Paleomagnetism of cretaceous continental redbed formations from Indochina and South China, their Cenozoic tectonic implications: a review

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Abstract. Available paleomagnetic data of Cretaceous redbed formations from Indochina and South China blocks are compiled and their tectonic significance is reviewed in a common reference frame of the Eurasian coeval paleopoles. The important factors that play a vital role in determining the tectonic significance of a paleomagnetic result have been taken into consideration and discussed.

Review of the Cretaceous paleomagnetic data from the South China block further confirms the conclusion of the previous researchers that the present geographic position of the South China block has been relatively stable with respect to Eurasia since Cretaceous time and shows that the paleomagnetically detected motion of a coherent lithospheric block must be based on the representative data obtained from different places across the block; so the local tectonic movements can be distinguished.

Cretaceous paleomagnetic data from the Indochina - Shan Thai block reveal complex intra-plate deformations that have been occurred due to the India - Eurasia collision. Paleomagnetically detected motions from the block-margin areas are mainly reflecting the displacement of upper crustal blocks due to folding and faulting processes, thus a rigid lithospheric block rotation and translation cannot be assumed. The paleomagnetic results from the areas located next to the south of the Red River fault suggest that the fault does not demarcate non-rotated and significantly rotated regions. Accordingly, given the difficulty in separating true lithospheric plate motions from those of superficial crustal blocks, we advocate extreme caution in interpreting the paleomagnetic record in regions such as Indochina where block interaction and strong deformation are known to have occurred.

Keywords: Paleomagnetism; Cretaceous; Indochina; South China; Tectonics.

1. Introduction

The tectonics of Southeast Asian region has attracted the attention of successive generations of geologists in the world. Many active tectonic-geodynamic evolutions have been occurring at this region, such as: the subduction of the Indo-Australian plate under the Eurasia plate along the Indonesia arc; the India-Eurasia collision and different intra-plate deformation processes. Therefore, it can consider the Southeast Asian
region as a natural laboratory for active tectonics - geodynamics, facilitating geologists to use the region’s modern tectonics as an analog for processes interpreted in the geological record. During the last two decades of the 20th Century, the model of extrusion tectonics [21] has emerged as the predominant model for the tectonics of Southeast Asia.

During recent years, paleomagnetic studies on geological formations from Southeast Asian region have been increased both in quantity and quality, contributing to elucidate the tectono-geodynamic context, the paleogeographic reconstruction of lithospheric blocks, microcontinents that were welded together to form the actual Eurasia continent (Fig. 1). However, it is not quite straightforward to interpret the paleomagnetic results of an active tectonic region such as Southeast Asia, because the primary paleomagnetic vector may be modified by subsequent tectonic effects, such as stress and temperature changes, or fluid migration, etc. Paleomagnetically detected movements may sometimes reflect local rotations related to shear zones [13, 17], they can also be caused by local deformation in thrust sheets, or in arc related deformation [14]. Therefore, coherent movements of plates, or microplates cannot be assumed. An important aspect of the interpretation of the paleomagnetic results of Southeast Asian region is therefore to understand the origin of the paleomagnetically observed movements. What is the extent in time and space of particular movement? Are there criteria we can establish to distinguish plate movements from upper crustal block movements?

The main goal of this paper is to compile the available paleomagnetic data of the Cretaceous continental redbed formations from Indochina and South China regions carried out by different researchers and to discuss their tectonic significance, especially the paleomagnetically detected movements of these formations caused by the India-Eurasia collision during the Cenozoic. The accuracy and reliability of the paleomagnetic data are not problem to be discussed but the tectonic interpretation of these data, therefore the typical factors such as: the origin of rock’s magnetization (primary or secondary?), the age of the rock formation, the effects of the tectonic deformation play a vital role in determining their tectonic significance.

The relative rotation and translation of a tectonic block detected from the paleomagnetic directions of geological formations located within that block are determined by comparing the observed directions with the coeval expected directions of a reference block or continent that its Apparent Polar Wander Path (APWP) is well determined for each geological period. Besse and Courtillot [1] has derived an APWP for the Eurasia continent from 200 Ma to present with a high precision, therefore the paleomagnetic directions of the Indochina and South China blocks presented in this paper will be compared with the expected directions calculated from this APWP for certain geological period (Table 1) for discussing their tectonic significance.

2. Cretaceous paleomagnetic results of the South China Block

According to Hsu et al. [11], the South China block consists of two micro-continents that are the Yangtze Craton situated to the northwest and the Hoa Nam block to the southeast. These two micro-continents were welded together during the subduction process of the paleo-Pacific plate under the Eurasia plate in late Mesozoic time, along the Jiangnan suture zone, which consists of Middle to Upper Proterozoic low-grade metamorphic rocks. Xu et al. [22], however, suggest that the entire eastern part of the Chinese landmass was dominated by a Mesozoic sinistral shear system. Xu et al’s view has been supported by the isotopic and paleomagnetic study on the Jurassic - Cretaceous intrusive rocks that are widely exposed to the southeastern part of the South China block [10].
Fig. 1. Tectonic sketch of the Southeast Asia region and the observed declinations of Cretaceous geological formations.

Table 1. Apparent Polar Wander Path for Eurasia derived by Besse and Courtillot (1991).

<table>
<thead>
<tr>
<th>Age (Ma)</th>
<th>( \lambda ) ((^\circ)N)</th>
<th>( \phi ) ((^\circ)E)</th>
<th>( A_{95} )</th>
<th>Age (Ma)</th>
<th>( \lambda ) ((^\circ)N)</th>
<th>( \phi ) ((^\circ)E)</th>
<th>( A_{95} )</th>
<th>Note</th>
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<td>205.8</td>
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<td>71.6</td>
<td>173.0</td>
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</tr>
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<td>50</td>
<td>77.9</td>
<td>149.0</td>
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<td>198.9</td>
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<td>180</td>
<td>64.2</td>
<td>116.7</td>
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<td>190</td>
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<td>109.0</td>
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<td></td>
<td>60 Ma - 100 Ma poles</td>
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<td>110 Ma - 140 Ma poles</td>
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<td></td>
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<td>110 Ma - 160 Ma poles</td>
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Most of the geologists agree that, up to Late Jurassic, the South China block has been already accreted to the North China block along the Qinling suture belt, forming the stable Eurasia continent. During the last decades of the 20th Century, a series of paleomagnetic studies have been carried out on the Mesozoic and Cenozoic rock formations in China, which allow to construct the apparent polar wander paths (APWP) of the South China and North China blocks since Late Permian time to present. Comparison of these APWPs with the APWP of the Eurasia continent indicates that: since the Cretaceous, the South China and North China blocks have been relatively stable to the Eurasia plate [7]. The India-Eurasia collision during the Cenozoic has not significantly affected to the South China and North China blocks [4, 7].

Paleomagnetic data of the Cretaceous continental redbed formations from the South China block are listed in Table 2. The relative rotation and latitudinal translation of studied localities are illustrated in Fig. 2 and Fig. 3 respectively. Among 23 paleomagnetic studied localities, there are only 6 localities have been subjected to both relative rotation and latitudinal translation, mainly from the Late Cretaceous - Eocene continental redbed formations; from other 6 sites only relative rotation has been found and two other sites show only the latitudinal translation.

When comparing the Early Cretaceous, Late Cretaceous and Cretaceous mean paleopoles of the South China block to the corresponding paleopoles of the Eurasia, however, they show that there is neither significant rotation nor latitudinal translation of the South China block relative to the Eurasia continent. This further confirms the conclusion of other researchers mentioned above [4, 7]. The relative rotation and translation found from some study localities only reflect a local tectonic movement of the upper crustal blocks but not the motion of the whole lithospheric block. That is why, bigger degrees of rotation have been found from younger rock formations (Eocene, Late Cretaceous) while the older, underlying rock formations have been less dislocated or unaffected (Early Cretaceous).

![Fig. 2. Relative rotation of the South China terranes with respect to Eurasia.](image-url)
Table 2. Cretaceous - Eocene paleomagnetic results of the South China block.

<table>
<thead>
<tr>
<th>N</th>
<th>Location</th>
<th>Observed VGP</th>
<th>Expected VGP</th>
<th>Rotation</th>
<th>Translation</th>
<th>Sign.</th>
<th>Ref.</th>
</tr>
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<tbody>
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<td></td>
<td></td>
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<td>$\phi$ (°E)</td>
<td>$\lambda$ (°N)</td>
<td>$\phi$ (°E)</td>
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<td>$\phi$ (°E)</td>
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<td>101.3 E</td>
<td>72.3</td>
<td>218.4</td>
<td>4.5</td>
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<td>26.1</td>
<td>101.7 E</td>
<td>70.1</td>
<td>224.6</td>
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<td>79.8</td>
<td>143.1</td>
</tr>
<tr>
<td>3</td>
<td>25.7</td>
<td>102.1 K2-E</td>
<td>61.8</td>
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<td>77.2</td>
<td>193.9</td>
</tr>
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<td>66.0</td>
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</tr>
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<td>102.9 K2</td>
<td>72.8</td>
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<tr>
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<tr>
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<td>118.2 K2</td>
<td>83.8</td>
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<td>77.2</td>
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</tr>
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<td>12</td>
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<td>49.2</td>
<td>178.0</td>
<td>11.4</td>
<td>75.9</td>
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<tr>
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<td>30.1</td>
<td>103.0 K1</td>
<td>76.3</td>
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<td>11.1</td>
<td>75.9</td>
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<tr>
<td>14</td>
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<td>143.0</td>
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<td>74.3</td>
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<td>108.7 K1</td>
<td>86.5</td>
<td>26.4</td>
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<td>18</td>
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<td>66.9</td>
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<td>74.3</td>
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<td>69.0</td>
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<td>21</td>
<td>27.9</td>
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<td>22</td>
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<td>77.1</td>
<td>227.6</td>
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<td>198.1</td>
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<td>Mean K1 poles (13-23):</td>
<td>80.0</td>
<td>216.1</td>
<td>5.4</td>
<td>74.3</td>
<td>198.1</td>
<td>-7.1± 8.8</td>
<td>2.2± 8.1</td>
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<tr>
<td>Mean K2 poles (3-11):</td>
<td>69.2</td>
<td>203.6</td>
<td>6.6</td>
<td>77.2</td>
<td>193.9</td>
<td>8.4± 7.5</td>
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<td>196.0</td>
<td>1.4± 6.1</td>
<td>2.6± 5.6</td>
</tr>
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</table>

Note: Sign. = Significance (Y: Yes, N: No), Ref. = Reference, K1 = Early Cretaceous, K2 = Late Cretaceous, K = Cretaceous, J3-K = Late Jurassic - Cretaceous, K2-E = Late Cretaceous - Eocene, E= Eocene. Rotation and latitudinal translation were calculated at each study locality following Butler (1992); negative (positive) sign indicates CCW (CW) rotation and southward (northward) translation, respectively. Expected VGP's are calculated from Eurasian poles (Table 1) derived by Besse and Courtillot (1991).

We can also see that the tectonic interpretation of a whole lithospheric block based on the paleomagnetic results from several study localities, especially from active tectonic areas, can be inaccurate. It is important that the paleomagnetically detected motion of a lithospheric block must be based on the representative data obtained from different places within the block; so the local tectonic movements can be distinguished.
3. Cretaceous paleomagnetic results of the Indochina - Shan Thai Block

One of the terminologies that has been often referred in the Cenozoic tectonic models of Southeast Asia region is the "Sundaland" plate. The Sundaland plate is bordered to the north by the Red River fault, to the west by the Sagaing fault in Myanmar, to the east by the Philippine subduction zone, and to the south by the Indonesia subduction zone. This plate consists of the Shan-Thai and Indochina blocks, South China Sea, Borneo, Malaya-Indonesia Islands. During the decade 90s of the 20th Century, there have been some reviews of paleomagnetic data from Southeast Asia [8, 16] for discussing the Cenozoic tectonic evolution of this region. A most common aspect from these studies is: regardless the paleomagnetic data have been compiled at different times, they always reflect the tectonic complexity of the Southeast Asian region. Contradicting rotations with various angles have been observed from the same terrane or from different terranes; from clockwise rotation of the paleomagnetic vectors on the continental part to the counterclockwise rotation of the paleomagnetic vectors on the peninsula and islands located to the southeastern part of the region (Fig. 1).

In this paper, the author will present and discuss only the Cretaceous paleomagnetic data of the Shan-Thai and Indochina blocks that have been carried out during the last 20 years in order to highlight the nature of intraplate deformation due to the impact of the India-Eurasia collision.

According to the Extrusion model, the Indochina block has been rotated about 40° clockwise and southward extruded about 800 - 1000 km along the sinistral Red River fault and Me Kong River fault in order to accommodate the convergence of the India -Eurasia collision. One of the paleomagnetic study carried on the Late Jurassic - Early Cretaceous sedimentary formation from the Khorat Plateau (16.5°N, 103.0°E), Thailand [23] has been often cited as an evidence supporting this model. Selecting five Late Jurassic - Early Cretaceous paleopoles
from the South China block, the authors have
determined that the Indochina block has been
rotated $14.2\pm7.1^\circ$ clockwise and southward
extruded $11.5\pm6.7^\circ$ relative to the South China
block since the Cretaceous time. In this study,
however, when we use the J-K paleopole of
the Eurasia continent as a reference, the Khorat
Plateau has been rotated only $10.2\pm7.3^\circ$ clockwise
and is insignificantly southward extruded $3.4 \pm
6.9^\circ$ relative to the Eurasia (Table 3, Fig. 4 and
5). So, we can see here the importance of
selection of the reference paleopole for the
tectonic interpretation of a paleomagnetic result
from a particular area. In order to select a
representative paleopole of a tectonic block for
a certain geological period, there are two
critical factors that decide the accuracy,
reliability of the reference paleopole, which are
the age of the rock formation, and the reference
paleopole must be computed from the coeval
paleopoles observed from different areas within
the block. Certainly, those anomalous paleopoles,
which are clearly affected by the
local tectonic activities should be excluded.

In Vietnam, the paleomagnetic study results
of the Cretaceous extrusive, intrusive, and
sedimentary rock formations from southern
and northwestern Vietnam [5, 6] show that: 1)
Since the Cretaceous, the southern part of
Vietnam has not been significantly rotated but
has been translated $6.6\pm6.4^\circ$ southward relative
to the Eurasia continent [5]; 2) the northwestern
Vietnam (Tu Le depression) has not been
significantly rotated nor latitudinal translated
relative to the Eurasia continent since the
Cretaceous [6].

The Cretaceous paleomagnetic results of
the northwestern Vietnam are similar to the
paleomagnetic data of the Late Cretaceous
redbed formation from the Xiaguan locality -
Yunnan, China, situated next to the Red River
fault [12]. Recently, Takemoto et al. [20] has
carried out a paleomagnetic study on the Yen
Chau redbed formation (Song Da Terrane) and
also obtain consistent results with the results of
the Tu Le Depression (Table 3, Fig. 4 and 5).
Thus, it can conclude that the Red River fault is
not a demarcation between the South China
block and the Indochina block [6, 12, 20], and
there are insignificant displacements of the
Indochina terranes located just to the south of
the Red River fault, a basic tenet of the
extrusion tectonic model.

In recent years, many paleomagnetic
studies have been carried out on the Eocene-
Cretaceous redbed formations from the Simao
terrane in Yunnan, China [3, 12, 18, 24]. In terms
of geographical position, this area belongs to
the Yunnan Province of China, but in terms of
tectonic aspect, this area situates within the
Shan Thai block near to the Eastern Syntaxis
of the India-Eurasia collision belt (Fig. 1); where
strong folding and faulting deformations
occurred due to the impact of the India-Eurasia
collision. Therefore, different paleomagnetic
results have been observed on the Eocene-
Cretaceous redbed outcrops from different
localities in this area, reflecting the local
tectonic displacements. Clockwise rotations
with different angles up to $100^\circ$ and
insignificant latitudinal translations relative
to the Eurasia (Table 3, Fig. 4 and 5) clearly reflect
the nature of local tectonic movement of the
upper crustal blocks during folding processes
[14]. Furthermore, at the several localities such
as Lanping, Mengla bigger clockwise rotations
have been observed on the Eocene overlying
redbed layers and smaller clockwise rotations
of the Late Cretaceous underlying redbed layers
(Fig. 4); as well as contradicting latitudinal
translations of the over- and underlying redbed
layers (Fig. 5) clearly indicate the complexity
of local tectonic displacements. Another possible
explanation might be the reliability of the rock’s
age; as mentioned above, it is difficult to
determine precisely the age of continental
redbeds because the fossils are often rarely
found in the rock. Therefore, the detailed age
classification of the redbed formations is difficult, in many cases it is based mostly on the stratigraphic correlation, and this can lead to a wrong or inaccurate tectonic interpretation of paleomagnetic data and sometimes making controversial conclusions, especially where has been strongly deformed like the Simao terrane.

Another paleomagnetic study on Late Jurassic - Cretaceous continental redbeds situated at the western margin of the Shan Thai block [16], near to the Sagaing right-lateral strike-slip fault (Fig. 1), shows that the study area has been rotated $29.1\pm5.2^\circ$ clockwise and northward translated $7.8\pm4.0^\circ$ (Table 3, Fig. 4 and 5). The observed motion of this area should also reflect the dextral displacement of the Sagaing fault, because it is a great longitudinal trending fault with a length of more than 1000 km that has been formed and being presently active during the India-Eurasia collision process. Therefore, geological formations, which situate within the fault zone certainly will be affected by the fault activity.

That is why, the paleomagnetically detected motions of the rock formations, which located within active tectonic areas (fault zone, extension zone, collision belt, interactive area between blocks or plates, etc.), are likely representative for the study area itself. It would be so subjective and ignorant if one uses the observed paleomagnetically detected rotation and translation of such area to make conclusion that these data reflect the coherent motion of the whole lithospheric block.

Table 3. Cretaceous - Eocene Paleomagnetic results of the Indochina block.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Lat (°N)</th>
<th>Long (°E)</th>
<th>Age</th>
<th>Observed VGP $\lambda$ (°N) $\phi$ (°E)</th>
<th>Expected VGP $\lambda$ (°N) $\phi$ (°E)</th>
<th>Rotation $\Delta \lambda$ $\Delta \phi$</th>
<th>Translation $R$ $\Delta R$</th>
<th>Sign.</th>
<th>Ref.</th>
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<td>SongDa terrane</td>
<td>21.7</td>
<td>103.9</td>
<td>K2</td>
<td>82.9 220.7 6.9</td>
<td>77.2 193.9</td>
<td>-7.0±7.6 2.7±7.1</td>
<td>N/N [20]</td>
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<tr>
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<td>104.2</td>
<td>J3-K</td>
<td>83.9 233.1 11.9</td>
<td>75.4 186.6</td>
<td>-10.7±13.1 5.1±12.4</td>
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<td></td>
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<tr>
<td>Vinh locality</td>
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<td>105.4</td>
<td>K</td>
<td>-   -</td>
<td>76.7 197.1</td>
<td>25.9±9.0 -13±10.7</td>
<td>Y/Y [15]</td>
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<td>108.2</td>
<td>K</td>
<td>74.2 171.1 5.9</td>
<td>75.9 196.0</td>
<td>0.4±6.7 -6.6±6.4</td>
<td>N/Y [5]</td>
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<td>J3-K</td>
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<td>73.7 181.8</td>
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<td>Y/N [23]</td>
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<tr>
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<tr>
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<td>99.3</td>
<td>E</td>
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<td>Y/Y [18]</td>
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<td>65.7±10.1 -3.9±9.1</td>
<td>N/Y [12]</td>
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<td>100.4</td>
<td>K2</td>
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<td>K2</td>
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<td>77.2 193.9</td>
<td>8.2±8.4 -7.5±7.1</td>
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<td>99.5</td>
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<td>74.3 198.1</td>
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<td>Jinggu</td>
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<td>100.7</td>
<td>K1</td>
<td>-13.9 161.3 4.3</td>
<td>74.3 198.1</td>
<td>99.2±7.9 0.6±7.4</td>
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<td>Shan Plateau</td>
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<td>96.3</td>
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<td>29.1±5.2 7.8±4.0</td>
<td>Y/Y [16]</td>
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<td></td>
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</tbody>
</table>

Note: Ref. = Reference, Sign. = Significance (Y = Yes, N = No). K1 = Early Cretaceous, K2 = Late Cretaceous, K = Cretaceous, J3-K = Late Jurassic-Cretaceous, J3-K1 = Late Jurassic- Early Cretaceous, E= Eocene. Rotation and latitudinal translation were calculated at each study locality following Butler (1992); negative (positive) sign indicates CCW (CW) rotation and southward (northward) translation, respectively. Expected poles are calculated (Table 1) from Eurasian poles derived by Besse and Courtillot (1991).
Conclusions

The compilation and review of Cretaceous paleomagnetic data of the South China and Indochina regions lead us to conclude that:

- The present geographical position of the South China block has been relatively stable with respect to the Eurasia continent at least since the Cretaceous. The rotations and latitudinal translations, which have been recorded from some study localities reflect the local tectonic displacement of the upper crustal blocks due to active tectonic activities occurred during the Cenozoic.

- The India-Eurasia collision process has strongly deformed the Indochina - Shan Thai block, especially the areas located near to the collision belt. During the Cenozoic, Indochina
and parts of Sundaland underwent complex internal deformation and did not behave as a coherent block as suggested by the extrusion model.

- The Red River fault does not demarcate the South China block and the Indochina block; the terranes that are located just to the south of this fault have not been rotated nor translated significantly relative to the Eurasia continent since the Cretaceous time. Thus, the tectonic boundary of the South China and Indochina blocks in the extrusion model, if ever exists, must be located somewhere further to the south of the Red River fault.

- The southward displacement of the southern part of Vietnam is in accordance with the extrusion model, however, no clockwise rotation has been observed from this area as well as the apparent counterclockwise rotations have been recorded from Borneo and Malaya peninsula located further to the south [8] indicating that the complex tectonic evolution of the Southeast Asian region can not be completely explained by any simple tectonic model.

- The Cretaceous - Eocene paleomagnetic results from the Simao terrane ( Shan Thai block) mainly reflect the displacements of the upper crustal blocks during the folding and faulting process caused by the India-Eurasia collision.

The history of the Earth crust evolution has been a complex process, there are many problems relating to the tectonic-geodynamic mechanism that have been not elucidated yet; what is the role of the Mantle flow under the continental crust relating to the plate interaction? Whether the collision, movement processes among continents, microcontinents associated with macma-orogenesis activities and intra-plate deformation have been taken place as a result of the active plate motion or they are the consequences of the Mantle flow beneath? With the effort of the interdisciplinary studies of various geologist generations, these problems will be certainly clarified in future.

References


