Paleomagnetism of the Upper Triassic rocks from south of the Ailaoshan Suture and the timing of the amalgamation between the South China and the Indochina blocks

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Abstract

A high temperature remanence with thermally-discrete unblocking temperature spectra has been isolated from the redbed samples of the Upper Triassic Yiwanshui Formation collected from south of the Ailaoshan Suture in southern Yunnan Province of China. Two groups of directions were observed: the tilt-corrected mean is $D/I = 141.4^\circ/31.2^\circ$ with $\alpha_{95} = 13.0^\circ$ based on 12 sites for the first group, and $D/I = 207.5^\circ/4.9^\circ$ with $\alpha_{95} = 16.0^\circ$ based on 5 sites for the second group. The second group of directions was derived from massively bedded rocks with large uncertainties in determination of the paleo-horizontal and is thus deemed inaccurate. The first group of directions passes the foldtest with dual polarity, and is consistent with results previously reported from the same type section, and probably represents primary magnetization of the rock formation. Comparison with the Triassic paleomagnetic poles for the Baoshan Terrane and the South China Block indicates that the Simao and the Baoshan terranes

were probably already amalgamated by late Triassic times but the coalescence between them and the South China Block may have not been completed until near the end of the Triassic.

Keywords

Upper Triassic, Yiwanshui Formation, Ailaoshan Suture, South China Block, Simao Terrane, Baoshan Terrane, Indochina Block, amalgamation

1. Introduction

China is a collage of continental blocks/terranees of various sizes (e.g. Ren, 1996). These include three major blocks, i.e. North China (Sino-Korea), South China (Yangtze plus Huanan), and Tarim, and a number of smaller terranees such as Qaidam, Qiangtang, Lhasa, Simao, Baoshan, just name a few. To unravel the amalgamation history of these blocks has been the aim of multi-country, multi-discipline campaign since the theory of plate tectonics was introduced in China in the early 1970s. Paleomagnetism has played a major role in such an endeavor. It is now generally accepted that most of these blocks/terranees originated from northern Gondwana and were accreted onto Eurasia in the Mesozoic and Cenozoic times (e.g. Sengor, 1984; Metcalfe, 2013). While great strides have been made in the understanding of the evolutionary history of these blocks/terranees, many questions remain to be answered. One of them is when and how the South China Block (SCB) and the Simao Terrane, which is the northwestern extension of the Indochina Block (Metcalfe, 2013), were assembled. To aid in the resolution of this question, we sampled the Upper Triassic rocks from 1986 to 1995 in northwestern and southern Yunnan Province extensively. We report these paleomagnetic

results and discuss the timing of the amalgamation between the South China and the Indochina blocks in this paper.

Figure 1 here

2. Geology and Sampling

Within the Chinese territory, the Simao Terrane is separated from the South China Block to the northeast by the NW-SE striking Ailaoshan Suture, and is bounded to the west by the roughly north-south-trending Changning–Menglian Suture (Wu et al., 1995). Most of the Simao Terrane is now covered by a thick continental redbed succession of Jurassic through early Tertiary age; the Lower Triassic is missing (BGMRY, 1990). Middle – Upper Triassic rocks of marine facies are exposed sporadically in the central part of the Simao Terrane and are disconformably overlain by the Mid-Jurassic Hepingxiang Formation. To the south of the Ailaoshan Suture, the Middle - Upper Triassic sequence crops out discontinuously. In the Lanping–Weishan area in northwestern Yunnan Province, the Upper Triassic Series unconformably overlies the folded, slightly metamorphosed Middle Triassic rocks (Ren and Qiu, 1966), and is divisible into four formations, in ascending order, Waigucun, Sanhedong, Waluba, and Maichuqing formations. The Waigucun Fm is mainly of fluvial-littoral clastics and *Carnian* in age. The Sanhedong Fm is composed of neritic carbonates and may be a diachronous unit but is mostly of late *Carnian* age. The Waluba Fm of *Norian* age is characterized by dark-grey fine-grained clastics and rich bivalve and ammonoid fossils. The disconformably overlying *Rhaetian* Maichuqing Fm is represented by marine sediments deposited during the regression indicated by brackish bivalve and plant fossils and thin coal seams, and conformably grades into the overlying Lower Jurassic

61 Yangjiang Formation. Such a subdivision scheme for the Upper Triassic strata was proposed to
62 simplify the various rock formation names used for the Lanping-Mojiang region during the
63 1:200,000 geologic mapping (BGMRY, 1990). In the Mojiang–Luchun area immediately south
64 of the Ailaoshan Suture, the Upper Triassic was divided into two formations: Yiwanshui and
65 Luma formations. The Yiwanshui Fm was further divided into the Lower and Upper members.
66 The Lower Yiwanshui Fm totals 485 m in thickness at the type section and unconformably rests
67 on the Devonian rocks. The lower two thirds of the Lower Yiwanshui Fm consist of thick- or
68 massive-bedded purplish grey conglomerates and pebbly coarse-grained sandstones with minor
69 muddy sandstone intercalations. The remaining part of the Lower Yiwanshui Fm is made
70 mainly of purplish red or dark purple mudstones and muddy sandstones. The lower part of the
71 Upper Yiwanshui Fm is 50 m thick at the type section and is composed of dark-grey limestones
72 with interbedded brecciated limestones. The upper part of the Upper Yiwanshui Fm comprises
73 greyish black shales, silty shales and muddy siltstones, and is 152 m thick at the type section,
74 and yields such bivalves as *Halobia convexa*, *H. cf. pluriradiata*, *H. cf. talauana*, *H. yunnanensis*,
75 *Palaeonucula sp.*. The Luma Fm is 864 m thick at the type section, and contains bivalves such as
76 *Halobia cf. superbascen*, *Burmesia krumbecki*, *B. praecursor* and plant fossil such as
77 *Podozamites sp.*, and is made up of shales, silty shales and fine-grained sandstones, with the
78 lower part being dark-colored and the upper part more variegated (RSTCGY, 1978).
79 Apparently, the Lower Yiwanshui Fm, the lower and upper parts of the Upper Yiwanshui Fm and
80 the Luma Fm are well correlative with the Waigucun, Sanhedong, Waluba, and Maichuqing
81 formations in the Lanping-Weishan area (BGMRY, 1990).

Our sampling targeted the red-colored Waigucun Fm and the Lower Yiwanshui Fm. In the Lanping–Weishan area, we collected 14 sites from the Waigucun Fm at two localities: 8 sites from the Shizhongshan–Maliqing section (26.46°N, 99.70°E) and 6 sites from the Waigucun type section (25.25°N, 100.10°E). A total of 38 sites were collected from the Lower Yiwanshui Fm at three localities in the Mojiang-Luchun area. Unfortunately, none of the sites from the Waigucun Fm yielded consistent, stable directions. We will describe sampling detail and paleomagnetic results from the Yiwanshui Fm in the next section.

A portable gasoline-powered rock drill was used in the field for sample extraction, and the cores were oriented with an orienting device mounted with a magnetic compass. Local magnetic declinations were computed using the online calculator at <http://www.ngdc.noaa.gov/geomag>. Five to six cores were usually collected from each site.

3. Results

All samples from the Yiwanshui Fm are redbeds, so progressive thermal cleaning was used throughout. Thermal demagnetization was performed in an ASC TD-40 oven. Remanence was measured in a 2G discrete sample superconducting rock magnetometer. The instruments are housed in a magnetically shielded room at the Department of Geological Sciences, University of Florida. Orthogonal vector plots (Zijderveld, 1967) were used to examine the demagnetization behavior of the samples. Component directions were calculated using principal component analysis (PCA) (Kirschvink, 1980). Computation of site and formation means follows Fisher (1953).

3.1 Yiwanshui, Mojiang County (101.67°E, 23.56°N)

The first sampled locality is near a village called Yiwanshui, about 12 km north of downtown Mojiang County on the provincial highway #218. Sampling was carried out at two locations, one at the type section for the Yiwanshui and Luma formations on a hill slope just north of the village (Location 1), the other about one kilometer further north and down into the valley (Location 2). Both locations are on the western limb of a NW-trending, fault-disrupted syncline with the Luma Fm constituting its core and the Yiwanshui Fm cropping out along the limbs. The rocks dip **towards** 89–133° at 14–25° at Location 1 and dip **towards** 54–64° at 44–59° at Location 2; the variation in bedding attitude between the locations may result from structural flexure. All the samples were taken from the upper part of the Lower Yiwanshui Fm and most of them are purplish-red fine-grained sandstones or siltstones. The exposures at Location 1 were a bit weathered; we managed to drill nine sites (86-1 through 86-9). The rocks at Location 2 were very fresh; twelve sites (95-5 through 95-16) were taken from the stream bed upstream of a small (Bakahe) hydropower station.

Figure 2 here

The initial intensities of natural remanent magnetization (NRM) of the samples from this locality vary from 0.7 to 6.4 mA/m with the majority in the range 1.0–3.2 mA/m. After removal of a very soft, probably viscous remanent magnetization (VRM) below 100°C or 200°C, two magnetic components were revealed from most samples: a thermally-distributed low temperature component (LTC) in the temperature range 100–650°C and a thermally-discrete high temperature component (HTC) above 650°C (Fig. 2). Both components are probably carried by hematite. The LTC is sub-parallel to the geocentric axial dipole (GAD) direction at the

sampling locality ($D = 0^\circ$, $I = 41.1^\circ$) before tilt correction; it became more scattered after correcting for bedding tilt (Fig. 3a). Therefore, the LTC appears to be a remagnetization of recent origin. For most samples, the HTC linearly decayed towards the origin of the plotting coordinates and can thus be classified as characteristic remanent magnetization (ChRM). The HTC from most sites of Location 1 shows two polarities: the mean tilt-corrected directions of sites 86-1 through 86-4 are southeast-easterly and down whereas those of sites 86-5 and 86-9 are northwest-westerly and up after bedding correction. However, the in-situ HTC directions of sites 86-6 and 86-7 are close to the GAD, and their unblocking temperature spectra are decrementally distributed (Fig. 2c), an indication that these two sites were remagnetized probably due to weathering. Site 86-8 failed to generate consistent, stable directions. These three sites are excluded from further analysis. The samples from Location 2 are characterized by partially overlapping unblocking temperature spectra between the LTC and HTC, evidenced by a curved transition from the LTC to HTC in the demagnetization trajectories (Fig. 2d, e). Ten out of twelve sites yielded well-defined, ChRM-natured HTC that could be determined using PCA approach. The tilt-corrected HTC directions from these sites are southeasterly and down, similar to one of the two polarities observed at Location 1. The remaining two sites (95-7 and 95-15) were dominated by the thermally-distributed LTC and failed to yield PCA-determinable ChRM directions (Fig. 2f).

Figure 3 here

3.2 Anding, Yuanjiang County (101.76°E, 23.43°N)

The second sampled locality is along the national highway #213 near a village named Anding between Mojiang and Yuanjiang counties, about 11 km east of downtown Mojiang. Sampling was also conducted at two locations: one near the kilometer marker 2448 west of Anding (Location 3) and on the southern limb of a subordinate anticline where the purplish-red fine-grained sandstone beds are overturned verging north or dip steeply to the south and four sites were collected (95-1 through 95-4), the other near the kilometer marker 2435 east of Anding but off highway #218 onto a country road (Location 4) where three sites were taken from the purplish red sandstones (95-17 through 95-19), the bedding of which appeared to dip towards 220° at 30° but were not readily recognizable due to the massive beds of the rocks.

Figure 4 here

The initial NRM intensities of the samples from Location 4 are comparable to those from Locations 1 and 2, varying between 0.7 and 2.2 mA/m, but the samples from Location 3 appear to be more strongly magnetized with most of the initial NRM intensities ranging 1.8-6.3 mA/m. The thermally-distributed LTC directions were a bit scattered, but its mean direction falls close to the GAD (Fig. 2b), suggestive of a recent origin. After the LTC was eliminated, mostly below 625°C, three out of four sites from Location 3 (95-1 through 95-3) and all three sites from Location 4 yielded well-defined, ChRM-natured HTC that was discretely unblocked in the temperature range 650-680°C (Figs. 4a,b,d). Again, both the LTC and HTC are probably carried by hematite. The HTC directions from Location 3 are of dual polarity with those from sites 95-1 and 95-3 being southeasterly and down and that from site 95-2 northwesterly and up after tilt correction, similar to the HTC directions observed at Location 1. However, the HTC directions

derived from Location 4 are southwesterly directed with shallow inclinations after correcting for bedding tilt. Site 95-4 from Location 3 was dominated by the thermally-distributed LTC that is sub-parallel to the GAD and the HTC was not well isolated (Fig. 4c), so this site is excluded from further analysis.

3.3 Laibeng, Luchun County (102.08°E, 23.00°N)

The third sampled locality or Location 5 is near a village called Laibeng on the provincial highway #214 about 35 km west of Luchun County and 70 km southeast of Mojiang County. According to the Yunnan Geological Survey, the Yiwanshui Fm reaches 671.5 m at this location and the upper two thirds of the formation are made chiefly of thick- or massive- bedded mudstones, silty mudstones and muddy siltstones. The sampled structure is a monocline and the bedding appeared to dip north at 48-72°, but as at Location 4 the massive beds of the rocks made determination of the bedding attitude difficult. Ten sites were collected from the purplish-red mudstones and siltstones.

Figure 5 here

The initial NRM intensities of the samples from this location range 0.7-5.4 mA/m. Eight sites out of ten were dominated by the thermally-distributed LTC, which is sub-parallel to the GAD direction in geographic coordinates (Figs. 3c). The LTC persisted to as high as 690°C, and bypassed the origin of the plotting coordinates, and then became too viscous to be measured. The LTC is apparently carried by hematite (Figs. 5b, c). Thermally-discrete, ChRM-natured HTC was only resolved from the samples of sites 87-1 and 87-2 (Fig. 5a) at above 660°C and is

185 southwesterly-directed with shallow inclinations in stratigraphic coordinates, similar to those
186 observed at Location 4.

187 Statistics for site and formation means of the HTC from all five sampled locations are
188 summarized in Table 1 and Fig. 6. It should be noted that some of the sampled locations are
189 tens of kilometers apart but that the difference between a site direction as observed and that
190 transferred to another location through the VGP is less than 0.6° . For this reason, a global
191 mean direction was computed from the site directions as observed. Two groups of directions
192 appear to be observed: the first group includes locations 1 to 3, and the second group includes
193 locations 4 and 5. Based on 12 sites that have α_{95} less than 15° , the mean direction for the first
194 group is $D = 151.4^\circ$, $I = 20.0^\circ$, $\alpha_{95} = 21.1^\circ$, and $\kappa = 5.2$ in geographic coordinates; $D = 141.4^\circ$, $I =$
195 31.2° , $\alpha_{95} = 13.0^\circ$, and $\kappa = 12.1$ in stratigraphic coordinates. The ratio of $\kappa_s/\kappa_g = 2.33$ is greater
196 than McElhinny's (1964) threshold value (2.05) for a foldtest to be positive at the 95%
197 confidence level. McFadden's foldtest (1990) is also positive with $\xi = 9.295$ in the *in-situ*
198 position which exceeds the critical value at 99% confidence level (5.624) and $\xi = 0.256$ in fully
199 unfolded position which is less than the critical value at 95% confidence level (4.036).
200 McFadden and McElhinny's reversal test (1990) is indeterminate. The mean direction of the
201 second group based on 5 sites is $D = 208.2^\circ$, $I = 9.3^\circ$, $\alpha_{95} = 37.5^\circ$, and $\kappa = 5.1$ in geographic
202 coordinates; $D = 207.5^\circ$, $I = 4.9^\circ$, $\alpha_{95} = 16.2^\circ$, and $\kappa = 23.3$ in stratigraphic coordinates. The site
203 mean directions of the second group passed both McElhinny's and McFadden's foldtest as well,
204 with $\kappa_s/\kappa_g = 4.57 > 3.44$ (the threshold value at 95% confidence limit) (McElhinny, 1964), and ξ_g
205 $= 4.428 > 3.573$ (the critical value at 99% confidence) but $\xi_s = 1.794 < 2.609$ (the critical value at
206 95% confidence) (McFadden, 1990).

207 *Figure 6 here*

208 *Table 1 here*

209 **4. Discussion**

210 *4.1 Reliability of the HTC magnetization*

211 The second group of HTC directions involves only five sites and shows only one polarity. More
212 importantly, as we described earlier, these sites were collected from the rocks of massive beds
213 and we had a hard time in the field to confidently determine the bedding attitude; only two
214 different bedding attitudes were used for tilt correction. Thus the positive foldtest is likely a
215 coincidence. We have little confidence that this group of directions represents the true
216 paleomagnetic direction for the Yiwanshui Fm. On the other hand, the first group of HTC
217 directions was derived from three locations where the rocks present distinct, reliable bedding
218 attitudes and passed the foldtest with dual polarity. **Regional geology indicates that the Upper**
219 **Triassic – Eocene rocks in the study area were folded near the end of the Eocene caused by the**
220 **India-Asia collision (BGMRY, 1990). The acquisition of the second group of HTC directions**
221 **should be pre-Eocene.** Therefore, this group of HTC directions is possibly a primary
222 magnetization acquired during or shortly after the deposition of the Yiwanshui Fm. This
223 assertion was further supported by the observation that unlike the thermally-distributed LTC,
224 the HTC is thermally discrete and was unblocked above 625°C, mostly around 675°C, the Neel
225 temperature of hematite. Fine hematite particles, often of varying grain sizes and chemical
226 (CRM) in origin, are responsible for the distributed spectra while larger, specular hematite
227 particles, depositional or detrital (DRM) in origin, exhibit discrete spectra (Tan et al., 2007).

Paleomagnetic results from the pre-Jurassic rocks in the Simao Terrane are scarce. There are two preliminary paleomagnetic studies on the Yiwanshui Fm in the Mojiang area. Li et al. (1999) listed two sets of results in their monograph: $D = 42.2^\circ$, $I = 43.0^\circ$, $\alpha_{95} = 10.8^\circ$, $\kappa = 10.5$, $N = 16$ samples; and $D = 321.3^\circ$, $I = 42.1^\circ$, $\alpha_{95} = 7.7^\circ$, $\kappa = 15.2$, $N = 22$ samples. No demagnetization details were given and no field test was attempted, so it is difficult to evaluate the accuracy and reliability of these results. None of them resembles the HTC's that we observed. Chan et al. (1984) reported a tilt-corrected mean direction of $D = 133.6^\circ$, $I = 16.3^\circ$, $\alpha_{95} = 7.1^\circ$, $\kappa = 10.5$, $N = 4$ samples. The exact sampled location was not specified, but from their description of the bedding attitude at the sampled section, it looks like the same type section as we sampled (Location 1). Although they used the magnetic directions at 669°C as the stable direction for the specimens, the orthogonal vector plot and the plot of normalized intensities vs temperature steps that they presented are very similar to ours. The 95% confidence circles around our mean direction of first group HTC and Chan et al.'s mean direction overlap with an angular distance between the two being $16.5^\circ < 20.1^\circ (13.0^\circ + 7.1^\circ)$. Therefore, our first group HTC substantiated and should supersede Chan et al.'s results. We will use the first group HTC to discuss the timing of the amalgamation between the SCB and the Simao Terrane.

4.2 Timing of the amalgamation between the South China and the Indochina blocks

Metcalf (2002) once concurred with Wu et al.'s (1995) suggestion that the Simao Terrane was a separate terrane, but in a recent review he reconsidered it as a northwestern sub-terrane extension of the Indochina Block (Metcalf, 2013), because the South China, Indochina blocks

and the Simao Terrane share the warm-water Tethysian faunas and Cathaysian floras and do not include any Gondwanan elements during the Permian-Carboniferous times and are absent from Late Carboniferous-Early Permian glacial-marine diamictites. For the same reason, some authors' proposal that the Simao Terrane is part of the Shan-Thai (Sibumatu) Block is **unsupported**. Sone and Metcalfe (2008) propose a Sukhothai Arc between the Sibumatu Block and the Simao Terrane with the Changning-Menglian, Inthanon, and Bentong-Raub suture zones as its western boundary and the Jinghong (Lancangjiang), Nan-Uttaradit, and Sra Kaeo suture zones as its eastern boundary (Fig. 1a). This would reduce the size of the Simao Terrane. Nonetheless, most researchers agree that the NW-striking Ailaoshan Suture separates the SCB from the Simao Terrane and its northern continuation is the Jinshajiang Suture and its southern extension is the Song Ma Suture in North Vietnam. On the other hand, the roughly E-W-trending Dian-Qiong Suture recently proposed by Cai and Zhang (2009) requires more petrological, geochemical, chronological and structural data to confirm it (Lai et al., 2014; Faure et al., 2014).

Although differing timing has been put forth for the amalgamation between the SCB and the Indochina Block, most geological evidences appear to favor an end-Middle Triassic collision. First, in south of the Ailaoshan Suture the Upper Triassic Waigucun Fm and its stratigraphic equivalent unconformably overlies the slightly metamorphosed Middle Triassic or older rocks (Ren and Qiu, 1966). This unconformity is widely observed in northwestern Vietnam and northeastern Laos, where the undeformed Upper Triassic conglomerates and sandstones unconformably rest on deformed and metamorphosed pre-Norian sequences (Lepvrier et al., 2004; Faure et al., 2014). Second, the basal part of the Yiwanshui Fm is typical molasse

deposits, and ultramafic clasts, probably derived from the underlying ophiolite, were reported to be found in the Yiwanshui Fm (Yi and Zhong, 1991). Third, extensive $\text{Ar}^{40}/\text{Ar}^{39}$ and U-Pb zircon dating has recently been conducted in the Ailaoshan and Song Ma suture zones and neighboring areas (e.g. Lepvrier et al., 1997, 2004; Yan et al., 2006; Carter et al., 2001; Liu et al., 2011; Zi et al., 2012; Zhang et al., 2013; Lai et al., 2014). These studies reveal two Triassic age groups among others: one around 245-250 Ma, and the other around 230-237 Ma. In the Jinshajiang – Ailaoshan Suture zone, these two age groups are associated with collision-related volcanism, whereas in Song Ma Suture and adjacent areas they are interpreted as two deformation/metamorphism phases of Indosinian orogeny.

Figure 7 here

Most recently, Zhao et al. (2015) reported a paleomagnetic direction from the basaltic rocks of the Upper Triassic Niuhetang Fm from the Yongde area of southwestern Yunnan Province: $D = 122.8^\circ$, $I = 26.9^\circ$, $\alpha_{95} = 6.6^\circ$, $N = 15$ sites. The primary nature of the magnetization is supported by positive fold and reversal tests. This direction is very similar to the first group HTC direction that we observed from the Yiwanshui Fm, but it has much better associated statistics. The Yongde area (99.3°E , 23.8°N) is about 235 km west of the Mojiang area but tectonically belongs to the Baoshan Terrane, the northernmost part of the Sibumatu Block (Fig. 1a) (Metcalf, 2013). The declinations of the tilt-corrected mean directions observed from the Early Permian, Late Triassic and Middle Jurassic rocks in the Yongde area are similarly southeast-east but the inclinations change from steep negative in the Lower Permian (-63.9°) to shallow (26.9°) and modest (35.2°) positive in the Upper Triassic and Middle Jurassic. This observation led Zhao et

al. to believe that by late Triassic the Yongde area had already come from the southern to northern hemisphere at $14.2 \pm 3.9^\circ$ north latitude although the drifting rate was very high for the early Permian to late Triassic period (*ca.* 9.5 cm/yr). Consequently, the corresponding Late Triassic north pole for the Baoshan Terrane would be at $160.9^\circ\text{E}/21.7^\circ\text{S}$ ($A_{95} = 6.1^\circ$). Assuming that the Mojiang area sampled by us was also in the northern hemisphere during the late Triassic times, the first group HTC direction would yield a paleomagnetic pole at $147.5^\circ\text{E}/34.8^\circ\text{S}$ with $A_{95} = 13.5^\circ$. It comes as no surprise that these two poles overlap each other (Fig. 7), which implies that by Late Triassic, probably by the late Carnian epoch, the Simao and Baoshan terranes were already coalesced on the condition that the relative position of the two sampled areas has not been significantly changed since. On the other hand, these two poles fall far apart from the Middle Triassic pole for the SCB (Fig. 7). Extensive paleomagnetic investigations conducted on the Jura-Cretaceous redbeds in recent years have revealed variable, large clockwise rotations in the Simao and Baoshan terranes, particularly in the central part of the Simao Terrane, due to the India-Asia collision during the Eocene (Otofuji et al., 2010; Huang and Opdyke, 2015; and references therein). Assuming that both the Mojiang and the Yongde areas were rotated clockwise by 105° post late Triassic, the paleomagnetic poles would be shifted to $195.9^\circ\text{E}/55.3^\circ\text{N}$ and $215.8^\circ\text{E}/70.7^\circ\text{N}$, respectively, after correcting for such a rotation. As can be seen in Fig. 7, the Yiwanshui pole barely overlaps the Mid-Triassic pole for the SCB, due in part to its large A_{95} uncertainty, while the Niuhetang pole would never intersect it. It seems that post-Triassic vertical axis rotation alone cannot explain such **discordance**. There are several possibilities. First, because reliable Late Triassic paleomagnetic pole is unavailable at present for the SCB, Mid-Triassic pole is used instead for comparison. Age difference may be a

contributing factor. Second, if by the end of Middle Triassic the Simao and the Baoshan terranes were already coalesced with the SCB, the inclinations for the Yongde and Mojiang areas expected from the Mid-Triassic SCB pole would be $0.1\pm 10.2^\circ$ and $1.8\pm 10.2^\circ$, respectively, which are far too shallower than the values observed. The paleomagnetic result from the Niuhetang Fm is obtained from the volcanic rocks and magnetite is the major carrier of the ChRM and should thus be free from suspicion of inclination shallowing, whereas the Mid-Triassic pole for the SCB was exclusively derived from sedimentary sequences. Therefore, it is possible that the latter might have suffered some degree of inclination error due to depositional and/or post-depositional processes. Alternatively, one may consider such inclinational difference as a consequence of intracontinental translation along the Red River fault during the Cenozoic (e.g. Tapponnier et al., 1982). If this is the case, the southward latitudinal movement for the Yongde and Mojiang areas would amount to $14.1\pm 3.9^\circ$ and $15.9\pm 9.6^\circ$, equivalent to 1565 ± 710 and 1765 ± 1066 kilometers. These amounts are even larger than the extrusion model originally predicted (Tapponnier et al., 1986). Third, the collision between the SCB and the Simao and Baoshan terranes may be still continuing by the end of the Middle Triassic. Regional stratigraphy indicates that shallow marine limestones and clastics were deposited across the Ailaoshan Suture during the *Carnian* – *Norian* period. The terrestrial coal-bearing sequences on both sides were formed during the *Rhaetian* epoch (BGMRY, 1990). Therefore, the collision process may have not been completed until towards the end of the Triassic. With all things considered, we favor the last possibility.

4. Conclusion

336

337 The high temperature component direction observed from the Upper Triassic Yiwanshui Fm
338 passes the foldtest with dual polarity and is possibly of primary origin. It should supersede a
339 preliminary result previously reported from the same type section. Comparison with the Late
340 Triassic paleomagnetic pole for the Baoshan Terrane and the Middle Triassic paleomagnetic
341 pole for the SCB indicates that by late Triassic the Simao and the Baoshan terranes were
342 probably assembled but the collision process between them and the SCB may have not been
343 completed until toward the end of the Triassic. These interpretations can be tested in the
344 future by acquisition of good quality Late Triassic paleomagnetic pole for the SCB and by
345 paleomagnetic investigation on the Cretaceous or younger rocks near the sampled area for the
346 Yiwanshui Fm to see if the area was affected by large clockwise rotations during the early
347 Tertiary.

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446 Table 1. Site and formation statistics

Site	S(°)/d(°)	n/N	D _g (°)	I _g (°)	D _s (°)	I _s (°)	κ _s	α _{95s} (°)	Plon(°)	Plat(°)
Location 1, Yiwanshui type section, Mojiang (101.67°E, 23.67°N)										
86-1	23/14	4/5	99.6	44.1	101.9	30.5	144.4	7.7	171.8	-3.8
86-2*	36/17	3/6	130.8	30.6	130.3	13.6	65.3	15.4	165.9	-32.6
86-3*	36/17	3/5	112.7	40.1	115.0	23.5	23.3	26.2	169.0	-17.3
86-4	26/25	4/4	103.3	33.7	105.1	9.2	66.6	11.3	181.0	-12.0
86-5	26/25	4/4	278.7	-52.0	284.1	-27.8	61.0	11.9	352.4	6.4
86-6**	359/18	5/5	10.5	41.4	24.3	35.7	58.7	10.1	196.0	66.8
86-7**	43/16	4/5	13.3	33.0	24.1	39.7	34.6	15.8	187.6	67.4
86-9*	7/25	4/5	330.0	-53.4	312.6	-35.2	23.8	19.2	331.8	27.3
Location 2, Bakahe hydropower station, Mojiang (101.67°E, 23.67°N)										
95-5	329/55	6/7	169.4	28.4	134.5	31.6	25.3	13.6	153.6	-29.2
95-6*	329/55	4/6	168.1	22.1	140.3	27.6	14.7	24.8	151.5	-34.8
95-8	324/55	5/6	174.0	13.9	149.5	32.3	45.6	11.5	140.1	-39.2
95-9	326/52	6/6	176.4	1.5	164.7	24.6	242.0	4.3	125.6	-50.6
95-10*	331/47	3/6	168.3	15.7	150.8	23.2	8.4	45.4	144.1	-43.6
95-11	331/47	4/6	164.9	23.7	141.8	25.7	106.4	8.9	150.8	-37.3
95-12	334/46	4/6	177.7	6.9	165.8	21.8	67.8	11.2	125.0	-52.4
95-13*	329/44	5/7	164.2	24.2	141.6	27.5	12.3	22.7	150.1	-36.0
95-14	314/44	5/6	182.3	18.2	158.9	45.9	79.0	8.7	124.2	-35.1
95-16	326/53	4/5	169.0	7.0	154.5	22.5	355.2	4.9	139.6	-46.8
Location 3, National highway 213, west of Anding, Yuanjiang (101.76°E, 23.43°N)										
95-1	164/114	6/7	308.5	21.3	335.6	-39.9	69.5	8.1	310.1	37.8
95-2	159/94	3/7	123.2	0.8	162.8	35.6	135.1	10.6	124.4	-43.7
95-3*	159/94	5/6	325.3	36.0	309.4	-19.7	17.9	18.6	343.3	29.9
FM1 ^a		12/25	151.4	20.0	141.4	31.2	12.1	13.0	147.5	-34.8
Location 4, National highway 213, east of Anding, Yuanjiang (101.76°E, 23.43°N)										
95-17	129/30	5/6	174.1	39.1	184.3	15.7	97.2	7.8	93.4	-58.2
95-18	129/30	4/6	207.1	25.0	208.2	-4.5	96.7	9.4	45.5	-55.5
95-19	129/30	6/6	201.1	26.9	203.1	-1.9	113.8	6.3	53.6	-58.3
Location 5, Laibeng, Luchun (102.08°E, 23.00°N)										
87-1	263/48	5/5	224.5	-26.4	217.9	6.7	96.5	7.8	42.6	-44.6
87-2	263/48	6/6	228.0	-22.5	222.8	8.0	51.2	9.5	39.5	-40.3
FM2 ^b		5/13	208.2	9.3	207.5	4.9	23.3	16.2	52.3	-52.9

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449 Fig. 1

452 Fig. 2

454 Fig. 3
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458 Fig. 4

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Table and figure captions

Table 1

s/d = bedding strike/dip; n/N = number of samples (sites) used/measured; $D_g/I_g/\kappa_g/\alpha_{95g}$ = declination/inclination/precision parameter/radius of 95% confidence circle in geographic coordinates; $D_s/I_s/\kappa_s/\alpha_{95s}$ = declination/inclination/precision parameter/radius of 95% confidence circle in stratigraphic coordinates; $Plon/Plat$ = VGP longitude/latitude; A_{95} = radius of 95% confidence circle around pole.

* excluded from formation mean computation due to $\alpha_{95s} > 15^\circ$.

** possible recent remagnetization, excluded from mean computation.

^a computed based on sites from locations 1, 2, 3. $\kappa_g = 5.2$, $\alpha_{95g} = 21.1^\circ$, $A_{95} = 13.5^\circ$.

^b computed based on sites from locations 4, 5. $\kappa_g = 5.1$, $\alpha_{95g} = 37.5^\circ$, $A_{95} = 14.7^\circ$.

Fig. 1. (a) Tectonic map of Southeast Asia (after Metcalfe, 2013) showing the major terranes and sutures. Stars denote the sampled areas: **w. Lanping-Weishan; m. Mojiang-Luchun. Also indicated is the sampled location (y) by Zhao et al. (2015) for the Upper Triassic basaltic formation from the Baoshan Terrane.** C-M S. = Changning-Menglian Suture. Red lines are major faults, blue lines sutures, and green lines territory boundaries between countries. (b) Simplified geologic map of the Mojiang-Luchun area. Black lines are boundaries between rock formations, red lines faults, and green lines major highways. Numbered stars denote the five sampled locations described in the text. Strata: AC = pre-Cambrian, Pz₁ = Lower Paleozoic, Pz₂ = Upper Paleozoic, D = Devonian, P = Permian, (T₂)T = (Middle) Triassic, T_{3y} = Yiwanshui Fm, T_{3l} = Luma Fm, J = Jurassic, K = Cretaceous, N = Neogene, Q = Quaternary. Igneous rock bodies: Σ = ultramafic, Y = granitic (Indosinian).

Fig. 2. Representative orthogonal plots of thermal demagnetization for the samples from locations 1 and 2. Geographic coordinates. Open (close) circles are plotted on vertical (horizontal) plane. Treatment steps are °C. Also shown are normalized intensities vs temperature steps.

Fig. 3. Equal-area projections of sample LTC directions. Open (close) circles represent directions plotted on the upper (lower) hemisphere. Black square denotes global mean direction, black triangle the geocentric axial dipole direction (GAD) at the sampling locality, blue ellipses α_{95} confidence circles around the global mean direction.

Fig. 4. Representative orthogonal plots of thermal demagnetization for the samples from locations 3 and 4. Coordinates and symbols are the same as in Fig 2.

Fig. 5. Representative orthogonal plots of thermal demagnetization for the samples from Location 5. Coordinates and symbols are the same as in Fig 2.

507 Fig. 6. Equal-area projections of site HTC directions. Symbols are the same as in Fig. 3 except
508 that black ellipses are α_{95} confidence circles around the site mean directions.

509 Fig. 7. Orthographic projection showing the paleomagnetic poles derived from the Upper
510 Triassic Yiwanshui Fm (T_{3y}) in the Simao Terrane (this study) and Niuhetang Fm (T_{3n}) in the
511 Baoshan Terrane (Zhao et al., 2015) in comparison with the Late Permian-Early Triassic (P_2-T_1)
512 and Middle Triassic (T_2) poles for the SCB (Su et al., 2005). Poles T_{3y}' and T_{3n}' are computed by
513 assuming that the sampled areas were rotated by 105° clockwise post Late Triassic (see
514 discussion in the text). Colored bands indicate the pole paths when the sampled areas are
515 rotated about a vertical axis. Red square denotes the sampling area for the Yiwanshui Fm.