ScienceAsia 28 (2002) : 277-290

Magnetic Characterization of the Thung-Yai Redbed of Nakhon Si Thammarat Province, Southern Thailand, and Magnetic Relationship with the Khorat Redbed

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Received 26 Jul 2001
Accepted 6 Feb 2002

ABSTRACT A total of 57 standard specimens are prepared from 31 oriented core samples drilled from the Thung-Yai redbed of Upper Jurassic - Lower Cretaceous age. All specimens are characterized magnetically. Results show that distributions of the magnetic susceptibility (73.5 - 144.7 μSI), natural remanent magnetization (3.19-13.59 mA/m) and Köenigsberger ratio (0.96-3.65) of the specimens are similar to those of the Khorat redbeds. Low anisotropy degree Pj of 1 - 7 % indicates a low degree of deformation in the Thung-Yai redbed. Distribution of the principal axes of susceptibility indicates an imbrication of the minimum axes (K_3) toward the West which is interpreted as the palaeo-current direction during deposition of sediments. There are probably gravitational and hydrodynamic forces of flowing water that affect the Thung-Yai redbed at the time of deposition. Analyses of magnetic data and fluorescent X-ray images indicate that magnetite and haematite are the predominant magnetic minerals in the Thung-Yai redbed. This shows a non-marine environment during sedimentation. Remanent magnetization derived from a high temperature range of 530 - 630 °C directed at Dec/Inc = 32.6°/18.8° is considered to be primary remanent magnetization and its pole position is at Plat/Plon = 57.8°N/184.6°E. This pole overlaps well with the pole position derived from the Khorat redbeds (Plat/Plon = 60.7°N/181.0°E). This indicates that the Shan-Thai block, the parent block of southern Thailand and Indochina block, the parent block of the Khorat plateau, have not moved with reference to each other since the Upper Jurassic – Lower Cretaceous.

KEYWORDS: magnetic characterization, Thung-Yai redbed, Khorat redbed, palaeomagnetic, AMS.

INTRODUCTION

Magnetic characteristics of rocks are the responses of physical and chemical properties of rock materials, which can be measured or examined using the advanced, high-sensitivity magnetic instruments. Types and sources of magnetic minerals probably relate to chemical and physical environments during long history of the rocks since the time of rock formation. For example, presence of goethite (α-FeOOH) may indicate marine environment, while magnetite (Fe_3O_4) and haematite (Fe_2O_3) often indicate a continental or fresh-water environment in sedimentary rocks. Pyrite (FeS_2), a paramagnetic mineral generally found in marine limestone, is probably biogenic.[1] Under certain physical and chemical conditions, pyrite will transform to ferromagnetic minerals, ie, pyrrhotite (FeS_{1+X}), magnetite and haematite.[2,3,4] Therefore magnetic characteristics of rocks can be related to the palaeo-environment during the long history of rocks.

Magnetic properties measured in rock include an initial or low-field magnetic susceptibility (k), intensity and direction of natural remanent magnetization (NRM), the Köenigsberger ratio, the anisotropy of magnetic susceptibility (AMS) and its parameters, orientation of the principal axes of susceptibility ellipsoid, thermal and alternating field demagnetization, and variation of magnetic susceptibility with temperatures. These magnetic properties have been used as an important tool for geoscientists to solve their problems. The followings are some examples. Bhongsuwan and Elming used the magnetic properties, ie, k-value, NRM and Köenigsberger ratio, to differentiate the rock formations in the Khorat Group.[5] Özdemir and Dunlop studied the origin of magnetite from dehydration of goethite.[6] Riller and coworkers used the AMS to study microstructure of old tectonically stressed igneous rocks and Grégoire and coworkers used the AMS to study grain orientation of magnetite in 3 dimensions.[7,8] The AMS has been used to study the palaeo-environment. For example, Kissel and coworkers used the AMS to study a variation of palaeo-environment from sediment core of Norwegian sea and north Atlantic ocean.[9] Palaeo-current direction of loess in China was studied using the AMS analysis.[10] Tectonic stress field can affect the orientation of susceptibility ellipsoid and the degree of anisotropy.[11] The AMS has been used to study palaeo-stress field affecting the rocks resulted in both deformed rock and apparently undeformed or weakly deformed rocks, such as the work of Aubourg.[12] Bhongsuwan and Elming demonstrated that the AMS of rock could be a useful tool in selecting the most reliable data for further palaeomagnetic analyses.[13]

Another main application of magnetic characterization of rocks is to use the progressive stepwise demagnetization to clean the NRMs preserved in the oriented rock specimens and then analyse them to obtain the direction of the characteristic remanent magnetization in the present geographic coordinate system. This component of NRM is probably preserved in the rock at the time of rock formation and is called the primary remanent magnetization. Analyses of the primary magnetization or palaeomagnetic analyses can be used to solve the plate tectonic problems, continental drift, and relation between the plates in the ancient time. Some works in this field of application and in the area involved in this study are present in the next section.

This work aims to study the rock magnetism and palaeomagnetism of a Mesozoic redbed newly exposed in Thung-Yai district, Nakorn Si Thammarat province of Southern Thailand. Exposures of Mesozoic redbed are rarely found in Southern Thailand, but widely exposed in the Khorat plateau of Northeastern Thailand. The Thung-Yai redbed is a Mesozoic redbed of the Shan-Thai block. It is equivalent in age with a part of the redbed of the Khorat Group of Indochina block according to a new geological map of Thailand.[27] The magnetic characteristics and a preliminary palaeomagnetic analysis of the Thung-Yai redbed are discussed here and are used in comparison with those of the Khorat redbed, which has been studied by many workers.[5, 18-19] Similar rock type and well-defined age of the Thung-Yai redbed of the Shan-Thai block and Khorat redbed of Indochina block are considered to be the good controls for rock magnetic and palaeomagnetic analyses in terms of plate relation between the Shan-Thai and Indochina blocks, the parent plates of the two redbeds.

Previous Rock Magnetic and Palaeomagnetic Studies in Thailand

Palaeomagnetic studies in Thailand are pioneered by Barr and McDonald, Bunopas, Achache and Courtillot, and Maranate and Vella.[15-18] Yang and Besse studied the palaeomagnetism of the Khorat rocks and reported a positive fold test (**Note** positive fold test means that characteristic magnetization is acquired for rock before the time of folding) in the Huai Hin Lat and Nam Phong formations aged Triassic/Jurassic of the Khorat basin, Northeastern Thailand.[19] The authors suggested in their tectonic reconstruction that Indochina, the parent block of the Khorat basin, had been subject to a latitudinal displacement of 11.5° ± 6.7°, a rotation of 14.2° ± 7.1° and a sinistral motion of 1500 ± 800 km along the Red River fault since the boundary of Jurassic/Cretaceous time. Bhongsuwan and Elming reported palaeomagnetic results from rocks of the Khorat Group collected from the Western rim of the Khorat plateau, Northeastern Thailand. The authors demonstrated the positive fold tests for the Middle Jurassic redbeds (the Phu Kradung and Phra Wihan formations) and for the Upper Jurassic Sao Khua Formation, while the fold test was insignificant for the Lower Cretaceous Phu Phan and Khok Kruat formations.[5] In their tectonic analyses, the authors suggested that Indochina was attached to the northwestern part of the South China Block before extrusion of Indochina was initiated in the Upper Jurassic.[5]

A few rock magnetic and palaeomagnetic studies have been done in southern Thailand.[13-14, 16] Most of Palaeozoic rocks collected from southern and northern Thailand of the Shan-Thai block were found to be bad magnetic recorder and unsuitable for palaeomagnetic analyses.[13-14] Only few rock exposures were reported to be useful for palaeomagnetic analyses, for examples, baked sediment at the contact between Mesozoic granite and Palaeozoic sedimentary rocks, and a few fresh exposures of Mesozoic sedimentary rocks.[13-14] The main reason for unsuitability of most Palaeozoic rocks for palaeomagnetic study is the magneto-thermochemical history of the rocks. Fresh rock exposures with enough age controls will be needed to further improve the palaeomagnetic results of Southern Thailand and of the Shan-Thai block as a whole.

Regional Tectonic Setting and Geology of Sampling Site

It is generally accepted that Thailand comprises two terranes, ie the Shan-Thai terrane in the west and the Indochina terrane in the east (Fig 1a).[16, 20-21] The Shan-Thai terrane includes eastern Myanmar, western Thailand, Thai-Malay Peninsula and northern Sumatra. The Shan-Thai terrane consists of Precambrian granitoids, high-grade metamorphic rocks, and Palaeozoic sedimentary and Mesozoic granitic rocks.[16, 22] Indochina terrane includes Eastern Thailand, Laos, Cambodia and Vietnam. The terrane comprises mainly of Palaeozoic sedimentary rocks, Permian platform carbonate and deep water clastic rocks, which are covered by gently folded Mesozoic continental sedimentary sequences of the Khorat Group. The Shan-Thai terrane has probably been attached to Gondwanaland until the early Permian as indicated by early Permian glaciomarine deposits, cool-water faunas of Australian affinities,[23] and by middle-late Permian and early Triassic faunas showing Cathaysian affinities.[24] In Upper Permian time, Shan-Thai collided with Cathaysialand and the suturing to the Indochina block was largely completed in the Upper Triassic time.[16, 25] The I- and S-type granites intruded during the Upper Triassic to Lower Jurassic which also supports a collision in the Upper Triassic.[26] No significant latitudinal displacement (2.6 °) between the Shan-Thai and Indochina blocks since the Upper Triassic-Lower Jurassic has been reported.[13]

Sampling site is in Southern Thailand of the Shan-Thai terrane. It is situated beside the Petkasem road between Thung-Song district and Surat Thani province at latitude 8.38 °N and longitude 99.42 °E (Fig 1b). Rock at this site is exposed due to construction of the new 4-lane highway (Petkasem road). The sampled rock is a member of the Lam Thap Formation, which consists of arkosic and lithic sandstone, mudstone siltstone, cross-bedded, conglomerate and sandstone.[27] At the sampling site, a thick bed of fresh red silt/sandstone is exposed. Bedding strike/dip is 220°/22°. No evidence of structural deformation is observed. This indicates that the rock at this site has been apparently undeformed by a tectonic stress since the time of formation. We propose the name Thung-Yai redbed for this new rock exposure. Age of the redbed is Upper Jurassic – Lower Cretaceous (ca 160-100 Ma), which is equivalent with the age of the Phra Wihan Formation of the Khorat Group of Indochina block according to the geological map of Thailand.[27]

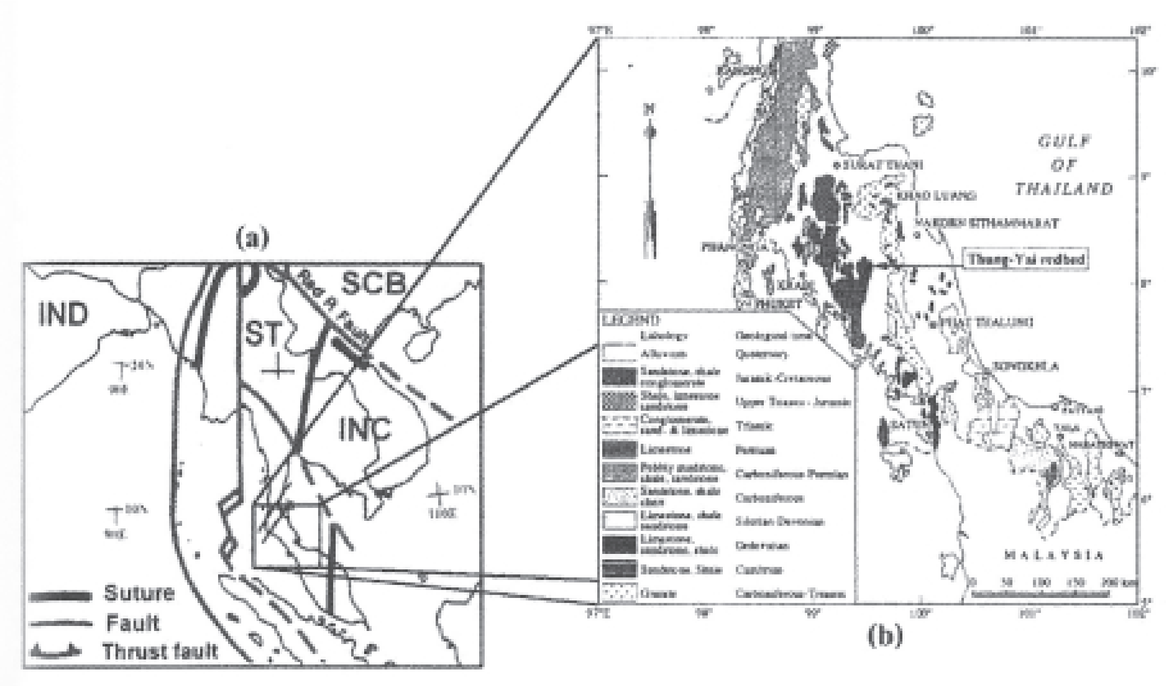

Fig. 1 Maps of the sampling site: (a) Schematic tectonic map of SE Asia, showing the main sutures and tectonic blocks. This tectonic map was first presented by Enkin and co-workers.[41] The major blocks are the South China block (SCB), Shan-Thai (ST), Indochina (INC), and India (IND). (b) Simplified geological map of Southern Thailand denoted by a rectangle in (a). The sampling site of the Thung-Yai redbed is shown with arrow line. Redrawn from Bhongsuwan and Elming.[13]

Materials and Methods

Oriented sampling using a portable petrol-powered core drill is performed in a geographic reference system. Altogether 31 rock cores of 1" in diameter and 3-5" long are oriented using sun and magnetic compasses with help of orienting device. Bedding of rock is measured using both magnetic and sun compasses for bedding correction. A GPS (Timble Navigator BASIC+, USA) is used to measure the geographic coordinates (Lat/Long) of the sampling site. Fifty-seven standard palaeomagnetic specimens are prepared for rock magnetic measurements. Usually two to three specimens are prepared from each sample core.

Intensity and direction of the NRM are measured using a spinner magnetometer (UGF JR - 4, Czech Republic), which has a sensitivity of 2.4 x 10^{-6}A/m at the geophysical laboratory, Department of Physics, Prince of Songkla University. Progressive stepwise thermal (12 - 15 steps; 150 - 660 °C) and/or alternating field (12 - 15 steps; 10 - 60 mT) demagnetization are performed to all samples in order to erase the secondary components of the NRM.

The magnetic susceptibility of the specimen at each step of thermal demagnetization is measured using a Kappabridge (KLY-3S, AGICO, Czech Republic) to monitor any thermo-chemical changes of magnetic minerals in the specimen. The principal component directions of the NRM are analysed based on the PCA (principal component analysis) using a program called IAPD, which uses a least square fit of vectors in 3-dimensional space.[28-29] Fisher's statistic is used to determine the mean of the component directions and statistical parameters.[30] A 95 % confidence level is used to explain the scatter of individual direction about the mean. Magnetic susceptibility, AMS parameters, directions of the principal axes of susceptibility are measured using a Kappabridge, which has a sensitivity of 1.2 x 10^{-8} SI (**Note** volumetric susceptibility is dimensionless in the SI system). A program called ANISOFT (AGICO, Czech Republic) is used to analyse the AMS data, which include the corrected anisotropy degree (Pj), and shape parameter (T).[31] Elemental analysis of a polished section of representative rock sample is performed using a scanning electron microscope (Oxford instrument, JSM 5800LV, England) attached with an energy-dispersive X-ray fluorescence system (EDS ISIS300) at a 300X magnification.

The magnetic susceptibility can be considered to be a second-order tensor quantity and presented in the formula.[32]

$$\bar{M} = \underline{\underline{k}}\bar{H} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix}$$

where $\bar{M}$ is an induced magnetization, $\bar{H}$ is an external magnetic field and $\underline{\underline{k}}$ is the susceptibility tensor.

Due to its symmetry $k_{xy}=k_{yx}$, $k_{xz}=k_{zx}$, $k_{yz}=k_{zy}$, the magnitude of the anisotropy of k can be modeled by a susceptibility ellipsoid, which contains three principal axes representing K_1, K_2, K_3 or maximum, intermediate and minimum axes of the ellipsoid, respectively.

Corrected anisotropy degree (Pj) is a parameter used to represent degree of anisotropy of k while the shape factor (T) represents the shape of ellipsoid. The Pj and T can be calculated from the following equations.[11]

$$Pj = \exp\left[2\left\{(\eta_1-\eta_m)^2+(\eta_2-\eta_m)^2+(\eta_3-\eta_m)^2\right\}\right]^{1/2}$$

$$T = \frac{(2\eta_2-\eta_1-\eta_3)}{\eta_1-\eta_3}$$

where

$$\eta_1 = \text{In } K_1; \eta_2 = \text{In } K_2; \eta_3 = \text{In } K_3 \textit{ and } \eta_m = \sqrt[3]{\eta_1\cdot\eta_2\cdot\eta_3}$$

T > 0 represents oblate or plate-like ellipsoid and T < 0 shows a prolate or rod-shaped ellipsoid.

An undeformed rock carries a primary magnetic fabric that corresponds to the rock type, its mineral composition and the environment in which it was formed. Sedimentary rocks generally show an oblate-shaped susceptibility ellipsoid orientated parallel to the bedding plane, thus with the minimum principal axis orthogonal to the bedding. Magnetic lineation can be developed if the grains were deposited in a slope or in streaming water, otherwise the K_1 and K_2 axes form a girdle pattern.[11] Flow fabrics have been recognized in many granites from alignments of the crystalline axes and shapes of minerals, such as those of feldspars, and identical patterns have been found in magnetic fabric studies of granites.[33-34] The original fabric in granites may be modified later by metamorphic events, which appear to intensify the original fabric, probably by the mimetic growth of magnetite in previously oriented micas.[2] AMS is a well known indicator of the direction of magma flow in basic dykes and the method has been used in several studies to define flow fabric.[35-37]

Results and discussions

Magnetic properties of the Thung-Yai redbed including the mean susceptibility (k_m), the NRM, AMS parameters (Pj, T) and the principal axes orientation (Dec./Inc.) of K_1 and K_3 of 25 rock specimens are shown in Table 1.

Magnetic susceptibility and intensity of natural remanent magnetization

The susceptibility of specimens of the Thung-Yai redbed ranges between 73.5 and 144.7 µSI with a mean of 92 µSI (σ = 19 µSI, N = 25). The NRM intensity values are 3.2 – 13.6 mA/m with a mean of 6.3 mA/m (σ = 2.0 mA/m, N = 25). These values are typical for silt/sandstone, which has a low k due to a low concentration of ferromagnetic minerals in the rock.

Comparing with the k of specimens of the redbed of the Northeastern Thailand, the Khorat redbed, it is found that the k of the Thung-Yai redbed distributes overlapped with the k of samples from the Phu Phan Formation, the Khok Kruat Formation and the Phra Wihan Formation as shown in Fig 2.

However, the NRM intensity of specimens of the Thung-Yai redbed overlaps well with those of the Phu Phan Formation (Fig 3) while the Q-values or Köenigsberger ratio of the Thung-Yai redbed range between 0.96 and 3.65. These results indicate a slightly high stability of the NRM in the Thung-Yai redbed similar to those of the Phu Phan Formation (Fig 4).

Table 1. Magnetic properties of some 25 samples from the Thung-Yai redbed.

Specimen	NRM	k_m				K_1 axis		K_3 axis	
Name	(mA/m)	(µSI)	Pj	T	Q-value	Dec(°)	Inc(°)	Dec(°)	Inc(°)
TY03-1	13.59	93.10	1.05	0.01	3.65	37.6	23.4	257.3	60.6
TY04-1	5.74	114.70	1.05	0.05	1.25	32.6	24.7	234.8	63.6
TY06-1	7.42	135.80	1.06	-0.10	1.37	14.3	22.2	236.6	61.1
TY07-1	3.19	82.60	1.04	0.51	0.96	44.5	32.8	239.7	56.3
TY08-1	4.29	101.50	1.05	0.37	1.06	56	37.4	255.1	51
TY09-1	5.48	83.80	1.02	-0.40	1.64	164.8	0.6	255.5	48.1
TY10-1	6.66	98.50	1.05	0.04	1.69	46.8	38.6	242.3	50.4
TY11-1	7.28	144.70	1.05	-0.07	1.26	5.5	20.8	226.9	63.2
TY12-1	5.57	84.80	1.03	0.71	1.64	107.9	43.9	305	44.8
TY13-1	5.85	97.10	1.03	0.67	1.51	121.9	23.2	254	57.4
TY14-1	6.28	102.90	1.04	-0.12	1.53	9.2	28.6	221.1	57.3
TY16-1	4.98	74.00	1.05	-0.06	1.68	350.6	16.7	215.5	67
TY16-2	7.37	75.80	1.04	-0.30	2.43	351.6	18.3	200.7	69.2
TY17-2	6.05	80.30	1.03	-0.47	1.88	356	26.3	192.9	62.7
TY18-2	5.10	90.90	1.03	0.21	1.40	11.6	34.7	226.4	49.8
TY20-1	5.38	101.20	1.04	0.06	1.33	39.5	42.4	224.1	47.5
TY22-1	7.32	79.10	1.04	-0.06	2.31	169.7	15	279.5	51.5
TY24-2	5.06	73.50	1.02	0.44	1.72	326.5	11.5	68.4	45.5
TY25-2	4.69	73.70	1.02	-0.12	1.59	9.6	9.7	268.7	47.8
TY26-2	4.76	75.10	1.01	-0.53	1.58	174.1	1.2	271.6	81.1
TY27-2	5.35	73.70	1.02	0.35	1.82	347	1.3	253.4	70.7
TY28-2	5.04	75.50	1.03	-0.19	1.67	7.2	15.4	207.3	73.7
TY29-2	8.08	103.40	1.03	-0.28	1.95	7.2	17.4	233.6	65.5
TY30-2	9.01	86.90	1.05	0.01	2.59	25.4	31.3	220.7	57.7
TY31-2	6.93	99.50	1.03	-0.01	1.74	27.6	22	205.4	68
Mean	6.26	92.08	1.04	0.03	1.73	-	-	-	-
Stdev (σ)	2.01	18.77	0.01	0.33	0.55	-	-	-	-

Note All magnetic parameters are measured for these samples. For other 32 samples (data not shown), magnetic parameters except the NRM were measured.

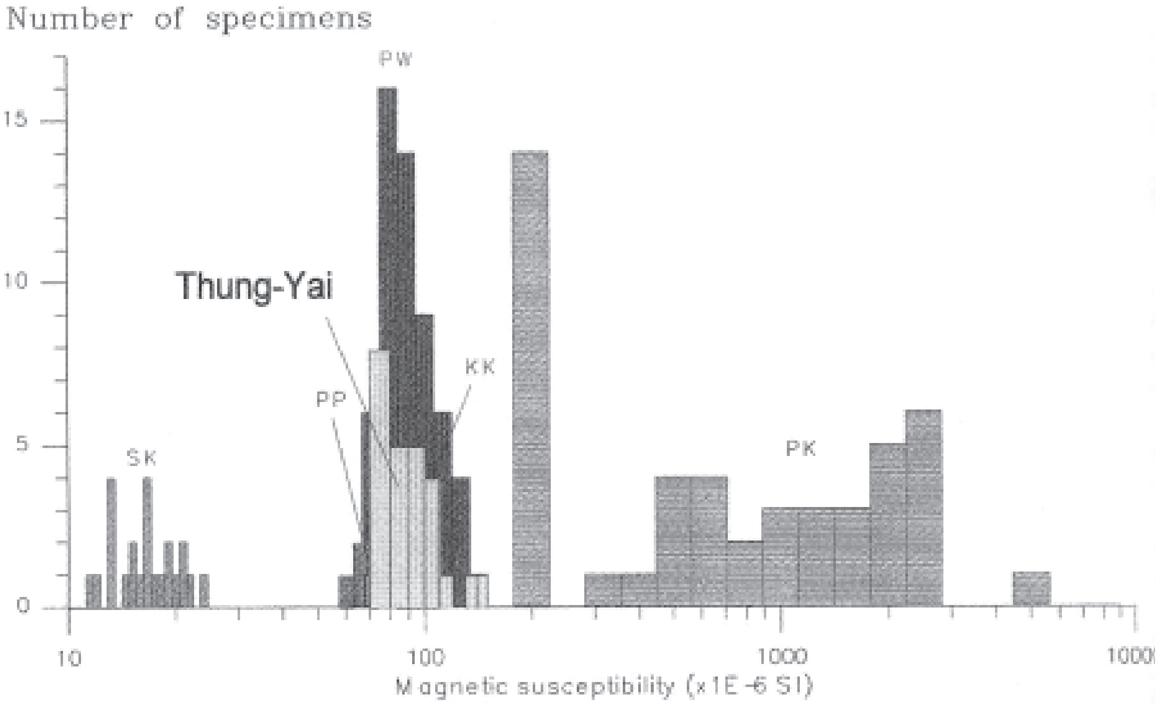

Fig. 2 The distribution of magnetic susceptibility of rock samples from the Thung-Yai redbed comparing with that of the Khorat redbeds. Abbreviations include PK: Phu Kradung, PW: Phra Wihan, SK: Sao Khua, PP: Phu Phan, KK: Khon Kruat formations. Khorat data are from Bhongsuwan and Elming.[5]

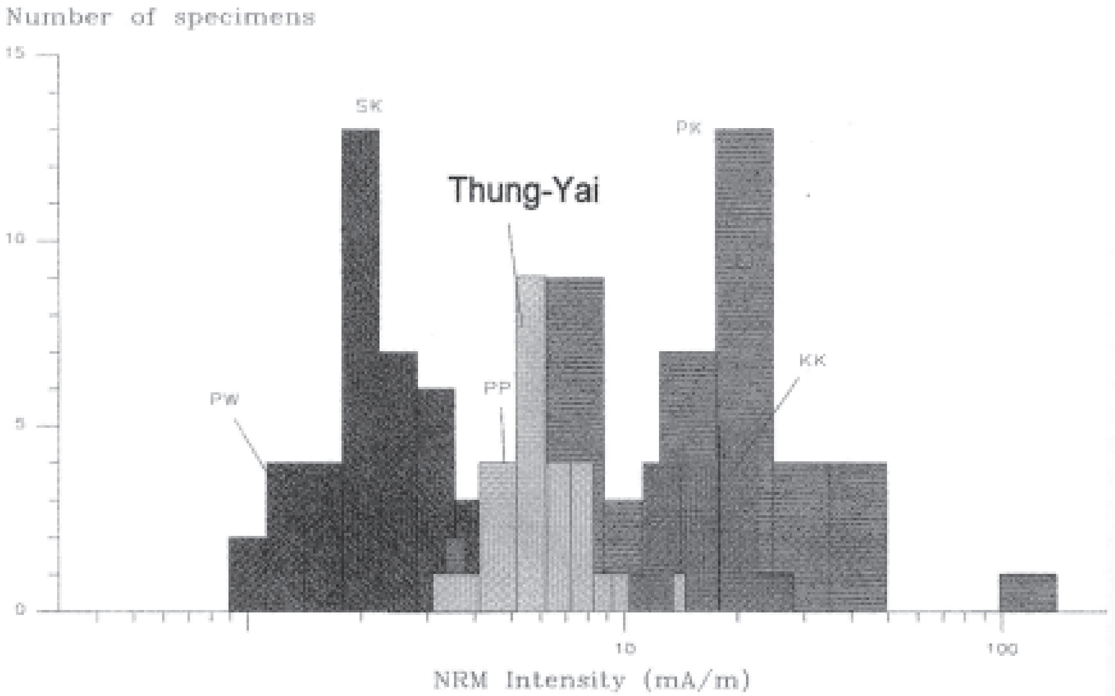

Fig. 3 The distribution of the NRM intensities of rock samples from the Thung-Yai redbed comparing with that of the Khorat redbeds. Abbreviation note sees Fig 2. Khorat data are from Bhongsuwan and Elming.[5]

(**Note** Q - value = $\frac{NRM}{40000k}$ where NRM is measured in unit of mA/m and k in SI: Q-value is used as a measure of the stability of NRM preserved in the rock. The Q-value is a function of type of magnetic mineral, grain size, and shape of magnetic domain)

Anisotropy of magnetic susceptibility

The Pj-T curve (Fig. 5) shows the Pj of the Thung-Yai redbed ranged between 1.01 and 1.07 with a mean of 1.04 (N = 57) or anisotropy degree of 1-7 %, which is relatively low. The T factor is between – 0.53 and + 0.78 (mean 0.06, N=57). Twenty-four specimens show their T less than zero (T < 0; prolate shape) while the T factor of 33 specimens is bigger than zero (T > 0; oblate shape). This indicates an oblate ellipsoid that is slightly different from a sphere. Low Pj of the Thung-Yai redbed indicates an absence of high Pj mineral such as pyrrhotite (FeS_{1+X}). In term of tectonic history of the Thung-Yai redbed, no structural deformation signs are observed at the rock exposure. As no high Pj minerals presented in the Thung-Yai redbed, so a low Pj of these samples probably indicates no tectonic deformation in the Thung-Yai redbed. The only gravitational force and hydrodynamics of water current may affect the Thung-Yai redbed during sedimentation resulted in a low Pj. The Pj of less than 10% was observed in the Khorat redbeds.[5]

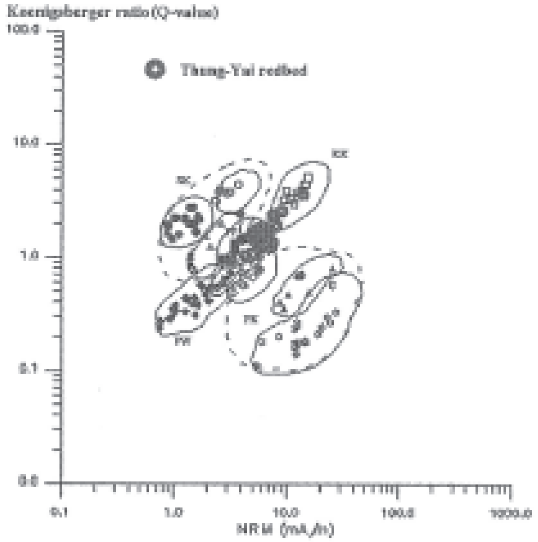

Fig 4. The distribution of the NRM intensities and the Köenigsberger ratio of rock samples from the Thung-Yai redbed comparing with those of the Khorat redbeds. Abbreviation note sees Fig 2. Khorat data are from Bhongsuwan and Elming.[5]

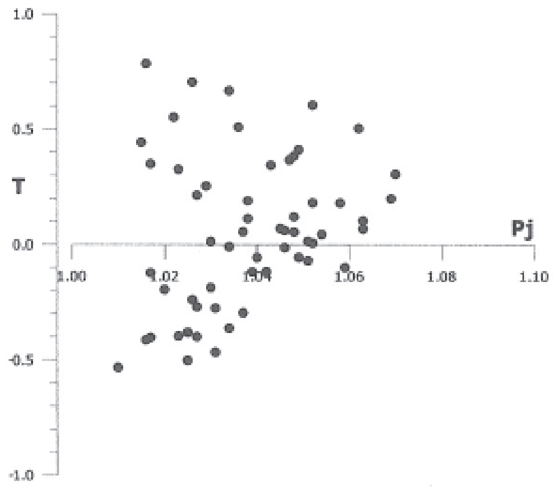

Fig 5. The anisotropy parameters Pj – T plot of rock samples from the Thung-Yai redbed.

(**Note** Strong stress field causes a structural deformation in rock. This stress affects the AMS parameter Pj of rock, see for example, the work of Tarling and Hrouda[11] and the work of Aubourg.[12])

Directional susceptibility

Orientation of the principal axes of susceptibility ellipsoid is present in a stereographic projection (Fig. 6), which shows a scatter of the principal axes, including K_1 (or K_{max}), K_2 (or K_{int}), and K_3 (or K_{min}) on a spherical surface. Analysis of the distribution of the principal axes shows that each of them is well grouped, while K_1 and K_2 form a girdle distribution and susceptibility ellipsoid significantly shows an oblate. This behavior has normally been found in an undeformed sedimentary rock.[11] Imbrication of mineral grains which is a result of water current during sedimentation, can modify the orientation of the principal axes.[11] For example, the K_3 axes are directed parallel to the bedding pole in an undeformed sedimentary rocks and no imbrication of mineral grains is observed in a weak current sedimentation.[11] However, orientation of the principal axes of the Thung-Yai redbed after bedding correction (Fig. 6b) shows that the K_3 axes are not coincident with the vertical axis indicating an imbrication of mineral grains towards the water current in a strong current environment. Imbrication toward the west of the Thung-Yai redbed probably indicates E-W palaeo-current direction (Fig. 6b). In the Khorat redbed, previous studies of some geological and geographical indicators, and grains orientation analysed by the Intercept method showed the E-W palaeo-current direction.[5, 38-40]

Susceptibility variation with temperatures during thermal demagnetization

A great change of susceptibility value observed during thermal demagnetization of a rock specimen usually indicates the chemical changes at a specific temperature. This behavior indicates a new magnetic mineral formed from a ferromagnetic or paramagnetic mineral formerly presented. Goethite (α-FeOOH), pyrrhotite (FeS_{1+x} : $0.10 < x < 0.14$) or pyrite (FeS_2) are known to be unstable at a high temperature range 120 – 450 °C.[2-4] Monitoring of susceptibility during heating is necessary to indicate such chemical changes. Natural remanent magnetization can be contaminated by a magnetic moment of newly formed ferromagnetic mineral in the oven. In this study, only a minor change of susceptibility of 24 thermally demagnetized specimens of the Thung-Yai redbed (Fig. 7a) indicates an absence of unstable ferromagnetic or paramagnetic minerals. This indicates that no chemical change has occurred in the Thung-Yai redbed during thermal demagnetization of rock specimens. A similar behavior was observed

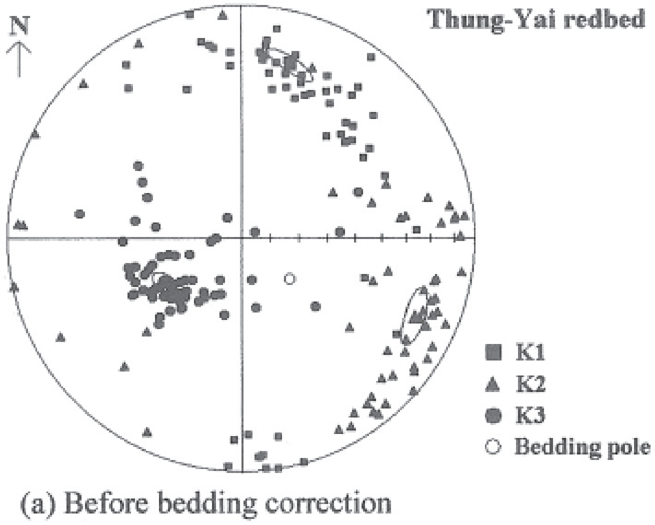

Fig 6. Stereographic projections of the principal susceptibility axes of all 57 rock specimens from the Thung-Yai redbed. (a) before and (b) after bedding correction. Symbols used include ■ (K_1 or K_{max} axis), ▲ (K_2 or K_{int} axis) and ● (K_3 or K_{min} axis). The mean axes are marked with larger symbols encircled with the 95% confidence ovals. Open circle indicates the bedding pole.

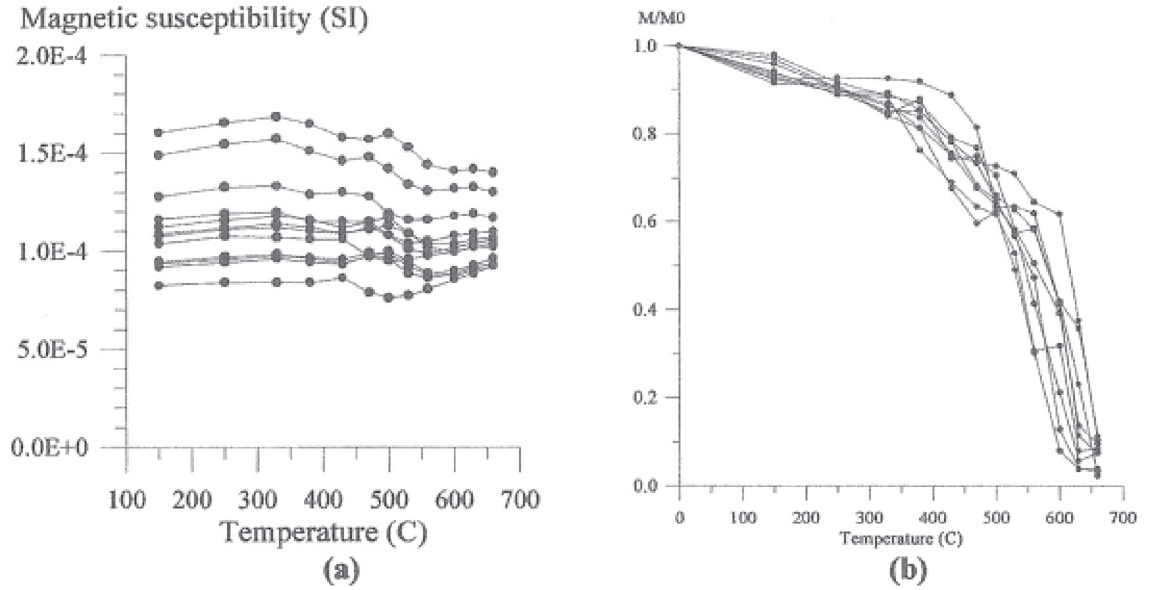

Fig 7. Thermal demagnetization results: (a) Variation of the magnetic susceptibility of some 12 rock samples of the Thung-Yai redbed during thermal demagnetization, (b) The decay plots of the remanence intensity of some typical samples of the Thung-Yai redbed during thermal demagnetization.

during thermal demagnetization of specimens from the Khorat redbed as well.[5]

Decay of remanent magnetization during thermal demagnetization

Decay of remanence at each temperature step indicates unblocking temperature of magnetic domain preserving the remanence. At any unblocking temperature some magnetic domains will be unblocked and then randomly oriented in a zero field in the thermal demagnetizer. The maximum unblocking temperature of the remanence is close to the Curie temperature of the remanence carrying mineral in the rock specimen. Fig. 7b shows a decay curve of remanence in the specimens of the Thung-Yai redbed. Some 40 % of remanence are erased at temperatures < 500 °C. Some 40 % of specimens lose their remanence completely in temperature 500 - 600 °C indicating that magnetite (T_C = 580 °C) is the remanence carrying mineral in such specimens. Some 60 % of specimens lose their remanence in temperature 600 - 700 °C indicating haematite (T_C = 675 °C) in them. Result shows that magnetite and haematite are present in the Thung-Yai redbed. These minerals are highly stable ferromagnetic minerals normally found in a typical redbed including the Khorat redbed.[5, 19]

Fluorescence X-ray emitted from surface of the Thung-Yai redbed

Ambiguity in identification of magnetic minerals can be easily overcome by examination the rock specimen using fluorescence X-ray imaging to determine the element composition of the rock specimen. In this study, an electron microscope attached with an EDS is used to analyse for some key elements of magnetic minerals, ie, iron, titanium and sulfur. Fluorescence X-ray emitted from the surface of a representative specimen at a 300X magnification is shown in Fig. 8. X-ray image shows the presence of O, Si, Na, Mg, Al, K, Ca, Fe and S. Si and O are present in the same grain indicating quartz grain (SiO_2). The other elements are found in matrix and cementing material. K, Mg, Al and Si are present in the same area indicating micas, ie, biotite (K (Mg, Fe)$_3$ (Al Si_3O_{10})$(OH)_2$) and muscovite (K Al_2 (Al Si_3O_{10}) $(OH)_2$). Micas are found in the Thung-Yai redbed and also present in the Khorat redbed of Indochina block.[5] Iron and oxygen are found in the same area indicating iron oxides, ie, magnetite and/or haematite. Though titanium and sulfur are present but in a very small amount and no relation with iron, which is not representing titanomagnetites or iron sulfides.

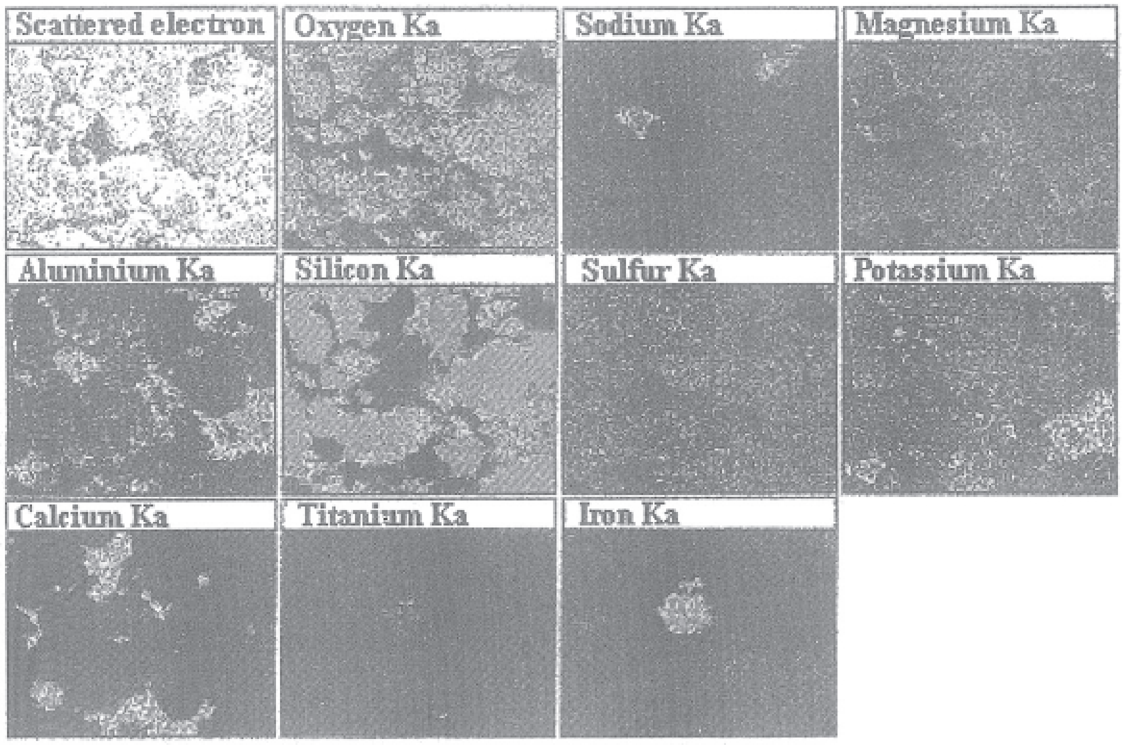

Fig 8. The scattered electron image and the fluorescent X-ray images emitted from key elements composed in a polished specimen from the Thung-Yai redbed.

Magnetic minerals in the Thung-Yai redbed

Magnetic examinations of the Thung-Yai redbed indicate no high anisotropy minerals presented as the rock carries a low Pj. X-ray imaging shows that iron sulfides are almost absent in the Thung-Yai redbed. Analyses of the thermal decay curve of the remanent magnetization to determine the Curie temperature thus indicate both magnetite (T_C = 580 °C) and haematite (T_C = 675 °C) as the remanence carrying minerals. Source of magnetite and haematite in the Thung-Yai redbed is most probably a result of alteration of micas during sedimentation of the rock.

It can be concluded that magnetic characteristics of the Thung-Yai redbed may indicate a fresh water sedimentation environment that is similar to what have been known for the Khorat redbed.[16]

Palaeomagnetism of the Thung-Yai redbed and preliminary palaeomagnetic analysis

Magnetite and haematite are commonly known to be the best magnetic recording minerals in rocks, which can preserve the direction of the past geomagnetic field since the time of rock formation. These minerals are presented as the main remanence carrying minerals in the Thung-Yai redbed of southern Thailand of the Shan-Thai block and also in the Khorat redbed of Indochina block as well.[5, 19] Bhongsuwan and Elming reported the positive fold tests at 95% confidence level in the Middle Jurassic and Upper Jurassic Khorat redbed indicating a primary origin of the remanent magnetization resided in the Khorat rock.[5]

Fig. 9 shows the orthogonal, stereographic and decay plots of the intensity and direction of remanent magnetization during thermal treatment of 3 typical specimens. Generally the remanence is stable up to 600 °C with nearly constant direction. Declinations are in range 30 - 60° and inclinations range from 20 to 30°. The most stable component of remanence is derived from a temperature range 530 – 630 °C. Table 2 shows the mean direction and statistical parameters of the high temperature principal component. Fig. 10 shows individual directions and the mean direction derived from 23 out of 24 thermally demagnetized specimens.

Although palaeomagnetic result is derived from a single site as no other exposures of this redbed are found elsewhere in the vicinity of the sampling site. However, 23 specimens are big enough number of sample for a time-averaged palaeomagnetic direction at the site. Especially, the magnetic characteristics of the Thung-Yai redbed are similar to those of the Khorat redbed, which a positive fold test has been proven.[5, 19] The characteristic magnetization carried by the stable magnetic minerals, magnetite and haematite, preserved in the Thung-Yai redbed is most probable a primary origin as well, that is, preserving the palaeomagnetic direction of the Upper Jurassic – Lower Cretaceous, which is the age of the Thung-Yai redbed. The palaeomagnetic pole derived from the Thung-Yai redbed is present in Table 3 in comparison with the poles from the Khorat redbed of the same age.[5, 19]

Comparing the pole derived from the Thung-Yai redbed with those derived from the Khorat redbed of the same age shows that the pole of the Thung-Yai redbed overlaps well with the Khorat poles especially with the pole from the Phu Phan Formation aged Lower Cretaceous (Fig. 11).[5] However, poles of the Khorat redbeds aged Middle Jurassic - Lower Cretaceous are not much different in their position.[5, 19]

Vertical axis rotation and poleward transport between the parent blocks of the redbeds

Palaeomagnetic poles derived from the same aged rocks collected in a block or in attached blocks must be at the same position. The palaeopoles derived from the same aged rocks collected from different blocks will be at the same position if those blocks have no relative motion with each other since the time of rock formation. A standard palaeomagnetic analysis in terms of vertical axis rotation and poleward transport is the most interesting method to determine a relative motion between the two blocks in question. In this study, palaeomagnetic result is derived from the Thung-Yai redbed of southern Thailand, so the block in comparison is the Shan-Thai block, which is the parent block of southern Thailand. The second block is Indochina, which is the reference block in comparison and is the parent block of the Khorat redbed. Age of the Khorat redbed overlaps with that of the Thung-Yai redbed.

Relative motion between the Indochina block, the parent plate of the Khorat redbed, and the Thung-Yai redbed of Southern Thailand, is determined by calculating the angular distances between the sampling location and the poles derived from both the Thung-Yai redbed and the Khorat redbed. The rotation angle (R) about the vertical axis is calculated using the formula.[1]

$$R = \cos^{-1}\left(\frac{\cos S - \cos P_o \cos P_r}{\sin P_o \sin P_r}\right)$$

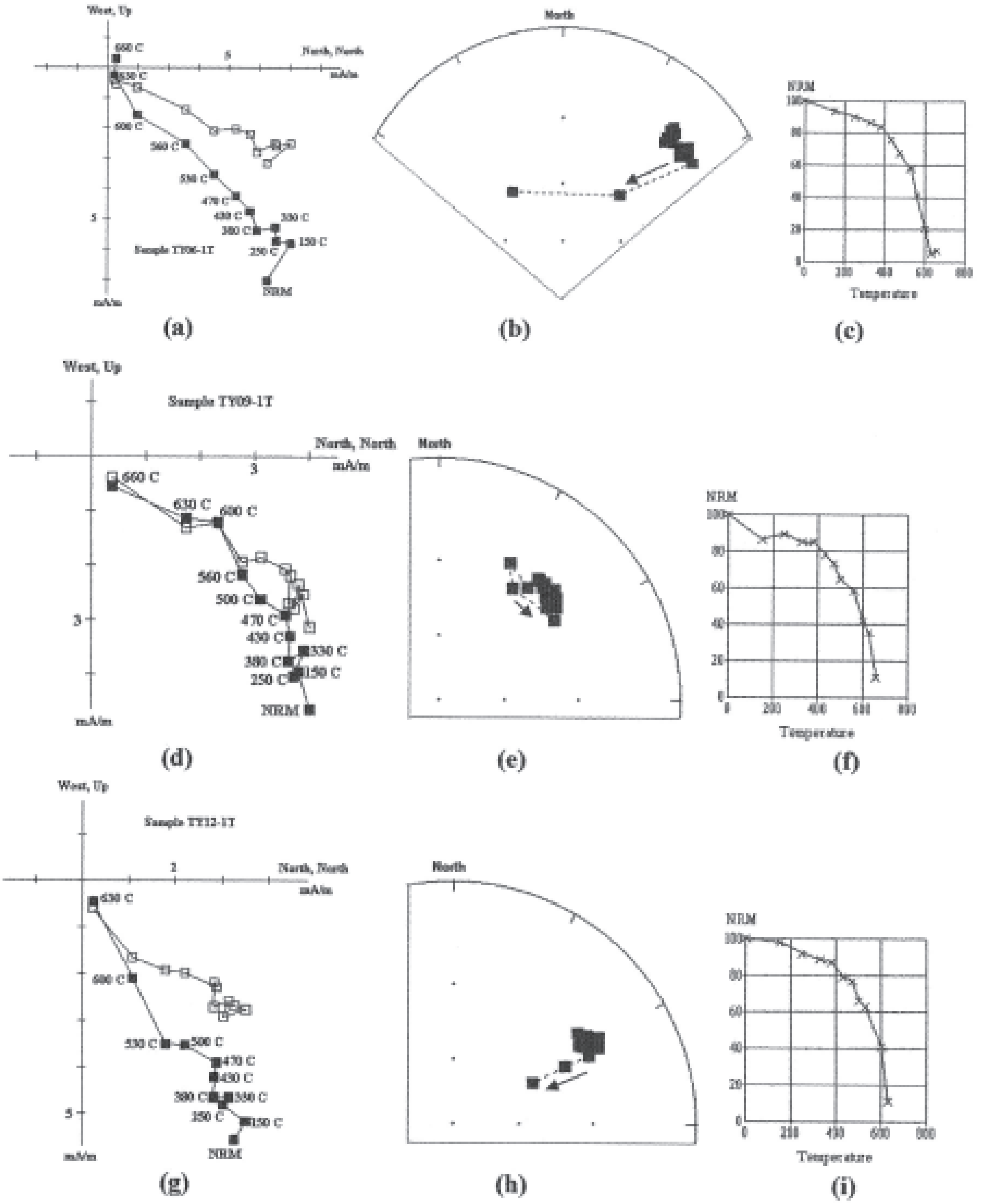

Fig 9. The orthogonal plots, stereographic projections and decays of remanence intensity of typical samples under thermal demagnetization of the Thung-Yai redbed, (a) (b) (c) sample TY06-1T, (d) (e) (f) sample TY09-1T, (g) (h) (i) sample TY12-1T.

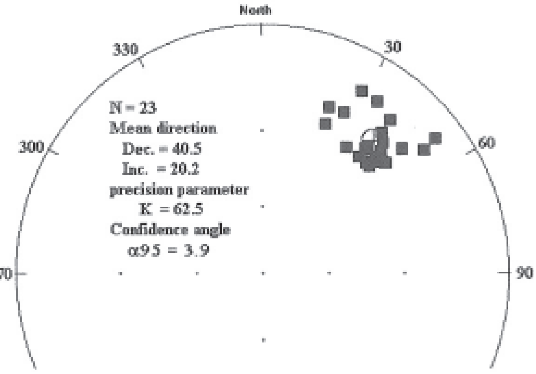

Fig 10. Stereographic projection of the directions of the high temperature component magnetization from 23 samples of the Thung-Yai redbed. These data are used to calculate the mean direction. The mean direction is marked by a cross and surrounded by a 95% confidence circle.

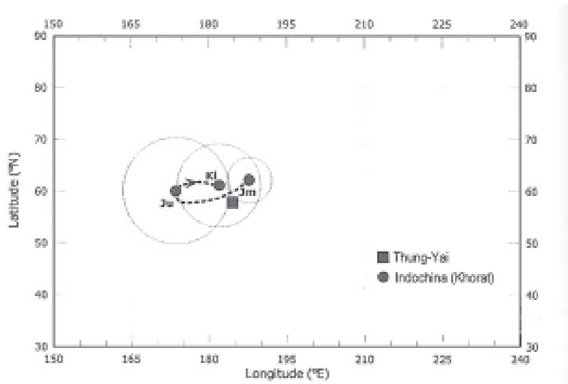

Fig 11. Palaeo-pole derived from the Thung-Yai redbed is plotted in relation with the apparent polar wander path and pole positions with 95% confidence circles of the Khorat redbeds.[5] Abbreviations include Jm : Middle Jurassic, Ju : Upper Jurassic, Kl : Lower Cretaceous.

Table 2. Mean direction of the high temperature component of magnetization derived from 23 samples of the Thung-Yai redbed before and after bedding correction.

			Mean direction					
	Bedding		Before bedding corr		After bedding corr			
Component	(strike/dip)	N/n	Dec	Inc	Dec	Inc	K	α_{95}
High temp	220°/22°	23/24	40.5°	20.2°	32.6°	18.8°	62.5	3.9°

Note n = number of samples thermally demagnetized
N = number of samples used to calculate the mean direction
K = the precision parameter of the Fisher's statistic
α_{95} = 95% confidence angle about the mean direction.

Table 3. The palaeopole position of the Upper Jurassic – Lower Cretaceous derived from the Thung-Yai redbed in comparison with the palaeopoles derived from the Khorat redbeds.

Age of Rock	Rock formation/ Site Location	Bedding-corrected Direction					Pole position		
		N/n	Dec	Inc	K	α_{95}	Plat	Plon	A_{95}
	Thung-Yai redbed								
JK_1 ♣	8.38 °N/99.42 °E	1/23	32.6°	18.8°	62.5	3.9°	57.8°	184.6°	-
	Khorat redbeds								
Jm ♦	Phu Kradung and F. Phra Wihan	11/65	30.3°	27.6°	97.5	4.6°	60.7°	187.4°	4.0°
Ju ♦	Sao Khua F.	5/37	30.4°	45.1°	59.1	10.0°	59.9°	173.7°	10.5°
Kl ♦	Phu Phan & Khok Kruat F.	3/29	30.2°	36.1°	108	11.9°	61.1°	182.1°	8.1°
Jm-Kl ♦	Mean for Khorat redbeds (3 poles)	19/131	-	-	-	-	60.7°	181.0°	5.3°
JK_1 ♥	Khorat redbeds	20/161	27.3°	38.9°	328	1.8°	63.8°	175.6°	1.7°

Note JK_1 = Upper Jurassic – Lower Cretaceous, Jm = Middle Jurassic, Ju = Upper Jurassic, Kl = Lower Cretaceous
N = Number of sites, n = number of samples
Plat = pole latitude; Plon = pole longitude
A_{95} = 95% confidence angle about the mean pole. A_{95} is calculated from >2 poles. A single pole is derived from the Thung-Yai redbed so that the A_{95} in this case is not provided.
♣ this study, ♦ data from Bhongsuwan and Elming[5], ♥ data from Yang and Besse[19]

Where P_0 is the angular distance between the observed pole and the sampling site
P_r is the angular distance between the reference pole and the sampling site
S is the angular distance between the observed pole and the reference pole

Reference pole, observed pole and sampling site are shown in Fig 12. Result shows that observed pole (the Thung-Yai redbed's pole) is not significantly different from the reference pole (the Khorat redbed's pole). The (P_0-P_r) is only 1.8° ± 4.8° while the rotation angle R is 3° ± 4.9°. This indicates no significant relative movement between Indochina block and Southern Thailand since the Jurassic-Cretaceous. This result is consistent with that of the previous work of Bhongsuwan and Elming who reported that Western Thailand including Southern Thailand (parts of the Shan-Thai block) and the Khorat plateau or Indochina block have a small relative movement (P_0-P_r = 2.6°) since the Upper Triassic-Lower Jurassic.[13]

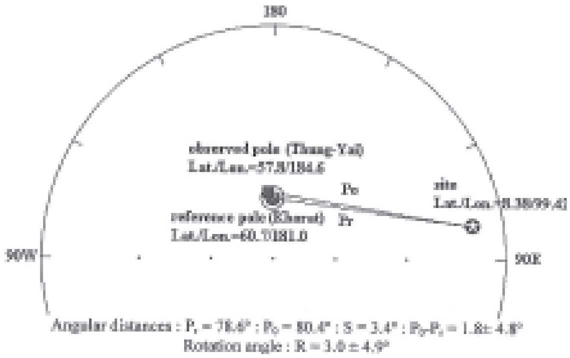

Fig 12. Poleward transport and the vertical axis rotation. The data was derived from the Thung-Yai pole (■) with reference to the Khorat mean pole (●). Sampling site (✪) is also shown.

Conclusions

Magnetic characteristics of the Thung-Yai redbed are very similar to those of the Khorat redbed though they are on the different blocks and very far away from each other (>1000 km). Magnetic susceptibility, NRM and the Köenigsberger ratio of the specimens from the Thung-Yai redbed well group close to those of the Phu Phan Formation (part of the Khorat redbed) of the lower Cretaceous age. Low degree of anisotropy of the Thung-Yai redbed probably indicates no tectonic deformation in the rock (undeformed) since the time of rock formation. Distribution of the principal axes of susceptibility indicates an oblate ellipsoid of susceptibility similar to what have been found generally in sedimentary rocks. The minimum axes imbricate toward the west probably representing the strong E-W palaeocurrent direction during sedimentation of the Thung-Yai redbed. X-ray fluorescence imaging supports the presence of iron oxides magnetite and haematite in the Thung-Yai redbed similar to those found in the Khorat redbed. These minerals probably indicate a non-marine environment during sedimentation of the Thung-Yai redbed similar to the sedimentation environment of the Khorat redbed. The mean declination and inclination of the characteristic magnetization direction of the Thung-Yai redbed is at 32.6°/18.8°, and the palaeomagnetic pole is derived at Plat/Plon = 57.8°N/184.6°E, which almost completely overlaps with the Khorat pole (Plat/Plon = 60.7°N/181.0°E). Tectonic analysis in term of relative motion between the two plates shows that the southern Thailand (part of the Shan-Thai block) and the Khorat plateau (part of the Indochina block) have no relative movement between each other since the Upper Jurassic-Lower Cretaceous.

Acknowledgements

The authors wish to express their gratitude and thanks to the IPPS, Uppsala University, Sweden, for supporting the rock magnetic instrumentation to the department of Physics, Faculty of Science, and thanks to the Physics department and the Faculty of Science for partly financial support to the project.

References

1. Butler RF (1992) *Palaeomagnetism*. Blackwell Scientific, Cambridge, 319 pp.
2. Tarling DH (1983) *Palaeomagnetism*. Chapman and Hall, London, 379 pp.
3. Suk D Peacor DR and Van Der Voo R (1990) Replacement of pyrite framboids by magnetite in limestone and implications for palaeomagnetism. *Nature* **345**, 611-3.
4. Bina M and Daly L (1994) Mineralogical change and self-reversed magnetizations in pyrrhotite resulting from partial oxidation; geophysical implications. *Phys Earth Planet Inter* **85**, 83-99.
5. Bhongsuwan T and Elming S-Å (2000a) Rock magnetic and palaeomagnetic study of rocks from the Khorat Group in northeastern Thailand. In *Research in Rock Magnetism and Palaeomagnetism of Recent Sediments and Palaeozoic to Tertiary Rocks in Thailand,* by Bhongsuwan T, PhD thesis, Division of Applied Geophysics, Luleå University of Technology, Luleå, Sweden.
6. Özdemir Ö and Dunlop DJ (2000) Intermediate magnetite formation during dehydration of goethite. *Earth and Planet Sci Lett* **177**, 59-67.
7. Riller U Cruden AR and Schwerdthen WM (1996) Magnetic fabric and microstructural evidence for a tectono-thermal overprint of the early Proterozoic Murray pluton, central Ontario, Canada. *J Structural Geology* **18**, 1005-16.

8. Grégoire V Darrozes J Gaillot P and Nédélec A (1998) Magnetite grain shape fabric and distribution anisotropy vs rock magnetic fabric : a three-dimensional case study. *J Structural Geology* **20**, 937-44.
9. Kissel C Laj C Mazaud A and Dokken T (1998) Magnetic anisotropy and environmental changes in two sedimentary cores from the Norwegian Sea and the North Atlantic, *Earth and Planet Sci Lett* **164**, 617-26.
10. Tistlewood L and Sun J (1991) A palaeomagnetic and mineral magnetic study of the loess sequence at Liujiapo, Xian, China. *J Quaternary Science* **6**, 13-26.
11. Tarling DH and Hrouda F (1993) *The Magnetic Anisotropy of Rocks*. Chapman and Hall, London, 217 pp.
12. Aubourg C Rocheete P and Bergmüller F (1995) Composite magnetic fabric in weakly deformed black shales. *Phys Earth Planet Inter* **87**, 267-78.
13. Bhongsuwan T and Elming S-Å (2000b) Rock magnetic and palaeomagnetic investigation of rocks in northern and southern Thailand. In *Research in Rock Magnetism and Palaeomagnetism of Recent Sediments and Palaeozoic to Tertiary Rocks in Thailand,* by Bhongsuwan T, PhD thesis, Division of Applied Geophysics, Luleå University of Technology, Luleå, Sweden.
14. Bhongsuwan T (1993) *Palaeomagnetic investigations in Thailand*. Licentiate Thesis, Division of Applied Geophysics, Luleå University of Technology, Luleå, Sweden, 128 p.
15. Barr SM and McDonald AS (1979) Paleomagnetism, age and geochemistry of the Denchai basalts, northern Thailand. *Earth Planet Sci Lett* **46**, 113-24.
16. Bunopas S (1981) *Paleogeographic history of western Thailand and adjacent parts of Southeast Asia: a plate tectonics interpretation*. Ph D Thesis, Victoria Univ Wellington, New Zealand, (reprinted as Geol Surv Paper No 5, DMR, Bangkok).
17. Achache J and Courtillot V (1985) A preliminary Upper Triassic paleomagnetic pole for the Khorat plateau (Thailand): consequences for the accretion of the Indochina against Eurasia. *Earth Planet Sci Lett* **73**, 147-57.
18. Maranate S and Vella P (1986) Paleomagnetism of the Khorat Group, Mesozoic, Northeast Thailand. *J Southeast Asian Earth Sci* **1**, 23-31.
19. Yang Z and Besse J (1993) Paleomagnetic study of Permian and Mesozoic sedimentary rocks from Northern Thailand supports the extrusion model for Indochina. *Earth Planet Sci Lett* **117**, 525-52.
20. Mitchell AHG (1981) Phanerozoic plate boundary in mainland SE Asia, the Himalayas, and Tibet. *J Geol Soc London* **138**, 109-22.
21. Piyasin S (1991) Tectonics events and radiometric dating of the basement rocks of Phitsanulok Basin. *J of Thai Geosciences* **1**, 41- 8.
22. Fontaine H (1986) The Permian of Southeast Asia. *CCOP Technical Bulletin* 18, 111 pp.
23. Waterhouse JB (1982) An early Permian cool-water faunas from pebbly mudstones in south Thailand. *Geol Magazine* **119**, 337-54.
24. Metcalfe I (1989) Triassic sedimentation in the central basin of peninsular Malaysia. In Thanasuthipitak T and Onchanum P (eds) *Proceedings of the international symposium on inter-montane basins, geology and resources*. Chiang Mai University, Department of Geological Sciences, Thailand. 173-86.
25. Chaodumrong P (1992) *Stratigraphy, sedimentology and tectonic implications of Lampang group, central north Thailand*. Unpublished PhD thesis, University of Tasmania, 230 p.
26. Cobbling EJ Mallick DIJ Pitfield PEJ and Teoh LH (1986) The granites of the South-East Asian tin belt. *J Geol Soc London* **143**, 537-550.
27. Department of Mineral Resource (1999) *Geological Map of Thailand, Scale 1: 2,500,000*. Geological Survey Division, DMR, Bangkok.
28. Torsvik TH (1986) *IAPD - Interactive analysis of palaeomagnetic data (User guide and program description)*. Institute of Geophysics, University of Burgen, Norway, 74 pp.
29. Torsvik TH Briden JC and Smethurst MA (1996) *Super IAPD program*. Geological Survey of Norway.
30. Fisher RA (1953) Dispersion on a sphere. *Proc R Soc London, Ser A* **217**, 295-305.
31. Jelinek V (1981) Characterization of the magnetic fabric of rocks. *Tectonophysics* **79**, 63-7.
32. Collinson DW (1983) *Methods in Rock Magnetism and Palaeomagnetism*. Chapman and Hall, London, 503 pp.
33. King RF (1966) The magnetic fabric of some Irish granites. *J Geol* **5**, 43-66.
34. Birch FS (1979) Magnetic fabric of the Exeter Pluton, New Hampshire. *J Geophys Res* **84**, 1129-37.
35. Knight MD and Walker GPL (1988) Magma flow directions in dykes of the Koolau Complex, Oahu, determined from magnetic fabric studies. *J Geophys Res* **93**, 4301-19.
36. Bates MP and Mushayandebvu MF (1995) Magnetic fabric in the Umvimeela Dyke, satellite of the Great Dyke, Zimbabwe. *Tectonophysics* **242**, 241-54.
37. Raposo MIB (1997) Magnetic fabric and its significance in the Florianopolis dyke swarm, southern Brazil. *Geophys J Int* **131**, 159-70.
38. Launeau P and Robin PYF (1996) Fabric analysis using the intercept method. *Tectonophysics* **267**, 91-119.
39. Heggemann H Helmcke D and Tietze K-W (1994) Sedimentary evolution of the Mesozoic Khorat Basin in Thailand. *Zbl Geol Paleont Teil I* 1992 (11/12), 1267-85.
40. Drumm A Heggemann H and Helmcke D (1993) Contribution to the sedimentology and sedimentary petrology of the non-marine Mesozoic sediments in northern Thailand (Phrae and Nan provinces). *Proc Int symp Biostratigraphy of Mainland Southeast Asia : Facies and Paleontology*, Chiang Mai, 31 Jan - 5 Feb 1993, 299-318.
41. Enkin RJ Chen Y Courtillot V Besse J Xing L Zhang Z Zhuang Z and Zhang J (1991) A Lower Cretaceous pole from South China and the Mesozoic hairpin turn of the Eurasian apparent polar wander path. *J Geophys Res* **96**, 4007-28.