Combined Paleomagnetic and geochronological study on Cretaceous strata of the Qiangtang terrane, central Tibet

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Abstract

A combined paleomagnetic and geochronological investigation has been performed on Cretaceous rocks in southern Qiangtang terrane (32.5° N, 84.3°E), near Gerze, central Tibetan Plateau. A total

18 of 14 sites of volcanic rocks and 22 sites of red beds have been sampled. Our new U-Pb
19 geochronologic study of zircons dates the volcanic rocks at 103.8 ± 0.46 Ma (Early Cretaceous)
20 while the red beds belong to the Late Cretaceous. Rock magnetic experiments suggest that
21 magnetite and hematite are the main magnetic carriers. After removing a low temperature
22 component of viscous magnetic remanence, stable characteristic remanent magnetization (ChRM)
23 was isolated successfully from all the sites by stepwise thermal demagnetization. The tilt-corrected
24 mean direction from the 14 lava sites is $D = 348.0^\circ$, $I = 47.3^\circ$, $k = 51.0$, $\alpha_{95} = 5.6^\circ$, corresponding to
25 a paleopole at 79.3° N, 339.8° E, $A_{95} = 5.7^\circ$ and yielding a paleolatitude of $29.3^\circ \pm 5.7^\circ$ N for the
26 study area. The ChRM directions isolated from the volcanic rocks pass a fold test at 95%
27 confidence, suggesting a primary origin. The volcanic data appear to have effectively averaged out
28 secular variation as indicated by both geological evidence and results from analyzing the virtual
29 geomagnetic poles (VGPs) scatter. The mean inclination from the Late Cretaceous red beds,
30 however, is 13.1° shallower than that of the ~ 100 Ma volcanic rocks. After performing an
31 Elongation/Inclination analysis on 174 samples of the red beds, a mean inclination of 47.9° with 95%
32 confidence limits between 41.9° and 54.3° is obtained, which is consistent with the mean
33 inclination of the coeval volcanic rocks. The site-mean direction of the Late Cretaceous red beds
34 after tilt-correction and inclination shallowing correction is $D = 312.6^\circ$, $I = 47.7^\circ$, $k = 109.7$, $\alpha_{95} =$
35 3.0° , $N = 22$ sites, with a corresponding to a paleopole at 49.2° N, 1.9° E, $A_{95} = 3.2^\circ$ (yielding a

paleolatitude of $28.7^{\circ} \pm 3.2^{\circ}$ N for the study area). The ChRM of the red beds also passes a fold test at 99% confidence, indicating a primary origin. Comparing the paleolatitude of the Qiangtang terrane with the stable Asia, there is no significant difference between our sampling location in the southern Qiangtang terrane and the stable Asia during ~100 Ma and Late Cretaceous. Our results together with the high quality data previously published suggest ~550 km N-S convergence between the Qiangtang and Lhasa terranes happened after ~100 Ma. Comparison of the mean directions with expected directions from the stable Asia indicates the Gerze area had experienced a significant counterclockwise rotation after ~100 Ma, which is most likely caused by the India-Asia collision.

Keywords: Tibetan Plateau; Qiangtang terrane; paleomagnetism; Cretaceous; inclination shallowing; convergence; tectonic rotation

1. Introduction

As the most extensive region of elevated topography on the Earth's surface, the Tibetan Plateau was formed by progressive accretion of several terranes to the stable Asian continent since Early Paleozoic ([Allègre et al., 1984](#), [Sengör, 1987](#); [Dewey, 1988](#); [Yin and Harrison,](#)

2000; Metcalfe et al, 2006; Zhu et al., 2009; 2013; 2015; Wang et al., 2014). The tectonic processes of the Tibetan Plateau were also closely related to the opening, expansion, and closure of the Paleo-Tethyan and Neo-Tethyan Oceans (Sengör, 1979, 1987; Sengör et al., 1988, 1993; Metcalfe, 1999; Dewey et al., 1988) and climaxed by the Cenozoic collision between India and Asia that has forcefully raised the Tibetan plateau (Argand, 1924; Molnar and Tapponnier, 1975; Aitchison et al., 2011; Dai et al., 2012; Guan et al., 2012; Xu et al., 2012), the most extensive region of elevated topography on the Earth's surface. Thus, the tectonic history of the plateau has attracted worldwide attention as it contains a complete record of subduction, collision and intra-continental convergence (Cao et al., 2011; Xia et al., 2011; Hébert et al., 2012; Replumaz et al., 2013; Zhang et al., 2010; 2014). The Qiangtang terrane, one of the major terranes of the Tibetan Plateau, accreted to the Asia continent in the Late Triassic and collided with the Lhasa terrane during the Jurassic-Cretaceous, accompanied by the closure of the Bangong-Nujiang Tethyan Ocean (Yin and Harrison, 2000; Kapp et al., 2000, 2003, 2007; Guynn et al., 2006; Zhu et al., 2006; 2013; 2015; Wu et al., 2011; Zhang et al., 2012; 2014; Li et al., 2013; Li et al., 2014; Zhang et al., 2014; Wang et al., 2014; Fan et al., 2014; 2015; Li et al., 2015a, b). It is generally accepted that the eastern and western segments of the Bangong-Nujiang suture zone experienced diachronous convergent processes (Dewey et al., 1988; Matte et al., 1996; Yin and Harrison, 2000; Wang et al., 2005; 2014). The closure time for the western segment, however, remains controversial, ranging from Middle

Jurassic (Kapp et al., 2003, 2007; Zhang et al., 2007; Qu et al., 2012; Li et al., 2014; Zhang et al., 2014) to Early or Middle Cretaceous (Wang et al., 2005; Zhu et al., 2006; 2015; Zhang et al., 2012; 2014; Li et al., 2013; 2015a; Wang and Wei, 2013; Wang et al., 2014; Fan et al., 2014; 2015). Continued north-south narrowing along the Bangong-Nujiang suture during the Cretaceous has been attributed to the substantial Cretaceous deformation in central Tibet (Yin and Harrison, 2000; Wang et al., 2005; Kapp et al., 2005; Wang et al., 2014; Fan et al., 2014; 2015; Li et al., 2013; 2015a). Likewise, the continental shortening in the central Tibet prior to the Indian-Asian collision is also hotly debated (Murphy et al., 1997; Yin and Harrison, 2000; Kapp et al., 2003, 2007; Guynn et al., 2006; Pan et al., 2006; Zhu et al., 2006, 2009, 2011). In addition, Vertical-axis rotations have been shown to be a common consequence of crustal deformation in settings with thrusting motions and bounding faults in major Asian tectonic terranes (Zhao and Coe, 1987; Chen et al., 1991, 1993; Rumerlhart et al., 1999; Cogné et al., 2013). Many geological and paleomagnetic data support that the eastern margin of the Qiangtang terrane had experienced a large scale clockwise rotation since Cretaceous (England and Molnar, 1990; Huang et al., 1992; Xu et al., 2006; Otofujii et al., 1990; 2007; 2010), while the rotation models of other parts are still puzzling. The paleogeographic position of the Qiangtang terrane in Cretaceous thus has very important significance of studying the evolution of the Bangong-Nujiang Ocean, the continental shortening and the rotation model of the central Tibet caused by the collision between the Qiangtang-Lhasa terranes.

Paleomagnetism remains the only method that can quantify the paleolatitudinal position and the amount of rotation of a plate. Previously published late Mesozoic and Cenozoic paleomagnetic studies have played a key role in understanding the tectonic evolution of the Tibetan plateau. Nevertheless, there are only a few Cretaceous paleomagnetic investigations in the Qiangtang terrane (Otofuji et al., 1990; Huang et al., 1992; Chen et al., 1993). Many of these results have the problems of inaccurate age of the sampled rocks, small number of samples and bad statistic parameters; and besides, all available data were obtained from sedimentary rocks, which need test of possible influence of the paleomagnetic inclination shallowing. More investigations and high quality data are therefore in demand.

In this paper, we report the new results obtained from a combined study including the geochronology and the paleomagnetism on ~100 Ma volcanic rocks and Late Cretaceous red beds outcropping in an area close to Gerze, southern Qiangtang terrane. We use our new data together with a selection of the previously published paleomagnetic data to discuss the paleogeographic position of the Qiangtang terrane, local rotations and the tectonic history of the Bangong-Nujiang suture.

2. Geological setting and sampling

108 The sampling area (32.5° N, 84.3°E) is ~30 km northeast to the Gerze town, being
109 located in the southern margin of the Qiangtang terrane and on the north side of mid-west portion of
110 the Bangong-Nujiang suture (Fig. 1A). The strata in this area mainly contain Triassic, Jurassic,
111 Cretaceous and Cenozoic. The Triassic and Jurassic strata are largely deformed and unconformably
112 overlain by the Cretaceous strata, which, in turn, are unconformably overlain by Cenozoic Kangtuo
113 Formation. Our sampling focused on the Cretaceous strata (Fig. 1B), which mainly consist of
114 volcanic rocks of andesite, basaltic andesite, basalt and rhyolite, with some red beds in the upper
115 and top of this sequence (Fig. 2). Age and correlation of these strata had long been a matter of
116 debate. It was mapped as Eocene strata in some older maps (e.g. 1:250,000 scale regional
117 geological survey report, Gerze, 2006), but Chang et al. (2011) obtained the U-Pb zircon ages of
118 ~110 Ma from the rhyolite rock of this succession in Rena-Co area (~20 km north to our sampled
119 section) and other in some new maps these volcanic-clastic strata were correlated to Early
120 Cretaceous Qushenla Formation (e.g. 1:50,000 scale regional geological survey report, Gerze,
121 2014). The progress and disputes compel us to date the paleomagnetic samples in our own study.
122 Our results indicate that the volcanic rocks are of Early Cretaceous, named Qushenla Formation
123 following the new maps. The Qushenla Formation used here is thus synchronous to the
124 Meiriquieuo Formation in southern Qiantang terrane (Zhu et al., 2015) and the Zenong group in the
125 Lhasa terrane (Chen et al., 2012; Ma et al., 2014). Details of our new geochronological analysis

will be reported in the section 3 of this paper.

Our sampled section contains four lithostratigraphic units (Fig. 2). The bottom unit, Member 1 of the Qushenla Formation, is mainly composed of basaltic andesite containing narrow phenocrysts. A total of 169 core samples from 15 sites (GZ30-45) were collected from the strata with SW dipping direction and dip of 26-31°. The overlying unit (Member 2) consists of andesite and sandy conglomerate (Fig. 2) with NW dipping direction and dips of 15°. This unit contains two quenching edges clearly indicating boundaries for two lava subunits (Fig. 2, 3A). A total of forty-five core samples were collected from the andesite of Member 2. The fact that the sandy conglomerate layer in the Member 2 is sandwiched in the lava flows strongly argue that the emplacement of the volcanic units at the sampling locality span sufficient time to likely average out the geomagnetic secular variation (Fig. 2). The Member 3 is characterized by black basaltic andesites with well developed square-shaped phenocrysts. 34 cores samples were collected from this unit with dips of ~23° and SW dipping direction. In addition, several block samples from fresh part of the basaltic andesite were collected for radiometric dating (Fig. 2). The uppermost unit, Member 4, comprises thin purple sandstone and siltstone, and are overlain with angular unconformably by the Paleogene Kangtuo Formation (40-30 Ma) (Zhong et al., 2008; Ding et al., 2015). A total of 242 core samples (22 sites) were collected from two sections of Member 4 (Fig. 2). 19 sites were collected from one section which the bedding dips steeply toward the NW at 77-90°

while the bedding of the other section dips at 18° towards west. The age of the red beds has not been well constrained thus far. They can be any age between ~ 100 and ~ 40 Ma, although they are considered as part of the Qushenla Formation (Zhu et al., 2014).

Paleomagnetic samples were collected using a gasoline-powered drill and a magnetic compass mounted on an orienting device. We corrected for the effect of local magnetic anomalies on magnetic orientation by taking solar azimuths using a sun compass. For most samples, the discrepancy between the two compass readings is within 3° . All cores were cut into 2.2-cm-length specimens in the laboratory for further measurements.

3. Zircon geochronology

3.1 Analytical techniques

Geochronological samples of the fresh volcanic rocks were collected for LA-ICP-MS zircon U-Pb dating. Zircons were separated by heavy-liquid and magnetic methods. More than 1000 grains were hand-picked under a binocular microscope from the basaltic andesite samples. The representative grains together with a standard zircon were coined in an epoxy-resin mount and polished to expose the crystal interiors. Then the polished mounts were photographed

under both transmitted and reflected light and cathodoluminescence (CL). Mount was vacuum-coated with a layer of gold. The U, Th and Pb isotope compositions were analyzed using laser ablation multicollector inductively coupled plasma mass spectrometry (LA-ICP-MS) at the Tianjin Institute of Geology and Mineral Resources, following the procedures described by Yuan et al. (2003).

3.2 Ages of the basaltic andesite

Zircons separated from the basaltic andesite sample are euhedral grains with size > 200 μm in length (Fig. 4a), with clearly identifiable regular banded structure. The shapes of the zircons are the characteristics of columnar or needle, strongly indicating a magmatic origin (Fig. 4a) (Li, 2009). A total of 40 zircon grains were analyzed, each with a probe spot.

The cumulative probability plot displays a population around 104 Ma (see supplementary data, Table A1; Fig. 4c). The results yielded a weighted-mean $^{206}\text{Pb}/^{238}\text{U}$ date of 103.8 ± 0.46 Ma with mean square of weighted deviates (MSWD) of 0.90 (Fig. 4b, c, d). We thus consider that the best estimate age of the volcanic rocks is 103.8 ± 0.46 Ma. It is consistent with the results previously reported by Chang et al. (2011), but is at odds with the ca. 70 Ma dates obtained from olivine basalt using K-Ar method (Zeng et al., 2006). We conclude that the ages of our

180 sampled volcanic rocks range from ~110 to ~100 Ma, and the red beds are of Late Cretaceous.

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182 4. Paleomagnetic laboratory techniques and measurements

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184 All specimens were subject to stepwise thermal demagnetization with an ASC-TD48
185 furnace (with an internal residual field less than 10 nT). Remanent magnetization measurements
186 were carried out using a 2G-755-4K cryogenic magnetometer for the red sandstones and an
187 AGICO JR-6A spinner magnetometer for the strongly magnetized volcanic rocks, in the
188 Paleomagnetism and Environmental Magnetism laboratory (PMEML) of the China University of
189 Geosciences, Beijing (CUGB). All the instruments are located in a shielded room with residual
190 fields less than 200 nT. Demagnetization temperature intervals are generally large (50-30°C) in the
191 low temperature part, and become smaller (10-5°C) at higher temperatures. In order to better
192 understand magnetic mineralogy and help interpret the paleomagnetic data, hysteresis loops were
193 performed on representative specimens. A KLY-3S Kappabridge susceptibility system was used to
194 measure the anisotropy of magnetic susceptibility (AMS) to assess if the rocks have affected by
195 tectonic strain. The experiment acquiring the hysteresis loops was performed in the Institute of
196 Geophysics, China Earthquake Administration, Beijing.

197 Characteristic remanent magnetization (ChRM) directions were determined for all the

specimens using principal component analysis (Kirschvink, 1980). Site-mean paleomagnetic directions were calculated using Fisher statistics (Fisher, 1953) and paleomagnetic data were analyzed using R. Enkin's and J.P. Cogné's program packages (Enkin, 1990; Cogné, 2003).

5. Rockmagnetic and paleomagnetic results

5.1 Volcanic rocks

Anisotropy of magnetic susceptibility (AMS) was firstly measured using a KLY-3S Kappabridge to detect possible disturbances of the rock fabric. The AMS of 107 lava specimens show that the directions of the maximum, intermediate and minimum susceptibility axes are scattered without any regulation which means that the Cretaceous lava has not been disturbed by any tectonic deformation (Fig. 6a) (Hrouda, 1982).

Thermal demagnetization behavior of the volcanic rocks shows that the unblocking temperatures of majority specimens are close to 675 °C suggesting that hematite is the main magnetic carrier (Fig. 6a, b, d, e, f). Obvious decay of the remanent magnetization near 575 °C in these samples suggests the existence of the magnetite as well. For the remaining lava specimens, magnetite is the main magnetic mineral as indicated by unblocking temperature up to 575°C (Fig. 6c). The magnetic minerals are supported by the hysteresis results from the represent specimens.

216 Fig. 5c shows an obvious wasp-waisted shape with a saturation field higher than 800 mT,
217 suggesting the existence of both high-coercivity and low-coercivity magnetic minerals (hematite
218 and magnetite). For the magnetite dominate samples, the wasp-waisted characteristics are not
219 present in the sample and the saturation field is generally lower than 400 mT (Fig. 5d), indicating
220 the presence of low coercivity magnetic carriers. Combined with the thermal demagnetization
221 behavior of the volcanic rocks, the fact that both magnetite and hematite present in the volcanic
222 rocks suggests that the hematite was probably formed by auto-oxidation processes during primary
223 cooling of the volcanic rocks.

224 In majority of the lava specimens, a single component appears in the behavior of the
225 stepwise thermal demagnetization that decayed toward the origin after removing a small and
226 unstable viscous magnetization component at ~100 °C (Fig. 6a-d). However, some specimens of
227 sites 25, 27, 33, and 38 show two components of magnetization (Fig. 6e, f). The low temperature
228 component (LTC) was isolated by the 230 °C or 500 °C. The *in situ* directions generally cluster
229 near the present geomagnetic field (PGF), indicating a recent viscous remanent magnetization
230 (VRM) origin (Fig. 8a). The high temperature component (HTC) was resolved above 300 °C
231 -500 °C and unblocked between 660 °C and 700 °C. The ChRM from the lava specimens shows a
232 northwesterly direction with a moderate to steep-down inclination (Fig. 8c, d). The site-mean
233 directions and the virtual geomagnetic poles (VGPs) corresponding to each site-mean direction are

listed in Table 1. It is worth mentioning that some previous studies failed to identify bedding for the volcanic rocks. In this study, the attitudes of the lava were marked clearly by the quenching edges, air bubbles and phenocryst (Fig. 3A). Furthermore, the attitude of stratum along the quenching edges is consistent with the regional occurrence and could be used to make exactly structural correction for the volcanic rocks (Fig. 3, Table 2). The site-mean directions for 14 sites is $D_g = 11.4^\circ$, $I_g = 39.9^\circ$, $k_g = 39.2$, $\alpha_{95} = 6.4^\circ$ *in situ*, and $D_s = 348.0^\circ$, $I_s = 47.3^\circ$, $k_s = 51.0$, $\alpha_{95} = 5.6^\circ$ after bedding correction (Fig. 8e, f, Table 2).

The paleomagnetic directions from the volcanic rocks are the instantaneous records of the geomagnetic field and free of inclination flattening effects. However, the results sometimes may be unable to average out the paleosecular variation (PSV) of the geomagnetic field. To test the PSV, a widely used approach is to calculate the statistical scatter of the VGPs under the condition that each VGP is a spot record of the geomagnetic field (e.g. Ma et al., 2014; Ren et al., 2015 among other recent studies). On the premise of enough lava flows engaged in the final statistic, we obtain a VGP scatter of 10.6° which is consistent with the expected value (11.4°) with the 95% confidence level (9.0° , 14.0°) at 29.3° N during the Cretaceous Normal Superchron (CNS: 84-125 Ma) (Cox, 1970; McFadden et al., 1988; Biggin et al., 2008). Furthermore, the VGP scatter (11.5°) is also within the limit of VGP scatter (10.1° , 15.4°) according to the formula and standard proposed by McFadden et al. (1991). We thus consider that the average paleomagnetic results from

the lavas (14 independent sites) is free of PSV influence.

The ChRM directions obtained from the volcanic rocks also pass a fold test of [McFadden and McElhinny \(1990\)](#) at 95% confidence: “Xi1” value in geographic coordinate is 5.9, and in stratigraphic coordinates 0.8, with the critical Xi 4.4 at 95% confidence level. Thus, the HTC is interpreted as a primary magnetization. Furthermore, the fact that all the inclinations isolated from the volcanic rocks are positive and is consistent with magnetization within the Cretaceous Long Normal Superchron with an age between ~83.6 and ~126 Ma ([Gradstein et al., 2012](#)). These observations support that the ChRM directions are carried by primary thermal remanence that are reliable records of the ancient field during the cooling. Its corresponding paleopole is at 79.3° N, 339.8° E ($A_{95} = 5.7^\circ$), yielding a paleolatitude of $29.3^\circ \pm 5.7^\circ$ N for the study area (reference point: 32.5° N, 84.3° E) during ~110-100 Ma.

5.2 Red beds

The AMS of the red beds ([Fig. 5b](#)) in the stratigraphic coordinates show that the most minimum susceptibility axes (K_3) are perpendicular to the bedding plane, while maximum (K_1) and intermediate axes (K_2) are dispersed on a bedding plane. The results indicate that the red beds preserve a normal sedimentary magnetic fabric and the rocks have not experienced tectonic

270 deformation since deposition (Tarling and Hrouda, 1993).

271 Most specimens of the red beds display similar unblocking-temperature near to 660 or
272 680 °C with a sharp decay of the remanent magnetization around 575 °C (Fig. 7), indicating that
273 these specimens may be dominated by hematite and magnetite. Furthermore, the hysteresis loops of
274 the red beds show a wasp-waisted shape and do not close until a higher field approximately 460 mT
275 (Fig. 5e, f), further suggesting the existence of both high coercivity and low coercivity magnetic
276 minerals. Therefore, both magnetite and hematite are main magnetic carriers in the red sediments.

277 174 out of 247 demagnetized specimens revealed a concordant high temperature
278 ChRM after removal of the LTCs that were isolated between 70 °C and 300 °C. For some of these
279 specimens, the LTC is accounted for 30% intensity of the natural remanence (NRM) and clustered
280 well around the PGF *in situ* for most specimens (Fig. 7, 8b). But for other specimens, a soft
281 magnetic component was removed by 100 °C and their directions are far from the PGF. We
282 interpret that the LTCs of the red beds are probably a mixture of the recent field VRM and a random
283 weak VRM obtained during preparing the specimens (Fig. 8b).

284 Directions of the HTC were obtained between 550 and 680 °C, pointing northwest
285 and down after tilt-correction (Fig. 7, 8h, j, Table 1). The site mean direction is $D_g = 170.0^\circ$, $I_g =$
286 60.4° , $k_g = 8.0$, $\alpha_{95} = 11.7^\circ$, $N = 22$, *in situ* and $D_s = 312.6^\circ$, $I_s = 34.2^\circ$, $k_s = 98.8$, $\alpha_{95} = 3.1^\circ$, $N = 22$,
287 after bedding correction (Fig. 8i, j, Table 1).

Fig. 9a shows that the ChRM of the red beds exhibits an E-W elongated distribution evidently, which is an important sign of the inclination shallowing (Tauxe and Kent, 2004). We applied the Elongation/Inclination (E/I) method to the 174 directions of the red beds which show east-west distribution evidently (Fig. 9a). The flattening correction factor (f) was 0.6. The inclination was corrected from 34.2° to 47.9°, with 95% confidence interval between 41.9° and 54.3° (Figs. 9b-e). The site-mean direction after the E/I correction is $D_s = 312.6^\circ$, $I_s = 47.7^\circ$, $k_s = 109.7$, $\alpha_{95} = 3.0^\circ$, $N=22$, in stratigraphic coordinates (Fig. 9c). These directions passed a fold test of McElhinny (1964) at 99% confidence level and a fold test of McFadden and McElhinny (1990) at 99% confidence level. The value of precise parameter “k” reaches maximum at 97.2% unfolding in the stepwise unfolding test (Fig. 9f; Watson and Enkin, 1993). These all suggest that the HTC can be interpreted as a pre-folding primary magnetization. The paleopole can be obtained by average all VGPs, at 49.2° N, 1.9° E, $A_{95} = 3.2^\circ$, yielding the paleolatitude of $28.7^\circ \pm 3.2^\circ$ N for the sampling area.

6. Tectonic implications

6.1 Cretaceous paleolatitude of the Qiangtang terrane

305 The available Cretaceous poles from the Qiangtang and Lhasa terranes are listed in
306 the [Table 2](#) and plotted in [Figs. 10a](#) with the sampling sites shown in [Fig.1A](#). There are five
307 previously published poles, with the sampled areas in southeast ([Otofuji et al., 1990; Huang et al.,](#)
308 [1992](#)) and northwest of the Qiangtang terrane ([Chen et al., 1993](#)). The Cretaceous paleomagnetic
309 data overall are still scarce in central Qiangtang terrane and significant discrepancy between the
310 different studies should be taken into account. The paleolatitude observed from the ~110-100 Ma
311 Lava in this study is well consistent with the paleolatitudes inferred from the three Early
312 Cretaceous paleomagnetic poles of the southeastern Qiangtang terrane (poles CW, LR, MK in
313 [Table 2; Otofuji et al., 1990; Huang et al., 1992](#)). But difference of the declinations between the two
314 studies is significant, which might be resulted from some local rotations that will be discussed in
315 section 6.3. Noticeably, the inclinations observed from the Cretaceous red sandstones in the
316 northwestern Qiangtang terrane (poles AS, LS in [Table 2](#)) are obviously shallower than that of
317 other studies (poles CW, LR, MK, GL and GR in [Table 2](#)) ([Fig. 10a](#)). We propose three hypotheses
318 to explain this difference: (1) the poles AS and LS were influenced by inclination shallowing of
319 sedimentary rock; (2) significant relative movement had once occurred between the NW end of the
320 Qiangtang terrane and the middle-eastern portion of this terrane; or (3) the poles are different in age.
321 They need further test.

The apparent polar wander paths for the stable Asia have been updated recently (e.g., [Torsvik et al. 2012](#), [Cogné et al. 2013](#)). Many previous paleomagnetic studies of the eastern Asia had focused on the sediments that are often affected by possible inclination shallowing ([Cogné et al., 1999](#); [Gilder et al., 2001, 2003, 2008](#); [Tan et al., 2003, 2007, 2010](#); [Tauxe and Kent, 2004](#), [Yan et al., 2005](#); [Dupont-Nivet et al., 2010a, 2010b](#)). To address this issue, [Torsvik et al. \(2012\)](#) applied a common correction factor value $f = 0.6$ to all the poles obtained from sedimentary rocks to establish their APWP. However, [Ding et al. \(2015\)](#) argued the “f” value sometimes depends on the grain size of the red beds. [Cogné et al. \(2013\)](#) reanalyzed 533 Cretaceous and Cenozoic poles obtained from both sedimentary and volcanic rocks from the Asian blocks and suggested that there is a $\sim 10^\circ$ lower paleolatitude anomaly statistically observed from Late Cretaceous rocks distributing throughout the Asian continent ([Fig. 10b](#)). Although flattening of paleomagnetic inclination due to sedimentary processes in red beds is present, it seems not the only mechanism responsible for this and the Cenozoic inclination anomalies observed over the Asian continent ([Wu et al., 2002](#)). With this in mind, we adopt the new reference APWP constructed by [Cogné et al. \(2013\)](#) to discuss the relative motion between the Qiangtang terrane and other blocks in Asia.

As shown in [Figs. 10b](#), the differences between our observed paleolatitudes and expected paleolatitudes from the data by [Cogné et al. \(2013\)](#), for the reference location (Gerze:

32.5° N, 84.3° E), are not significant, strongly suggesting that the Qiangtang terrane had become a part of stable Asia by ~110 Ma.

6.2 Convergence between Qiangtang and Lhasa terranes after ~100 Ma

Numerous studies suggested that the east and west segments of the Bangong-Nujiang suture experienced diachronous convergent processes, but the time of the closure of the Bangong-Nujiang Ocean has long been a subject of much debate (e.g., Dewey et al., 1988; Matte et al., 1996; Murphy et al., 1997; Yin and Harrison, 2000; Kapp et al., 2003, 2007; Guynn et al., 2006; Pan et al., 2006; Zhu et al., 2009, 2011, 2013, 2015; Zhang et al., 2012, 2014; Wang et al., 2014; Zhang et al., 2014; Fan et al., 2014, 2015; Li et al., 2015a,b). Comparing paleomagnetic results from coeval strata on both sides of the Bangong-Nujiang suture is critical to understanding the convergence history. Before that, some comments and a critical selection are necessary for the data from the Lhasa terrane.

The Cretaceous paleomagnetic data from volcanic and sedimentary rocks yield a wide range of paleolatitude of the Lhasa terrane, from 10.7° to 27.8° N (Table 2; Fig. 10b). Poles NL, QL and TL of Lin and Watts (1988) (Table 2) were defined by a small number of specimens, provided no field test and lack of precise determinations for structural attitude, thus, they are

excluded in further discussion. Pole SQ is derived from only 3 sites and has a large uncertainty. We thus ignore it too. We consider the other poles of Lhasa terrane listed in the Table 2 are more reliable.

Poles TP, TW and TA are obtained from the Takena Formation red beds in the Linzhou basin and they are consistent with each other (Fig. 10a) (Pozzi et al., 1982; Westphal et al., 1983; Achache et al., 1984). We thus combine these three studies to calculate a mean paleomagnetic pole (TM, in Table 2, Fig. 10a) for the Takena red beds. This pole has an Albian-Aptian age and is located at 63.6° N, 333.5° E, $A_{95} = 3.6^{\circ}$, yielding the paleolatitude of $20.4^{\circ} \pm 3.6^{\circ}$ N for the reference point (Gerze, 32.5° N, 84.3° E). This paleolatitudinal result is in good agreement with these inferred from two high quality poles ZN (~123 Ma) and QS (~120-132 Ma). However, other two poles WR and DZ, both obtained from well-dated volcanic rocks, indicate obviously lower paleolatitudes for the Lhasa terrane (Table 2; Fig. 10b) (Sun et al., 2008; Yang et al., in press).

For Late Cretaceous, there are three poles obtained from the Shexing Formation. Two of them (poles MX and SR, Table 2) are from red beds occurred in the upper Shexing Formation. Lippert et al. (2014) has reviewed the pole MX and suggested an inclination shallowing correction for it. We adopt this correction and notice that the paleolatitudes inferred from these two poles are fair close to that observed from the Gerze red beds by this study, being around 29° N.

376 However, other three poles (SL, JZS, CQ in [Table 2](#)) that are slightly or much older than the upper
377 Shexing red beds yield obviously shallower paleolatitudes for the Lhasa terrane ([Fig. 10b](#)).

378 Our analysis reveals some paleolatitudinal variations for the Lhasa terrane in
379 Cretaceous, although many need further test. There is no concisely coeval pole from the Lhasa
380 terrane which can be compared to the Gerze lava pole (GZV in [Table 2](#)) of the Qiangtang terrane.
381 The nearest ones are Early Cretaceous pole TM and Late Cretaceous pole CQ ([Table 2](#)). The pole
382 TM yields a paleolatitude of $20.4^{\circ} \pm 3.6^{\circ}$ N for the reference location, $\sim 10^{\circ}$ lower than our
383 observation. Meanwhile the pole CQ yields a paleolatitude of $10.7^{\circ} \pm 5.1^{\circ}$ N for the reference
384 point, almost $\sim 20^{\circ}$ lower than our observation. Our comparing indicates that there was
385 considerable paleolatitudinal discrepancy between the Qiangtang terrane and the Lhasa terrane
386 during the time interval around ~ 100 Ma. But a precisely quantitative discrepancy is difficult to be
387 concluded at this stage, especially under the consideration of the complexities of the paleomagnetic
388 data. Recently, [Lippert et al. \(2014\)](#) made a careful review over the data from Lhasa terrane and
389 suggested that the Lhasa terrane had remained at $\sim 24^{\circ}$ N (recalculated to Gerze reference point)
390 between ~ 110 and at least 50 Ma. If we adopted their analyses, the paleolatitudinal discrepancy
391 between the Qiangtang and Lhasa terranes would be $\sim 5^{\circ}$, during the time from ~ 110 Ma through
392 Late cretaceous.

In summary, our new results suggest that the Gerze reference point (32.5° N, 84.3° E) of the southern Qiangtang terrane was located at $29.3^{\circ} \pm 5.7^{\circ}$ N during ~110 -100 Ma. It is at least ~5° higher than that inferred from the paleomagnetic results of the Lhasa terrane, suggesting that ~550 km N-S shortening between the Qiangtang and Lhasa terranes has happened since 100 Ma, along the Bangong-Nujiang suture. There is no significant paleolatitudinal difference observed between the Gerze red beds and upper Shexing Formation, suggesting that the convergence likely ceased by deposition of the Late Cretaceous red beds.

Our paleomagnetic analysis is well consistent with the convergence models reported recently (Li et al., 2010; 2013; Wang et al., 2014; Zhang et al., 2014; Fan et al., 2014; 2015), which is largely based on geological evidence. Li et al. (2013) suggested that the oceanic lithosphere completely subducted between ~100 - 80 Ma and the significant thickening of the entire lithosphere happened during the Late Cretaceous caused by the Lhasa-Qiangtang collision. Moreover, Li et al. (2015a, b) considered that the Abushan volcanic rocks (~100 Ma) represents the magmatism caused by the Lhasa-Qiangtang collision and significant shortening (~650 km) happened during the Late Cretaceous collision.

6.3 Vertical-axis rotation observed in the Tibetan Plateau

Paleomagnetic declinations may represent the cumulative amount of rotation since the remanence acquired. The difference between an observed declination and expected ones can provide reliable kinetic evidence for the research of tectonic deformation. The expected direction of a specific locality could be calculated using the appropriate age reference paleomagnetic pole of the stable Asia (e.g., [Torsvik et al., 2012](#); [Cogné et al., 2013](#)). We have tested that the difference between expected declinations calculated from the APWPs proposed by [Torsvik et al. \(2012\)](#) and [Cogné et al. \(2013\)](#) is not significant, and we adopt [Cogné et al. \(2013\)](#)'s APWP as reference to calculate the expected declination and paleolatitude ([Table 3](#)). [Table 3](#) lists the observed directions of the Cretaceous rocks calculated from the reliable poles of the central Tibetan plateau and reference poles of the East Asia. In the study of [Huang et al. \(1992\)](#), two directions were reported which indicated the southern margin of the Qiangtang terrane had experienced a clockwise rotation of $47.1^{\circ} \pm 14.1^{\circ}$ since the Berriasian-Barremian (145-125 Ma) and $28.5^{\circ} \pm 11.7^{\circ}$ since the Aptian-Turonian (125-88.6 Ma) compared with expected directions from the East Asia, respectively ([Table 3, Fig. 1A](#)). The results of [Otofuji et al. \(1990\)](#) show the similar rotation model which suggests the Markam area had undergone a clockwise rotation of $44.5^{\circ} \pm 11.1^{\circ}$ since Early Cretaceous.

The paleomagnetic directions obtained from this study show more light on the tectonic rotational history of the Qiangtang terrane. As shown in [Table 3](#), the observed

429 paleomagnetic directions from the red beds demonstrate that the sampling area has rotated $55.0^\circ \pm$
430 4.9° counterclockwise with respect to the East Asia reference pole after the deposition of the red
431 beds (Fig. 10a), meanwhile the data from the ~110-100 Ma volcanic rocks suggest a $19.5^\circ \pm 7.6^\circ$
432 counterclockwise rotation with respect to the coeval reference pole of East Asia (Fig. 10a). This
433 large discrepancy may suggest that there may be considerable age difference between the red beds
434 and the lavas, and $\sim 35^\circ$ clockwise rotation had happened in this time interval.

435 The rotation pattern of the Qiangtang terrane holds critical clues for the understanding
436 of the regional tectonics. The clockwise rotation signature observed by this study is consistent in
437 both amount and sense with those previous reported, suggesting the clockwise rotation happened
438 during the mid-Cretaceous but stopped during the Late Cretaceous. It may reflect the oblique
439 collision of the Lhasa and Qiangtang terranes in Cretaceous, or right-lateral displacement of faults
440 within the Bangong-Nongjiang suture zone (Dewey et al., 1988; Matte et al., 1996; Yin and
441 Harrison, 2000; Wang et al., 2005; 2014). But the following large scale counterclockwise rotation
442 revealed from our results is likely due to the Indo-Asia collision, because the moving velocity of
443 the northeast corner of the India plate was always greater than the moving velocity of the northwest
444 corner (Molnar and Tapponnier, 1975). This discrepancy of moving velocity led to a large-scale
445 counterclockwise rotation in many locations in the Tibetan Plateau when the India plate collided
446 with the Asian plate (Fig. 1A).

In the Lhasa terrane, the Cretaceous paleomagnetic declinations show a remarkably consistent rotated trend (Fig. 1A, Table 3). Most studies suggest that the area of the central Lhasa had experienced different amount (20°-40°) of anticlockwise rotation since the Early Cretaceous (Pozzi et al., 1982; Westphal et al., 1983; Achache et al., 1984; Tan et al., 2010; Chen et al., 2012; Sun et al., 2012), except for four results which indicate a slight clockwise rotation of the middle-west part of the Lhasa terrane calculated from poles SL, CQ, WR and QS (Fig. 1A, Table 3) (Sun et al., 2008; Tan et al., 2010; Tang et al., 2013; Ma et al., 2014). As one of the most active tectonic region, the western Tibetan was not only controlled by the collision but also affected by some Cenozoic sinistral strike-slip faults. Therefore, the discrepancy between Cretaceous paleomagnetic declinations from the Lhasa terrane could be explained by these kinds of faults which caused some local rotation around different sampling areas (Yin and Harrison, 2000; Kapp et al., 2007; Yin and Taylor, 2011; Ratschbacher et al., 2011).

7. Conclusive remarks

1. We dated a sequence of volcanic rocks at ~110 -100 Ma, using zircon U-Pb method, and carried out a paleomagnetic investigation for these rocks and the overlying redbeds that are likely of Late Cretaceous in age.

2. Paleomagnetic results from both volcanic rocks and redbeds passed a fold test, respectively; paleosecular variation has been averaged out for the directions observed from the volcanic rocks and inclination shallowing test and E/I correction have been performed for the redbeds.
3. The new paleomagnetic results indicate that the Qiangtang terrane was tectonic coherent part of the Asian continent by ~110 Ma.
4. At least ~550 km N-S convergence between Qiangtang and Lhasa terranes happened after ~100 Ma.
5. The Gerze area had experienced a significant count-clockwise rotation after ~100 Ma, which is most likely caused by the India-Asia collision.

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819 **Figure captions**

820 **Fig. 1.** (a) Simplified tectonic map of the Tibetan Plateau showing the major terranes and main
821 sutures (modified from [Yin and Harrison, 2000](#)). The blue and red closed circle show the
822 location of reliable Cretaceous paleomagnetic investigations in the Qiangtang and Lhasa
823 terranes, respectively (abbreviation showed in [Table 2](#)). Solid arrows represent observed
824 paleomagnetic declination, dotted lines represent the expected paleomagnetic declination

825 calculated from the apparent polar wander path of Asia (reference site: 32.5°N, 84.3°E)
826 (Cogné et al., 2013). (b) Simplified geological map of the sampling area and
827 paleomagnetic sites (closed rectangle).

828 **Fig. 2.** Stratigraphic columns with paleomagnetic sampling sites, Gerze area.

829 **Fig. 3.** (a) Quenching edge was found in the lavas, Member 1, Qushenla Formation. (b) lava
830 boundary.

831 **Fig. 4.** (a) Cathodoluminescence (CL) images of representative zircons from the basaltic andesite
832 of the Member 3, Qushenla Formation, Gerze; Circles show the position of the
833 LA-ICP-MS spot analyses and the size of beam. (b) U-Pb concordia diagram of zircons
834 from the basaltic andesite. (c) Cumulative probability plot showing the distribution of
835 $^{206}\text{Pb}/^{238}\text{U}$ age, with a peak around 104 Ma. (d) Bar plot shows weighted mean $^{206}\text{U}/^{238}\text{Pb}$
836 ages and vertical bar means the result of single zircon.

837 **Fig. 5.** Rock magnetic results of the representative samples from volcanic rocks and red beds,
838 respectively. (a)-(b) Stereoplots (equal area, lower-hemisphere projection) of AMS
839 principal axes of the volcanic rocks and red beds: K1/K2/K3, directions of
840 maximum/median/minimum susceptibility axes. (c)-(d) Hysteresis loops of volcanic rocks.
841 (e)-(f) Hysteresis loops of red beds.

842 **Fig. 6.** Typical orthogonal vector plots in geographic coordinates for volcanic rocks. Solid (open)

symbols represent the projections onto the horizontal (vertical) plane. In stereoplots, closed (open) symbols represent positive (negative) inclination. NRM: natural remanent magnetization.

Fig. 7. Typical orthogonal vector plots in geographic coordinates for red beds. Solid (open) circles of the orthogonal vector plots represent the projections onto the horizontal (vertical) plane. In stereoplots, closed (open) symbols represent positive (negative) inclination. NRM: natural remanent magnetization.

Fig. 8. Equal area projections of paleomagnetic directions. LTC: Low temperature component; HTC: High temperature component; PGF: direction of the present geomagnetic field. (a), (b), (c), (d) (g) (h) are in sample level; (e), (f), (i), (j) are in site level, Five point stars indicate site-mean directions, ellipse representing 95% confidence circle of a mean direction.

Fig. 9. (a) Equal area projections of the HTC direction from red beds in stratigraphic coordinates. (b) Results after the Elongation/Inclination (E/I) correction (Tauxe and Kent, 2004), plotted at sample level, $N = 174$. (c) after E/I correction, plotted at site level. (c) Results after E/I correction plotted at site level, the star indicating the site-mean direction with the circle of 95% confidence. (d) Plot of elongation vs. inclination as a function of flattening factor (f). (e) Cumulative distribution of the corrected inclinations. (f) Stepwise unfolding

of the HTC directions after E/I correction.

Fig. 10. (a) Equal-area projections of the high quality Cretaceous paleomagnetic poles (listed in Table 2) from the Qiangtang and Lhasa terranes with the reference locations (Gerze); arcs of the small circles is calculated from the ~100 Ma Gerze lava pole and its uncertainty at 95% confidence; yellow/green dots with shaded 95% confidence circle are Cretaceous poles from the Qiangtang/Lhasa terranes; colorized rectangle are the poles of Asia during 130-60 Ma following Torsvik et al. (2012); gray dots with blue 95% confidence circle are the poles of Asia during 130-60 Ma following Cogné et al.(2013). (b) Plot of Cretaceous paleolatitudes of Asia, Qiangtang and Lhasa terranes at Gerze (reference point: 32.5° N, 84.3° E) calculated from the poles plotted in (a); the expected paleolatitudes of the stable Asia are calculated from APWPs (Torsvik et al., 2012; Cogné et al., 2013) while the paleolatitudes of the Qiangtang and Lhasa terrane are calculated from reliable poles (Fig. 10a); vertical bars and dot acclinic line display paleolatitude and age uncertainties, respectively.

Figure 01

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Table 1

Table 1 Site mean values and statistical parameters for the Cretaceous red beds and lava in Gaize area

Site	S/D	n/N	Coor	Direction				Palaeopole			
				D/(°)	I/(°)	k	α_{95} (°)	Plat/(°N)	Plon/(°E)	dp/(°)	dm/(°)
<u>Red Beds</u>											
GZ1	235/86	10/11	G	162.5	55.8	90.0	5.1	-19.2	99.2	5.2	7.3
			S	312.3	36.2	90.0	5.1	45.9	350.2	3.5	5.9
			S*	312.4	50.3	97.9	4.9	49.9	5.5	4.4	6.6
GZ2	238/84	7/9	G	166.4	54.3	236.1	3.9	-21.5	96.3	3.9	5.5
			S	313.6	39.4	235.8	3.9	47.9	352.4	2.8	4.7
			S*	313.7	53.6	281.9	3.6	51.6	9.8	3.5	5.0
GZ3	234/95	5/9	G	160.9	63.2	62.6	9.7	-10.9	98.0	12.1	15.3
			S	315.4	20.6	62.5	9.8	43.6	336.6	5.4	10.3
			S*	315.4	31.6	48.6	11.1	47.0	344.4	7.0	12.5
GZ4	238/90	6/6	G	171.3	48.5	59.4	8.8	-21.9	81.5	3.8	5.4
			S	308.1	37.3	59.6	8.7	37.7	348.1	2.3	4.2
			S*	308.1	51.0	57.5	8.9	41.6	358.3	3.0	4.9
GZ5	238/90	6/6	G	181.4	52.8	131.5	5.9	-27.5	92.8	7.6	11.6
			S	304.8	30.1	131.6	5.9	37.7	350.0	3.6	6.6
			S*	304.9	43.7	125.9	6.0	41.8	0.9	4.7	7.5
GZ6	238/90	7/11	G	169.6	47.9	39.7	9.7	-27.8	94.6	8.3	12.7
			S	309.0	38.5	39.7	9.7	43.8	354.1	6.8	11.5
			S*	308.3	52.6	55.9	8.1	47.0	9.9	7.7	11.2
GZ7	235/86	9/12	G	171.4	55.5	54.4	7.0	-21.0	91.7	7.1	10.0
			S	306.6	34.2	54.6	7.0	40.5	351.9	4.6	8.0
			S*	306.3	48.1	68.9	6.2	44.2	5.0	5.3	8.1
GZ8	240/88	12/13	G	179.0	51.9	73.5	5.1	-25.0	85.2	4.8	7.0
			S	308.1	34.4	73.3	5.1	41.8	351.2	3.4	5.8
			S*	308.4	48.3	77.7	5.0	46.0	4.4	4.3	6.6
GZ9	236/89	13/17	G	160.1	51.3	69.9	5.0	-22.8	102.6	4.6	6.8
			S	314.2	38.3	69.6	5.0	48.1	351.0	3.5	5.9
			S*	314.4	52.4	92.7	4.3	52.0	7.8	4.1	5.9
GZ10	240/91	5/11	G	155.3	53.6	30.2	14.1	-19.4	105.8	13.7	19.7
			S	325.7	35.2	31.1	13.9	56.7	339.7	9.3	16.0
			S*	325.1	49.2	41.4	12.0	60.2	359.1	10.5	15.9
GZ11	234/90	8/13	G	166.8	52.1	95.6	5.7	-23.6	96.4	5.3	7.8
			S	306.6	34.4	96.1	5.7	40.5	352.0	3.7	6.5
			S*	306.7	48.4	109.9	5.3	44.7	5.2	4.6	7.0
GZ12	238/87	12/15	G	157.7	48.1	47.8	6.3	-24.8	105.7	5.4	8.2
			S	311.3	40.4	47.8	6.3	46.3	354.6	4.6	7.6
			S*	311.4	54.0	57.7	5.8	49.8	11.0	5.7	8.1

GZ13	240/91	13/20	G	160.5	53.4	89.2	4.4	-21.1	101.6	4.3	6.1		
			S	318.0	38.5	91.2	4.4	51.3	348.8	3.1	5.2		
			S*	318.1	52.7	125.9	3.7	55.0	7.3	3.5	5.1		
GZ14	232/92	6/11	G	175.3	44.3	75.9	7.7	-31.3	89.2	6.1	9.7		
			S	309.9	39.1	76.3	7.7	44.7	354.2	5.5	9.2		
			S*	310.0	52.9	85.3	7.3	48.5	9.8	7.0	10.1		
GZ15	240/90	8/13	G	154.1	62.7	29.5	10.4	-9.9	102.9	12.8	16.3		
			S	327.3	27.2	29.5	10.4	55.2	330.8	6.2	11.3		
			S*	326.6	38.9	22.5	11.9	58.6	343.2	8.4	14.2		
GZ16	234/100	9/10	G	173.6	41.8	180.3	3.8	-33.1	91.3	2.8	4.7		
			S	297.8	31.3	180.4	3.8	32.2	354.7	2.4	4.3		
			S*	297.7	45.0	157.0	4.1	36.2	5.3	3.3	5.2		
			S	308.1	26.5	69.1	8.1	39.4	345.5	4.8	8.8		
			S*	308.1	39.1	59.6	8.8	43.2	355.1	6.3	10.5		
GZ18	237/102	7/8	G	166.0	48.3	77.1	6.9	-26.8	98.0	5.9	9.0		
			S	312.3	27.3	77.2	6.9	43.1	343.3	4.1	7.5		
			S*	312.2	40.2	76.4	6.9	47.0	354.0	5.0	8.3		
GZ19	237/102	7/8	G	168.2	43.7	94.2	6.3	-30.9	96.7	4.9	7.9		
			S	308.5	30.9	93.6	6.3	41.1	348.3	3.9	7.0		
			S*	308.4	44.4	86.5	6.5	45.0	0.1	5.1	8.2		
GZ20	175/20	6/12	G	345.6	41.9	175.7	5.1	74.9	324.6	3.8	6.3		
			S	329.9	36.0	176.0	5.1	60.4	336.8	3.4	5.9		
			S*	329.9	50.2	178.4	5.0	64.4	359.0	4.5	6.7		
GZ21	174/18	6/6	G	323.4	45.7	32.1	12.0	58.0	354.4	9.7	15.3		
			S	311.0	34.8	32.2	12.0	44.3	349.8	7.9	13.8		
			S*	311.5	47.9	26.9	13.2	48.5	2.7	11.2	17.2		
GZ22	163/15	6/13	G	331.7	39.9	40.4	10.7	63.2	340.0	7.7	12.9		
			S	320.4	35.6	40.3	10.7	52.5	344.3	7.2	12.4		
			S*	319.9	49.3	45.9	10.0	55.9	1.3	8.8	13.3		
Mean	N=22	G	170.0	60.4	8.0	11.7	29.8	279.9	A ₉₅ =8.6°				
			174/247	S	312.6	34.2	98.8	3.1	45.4	348.1	A ₉₅ =3.1°		
				S*	312.6	47.7	109.7	3.0	49.2	1.9	A ₉₅ =3.2°		
Lavas													
GZ23	164/23	6/6	G	9.7	41.9	418.2	3.3	78.1	216.2	2.5	4.0		
			S	347.1	47.8	418.8	3.3	78.3	339.6	2.8	4.3		
GZ24-25	164/23	4/4	G	351.1	42.2	91.2	9.7	78.7	310.5	7.3	11.9		
			S	330.4	40.8	91.1	9.7	62.4	342.5	7.1	11.8		
GZ26-28	194/15	6/9	G	2.8	45.0	343.4	3.6	83.6	241.3	2.9	4.6		
			S	347.6	45.3	346.5	3.6	77.8	329.6	2.9	4.6		
GZ29	194/15	9/9	G	8.7	44.5	616.4	2.1	80.1	212.0	1.7	2.6		

			S	353.5	46.3	622.7	2.1	82.6	315.0	1.7	2.7
GZ30	163/28	5/6	G	8.4	28.6	790.7	2.7	71.1	238.5	1.6	3.0
			S	350.7	36.8	792.5	2.7	75.4	301.3	1.8	3.2
GZ31	163/28	7/7	G	9.4	30.5	71.4	7.2	71.8	234.2	4.5	8.0
			S	350.4	39.0	71.1	7.2	76.5	305.8	5.1	8.6
GZ32*	166/28	4/4	G	16.2	23.7	112.0	8.7	65.0	224.2	4.9	9.3
			S	1.4	36.2	111.2	8.8	77.5	258.2	6.0	10.2
GZ33-34	166/28	7/8	G	12.8	30.5	145.5	5.0	70.2	225.5	3.1	5.6
			S	353.7	39.3	145.2	5.0	78.3	294.5	3.6	6.0
GZ35-36	158/31	9/12	G	27.5	49.1	267.5	3.2	66.4	173.0	2.8	4.2
			S	349.3	60.5	265.9	3.2	77.6	43.8	3.7	4.9
GZ37	158/31	8/10	G	30.1	50.3	836.1	1.9	64.5	169.4	1.7	2.5
			S	349.9	62.6	840.6	1.9	76.1	52.7	2.3	3.0
GZ38	158/31	8/12	G	30.8	47.6	207.5	3.9	63.3	174.3	3.3	5.1
			S	354.7	61.1	207.3	3.9	79.5	62.3	4.6	6.0
GZ39-41	158/31	9/9	G	27.9	45.1	323.6	2.9	65.1	180.6	2.3	3.7
			S	355.1	57.8	324.8	2.9	82.8	51.8	3.1	4.3
GZ42-43	152/26	5/5	G	0.5	38.6	195.9	5.5	79.2	261.8	3.9	6.5
			S	337.1	46.4	196.3	5.5	69.7	346.7	4.5	7.1
GZ44-45	152/26	4/4	G	353.7	32.2	204.8	6.4	73.9	286.5	4.1	7.2
			S	335.4	38.0	205.1	6.4	65.5	333.4	4.5	7.6
Mean	N=14	G	11.4	39.9	39.2	6.4	76.0	213.2	A₉₅ =6.6°		
	91/105	S	348.0	47.3	51.0	5.6	79.3	339.8	A₉₅ =5.7°		

Notes: n/N: number of samples used to calculate mean/measured; Dg/Ig, declination/inclination in geographic coordinates; Ds/Is: declination/inclination in stratigraphic coordinates; D_{S*}/ I_{S*}: declination/inclination after E/I correction; k: best estimate of the precision parameter of direction; α_{95}/A_{95} : radius of circle of 95% confidence on the direction/pole; GPlat/GPlon, latitude/longitude of VGP in the geographic coordinates; Splat/SPlon: latitude/longitude of VGP in the stratigraphic coordinates; S*Plat/S*Plon: latitude/longitude of VGP after E/I correction; S/D: Strike/Dip; GZ32* (166, 28): the attitude of stratum of the quenching edges.

① fold test for red beds is positive at the 99% confidence (McElhinny, 1964): $K_s/K_g = 13.7 > F(2*(n_2-1), (n_1-1))$ at 1% point =2.1;

② fold test for red beds is also positive at the 99% confidence (McFadden and McElhinny, 1990): critical Xi at 99% =7.7. Xi1 IS =17.2, Xi1 TC =2.6;

③ fold test for volcanic rocks is positive at the 95% confidence (McFadden and McElhinny, 1990): critical Xi at 95% =4.4. Xi1 IS =5.9, Xi1 TC =0.8.

Table 2

Table 2. Summary of the Cretaceous paleomagnetic poles from the Qiangtang and Lhasa terranes

Site location (° N/ ° E)	Mnemonic	Rock-units	Age (Ma)	Plat (° N)	Plon (° E)	A ₉₅ (°)	Palat (° N)	N/n	Criterion (Q)	Reference
<i>Qiangtang terrane</i>										
Gaize (32.5, 84.3)	GZR	Red beds	Late Cretaceous- 103.8	49.2	1.9	3.2	28.7 ± 3.2	22/174	123F5□7 (6)	This study
Gaize (32.5, 84.3)	GZV	Volcanic rocks	103.8±0.46, U–Pb LA-ICP-MS	79.3	339.8	5.7	29.3 ± 5.7	14/91	123F5□7 (6)	This study
Markam (29.7, 98.7)	MK	Mangkang Fm, red beds	Aptian–Turonian	56.7	172.7	9.6	27.5 ± 9.6	11/79	123F5□7 (6)	Huang et al. (1992)
Markam (29.7, 98.4)	CW	Cuowa Fm, red beds	Berriasian–Barremian	40.6	170.5	11.9	23.1 ± 12.0	12/68	123F5D□ (6)	Huang et al. (1992)
Markam (29.7, 98.6)	LR	Laoran Fm, red sandstones	Barremian–Albian	48.5	175.8	9.5	22.8 ± 9.5	5/30	123□5□7 (5)	Otofujii et al. (1990)
Aksaichin (35.0, 79.7)	AS	Red sandstones	Albian–Aptian	66.3	256.5	5.1	9.0 ± 5.1	7/55	123F5D7 (7)	Chen et al. (1993)
Longmuco (34.5, 80.4)	LS	Red sandstones	Albian–Aptian	64.4	231.3	9.9	10.3 ± 9.9	4/50	123□5D7 (6)	Chen et al. (1993)
<i>Lhasa terrane</i>										
Cuoqin (31.2, 84.7)	JZS	Jingzhushan Fm, red beds	K2	49.0	344.3	5.3	18.0 ± 5.3	33/291	123F5D7 (7)	Yang et al., (in press)
Maxiang (29.9, 90.7)	MX	Shexing Fm, red beds	72.4 - 110, U–Pb SHRIMP	74.6	346.5	2.7	29.2 ± 2.7	100	123F5□7 (6)	Sun et al., (2012)
		Andesite								Lippert et al., (2014)
<i>Qelico (31.7, 91.0)</i>	<i>QL</i>	<i>Qelico lava</i>	<i>85 - 95, ⁴⁰Ar–³⁹Ar</i>	<i>74.0</i>	<i>318.0</i>	<i>14.6</i>	<i>22.3 ± 14.6</i>	<i>4/20</i>	<i>1□3□5□□ (3)</i>	<i>Lin and Watts. (1988)</i>
<i>Nagqu (31.5, 92.0)</i>	<i>NL</i>	<i>Nagqu lava</i>	<i>95 - 100, ⁴⁰Ar–³⁹Ar</i>	<i>78.0</i>	<i>282.0</i>	<i>5.3</i>	<i>21.0 ± 5.3</i>	<i>9/33</i>	<i>123□□□□ (3)</i>	<i>Lin and Watts. (1988)</i>
Linzhou (29.5, 91.1)	SR	Shexing Fm, red beds	Albian–Late Cretaceous	79.6	330.5	2.4	27.8 ± 2.4	43/196	123F5D□ (6)	Tan et al. (2010)
Linzhou (29.6, 91.2)	SL	Shexing Fm, lava	Albian–Late Cretaceous	69.1	191.7	4.2	24.3 ± 4.2	21/136	123F5D□ (6)	Tan et al. (2010)
Cuoqin (30.9, 84.9)	CQ	Andesite, tuff	93 - 99, ⁴⁰ Ar– ³⁹ Ar	63.1	224.6	5.1	10.7 ± 5.1	10/87	123F5□7 (6)	Tang et al., (2013)
Linzhou (29.2, 90.0)	TP	Takena Fm,red beds	Albian–Aptian	68.0	340.0	8.8	24.8 ± 8.8	7/68	123F5□7 (6)	Pozzi et al. (1982)
Linzhou (29.9, 91.0)	TW	Takena Fm, red	Albian–Aptian	64.0	348.0	7.3	26.3 ± 7.3	6/57	123F5D7 (7)	Westphal et al. (1983)
North of Linzhou (31.0, 92.0)	TNA	Takena Fm, red beds	Albian–Aptian	63.5	325.4	6.5	17.4 ± 6.5	6/57	123F5□7 (6)	Achache et al. (1984)
Linzhou (30.0 91.0)	TSA	Takena Fm, red beds	Albian–Aptian	71.2	288.4	7.9	15.1 ± 7.9	8/61	123F5□□ (5)	Achache et al. (1984)
Mean TNA+TSA (rotated)	TA	Takena Fm, red beds	Albian–Aptian	63.4	323.2	4.8	16.6 ± 4.8	14/118	123F5□7 (6)	Achache et al. (1984)
Mean for Takena Fm	TM	Takena Fm, red beds	Albian–Aptian	63.6	333.5	3.6	20.4 ± 3.6	27/243	123F5D7 (7)	Poles: TP, TW, TA
<i>Linzhou (29.9, 91.2)</i>	<i>TL</i>	<i>Takena Fm, red beds</i>	<i>Albian–Aptian</i>	<i>68.0</i>	<i>279.0</i>	<i>4.9</i>	<i>11.1 ± 4.9</i>	<i>8/51</i>	<i>123F5□□ (5)</i>	<i>Lin and Watts. (1988)</i>
<i>Shiquanhe (32.7, 80.2)</i>	<i>SQ</i>	<i>Limestones</i>	<i>Albian–Aptian</i>	<i>67.7</i>	<i>234.2</i>	<i>17.9</i>	<i>12.7 ± 17.9</i>	<i>3/62</i>	<i>123□5□7 (5)</i>	<i>Chen et al. (1993)</i>
Deqing (30.5, 90.1)	WR	Woronggou Gp, volcanics	114±1.1, U–Pb SHRIMP	66.4	220.3	6.9	14.4 ± 6.9	16/88	123□5□7 (5)	Sun et al. (2008)

Cuoqin (31.1, 84.4)	DZ	Dianzhong Fm, volcanics	117-121, U-Pb LA-ICP-MS	70.5	292.9	7.4	15.0 ± 7.4	12/116	123□5D7 (6)	Yang et al., (in press)
Cuoqin (31.3, 85.0)	ZN	Zenong Gp, volcanic rocks	123.1±0.9, U-Pb LA-ICP-MS	58.2	341.9	4.6	21.2 ± 4.6	18/162	123F5R7 (7)	Chen et al. (2012)
Yanhu (32.3, 82.6)	QS	Qushenla Fm, lava	120-132, U-Pb LA-ICP-MS	61.4	192.9	2.1	19.2 ± 2.1	51/444	123F5D7 (7)	Ma et al. (2014)

Notes: Site location: Paleomagnetic sampling location; Mnemonic: pole name plotted in Fig. 1 and Fig. 9; Fm: Formation; Plat/Plon: latitude and longitude of a pole; A_{95} : radius of circle of 95% confidence on a pole; Palat: Palaeolatitude calculated using the reference point (32.5° N, 84.3°); N/n: site/sample number used for final statistic; Criterion (Q): Data quality criteria and Q values (number of criteria met) according to the 7-point quality criterion system proposed by [Van der Voo \(1990\)](#) [1, well determined rock age; 2, sufficient number of samples, $n > 24$, k (or K) ≥ 10 , $\alpha_{95} \leq 16.0^\circ$; 3, step-wise demagnetization; 4 (F), positive fold test; 5, structural control and tectonic coherence with the craton discussed; 6, (R/D), positive reversals test/dual-polarity; 7, no resemblance to paleopole of younger age (by more than a period)]; “□”: failed to meet this criterion. For poles GZR, MX, SR: the inclinations of the red beds have been corrected using E/I method; TM: the mean paleomagnetic pole for the Takena red beds; Italics poles are excluded for tectonic interpretations (see in text).

Table 3

Table 3. Cretaceous paleomagnetic directions and the amount of rotation with expected directions calculated from the stable Eurasia

Mnemonic	Site Location (° N/ ° E)	Age (Ma)	Observed Direction			Reference pole (Eurasia)			Dec-exp. (°)	Rotation R ± ΔR (°)	Lat-exp. (°)	Displacement D ± ΔD (°)	Reference
			Dec.	Inc.	α ₉₅	Lat.	Lon.	A ₉₅					
			(°)	(°)	(°)	(° N)	(° E)	(°)					
Qiangtang													
GZR	32.5/ 84.3	60 - 103.8	312.6	47.7	3.0	80.5	219.5	2.9	7.4	-54.8±4.9	25.5	-3.2±3.5	This study
GZV	32.5/ 84.3	103.8 ± 0.46	348.0	47.3	5.6	82.2	205.4	3.5	7.6	-19.6±7.6	28.2	-1.1±5.4	This study
MK	29.7/ 98.7	88.6 - 125.0	39.0	52.5	8.5	80.3	204.0	1.9	10.5	28.5±11.7	26.7	-6.3±7.8	Huang et al. (1992)
CW	29.7/ 98.4	125.0 - 145.0	58.1	51.0	10.9	80.3	193.2	1.5	11.0	47.1±14.1	28.4	-3.2±1.5	Huang et al. (1992)
LR	29.7/98.6	99.6 - 130	48.2	49.0	8.8	80.9	197.4	1.5	10.2	44.5±11.1	27.9	-2.0±7.7	Otofuji et al. (1990)
AS	35.0/79.7	99.6 - 125.0	1.3	21.8	5.0	80.9	197.4	1.5	9.3	-8.0±5.5	30.4	19.1±4.3	Chen et al. (1993)
LS	34.5/80.4	99.6 - 125.0	12.4	22.2	9.7	80.9	197.4	1.5	9.4	3.0±10.3	30.0	18.5±8.0	Chen et al. (1993)
Lhasa													
JZS	31.2/ 84.7	60.0 - 100.0	317.6	31.2	5.3	80.5	219.5	2.9	7.4	-49.8±6.4	24.3	7.5±4.8	Yang et al., (in press)
MX	29.9/ 90.7	72.4 - 110.0	343.5	43.1	2.6	80.1	211.4	2.0	9.4	-25.9±3.7	24.5	-0.6±2.7	Sun et al. (2012)
													Lippert et al., (2014)
SR	29.9/ 91.1	65.0 - 110.0	350.2	41.5	2.5	80.5	219.5	2.9	8.1	-17.9±4.1	23.4	-0.5±3.0	Tan et al. (2010)
SL	29.9/ 91.2	65.0 - 110.0	22.6	41.5	4.4	80.5	219.5	2.9	8.1	14.4±5.6	23.5	-0.4±4.1	Tan et al. (2010)
TP	29.2/ 90.0	99.6 - 125.0	338.0	35.9	10.0	80.9	197.4	1.5	9.7	-31.7±9.5	26.1	6.2±7.1	Pozzi et al. (1982)
TW	29.9/ 91.0	99.6 - 125.0	332.7	37.9	8.0	80.9	197.4	1.5	9.8	-37.1±8.0	27.0	5.7±6.0	Westphal et al. (1983)
TNA	31.0/ 92.0	99.6 - 125.0	339.0	24.3	8.9	80.9	197.4	1.5	10.0	-31.6±6.9	28.2	14.7±5.3	Achache et al. (1984)
TSA	30.0/ 91.0	99.6 - 125.0	338.8	23.2	8.3	80.9	197.4	1.5	9.8	-15.5±8.2	27.1	15.1±6.4	Achache et al. (1984)
WR	30.5/ 90.1	114.0 ± 1.1	18.4	26.6	8.6	80.8	199.5	3.5	9.8	8.6±8.1	27.1	13.1±6.2	Sun et al. (2008)
DZ	31.1/ 84.4	117.0 - 121.0	350.6	25.9	7.4	80.6	192.9	2.9	10.1	-19.5±8.3	27.7	14.1±6.4	Yang et al., (in press)
ZN	31.3/ 85.0	123.1 ± 0.9	326.9	35.8	4.5	80.3	193.2	1.5	10.4	-43.5±5.2	27.8	8.0±3.9	Chen et al. (2012)
QS	32.3/ 82.6	120 - 132	28.4	34.8	2.0	80.3	193.2	1.5	10.3	18.0 ± 2.8	28.5	9.3 ± 2.1	Ma et al. (2014)

Notes: Mnemonic: pole name (details see [Table 2](#)); Site location: paleomagnetic sampling locality; Age: see in Table 2 and comparing the geological stages with the Geological Time Scale ([Gradstein et al., 2012](#)); Dec/Inc: declination/inclination calculated from the responding pole; α₉₅: radius of the 95% confidence circle about of a direction; Reference pole: the coeval Eurasia reference pole

chosen (or averaged) for the corresponding age (or age interval), based the data of [Cogné et al. \(2013\)](#); Lat/Lon: latitude/longitude of the reference pole; A_{95} : radius of the 95% confidence circle of a pole; Dec-exp./Lat-exp.: declination/latitude expected at the sampling site from the coeval Eurasia reference pole; Rotation ($R \pm \Delta R$): the vertical axis rotation calculated with respect to the expected declination with 95% confidence limit (+/-: clockwise/counterclockwise); Displacement ($D \pm \Delta D$): the North-South displacement calculated with respect to the expected latitude with 95% confidence limit.