation volcanic rocks.

Direction Group	Site	Strike /dip	n/n ₀	R/N	Direction				κ	α ₉₅ (°)	Devi.	Pole position	
					D _g (°)	I _g (°)	D _s (°)	I _s (°)				λ _p (°N)	φ _p (°E)
Section A (34° 06.3'N, 92°22.4'E)													
T01	Qt01	300/51	6/9	0/6	241.3	53.4	344.3	64.3	76.6	7.7	27.0	73.1	52.2
T02	Qt02	300/51	9/9	0/9	239.9	69	11.4	56	151.2	4.2	12.0	80.4	164.4
T03	Qt03	300/51	9/9	0/9	218.6	76.4	26.7	52.4	144.3	4.3	2.4	67.8	177.7
T04	Qt04	300/51	9/9	0/9	169.2	74.5	45.7	49.8	601.5	2.1	10.2	51.6	174.6
T05	Qt05	300/51	9/9	0/9	187	72	42.2	55.1	338.8	2.8	8.6	55.6	167.5
T06	Qt06	309/57	5/9	0/5	245.2	83.5	35.3	38.8	78.3	8.7	12.7	56.7	194.6
T07	Qt07	309/57	5/9	5/0	64.1	-77.8	211.8	-43.9	56.1	10.3	7.1	61.3	190.8
T08	Qt08 [†]	309/57	8/11	8/0	27.1	-59.1	232.4	-62.7	77.7	6.3	17.0	48.8	152.3
*T09	Qt09	309/57	6/7	6/0	9.2	42.5	17.2	-9.7	106.1	6.5	61.6	47.8	246.4
T10	Qt10	309/57	5/8	0/5	218	87.7	39.1	35.3	105	7.5	17.0	52.5	195.1
--	Qt11 ⁺	309/57	3/7	0/3	191.0	70.7	52.8	49.4	185.6	9.1	--	45.6	172.1
T11	Qt12 [†]	309/57	8/8	0/8	191.7	63.9	59.5	54.8	268.7	3.4	18.3	41.8	163.1
T12	Qt13	313/47	5/9	0/5	317.1	73.1	20.9	39.6	83.9	8.4	12.9	68.3	209.3
T13	Qt14	313/47	7/9	0/7	249.1	81.1	36.8	50.9	141.0	5.1	4.5	59.1	176.6
T14	Qt15	313/47	8/8	0/8	307.5	54.1	356.5	36.4	52.7	7.7	27.7	75.8	285.9
T15	Qt16 [†]	313/47	6/7	0/6	198.7	79.3	50.2	52.6	738.7	2.6	--	48.6	169.0
T15	Qt17 [†]	313/47	7/7	0/7	244.7	81.4	38	50.9	49.9	8.7	--	58.2	176.1
T15	Qt18 [†]	313/47	5/7	0/5	223.6	82.6	42.9	50.4	93.9	9.9	--	54.0	174.9
Mean (T15)	Qt16 [†] -18 [†]	313/47	18/20	0/18	220.4	81.6	43.6	51.4	414.2	6.1	8.7	53.7	173.1
--	Qt19 [±]	313/47	3/7	0/3	210.9	78.5	47.1	54.2	102.7	12.2	--	51.5	167.7
Section B (34° 06.03'N, 92°22.8'E)													
T16	Qt20	295/56	8/9	0/8	178.9	64.3	44.8	55.7	266.2	3.4	10.2	53.6	165.9
T17	Qt21	295/56	5/9	0/5	169.4	58.4	58.1	56	209.3	5.3	--	43.3	161.9
T17	Qt22	295/56	8/9	0/8	172.8	63.5	49.1	54.4	83.4	6.1	--	50.0	166.8
T17	Qt23	295/56	7/9	0/7	172.6	58.5	56.4	57.4	453.8	2.8	--	44.9	160.4
Mean (T17)	Qt21-23	295/56	20/27	0/20	171.8	60.5	53.8	55.9	139.4	2.8	15.1	46.6	163.2
T18	Qt24	295/56	9/9	0/9	176.7	55.3	59	61.1	663	2	19.1	43.8	154.1
T19	Qt25	295/56	8/9	0/8	183.3	55.5	53.4	63.8	1062	1.7	15.9	48.2	150.1
T20	Qt26	295/56	8/9	0/8	190.3	59.9	40.9	62.3	251.3	3.5	12.9	57.1	153.3
T21	Qt27	295/56	6/9	0/6	184.5	64.1	41.4	57.3	779.7	2.4	9.4	56.6	163.7
T22	Qt28	295/56	7/8	0/7	48.2	78.7	29.8	23.5	77.5	6.9	27.4	55.2	214.1
--	Qt29	295/56	7/9	0/7	49	54.6	39.7	7.5	16.4	15.4	--	42.3	212.9
T23	Qt30	295/56	5/8	5/0	347.7	-59.1	237.8	-54.9	174.9	5.8	--	43.2	163.5
T23	Qt31	295/56	5/9	5/0	358.6	-56.3	235.9	-61.3	277.5	4.6	--	46.1	154.3
Mean (T23)	Qt30-31	295/56	10/17	10/0	353.4	-57.8	237.0	-58.1	169.5	3.7	17.6	44.6	159.2
T24	Qt32	295/56	5/8	5/0	13.2	-56.0	221.8	-66.5	163.5	6.0	16.7	55.9	143.7
T25	Qt33	282/51	5/9	0/5	271.3	79.1	358.0	40.2	181.1	5.7	24.4	78.7	281.8
*T26	Qt34	282/51	8/9	0/8	350.1	62.4	1.8	12.9	60.1	7.2	44.2	62.4	268.5
Section C (34° 07.8'N, 92°22.4'E)													
T27	Qt35	186/51	7/8	0/7	50.6	-3.5	40.5	30.4	73.2	7.1	22.0	49.6	198.2
T28	Qt36	186/51	8/9	0/8	48.4	26.9	8.3	48.8	114.4	5.2	--	81.7	211.9
T28	Qt37	186/51	5/8	0/5	45.1	29.3	3.1	47.3	59.5	10.0	--	83.8	246.5
T28	Qt38	186/51	5/8	0/5	46.2	22.9	11.8	45.0	54.1	10.5	--	77.3	215.8
Mean (T28)	Qt36-38	186/51	18/25	0/18	46.9	26.5	7.9	47.4	76.4	4.0	14.6	81.3	219.8
--	Qt39	186/51	5/8	0/5	4.4	30.7	340.4	17.6	46.8	11.3	--	59.1	312.6
T29	Qt40	186/51	7/8	0/7	56.1	24.9	16.7	53.7	69.3	7.3	8.4	76.2	177.1
T30	Qt41	186/51	5/8	0/5	29.3	19.0	4.8	29.7	88.0	8.2	28.2	71.3	257.9
T31	Qt42	186/51	6/8	0/6	50.6	28.4	7.7	51.2	50.7	9.5	13.8	83.2	199.3
					n/n ₀	R/N	λ _p (°N)	φ _p (°E)	A ₉₅	K	S	I±ΔI	D±ΔD
Site mean-A		in situ coordinates			42/42	6/36	3.1	254.5	13.5	3.7	44.7	-66.6±7.9	28.0±16.7
		tilt-corrected coordinates			42/42	6/36	63.8	179.7	6.2	13.5	22.3	50.6±5.5	31.1±5.8
Site mean-B		in situ coordinates			38/42	5/33	3.5	252.5	13.5	3.9	42.8	-65.7±8.1	30.5±16.3
		tilt-corrected coordinates			38/42	5/33	63.9	177.7	6.2	15.1	21.0	51.6±5.4	31.2±5.9
Group mean-C		in situ coordinates			31/31	5/26	0.7	251.7	15.1	3.9	43.0	-67.3±8.7	33.5±19.2
		tilt-corrected coordinates			31/31	5/26	65.0	179.8	7.0	14.6	21.5	50.9±6.1	29.7±6.6
Group mean-D		in situ coordinates			29/31	4/25	0.7	252.4	14.0	4.6	37.8	-67.6±8.0	32.5±17.9
		tilt-corrected coordinates			29/31	4/25	64.0	174.7	6.6	17.2	19.5	53.0±5.5	31.4±6.3

Notes: Strike/dip, right hand strike/dip of beds; n/n₀, number of samples/groups used to calculate the site/group mean/number of demagnetized samples/groups; R/N, samples/groups showing reversed/normal polarity; D_g, I_g, D_s and I_s, declination and inclination in geographic and stratigraphic coordinates, respectively; κ , the best estimate of the precision parameter; α_{95} , the radius of the mean direction at the 95% confidence level; λ_p and ϕ_p , latitude and longitude of the corresponding virtual geomagnetic pole (VGP) in stratigraphic coordinates; Devi., angular difference of group directions from group mean direction; sites with delete lines are discarded due to n<5, k<50, or α_{95} >15°; * groups discarded from the final average due to large deviations (Devi.>30°); † sites measured at UCSC.

The fold and reversal tests of group mean direction of 29 volcanic groups (group mean-D):

(1) Fold test is positive at the 99% and 95% confidence level (McElhinny, 1964), $K_s/K_g=4.34 > F(2*(n_2-1), (n_1-1))$ at 99% point=1.87 and at 95% point=1.56;

(2) Fold test is positive at the 99% confidence level (MaFadden, 1990), $\xi_2=21.30$ before and $\xi_2=0.83$ after tilt correction, critical ξ at 99%=8.86 and 95%=6.26,

(3) Fold test is positive (Watson and Enkin, 1993), the optimum concentration is achieved at 103.6±3.7% unfolding;

(4) The classification of the reversal test is C at the 95% confidence (MaFadden and McElhinny, 1990), normal polarity: N₁=25, D₁=28.6, I₁=50.4; reversal polarity: N₂=4, D₂=224.5, I₂=-58.3; $\gamma_{calculated}=12.1^\circ < \gamma_{critical}=16.3^\circ$