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Large southward motion and clockwise rotation of Indochina throughout the Mesozoic: Paleomagnetic and detrital zircon U–Pb geochronological constraints

Yonggang Yan [a,b], Baochun Huang [c,a,*], Jie Zhao [f], Donghai Zhang [c], Xiaohui Liu [d,b], Punya Charusiri [e], Apivut Veeravinantanakul [e]

[a] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Key Laboratory of Orogenic Belt and Crust Evolution, Ministry of Education, School of Earth and Space Sciences, Peking University, Beijing 100871, China
[d] Key Laboratory of Continental Collision and Plateau Uplift, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China
[e] Earthquake and Tectonic Geology Research Unit (EATGRU), c/o Department of Geology, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand
[f] State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Northern Taibai Str. 229, Xi'an 710069, China

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ABSTRACT

We report a combined paleomagnetic and U–Pb geochronologic study of sedimentary rocks from the Huai Hin Lat and Nam Phong formations of Mesozoic age in NE Thailand in order to provide independent constraints on the tectonic movement of the Indochina Block during convergence of the major blocks now comprising East Asia. The maximum allowable depositional age of the two formations is estimated to be 227 Ma and 215 Ma, respectively, from detrital zircon U–Pb geochronologic analysis which also indicates a sediment source transition in the Khorat Plateau Basin during the Middle–Late Jurassic. A formation mean paleomagnetic direction of $D_g/I_g = 21.4°/38.1°$ ($k_g = 19.5$, $\alpha_{95} = 9.6°$) before and $D_s/I_s = 43.0°/48.0°$ ($k_s = 47.4$, $\alpha_{95} = 6.1°$, $N = 13$) after tilt correction is derived from samples with different lithologies, bedding attitudes, magnetic carriers and polarities and yields a positive fold test. Hence, the magnetization is likely primary. The revised Mesozoic APWP of the Indochina Block yields paleolatitudes (for a reference site of 22°N, 102°E) of 33.4 ± 7.2°N during the Norian Late Triassic, 25.9 ± 5.9°N during the Late Triassic to Early Jurassic, 23.9 ± 8°N during the Late Jurassic to Early Cretaceous, 27.5 ± 3.2°N during the Early Cretaceous and 24.5 ± 4.9°N by the Late Cretaceous; corresponding declinations are 45.2 ± 8.6°, 38.0 ± 6.6°, 36.3 ± 8.8°, 29.6 ± 3.6° and 24.9 ± 5.4° respectively. These data indicate a significantly southward displacement accompanied by clockwise rotation during the Mesozoic. A reconstruction of the Indochina Block within the now well-studied merging process of South China and North China indicates that the Indochina Block was located at a higher latitude than the South China Block during the Norian stage of Late Triassic times whilst no significant relative poleward displacement apparently occurred during the Early Jurassic to Early Cretaceous interval. Our study supports a post-Cretaceous tectonic extrusion model with a southeastward displacement of Indochina with respect to the South China Block estimated to be 1000 ± 850 km since the Late Cretaceous.

1. Introduction

Paleomagnetic studies of the Indochina Block to constrain its Mesozoic geography have been undertaken for several decades and are an essential complement to tectonic reconstructions (Barr and Macdonald, 1979; Bunopas, 1981; Achache and Courtillot, 1985; Maranate and Vella, 1986; Yang and Besse, 1993; Richter and Fuller, 1996; Charusiri et al., 2006; Hall et al., 2008; Hall, 2012; Singsoupho et al., 2014). The tectonic consequences of movements of the Indochina Block during the Mesozoic have long been debated because paleo-positions relative to the other Eastern Asia blocks have been drastically transformed by the Cenozoic India–Asia collision. In most reported Pangea reconstruction models, the Indochina Block has been considered to be attached to the South China Block traveling with it during the convergence of Eastern Asia blocks (Collins, 2003; Scotese, 2004; Golonka, 2007; Metcalfe, 2013); the validity of this proposition has not yet been

* Corresponding author at: School of Earth and Space Sciences, Peking University, No. 5, Yiheyuan Road, Haidian District, Beijing 100871, China.
E-mail address: bchuang@pku.edu.cn (B. Huang).

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properly tested due to a lack of reliable paleomagnetic data from the Indochina Block.

Current studies on Pre-Triassic rocks indicate the widespread impact of remagnetization in the Indochina Block (Chen and Courtillot, 1989; Yang and Besse, 1993; Richter and Fuller, 1996), which could be attributed to effects of the Indosinian Orogeny (Ridd et al., 2011). Investigations covering Late Triassic to Early Jurassic rocks show a general agreement between different authors (Achache and Courtillot, 1985; Maranate and Vella, 1986; Yang and Besse, 1993; Bhongsuwan and Elming, 2000; Singsoupho et al., 2014) and a significant southward movement since the Early Jurassic has been suggested. Although studies of Early Jurassic to Late Jurassic units are lacking, studies of Late Jurassic to Early Cretaceous rocks have provided plentiful and apparently reliable paleomagnetic data (Maranate and Vella, 1986; Yang and Besse, 1993; Bhongsuwan and Elming, 2000; Charusiri et al., 2006; Takemoto et al., 2009; Singsoupho et al., 2014). Studies of Middle to Late Cretaceous rocks however, show a discrepancy between different studies which are likely due to internal deformation of the Indochina Block (Takemoto et al., 2005; Charusiri et al., 2006; Otofuji et al., 2012; Singsoupho et al., 2014). Most paleomagnetic studies of the Indochina Block have focused on Jurassic to Cretaceous age rocks, but because Pangea was already fragmenting in the Early Jurassic (ca. 200–180 Ma), reliable paleomagnetic results derived from units prior to the continental breakup are needed to quantify the Mesozoic paleogeography.

In this paper, we present new paleomagnetic and U–Pb geochronologic data from Late Triassic sedimentary rocks from the Indochina Block in Thailand and synthesize the data with previous published results with the aim of interpreting the tectonic movement of the Indochina Block relative to the other Eastern Asia blocks.

2. Geologic settings and sampling

The Indochina Block is located within the Sundaland domain of Southeast Asia (Fig. 1) and is bounded by a suite of complex suture zones including the Changning–Menglian, and Inthanon (with the latter possibly extending to the Bentong–Raub suture in the eastern Malay Peninsula) to the west, the Song Ma suture zones to the northeast and an indistinct suture to the east which locates offshore in the South China Sea and extends to SW Borneo. This sector formerly comprised the eastern part of Yunnan south of the Red River fault, central Sundaland, eastern Malay Peninsular and SW Borneo (Sone and Metcalfe, 2008; Metcalfe, 2013).

The Mesozoic rocks of the Indochina Block in NE Thailand are dominated by continental sediments divided into seven formations based on lithostratigraphy, including (in ascending stratigraphic order) the Huai Hin Lat, Nam Phong, Phu Kradung, Phra Wihan, Sao Khua, Phu Phan and Khok Kruat formations. The Huai Hin Lat Formation overlies deformed Permian or older strata unconformably and is overlain by the Nam Phong Formation which is dominated by sandstone, shale and limestone and is considered to be Early–Middle Norian in age on the basis of a diverse and abundant fauna and flora content (Ridd et al., 2011). The Nam Phong Formation overlies the Huai Hin Lat Formation unconformably and is generally considered to be of Rhaetian Age (Chonglakmani and Sattayarak, 1978; Bunopas, 1992; Racey et al., 1996; Ridd et al., 2011). Oil geologists have suggested that the Nam Phong Formation can be subdivided into the Upper Nam Phong and Lower Nam Phong formations from recognition of an unconformity within the Nam Phong Formation recorded both in subsurface well and seismic sections (Racey et al., 1996, 1999; Ridd et al., 2011). The low-angle unconformity in the Nam Phong Formation is difficult to identify at the redbed outcrops due to similarities in bedding structures and it is unclear whether the samples collected from the Nam Phong Formation (this study and Yang and Besse, 1993) belong to the Upper or Lower Nam Phong Formation, of Rhaetian and Early to Late Jurassic ages respectively. The overlying member is the Phu Kradung Formation of uncertain age. Carter and Bristow (2003) suggested a Late Jurassic to Early Cretaceous depositional age from Fission Track (FT) and U–Pb geochronology investigations. A recent synthesis (Cuny et al., 2013) suggested a Late Jurassic age for most of the formation based on fossil vertebrate evidence and Early Cretaceous age for the uppermost part. In this paper, the Phu Kradung Formation is considered to be Late Jurassic to Early Cretaceous in age. The overlying successions are the Phra Wihan, Sao Khua, Phu Phan and Khok Kruat formations, generally interpreted to be the Early Cretaceous (Berriasian to Aptian) (Racey et al., 1996; Racey and Goodall, 2009; Ridd et al., 2011).

Late Triassic samples were collected from the Huai Hin Lat and Nam Phong formations (very likely formed prior to the breakup of the Pangea) at 13 sites along the main Road 2016–2216 southwest of Wang Saphung (Fig. 2). Samples were drilled using a portable gasoline-powered hand-drill and oriented by magnetic compass or both magnetic and sun compasses when sunshine was available. 45% of the orientation data were oriented by both methods and identified a local magnetization anomaly of -1° in agreement with the World Magnetic Model 2015 (Chulliat et al., 2014; see www.magnetic-declination.com).

3. Detrital zircon U–Pb geochronology

3.1. Analytical techniques

In the laboratory the field core samples, generally 2.5 cm in diameter and 5–10 cm in length, were cut into standard cylindrical specimens, $\sim$2.0–2.2 cm in length. Fresh end materials from each of the two formations were used to separate zircons for resolving the formation mean ages. Zircons were separated by conventional heavy liquid and magnetic separation techniques. Transmitted and reflected light images were used to characterize the zircon grains. Detrital zircon U–Pb geochronology was analyzed at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences (Beijing), using a New Wave Research UP193FX Excimer laser coupled with an Agilent 7500a Inductively-Coupled-Plasma Mass Spectrometer (LA-ICP-MS). A laser of 35 μm spot size and $\sim$8–10 J/cm^2 energy was used in this analysis. More detailed analytical procedures and the configuration of the LA-ICP-MS is provided in Cai et al. (2012). In this study, mass fractionation and instrumental bias were monitored using the Plesovice zircon (Slama et al., 2008) and NIST SRM 610 silicate glass standards (Pearce et al., 1997). The Harvard zircon 91500 with the recommended age 1064 $\pm$ 0.3 Ma (Wiedenbeck et al., 1995) was used as an external standard. Ages were calculated using GLITTER 4.0 (Griffin et al., 2008). Common Pb corrections were made following the method described by Andersen (2002). The relative age-probability diagrams were generated using the Isoplot Program 4 (Ludwig, 2008) and showed each age and distribution at the 2-σ level, after the exclusion of analyses with discordance >10%. The U–Pb geochronologic results in this study are summarized in Supplementary data.

3.2. Results

3.2.1. Huai Hin Lat Formation (sample HHL24X)

More than 1000 detrital zircon grains were separated from end materials of the Huai Hin Lat Formation, of which 100 grains were used to conduct U–Pb geochronology analysis. The sizes of the zircons are generally 80–120 μm and yield good quality results: 99 analyses with discordance <10% yield an age population ranging from Neoarchean to Late Triassic with a major peak at ca.

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