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Paleomagnetism of upper permian basaltic rocks of Cam Thuy formation from Thuan Chau locality, Son La, Northwest Vietnam

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ABSTRACT

Oriented-core samples (74) from eight sites collected from the Late Permian basaltic Cam Thuy formation exposed at Thuan Chau locality, Son La Province, northwestern Vietnam yield interpretable magnetizations in progressive demagnetization. The characteristic remanent magnetization (ChRM) components carried by magnetite and hematite are successfully isolated from secondary components reveal a mean, stratigraphic coordinates paleomagnetic direction of Ds = 216.1°, Is = 10.5° (α_{95} = 8.9°, k = 107.8, N = 7 site mean directions), corresponding to a virtual geomagnetic pole located at λ = 45.6 °N, ϕ = 226.8 °E and a paleo-latitude for the study area situated at ±5.3 °N during the Late Permian. A comparison of the pole we report in this study with the Late Permian pole of South China Block shows that this basaltic terrane of northwest Vietnam has been close to if not a coherent part of the South China Block since Late Permian. This result implies that insignificant cumulative displacement has occurred along the Ailao Shan/Red River fault system during the Cenozoic India-Eurasia collision.

1. Introduction

The Permian was a particularly important period in the geological evolution of Southeast Asia, where involved successive dispersion and northwards translation of continental blocks during the opening and closing the Paleo-, Meso-, and Neo-Tethys oceans, and their amalgamation and accretion to form present-day SE Asia. In the Southeast Asian region, continental collisions and accretion occurred in two distinct phases, one in the Late Paleozoic-Early Mesozoic and one in the Late Mesozoic and Cenozoic (Metcalfe, 2013).

On the basis of biogeographic and paleomagnetic data, paleogeographic reconstruction models of Permian eastern Pangea and Tethys have been proposed by different workers (Sengor, 1979, 1984, 1988, 1989; Hutchison, 1989; Gatinsky and Hutchison, 1986; Metcalfe, 1988, 1991, 1996, 2002, 2011; Scotese et al., 1992, 1995; Dercourt et al., 1993; Ziegler et al., 1997; Zonenshain et al., 1985; Li et al., 1993; Li and Powell, 2001). All of the reconstruction models broadly agree on the reconstruction of the principal components of Pangea.

Most models for the position of South China during the Permian have the sub-continent situated on, or slightly south of the equator and slightly counter-clockwise rotated; this configuration has been supported by paleomagnetic, biogeographic and climatic data and it did not experience

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significant latitudinal displacement during the Permian. The position of the Indochina Block, however, is somewhat in dispute. Scotese and McKerrow, 1990; Metcalfe 1998, 2002; Li and Powell, 2001)position Indochina and South China together, welded along the Song Ma Suture Zone during Late Devonian-Early Carboniferous and forming the South China- Indochina Super-terrane during the Permian, characterized by Tethyan fauna and Cathaysian flora (Ziegler et al., 1997, 1998), on the other hand, argue that these terranes remain separated during the Permian.

During the last twenty years, many paleomagnetic results from studies of Paleozoic to Mesozoic rock formations exposed in the South China block have been reported by different workers and these data enable the construction of an Apparent Polar Wander Path (APWP) for the South China Block and serve to define the approximate paleo-latitude and orientation of this block during the Permian. However, there are few paleomagnetic studies on Permian-Triassic rock formations from the Indochina Block, lying southwest of the South China Block (Achache and Courtillot, 1985; Chen and Courtillot, 1989; Yang and Besse, 1993), especially from the Vietnam region (Cung et al., 2000a).

In Vietnam, initial paleomagnetic work on these basalts was carried out by Cung, 1996, who collected in the Hoa Binh and Son La areas. Renewed sampling was carried out by the authors in northwest Vietnam in 2013 and efforts were concentrated on Upper Permian to Lower Triassic volcanic rock sequences that crop out from Hoa Binh to Lai Chau province near the border with the People's Republic of China. Independently oriented samples (as drilled cores) were collected from numerous localities, and these were and continue to be analyzed in the Paleomagnetism Laboratory at the University of Texas at Dallas, USA. In this paper, only the paleomagnetic results obtained from basaltic rocks at Thuan Chau locality are presented.

2. Geologic - tectonic setting and sampling area

The continental core of mainland Southeast Asia comprises the Sibumasu, Indochina and South China blocks and the Sukhothai island Arc terrane, located between Sibumasu and South China/Indochina (Sone and Metcalfe, 2008; Metcalfe, 2012). The South China and Indochina blocks are considered to have already amalgamated along the Song Ma Suture Zone in Carboniferous and therefore formed a superterrane in the Permian which has been termed 'Cathaysialand' by some authors (Figure 1).

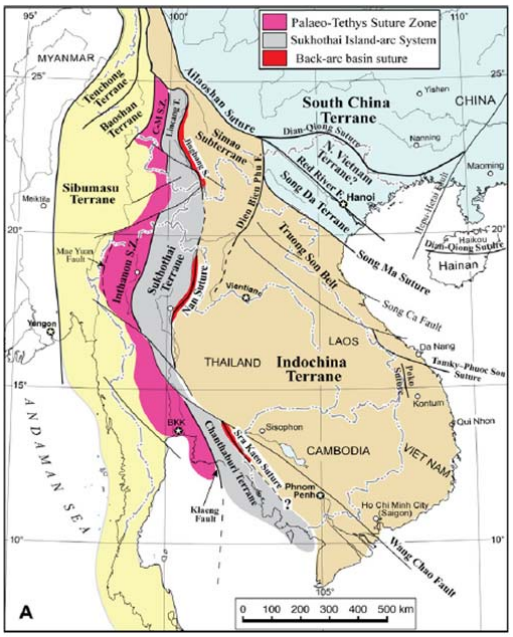

Fig. 1. Sketch map of major tectonic units of SE Asia (after Metcalf, 2012)

Upper Permian - Lower Triassic volcanic rocks are widely exposed in northwest Vietnam, mainly within the Song Da rift basin located NE of the Song Ma Suture Zone that forms the boundary between the South China Block and the Indochina Block. Permian basalts within the Song Da rift are considered distal equivalents of the Emeishan rift basalts; the geochemistry of these basalts and associated Permian-Triassic komatiites suggests a plume related source (Hanski et al., 2004; Zhou et al., 2008). On the other hand, Lepvrier et al., 2004, 2008) suggest that the Permian basalts exposed north of the Song Ma Suture Zone (within Song Da rift basin) could have been emplaced in a back-arc continental setting due to a north-dipping oceanic subduction system of Indochina beneath

South China, yet an inferred calc-alkaline magmatic arc of that age is not well documented. Some authors suggest that Indochina and South China were separated by oceanic crust in the Late Permian to Early-Middle Triassic and that they collided during the Indosinian Orogeny in the Late Triassic (Zhang et al., 2006; Zhang and Cai, 2009; Cai and Zhang, 2009).

Permian flood basalts and associated mafic-ultramafic intrusions form a narrow NW-trending belt in the Song Da rift terrane. The belt is bounded by the Red River fault zone to the northeast and the Song Ma suture to the southwest (Fig. 2).

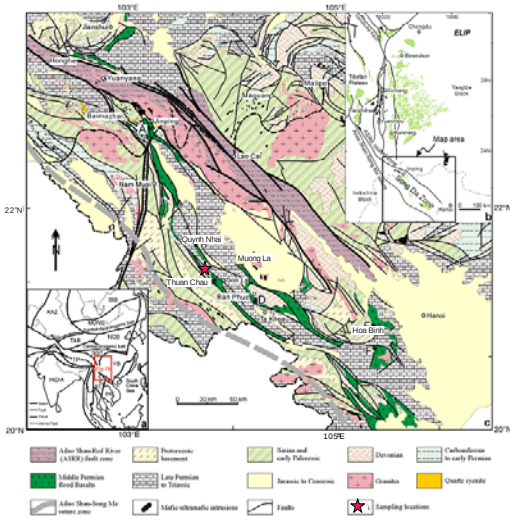

Fig. 2. Geological sketch map of the NW Vietnam region showing the study area, modified from Wang et al. (2007). The major blocks shown in inset (a) are: SIB, Siberia; MONG, Mongolia; NCB, North China Block; YB, Yangtze Block; INC, Indochina Block; TAR, Tarim; KAZ, Kazakhstan; TP, Tibet Plateau; SGT, Songpan-Ganze terrane. The Emeishan Large Igneous Province in SW China and northern Vietnam is shown in inset (b).

The flood basalts unconformably overlie the early Permian limestones, and are concordantly overlain by the early Triassic limestone and shale (Glotov et al., 2001). Folded Triassic sedimentary rocks are unconformably overlain by Cretaceous conglomerates, sandstones and pelites (Lacassin et al., 1998).

Upper Permian - Lower Triassic volcanic rocks in the Song Da rift terrane have been divided into the Cam Thuy and Vien Nam formations. The Upper Permian Cam Thuy Formation (Dinh Minh Mong, 1978) consists of mafic extrusive rocks, of tholeiitic affinity that are widely exposed in the southeast part of the Song Ma anticline within Thanh Hoa, Ninh Binh, Hoa Binh, Son La and Lao Cai provinces. The volcanic rocks of Cam Thuy Formation are, in general, basalt, basaltic andesite, or andesite and are up to 1000 m thick (Hoa Binh area). They are dominated by high magnesium, low titanium and alkaline basalt, equivalent to tholeiite series rocks (Polyakov et al., 1991, 1999; Hoa et al., 2001, 2004, and 2008). Based on isotopic age determinations (Polyakov et al., 1999; Tran Trong Hoa, 1996; Hanski et al., 2004), the interpreted age of the basaltic rocks is about 257 ± 24 Ma, corresponding to the Late Permian.

At Thuan Chau locality, eight sites with 74 core samples were collected on basaltic rocks of Cam Thuy Formation that crop out along the road from Son La city to Thuan Chau district.

3. Paleomagnetism and rock magnetism

Individual specimens of 25 mm in diameter and 22 mm in length were prepared from each sample in the laboratory. Natural remanent magnetizations (NRMs) were measured using a 2-G Enterprises three-axis, DC-SQUID pulse cooled cryogenic magnetometer. One specimen from each sample was subjected to stepwise thermal demagnetization up to 690°C using an ASC TDS-48 thermal demagnetizer with a residual field below 5 nT. Another specimen of the same sample was subjected to stepwise alternating field (AF) demagnetization up to 100 mT in order to choose the most effective demagnetization method for the rest of samples. Demagnetization results for each specimen were plotted on orthogonal vector diagrams (Zijderveld, 1967) to assess component structure as well as on equal-area projections to evaluate directional consistency. Principal component analysis (Kirschvink, 1980) was used to estimate components directions. Site-mean directions were calculated using Fisherian statistics (Fisher, 1953). The natural remanent magnetizations of basaltic rocks are rather strong, ranging from 24.4 mA/m to 4.45 A/m and consist of two or more components (Fig. 3 to Fig. 5). The ChRM components possess magnetite and hematite as the principal magnetic-bearer minerals that have high Curie temperatures (580^{o}C for magnetite and 675^{o}C for hematite) and high magnetic resistance during the thermal and AF

demagnetizations (Fig. 4). These samples show excellent response in progressive alternating field and/or thermal demagnetization; the ChRM components are successfully isolated from the secondary components at about 350°C and/or 20 mT and uniformly decayed toward the origin. There are some samples that have the ChRM components with very high magnetic resistances, which still exist at high alternative field - 100 mT (Fig. 3).

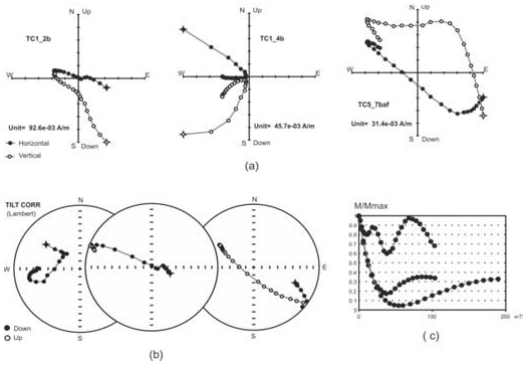

Fig. 3. Representative AF demagnetization plots of hard multi-NRM components samples; (a) Zijderveld plots, (b) stereographic plots, (c) normalized magnetization plots.

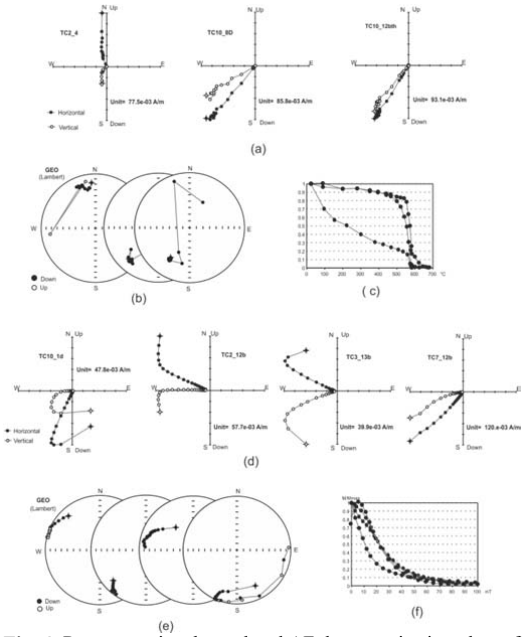

Fig. 4. Representative thermal and AF demagnetization plots of magnetite-bearer NRM samples; (a) & (d): Zijderveld plots, (b) & (e): stereographic plots, (c) & (f): normalized magnetization plots

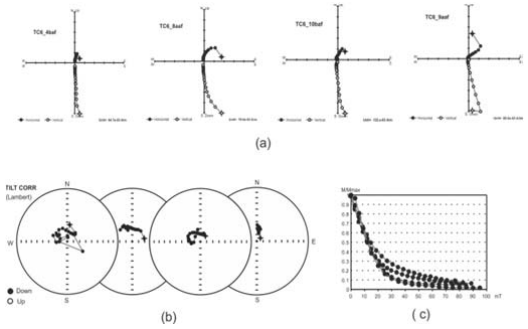

Fig. 5. Representative AF demagnetization plots of steep-inclination samples that probably, their NRM were acquired during the reversal process of the Earth's geomagnetic field; (a) Zijderveld plots, (b) stereographic plots, (c) normalized magnetization plots.

4. Paleomagnetic results

The site-mean directions of ChRM components are plotted on the Lambert equal-area projection together with the mean paleomagnetic direction of Thuan Chau locality (Fig. 6) and their values are listed in table 1. Only four sites, which have a clear flow bedding orientation, are used to calculate the mean paleomagnetic direction for Thuan Chau locality. Their paleomagnetic directions are clearly different from the present geomagnetic direction of the study area as well as the paleomagnetic direction of younger rock formations in the northwestern Vietnam region (Cung et al., 2000; Takemoto et al., 2005), which reflect an ancient paleomagnetic direction. The formation mean direction of 4 sites yields the values D_s = 216.1°, I_s = 10.5°, α_{95} = 8.9°, k = 107.8; corresponding to a virtual geomagnetic pole (VGP) located at λ = -5.6°N, ϕ = 46.8°E (or λ = 45.6°N, ϕ = 226.8°E). The mean paleomagnetic direction of Thuan Chau basalts is almost antipodal with that of Hoa Binh basalts (D = 33.8°, I = -28.4°) which indicates that the basaltic rocks from these localities had acquired their characteristic remanent magnetizations during a normal (Hoa Binh basalt) and reversed (Thuan Chau basalt) geomagnetic field. The reversal of the Earth's geomagnetic field during this time period has been also recorded in some samples from Thuan Chau locality with very deep inclination values (Fig. 5).

Table 1. Paleomagnetic results of Late Permian basaltic rocks of Cam Thuy Formation

Site	Location		Az/Dp	n/N	ChRM						VGP		dp	dm	λpaleo
	λ(°N)	ϕ(°E)	(o)		Dg	Ig	Ds	Is	α95	k	λ(°N)	ϕ(°E)	(o)	(o)	(°N)
TC1-2*	21.379	103.779	-	8/11	308.5	9.7	-	-	11.0	26.26	37.5	3.1	5.6	11.1	4.9
TC03*	21.380	103.779	-	12/13	298.0	6.0	-	-	4.3	102.7	27.1	5.9	2.2	4.3	3.0
TC06*	21.380	103.726	-	10/12	9.4	46.1	-	-	4.3	127.15	79.5	156.6	3.5	5.5	27.5
TC07	21.380	103.726	188/30	12/12	227.6	36.2	219.7	11.6	2.5	312.78	-42.0	44.3	1.3	2.5	5.8
TC08	21.380	103.726	188/30	9/9	226.9	36.6	219.0	11.8	2.1	589.54	-42.9	45.0	1.1	2.2	5.9
TC09	21.380	103.726	188/30	2/3	228.6	34.3	221.1	10.1	5.2	2328.9	-41.8	42.4	2.6	5.2	5.1
TC10	21.380	103.726	188/30	13/14	208.6	36.9	204.5	8.4	5.7	52.96	-54.8	57.9	2.9	5.8	4.2
Mean G	21.380	103.726		4/7	223.0	36.3			8.9	108.31	-30.8	55.5	6.0	10.3	20.2
Mean S	21.380	103.726		4/7					8.9	107.84	-45.6	46.8	4.6	9.0	5.3
Or:											45.6	226.8	4.6	9.0	-5.3

Note: (*)- sites are excluded from the calculation of site mean; Az/Dp: Azimuth of dip/Dip; ChRM: characteristic remanent magnetization; VGP: Virtual geomagnetic pole; lpaleo: Paleolatitude of the site.

Table 2. Late Permian virtual geomagnetic poles from South China and Indochina

Age	Locality		VGP coord		A_{95}	Rock type	Reference
	λ	ϕ	λ	ϕ			
South China Block:							
P2	29.6	103.4	52.7	252.1	6.0	Basalt and red sandstone (Emeishan, Sichuan)	McEnhinny et al. 1981
P2	29.6	103.4	49.7	252.0	2.8	Emeishan basalt	Zhao and Coe, 1989
P2	29.6	103.4	54.1	241.8	19.0	Basalt and limestone (Emeishan, Sichuan)	Chan et al. 1984
P2	29.6	103.5	38.5	231.6	4.9	Emeishan basalt, Xihekou	Liu et al. 1985
P2	28.1	102.9	58.9	246.1	6.6	Basalt, Zhaojue, Sichuan	Liu et al. 1985
P2	27.6	101.9	63.5	264.3	9.8	Basalt, Yanguan, Sichuan	Liu et al. 1985
P2	28.3	103.0	54.3	251.2	20.0	Basalt, Meigou, Sichuan	Zhou et al. 1986
P2	26.8	101.8	25.6	216.4	12.6	Basalt, Miyi, Sichuan	Zhou et al. 1986
P2	26.7	102.9	53.5	241.8	10.1	Basalt, Huidong, Sichuan	Huang et al., 1986
P2	26.1	103.1	52.5	226.0	25.0	Basalt, Dongchuan, Yunnan	Huang et al., 1986
P2	25.9	100.6	24.7	204.3	24.8	Basalt, Binhchuan, Yunnan	Huang et al., 1986
P2	26.4	105.7	29.3	235.3	13.4	Basalt, Xiongjiachang, Guizhou	Lin, 1984
P2	25.6	103.0	50.0	241.0	6.1	Basalt, Kunming, Yunnan	Fang & Vander Voo, 1990
P2	29.6	103.5	38.5	231.6	4.9	Emeishan basalt, Xihekou	Liu et al. 1985
P2	26.5	101.8	23.6	210.3	9.1		Zhou et al., 1988
P2	26.5	101.8	28.9	218.2	6.4		Zhou et al., 1988
P2	28.3	103.0	57.0	277.1	12.7		Zhou et al., 1988
P2	28.3	103.0	47.1	231.0	19.0		Zhou et al., 1988
P2	29.6	103.4	54.1	241.8	19.5		Lung et al., 1984
P2	29.6	103.4	51.2	232.5	2.9		Zhang 1984
P2	29.6	103.4	48.9	251.1	4.0		Zhao and Coe, 1987
P2	26.4	104.7	41.5	222.7	4.5	Emeishan basalt	Huang and Opdyke, 1998 P2
Mean of 22 poles:	47.4	235.5	6.7				
Indochina Block:							
P2	16.7	101.8	58.4	176.2	7.2	Limestone, Khorat Plateau, Thailand Yang& Bese, 1993	
P2	21.5	103.7	45.6	226.8	8.9	Basalt, Thuan Chau, NW Vietnam	This study
P2	29.6	103.4	48.9	251.1	4.0		Zhao and Coe, 1987
P2	26.4	104.7	41.5	222.7	4.5	Emeishan basalt	Huang and Opdyke, 1998 P2

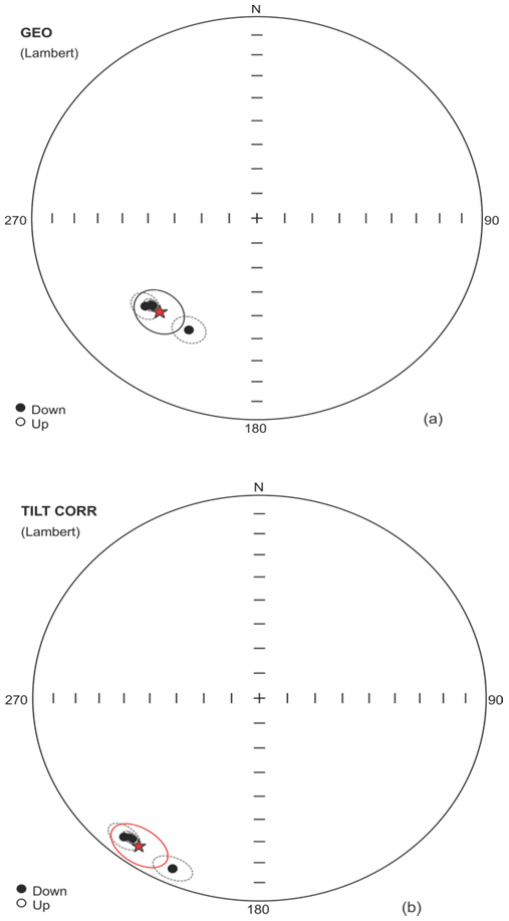

Fig. 6. Lambert equal-area diagram showing the site mean direction and the mean direction of 4 sites with the ellipse of 95% confidence. (a) in geographic coordinates; (b) in stratigraphic coordinates

The paleopole position of Thuan Chau basaltic rocks is basically indistinguishable from that of Late Permian-Early Triassic basaltic rocks from Hoa Binh locality (λ = 41.1°N, ϕ = 239.8°E) and from the paleopole of Permian Emeishan basalts in South China (Fig. 7). The similar paleopole positions of two distal basaltic rock formations from NW Vietnam and South China further corroborate the hypothesis of coeval time emplacement. The paleolatitude of the study area calculated from the formation mean direction is λ_{obs} = ± 5.3°N indicating that the Thuan Chau basaltic rock formation was emplaced on the Earth during Late Permian time near the equatorial region.

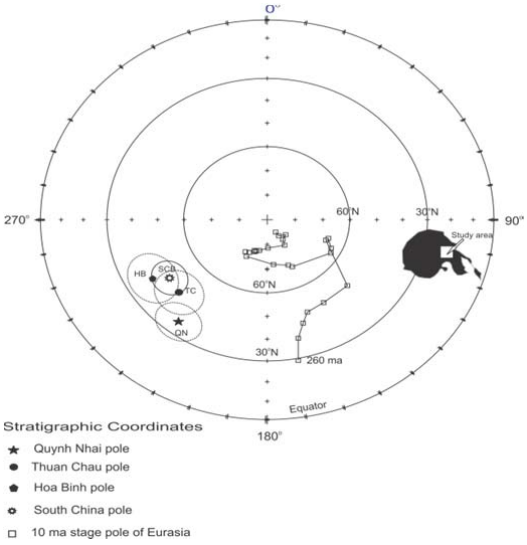

Fig. 7. Equal-area diagram showing the position of VGP pole of Thuan Chau locality relative to coeval paleopoles of Hoa Binh, Quynh Nhai areas and the South China Block, and the APWP of Eurasia

Using the mean paleopole of Upper Permian volcanic rock formations from South China Block (table 2), the expected paleomagnetic direction of Thuan Chau locality is computed and has the values: D_{ex} = 30.7°, I_{ex} = -16.8°, λ_{ex} = -8.6°N.

5. Discussion

According to the paleogeographic reconstruction models, the northwestern Vietnam, in general, and the Thuan Chau locality, in particular, belongs to the South China Block but not to the ancient Indochina Block as described by Metcalfe, 2011, 2012 because the Song Ma Suture situates to the southwest of this region. The rotation and latitudinal translation of Thuan Chau locality relative to the South China Block are calculated and have the values as follow: R = 5.4° ± 9.0°, d = -3.3° ± 8.9°; which are statistically insignificant indicating that the Thuan Chau locality has been relatively stable with respect to the South China Block since the Late Permian. The stable position of Thuan Chau area with respect to the South China Block deduced from the paleomagnetic results of this study is consistent with that of Late Permian-Early Triassic basaltic formations from Hoa Binh and Quynh Nhai area (Cung et al., 2015 - in press) and also consistent with that of

Cretaceous red-bed formations from NW Vietnam region reported by (Cung et al., 2000b; Takemoto et al., 2005).

The consistency of paleomagnetic information on relative tectonic displacement of northwestern Vietnam region obtained from different rock formations with different geological ages shows that this region has been close to if not a coherent part of the South China Block since the Late Permian. This result implies that insignificant cumulative displacement has occurred along the Ailao Shan/Red River fault system during the Cenozoic India-Eurasia collision.

6. Conclusions

The characteristic remanent magnetizations of basaltic rocks from Thuan Chau area have been acquired during a reversal of the Earth's geomagnetic field occurred in the Late Permian time and their paleomagnetic directions are almost antipodal with that of Hoa Binh basaltic rocks.

The Thuan Chau locality, in particular, and the northwestern Vietnam region, in general, has been a coherent part of the South China Block and situated near the Equator during the Late Permian.

The Ailao Shan/Red River fault system has played a minor role during the Cenozoic India-Eurasia collision and there is insignificant cumulative displacement along this fault in terms of paleomagnetism.

If the Indochina Block had been indeed extruded southward during the India-Eurasia collision, this motion would be occurred along some other faults located to the south of the study area.

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