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Tectonic evaluation of the Indochina Block during Jurassic-Cretaceous from palaeomagnetic results of Mesozoic redbeds in central and southern Lao PDR

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ABSTRACT

Rock magnetic and palaeomagnetic studies were performed on Mesozoic redbeds collected from the central and southern Laos, the northeastern and the eastern parts of the Khorat Plateau on the Indochina Block. Totally 606 samples from 56 sites were sampled and standard palaeomagnetic experiments were made on them. Positive fold tests are demonstrated for redbeds of Lower and Upper Cretaceous, while insignificant fold test is resulted for Lower Jurassic redbeds. The remanence carrying minerals defined from thermomagnetic measurement, AF and Thermal demagnetizations and back-field IRM measurements are both magnetite and hematite. The positive fold test argues that the remanent magnetization of magnetite or titanomagnetite and hematite in the redbeds is the primary and occurred before folding. The mean palaeomagnetic poles for Lower Jurassic, Lower Cretaceous, and Upper Cretaceous are defined at Plat./Plon. = 56.0°N/178.5°E (A_{95} = 2.6°), 63. 3°N/170.2°E (A_{95} = 6.9°), and 67.0°N/180.8°E (A_{95} = 4.9°), respectively. Our palaeomagnetic results indicate a latitudinal translations (clockwise rotations) of the Indochina Block with respect to the South China Block of $-10.8 \pm 8.8°$ ($16.4 \pm 9.0°$); $-11.1 \pm 6.2°$ ($17.8 \pm 6.8°$); and $-5.3 \pm 4.7°$ ($13.3 \pm 5.0°$), for Lower Jurassic, Lower Cretaceous, and Upper Cretaceous, respectively. These results indicate a latitudinal movement of the Indochina Block of about 5–11° (translation of about 750–1700 km in the southeastward direction along the Red River Fault) and clockwise rotation of 13–18° with respect to the South China Block. The estimated palaeoposition of the Khorat Plateau at ca. 21–26°N during Jurassic to Cretaceous argues for a close relation to the Sichuan Basin in the southwest of South China Block. These results confirm that the central part of the Indochina Block has acted like a rigid plate since Jurassic time and the results also support an earlier extrusion model for Indochina.

1. Introduction

Intercontinental collisions and deformations have taken place in a variety of modes in the Asia continent. The deformations of Southeast Asia have been modeled in a number of laboratory and numerical experiments during the last two decades (e.g. Tapponnier et al., 1982; Cohen and Morgan, 1986; Houseman and England, 1993; Royden et al., 2008). An extrusion tectonic model has been proposed to explain the tectonic of Southeast Asia after the Pre-Tertiary India-Asia collision which occurred in the Lower Eocene (ca. 50 Ma) (e.g. Molnar and Tapponnier, 1975; England and Houseman, 1986; Beck et al., 1995; Rowley, 1996; Tong et al., 2008) or in the Oligocene (ca. 35 Ma) (Aitchison et al., 2007). The southeastward movement of Indochina along the Ailao Shan-Red River (ASRR) shear zone is partly supported by geological evidences (Leloup et al., 1995, 2001; Wang et al., 1998, 2000, 2001; Gilley et al., 2003; Replumaz and Tapponnier, 2003; Replumaz et al., 2004; Ali et al., 2010) and geochronological data (Lacassin et al., 1997; Gilley et al., 2003). Palaeomagnetic studies have been performed in South China and Indochina blocks in attempts to reconstruct tectonic events in these regions (Zhu et al., 1988; Kent et al., 1986; Gilder et al., 1993, 1999; Morinaga and Liu, 2004; Li et al., 2005; Bai et al., 1998; Yokoyama et al., 2001; Enkin et al., 1992; Tanaka et al., 2008; Takemoto et al., 2009; Otofuji et al., 2010, 2012; Cung and Geissman, 2013). On the basis

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of reliable palaeomagnetic data from the Indochina Block a consecutive translation and rotation of Indochina during Mesozoic has been suggested (Yang, 1992; Yang and Besse, 1993; Bhongsuwan and Elming, 2000; Charusiri et al., 2006; Takemoto et al., 2005, 2009; Tanaka et al., 2008; Otofuji et al., 2010, 2012; Cung and Geissman, 2013). However, such translation and rotation interpreted from paleomagnetic data seems to have varied within the block, i.e. no significant rotation has been indicated for the parts, northwest and south of Vietnam when comparing with the Eurasia Apparent Polar Wander Path (APWP) (Takemoto et al., 2005; Otofuji et al., 2012; Cung and Geissman, 2013), while palaeomagnetic results from the Khorat Plateau Basin in the central part of the Indochina Block indicate a clockwise rotation and latitudinal translation relative to the South China Block (Yang and Besse, 1993; Bhongsuwan and Elming, 2000; Charusiri et al., 2006; Takemoto et al., 2009). These differences may be the results of complex internal deformation of the Indochina Block and parts of the Sundaland caused by the Indian–Asia collision. In order to test the coherency of the Indochina Block and to constrain the number of tectonic models, palaeomagnetic data from other parts of the blocks are necessary.

In this paper, we are going to provide new palaeomagnetic results and propose a tectonic model for the Indochina Block. This model is based on interpretation of palaeomagnetic data from Jurassic to Cretaceous redbeds in Laos. Anisotropy of magnetic susceptibility (AMS) data is also provided in order to determine eventual deformation of the studied rocks that may have affected the remanence directions.

2. Geological setting

The Indochina Peninsula includes the Indochina Block (INC) and part of the Shan-Thai Block (ST). The ST comprises eastern Myanmar, western Thailand, western peninsular Malaysia, and northern Sumatra (Fig. 1). The INC comprising northeastern and eastern Thailand, Laos, Cambodia, and parts of Vietnam is separated from the South China Block (SCB) by the NW–SE trending active Ailao Shan-Red River Fault (ASRRF) system, and is bounded by the Three Pagodas (TPF) and Wang Chao faults (WCF) in the southwest (Morley, 2001; Morley et al., 2001; Kornsawan and Morley, 2002; Akciz et al., 2008). The boundary between the Shan-Thai and the Indochina blocks is expressed by the Nan-Uttaradit Suture (NUS) in the west (Barr and MacDonald, 1987, 1991; Hada et al., 1999; Metcalfe, 1999) (Fig. 1a). There are several redbed basins of Mesozoic age within the Indochina Peninsula (BGMRY, 1990; Tien et al., 1991; Mantajit et al., 2002). The Khorat Plateau Basin, located in the northeastern Thailand and extending to western Laos and northern Cambodia, is the largest basin in the central part of the INC. The basin mostly comprises upper rock units of the INC, which is dominated by Mesozoic continental redbed sequences from the principal rock unit of the Khorat Group (Mantajit et al., 2002). The Khorat Group mainly comprises continental red and grey sandstone, siltstone, and shale. The Mesozoic sedimentary rocks in the central and southern Laos are also dominated by rocks of the Khorat Group. The age of the Khorat Group ranges from Upper Triassic to Cretaceous (Workman, 1977; Chonglakmani and Sattayarak, 1978; Buffetaut and Ingavat, 1987; DMR, 1999) or Upper Jurassic to Lower Cretaceous (Racey et al., 1997; Racey, 2009; Racey and Goodall, 2009; Buffetaut et al., 2006, 2009). The ages of the rocks in this study are obtained from the 1:1,000,000 geological and mineral resources map of Lao PDR (Department of Geology and Mines, 1991) and the study is focused on Lower Jurassic to Upper Cretaceous red beds exposed in the northeastern and eastern part of Khorat Plateau (in the central and southern Laos). These strata are similar to those of the Khorat Group with a large non-marine depositional system in the mainland Southeast Asia.

3. Sampling and laboratory procedures

Mesozoic redbeds were sampled from 56 sites (total of 606 samples) in central and southern Laos (Fig. 1b) using a portable gasoline-powered core drill. The orientation of the core samples was determined using both sun and magnetic compasses. The location of sampling sites was positioned using a GPS.

For laboratory procedure, 2–3 standard specimens of 2.5 cm in diameter and 2.2 cm in length were cut from each core sample. The remanent magnetizations were measured using a spinner magnetometer JR-6 (Agico, Czech Republic) and a DC-SQUID magnetometer (2G-Enterprises, USA) in the palaeomagnetic laboratories of the Prince of Songkla University, Thailand, Luleå University of Technology, and Lund University, Sweden. To evaluate magnetic stability and eliminate viscous magnetic components, progressive stepwise alternating field demagnetization up to 100 mT was performed with coils incorporated in the DC-SQUID system. Progressive stepwise thermal demagnetization (12–15 steps, up to 700 °C) was performed using MMTD18 (Magnetic Measurement, England) for high coercivity samples. Demagnetization results were analyzed using orthogonal plots (Zijderveld, 1967) and the components of remanent magnetizations were defined using principal component analysis (Kirschvink, 1980). The Super-IAPD software (Torsvik et al., 2000) was used for the componential analysis. At least four demagnetization steps were used to define remanence vectors. The site mean and formation mean directions were calculated using the statistics of Fisher (Fisher, 1953). Direction-correction (DC) fold test for individual sample mean directions at the 95% confidence level was performed using the method proposed by Enkin (2003). The test was run on Pmagtools 4.2a software written by Mark Hounslow (Hounslow, 2006). The magnitude of magnetic susceptibility and the orientations of the principal axes of Anisotropy of Magnetic Susceptibility (AMS) were measured at room temperature, using a low field Kappabridge KLY-3S (Agico, Czech Republic) in order to define the magnetic fabric of the rocks. The technique of Jelinek (1978) was used for statistical analyses of the AMS data. The AMS parameters, including shape parameter (T) and corrected anisotropy degree (Pj) proposed by Jelinek (1981), were used to define magnetic fabric and degree of anisotropy of the rocks, respectively. For analyses of magnetic minerals a CS3 furnace (Agico, Czech Republic) installed with the Kappabridge KLY-3S was used to measure the temperature dependence of magnetic susceptibility.

Saturation of isothermal remanent magnetization (SIRM) using a field of 1 T and the back-field IRM performed on a reversed field generated by an electromagnet were also performed step by step up to 500 mT. The IRM was measured using a Minispin magnetometer (Molspin, England).

4. Results and discussions

4.1. Anisotropy of Magnetic Susceptibility (AMS)

The mean bulk susceptibility of the redbeds varies between 13.7×10^{-6} and 542.5×10^{-6} SI, suggesting a low concentration of ferromagnetic and/or paramagnetic minerals in the rocks (Tarling and Hrouda, 1993) and the degree of anisotropy (Pj) is less than 8% ($Pj < 1.08$; Fig. 2). On the basis of the low degree of anisotropy the rock samples are interpreted to be undeformed or only weakly deformed (e.g. Tarling and Hrouda, 1993; Parés et al., 1999; Frizon De Lamotte et al., 2002; Parés, 2004; Borradaile and Jackson, 2010). This also suggests that the remanence directions have not been affected by any tectonic deformation. The shape parameter (T) of rocks in most sites is positive ($T > 0$) indicating predominantly oblate magnetic fabric most probably plate-like hematite. The majority of sites are characterized by well grouped