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Further paleomagnetic results from the ~155 Ma Tiaojishan Formation, Yanshan Belt, North China, and their implications for the tectonic evolution of the Mongol–Okhotsk suture

Qiang Ren [a], Shihong Zhang [a,*], Huaichun Wu [a], Zhongkai Liang [a], Xianjun Miao [a], Hanqing Zhao [a], Haiyan Li [a], Tianshui Yang [a], Junling Pei [b], Gregory A. Davis [c]

[a] State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing 100083, China
[b] Key Laboratory of Paleomagnetism, Institute of Geomechanics, CAGS, Beijing 100081, China
[c] Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, USA

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ABSTRACT

A new paleomagnetic study on well-dated (~155 Ma) volcanic rocks of the Tiaojishan Formation (Fm) in the northern margin of the North China Block (NCB) has been carried out. A total of 194 samples were collected from 26 sites in the Yanshan Belt areas of Luanping, Beipiao, and Shouwangfen. All samples were subjected to stepwise thermal demagnetization. After removal of a recent geomagnetic field viscous component, a stable high temperature component (HTC) was isolated. The inclinations of our new data are significantly steeper than those previously published from the Tiaojishan Fm in the Chengde area (Pei et al., 2011, Tectonophysics, 510, 370–380). Our analyses demonstrate that the paleomagnetic directions obtained from each sampled area were strongly biased by paleosecular variation (PSV), but the PSV can be averaged out by combining all the virtual geomagnetic poles (VGPs) from the Tiaojishan Fm in the region. The mean pole at 69.6°N/203.0°E ($A_{95} = 5.6°$) passes a reversal test and regional tilting test at 95% confidence and is thus considered as a primary paleomagnetic record. This newly determined pole of the Tiaojishan Fm is consistent with available Late Jurassic poles from red-beds in the southern part of the NCB, but they are incompatible with coeval poles of Siberia and the reference pole of Eurasia, indicating that convergence between Siberia and the NCB had not yet ended by ~155 Ma. Our calculation shows a ~1600-km latitudinal plate movement and crustal shortening between the Siberia and NCB after ~155 Ma. In addition, no significant vertical axis rotation was found either between our sampled areas or between the Yanshan Belt and the major part of the NCB after ~155 Ma.

1. Introduction

The collisional Mongol–Okhotsk suture (MOS) which extends westward from the Udsky Gulf of the Okhotsk Sea to central Mongolia (Fig. 1) is widely accepted as an important tectonic boundary between the Mongolia–North China Block (MOB–NCB) and the Siberian component of a stable Eurasian continent (Zonenshain et al., 1990; Xu et al., 1997; Zorin, 1999; Cogné et al., 2005). The age and tectonic evolution of this suture has long been a subject of much debate. Most researchers agree that the suture formed by the progressive closure of the Mongol–Okhotsk Ocean from west to east in a 'scissor-like' manner (Zhao et al., 1990; Zonenshain et al., 1990; Kravchinsky et al., 2002; Tomurtogoo et al., 2005; Metelkin et al., 2010). However, the reported timing of final closure has ranged from Triassic to the Early Cretaceous (Zonenshain et al., 1990; Maruyama et al., 1997; Halim et al., 1998; Zorin, 1999; Parfenov et al., 2001; Tomurtogoo et al., 2005).

Paleomagnetism remains the most powerful tool in studying the convergence process between two continental blocks. Comparing paleomagnetic results from coeval strata on both sides of the Mongol–Okhotsk suture is critical to understanding its convergence history (Cogné et al., 2005; Metelkin et al., 2007a). With respect to the MOS, two concordant and well-dated Late Jurassic (~155 Ma) paleomagnetic poles have been published from the Siberian side of the suture (Kravchinsky et al., 2002; Metelkin et al., 2007a, 2010). In contrast, previously available Mesozoic data from the southern side of the MOS are contradictory to each other. The likely reason for this is that most Jurassic strata are not well-dated (Lin et al., 1985; Fang et al., 1988; Zhao et al., 1990; Gilder and Courtillot, 1997; Gilder et al., 1999). Recently, a new Late Jurassic paleomagnetic pole was obtained from ~155 Ma volcanic rocks of the Tiaojishan Formation (Fm) in the Chengde basin (Pei et al., 2011), north China (Fig. 1), thus providing an opportunity for comparing this pole to the coeval Siberian poles (Kravchinsky et al., 2002; Metelkin et al., 2007a). However, the Tiaojishan paleopole indicates an abnormally lower paleolatitude than other Late Jurassic poles from the southern part of the NCB (Gilder

* Corresponding author. Tel.: +86 10 82322257.
E-mail address: shzhang@cugb.edu.cn (S. Zhang).

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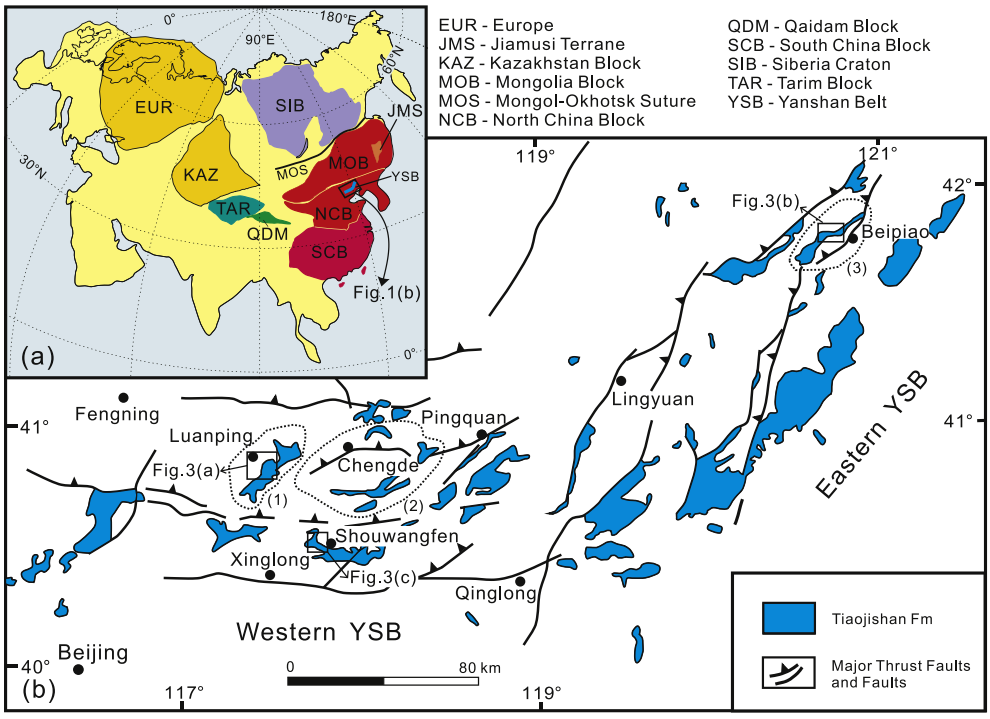

Fig. 1. (a) Tectonic setting of the Yanshan Belt (YSB) and the North China Block (NCB). (b) Distribution of the Tiaojishan Formation in the YSB, northern margin of the NCB, after Liu et al. (2006). Black dot lines are boundaries of the (1) Luanping basin, (2) Chengde basin, and (3) Beipiao basin.

and Courtillot, 1997; Gilder et al., 1999). More data are needed to test whether the Chengde basin pole could average out the paleosecular variation (PSV) of the paleogeomagnetic field, or whether the sampled section was affected by local vertical axis rotations in the Yanshan fold-thrust belt (YSB; Davis et al., 2001).

In this paper, we report new paleomagnetic results from four additional well-dated (~155 Ma) or well-correlated sections of the Tiaojishan Fm in the YSB (Fig. 1). Based on this new data, we discuss the PSV and local rotation issues, and the Late Jurassic–Cretaceous paleogeographic evolution of major crustal blocks in NE Asia.

2. Geological setting and paleomagnetic sampling

The YSB is a crustal deformation belt within the northern margin of the NCB (Fig. 1). In this region, Archean and Paleoproterozoic metamorphic rocks considered to be exposures of the cratonal basement are unconformably overlain by thick Mesoproterozoic to Neoproterozoic and Paleozoic sedimentary successions. They, in turn, are overlain unconformably by Mesozoic and Cenozoic terrestrial volcanic and clastic strata that were deposited in separate commonly fault-bounded basins (Fig. 1b). During an Early Jurassic through to Middle Cretaceous time interval, the YSB experienced major episodes of compressional and extensional deformations, which resulted in extensive development of folds, thrusts, normal faults, and shear zones (Zhao, 1990; Davis et al., 2001, 2009; Wang et al., 2010, 2013; Zhang et al., 2014b).

The Upper Jurassic Tiaojishan Fm is widely exposed in the YSB (Fig. 1). The thickness of the Tiaojishan Fm varies from basin to basin (~216 to 1953 m), and its fresh volcanic rocks are amenable to paleomagnetic study. The Tiaojishan Fm is composed of diverse volcanic rocks (basalt, andesite, dacite, rhyolite, tuff) and sedimentary rocks bearing plentiful plant fossils. It is conformably or disconformably underlain by the Jiulongshan (=Haifanggou) Fm and is overlain conformably by the Houcheng (=Tuchengzi) Fm (Bureau of Geology and Mineral Resources of Hebei Province, 1989; Bureau of Geology and Mineral Resources of Liaoning Province, 1989; Liu et al., 2006). The Jiulongshan and Houcheng Formations are mostly clastic rocks and have been dated, respectively, at 177.8 ± 7.7 to 161.6 ± 1.6 Ma by K/Ar whole rock analysis (Chen and Chen, 1997) and at 153.7 ± 1.1 to 137.4 ± 1.3 Ma, Zircon U-Pb ages of tuff beds (Zhang et al., 2008b; Xu et al., 2012; Fig. 2).

Recently, several U–Pb and $^{40}Ar/^{39}Ar$ ages of Tiaojishan volcanic rocks in the Luanping and Beipiao basins have been reported (Fig. 2; Fig. 3; Zhang et al., 2005, 2008a; Chang et al., 2009). An andesite flow near the top of the Tiaojishan Fm has been dated at 153.8 ± 5.2 Ma in Changshanyu of the Luanping basin, and a rhyolite dacite sample in the upper part of the formation near Beipiao city in Beipiao basin is dated at 154.0 ± 4.7 Ma; both age determinations by zircon U–Pb LA-ICP-MS method (Zhang et al., 2008a). Two precise $^{40}Ar/^{39}Ar$ dates (160.7 ± 0.4 Ma and 158.7 ± 0.6 Ma) for tuff-beds from the lowest part of the Tiaojishan Fm near Beipiao city were reported by Chang et al. (2009). Thus, the best estimated age for the Tiaojishan volcanic rocks was ca. 155 Ma (Pei et al., 2011).

Yanshan folds and thrusts trend roughly E–W in the western areas, whereas similar structures trend roughly NE in the eastern areas (Fig. 1b). It would be of wide interest to ascertain whether the eastern areas of the YSB have been rotated relatively to western areas after ~155 Ma (Wang, 1996; Davis et al., 2001; Liu et al., 2007; Wang et al., 2011b; Zhang et al., 2014b). Our sampled sections were, thus, collected in both western (Luanping and Shouwangfen basins) and eastern areas (Beipiao basin) of the YSB (Fig. 1b; Fig. 3).

A total of 194 core samples from 26 sites were collected from the Tiaojishan volcanic rocks in the Luanping basin (12 sites), Shouwangfen basin (3 sites), and Beipiao basin (11 sites). Volcanic and clastic rocks are interlayered in the sampled section in Luanping basin. The attitudes of the strata were measured on the beds of sandstone intercalated with the sampled volcanic rocks. In Shouwangfen basin, we sampled volcanic rocks at the top of the Tiaojishan Fm, which is marked by the boundary between the Tiaojishan and Houcheng Fms. The attitudes of the strata were also measured on the clastic interbed. In the Beipiao basin, we sampled two sections that are ~6 km apart; section I containing sites