Magnetic Anisotropy of Basalt from Twenty-Seven Locations in Thailand

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Abstract

Magnetic properties of Cenozoic basalt samples from 27 locations in Thailand were investigated. These samples were from basalt exposures in Denchai, Wichianburi, Bo ploi, Nakhon Ratchasima, Burirum, Surin, and Sisaket-Ubon Ratchathani. The analysis of the samples' magnetic susceptibility anisotropy suggests that the shape of the ellipsoid is prolate for alkali olivine and nepheline type basalt and oblate for Hawaiite type basalt. The thermomagnetic and temperature dependence of the susceptibility indicate that titanomagnetite is the magnetic phase for the alkali olivine and nepheline type basalt and magnetite for the Hawaiite type basalt. Alkali olivine and nepheline type basalt are corundum-bearing basalt.

KEYWORDS: Magnetic susceptibility anisotropy, thermomagnetic, Thailand basalt.

INTRODUCTION

For certain rock types, magnetic susceptibility anisotropy can be a fast and non-destructive way to investigate rock fabrics. The required cylindrical samples can be drilled in the field and need little further preparation in the laboratory. The laboratory measurement of the magnetic susceptibility anisotropy is fast and easily done. For this reason, this method has been widely used to determine quantitatively three-dimensional petrofabrics (Tarling and Hrouda, 1993; Gil and others, 2002; Irene and others, 2007; Aubourg and others, 2008). The method's principle relies on the magnetic properties of rocks that reflect the magnetic fabric of a geological material due to a preferred alignment of anisotropic magnetic minerals. The magnetic susceptibility anisotropy of rocks depends on the intrinsic anisotropy of individual grains, grain shape, grain preferred orientation, and grain distribution (Callot and others, 2001; Sheng Gao Lu and others, 2007). Although magnetic susceptibility anisotropy can arise from a variety of causes, in titanomagnetite-bearing rocks it is mainly related to shape anisotropy, which reflects the statistical alignment of elongated or planar magnetic grains within a rock. The magnetic susceptibility anisotropy is a second-rank tensor ellipsoid given by the length and orientation of the three principal susceptibility axes, k_1, k_2, and k_3, these being maximum, intermediate, and minimum, respectively. In general, k_1 corresponds to the mineral lineation and k_3 is taken as the pole to the foliation.

The intent of this investigation of basaltic rocks is to establish magnetic susceptibility anisotropy and magnetic rock properties as reliable indicators of corundum-bearing basalt.

GEOLOGICAL SETTING

Late Cenozoic basalt in Southeast Asia forms a large continental volcanic province. Exposures in Thailand and western Cambodia are generally small and scattered, whereas those in eastern Cambodia, southern Laos, and Vietnam are larger and more extensive. Late Cenozoic basalt also occurs in Malaysia and southern China.

Late Cenozoic basalt in Thailand has whole rock absolute ages ranging from 24 million years to less than 0.5 million years (Sutthirat and others, 1995). The intra-plate basaltic rock in Southeast Asia erupted in a continental rift environment and may be related to the fracture openings between the Gulf of Thailand and the South China Sea (Barr and James, 1990; Jungyusuk and Khositanont, 1992; Hoke and Campbell, 1995).

The Cenozoic basalt in Thailand has two major groups: corundum-bearing basalt and non-corundum bearing basalt (Vichit, 1992). Most of these Cenozoic alkali basalt rocks have been considered corundum-bearing alkali basalt. These basalt rocks commonly contain a variety of crustal and mantle xenoliths, such as in the basalt in Chantaburi and Trat provinces, the Denchai basalt, the basalt in Ubon Ratchathani and Si Sa Ket provinces, the Wichianburi basalt, and the Bo Ploi basalt. The location, type, and age of these basalt occurrences are summarized in Table1 and in Figure 1.

Table 1. Location, type, and age of Thai basalt (modified from Saminpanya, 2000)

Geographic name	Location	Type	Age (Ma)
Denchai basalt	Den Chai: DC	Transition hawaiite, hawaiite, basanite, basaltic andesite of calc-alkali affnities	5.64 ± 0.28
Wichianburi basalt	Wichian Buri: WB	Alkali olivine basalt, hawaiite	9.08 ± 0.29
Bo Ploi basalt	Bo Ploi: BP	Nepheline hawaiite, basanitoid	3.14 ± 0.17
Nakhon Ratchasima-basalt	Southeast of Nakhon-Ratchasima: NR	Hawaiite	
Burirum basalt	Khao Kradong: BR Phu Pra AngKhan: PPK	Hawaiite Hawaiite	0.92 ± 0.03
Surin basalt	Khao Pha Nom Sawai: SR	Hawaiite	
Si Sa Ket basalt	Phu Fai: PF	Hawaiite	3.28 ± 0.48
Ubon Ratchathani basalt	Ban Nam Khun: NNK Ban Nam Yun: NY	Hawaiite Alkali olivine basalt	3.28 ± 0.48

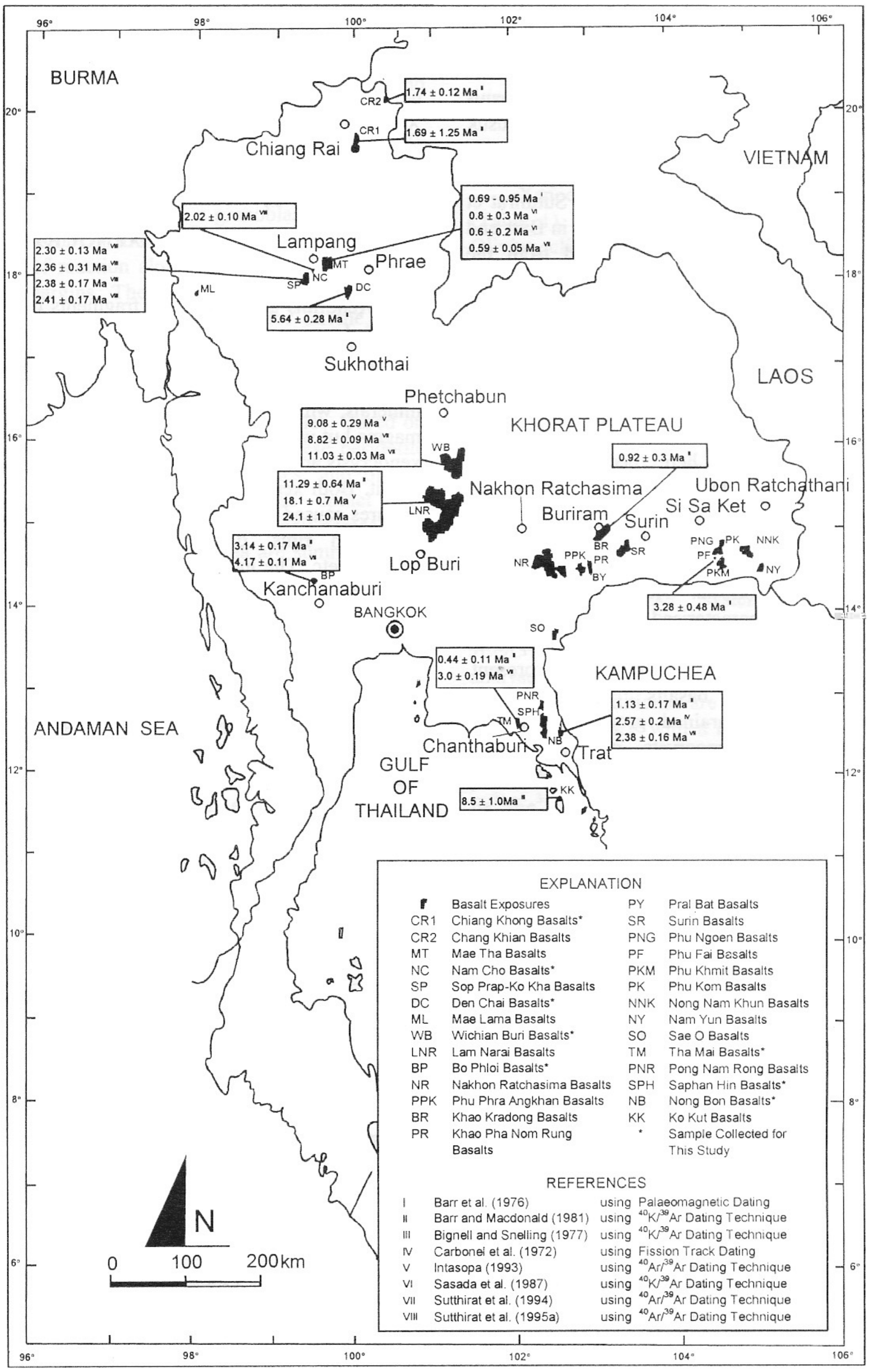


Figure 1. Basalt distribution in Thailand (Jungyusuk and Khoisitanont, 1992).

MAGNETIC MEASUREMENTS

Oriented samples with respect to the geographic reference system were taken using a portable core drill. Magnetic measurements were made on cylindrical specimens 2.5 centimeters in diameter and 2.2 centimeters long that were drilled from core samples from 27 sites in Thailand. Sampling site locations were determined from geographic positioning system observations. The intensity and the direction of the natural remnant magnetism were measured using a spinner magnetometer that had a sensitivity of 2.4×10^{-6} ampere per meter.

The magnetic susceptibility of a specimen at each step of the thermal demagnetization is measured to monitor any thermo-chemical changes of magnetic minerals in the specimen. The principal component directions of the natural remnant magnetism are analyzed based on the principal component analysis using a program called IAPD, which uses a least square fit of vectors in three-dimensional space. Fisher's statistic is used to determine the mean of the component directions and statistical parameters. A 95 percent confidence level is used to explain the scatter of individual direction about the mean. For this investigation, the magnetic susceptibility, magnetic susceptibility anisotropy parameters, and direction of principal axes of susceptibility were measured using a Kappabridge, which has a sensitivity of 1.2×10^{-8} (SI). A program called ANISOFT was used to analyze the magnetic susceptibility anisotropy data, which include the corrected anisotropy degree, Pj, and shape parameter, T.

The magnetic susceptibility can be considered a second-order tensor quantity and is presented in the formula:

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

where $\vec{M}$ is induced magnetization, $\vec{H}$ is external magnetic field, and $\underline{\underline{k}}$ is 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.

The corrected anisotropy degree, Pj, is a parameter used to represent the degree of anisotropy of k, while the shape factor, T, represents the shape of the ellipsoid. Pj and T can be calculated from the following equations:

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

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

where $\eta_1 = \ln K_1$; $\eta_2 = \ln K_2$;$\eta_3 = \ln K_3$ and $\eta_m = \sqrt[3]{\eta_1 \cdot \eta_2 \cdot \eta_3}$

T > 0 represents an oblate or plate-like ellipsoid and

T < 0 shows a prolate or rod-shaped ellipsoid.

RESULTS AND DISCUSSION

The mean susceptibility, k_m, the natural remnant magnetism, and magnetic susceptibility anisotropy parameters of the basaltic rocks are shown in Table 2.

Khorat

The measured magnetic susceptibility values of the samples range from 4088x10^{-6} to 11870x10^{-6} (SI) from sites S1, S2, and S3. A comparison of the k values with specimens from other sites is shown in Figure 2. The natural remnant magnetism intensity values are between 1598.9 and 6848.4 milliampere per meter

The degrees of anisotropy of the samples were 1.013, 1.021, and 1.031 from sites S1, S2, and S3, respectively. The T factors of the samples were 0.227 and 0.454 from sites S1 and S2 and indicate an oblate shape. Site S3 T factor indicates a prolate shape, being -0.195.

Burirum

The measured magnetic susceptibility of the samples was 2579x10^{-6} to 27120x10^{-6} (SI) for sites S4, S5, S11, S12, N9, and N10 (Figure 2). The natural remnant magnetic intensity values varied from 163.5 to 6397.2 milliampere per meter The degrees of anisotropy of the samples were 1.015, 1.046, 1.036, 1.028, 1.018, and 1.019. The T factor values of the samples were 0.345, 0.537, 0.586, 0.234, 0.437, and 0.078, indicating an oblate shape (Figure 3a). The magnetic susceptibility anisotropy ellipsoid of the sample from site S11 indicates an oblate shape, with a northeast direction of the minimum susceptibility axes and with the maximum and intermediate susceptibility axes scattered, or defining a girdle pattern (Figure 4).

Sisaket

The natural remnant magnetism intensity values are 4121.7 to 10487.0 milliampere per meter for sites S6, S7, S8, S9, and S10. The measured magnetic susceptibility of the samples was 2374x10^{-6} to 12580x10^{-6} SI (Figure 2). The degrees of anisotropy of the samples were 1.073, 1.039, 1.038, 1.048, and 1.020. The T factors of the samples from sites S6, S8, and S10 were 0.032, 0.025, and 0.131, indicating an oblate shape. Samples of sites S7 and S9 have prolate shapes (Figure 3d) and their T factors are -0.325 and -0.219. The sample shapes from site S7 indicate a prolate shape, with the maximum susceptibility axes oriented southwest and the intermediate and minimum susceptibility axes are scattered, or define a girdle pattern (Figure 4).

Table 2. Magnetic properties of sampled basaltic rocks.

Site	N	NRM	Mean MSA parameters				
		(mA/m)	K_m (10^{-6})	L	F	P'	T
Khorat : NR							
S1	21	1598.9	10100	1.004	1.008	1.013	0.227
S2	14	1778.2	11870	1.005	1.014	1.021	0.454
S3	19	6848.4	4088	1.021	1.009	1.031	- 0.195
Burirum : BR							
S4	29	222.7	2579	1.005	1.010	1.015	0.345
S5	30	163.5	2922	1.009	1.033	1.046	0.537
S11	23	2752.6	27120	1.007	1.027	1.036	0.586
S12	49	3094.5	13040	1.011	1.015	1.028	0.234
N9	33	3428.1	24620	1.004	1.012	1.018	0.437
N10	37	6397.2	18760	1.008	1.011	1.019	0.078
Sisaket : NY, NK							
S6	40	5077.2	12580	1.035	1.036	1.073	0.032
S7	13	4121.7	10900	1.024	1.014	1.039	- 0.325
S8	35	1897.1	8089	1.017	1.020	1.038	0.025
S9	27	10487.0	6734	1.031	1.015	1.048	- 0.219
S10	23	4138.8	2374	1.008	1.012	1.020	0.131
Denchai : DC							
N1	19	3111.1	20110	1.024	1.026	1.052	0.042
N2	13	1821.2	18650	1.015	1.020	1.036	0.173
N3	19	5372.0	2063	1.006	1.009	1.016	0.148
N4	8	2479.9	3646	1.009	1.005	1.014	- 0.169
N5	22	1136.7	5728	1.005	1.018	1.024	0.452
Wichianburi: WB							
N6	16	3605.1	3850	1.011	1.017	1.029	0.181
N7	37	820.3	20750	1.016	1.019	1.036	0.129
N8	17	633.0	27810	1.029	1.026	1.057	- 0.046
Surin : SR							
N11	36	444.6	29500	1.004	1.016	1.022	0.531

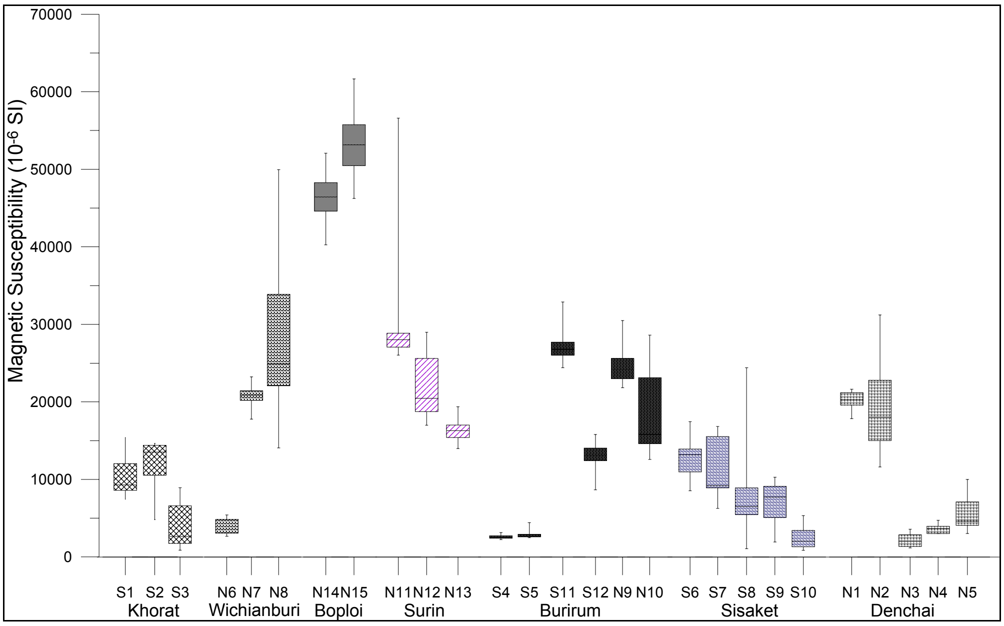
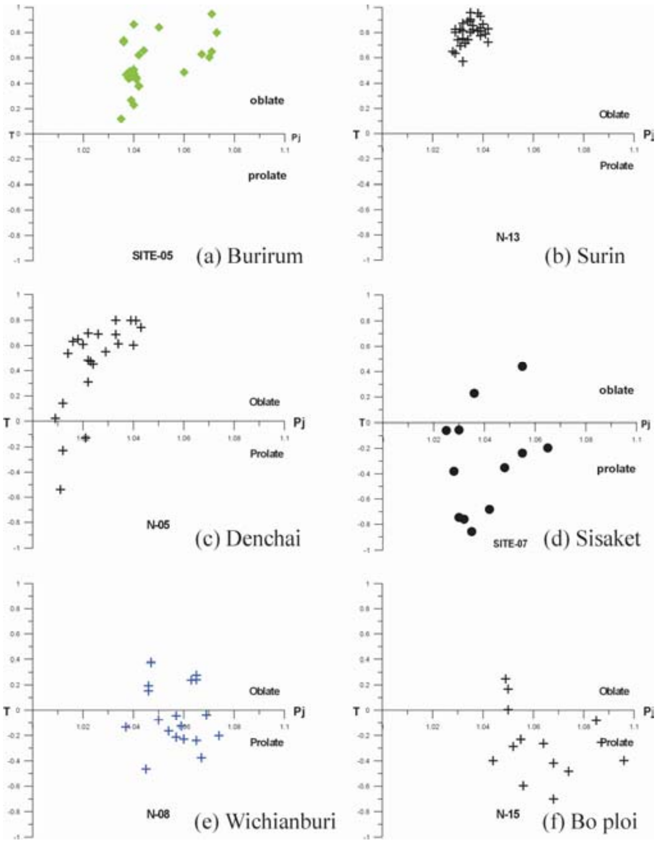


Figure 2. Magnetic susceptibility of basalt rock samples.



(a) Burirum
(b) Surin
(c) Denchai
(d) Sisaket
(e) Wichianburi
(f) Bo ploi

Figure 3. Pj and T anisotropy parameters of rock samples. Values are shown in Table 2.

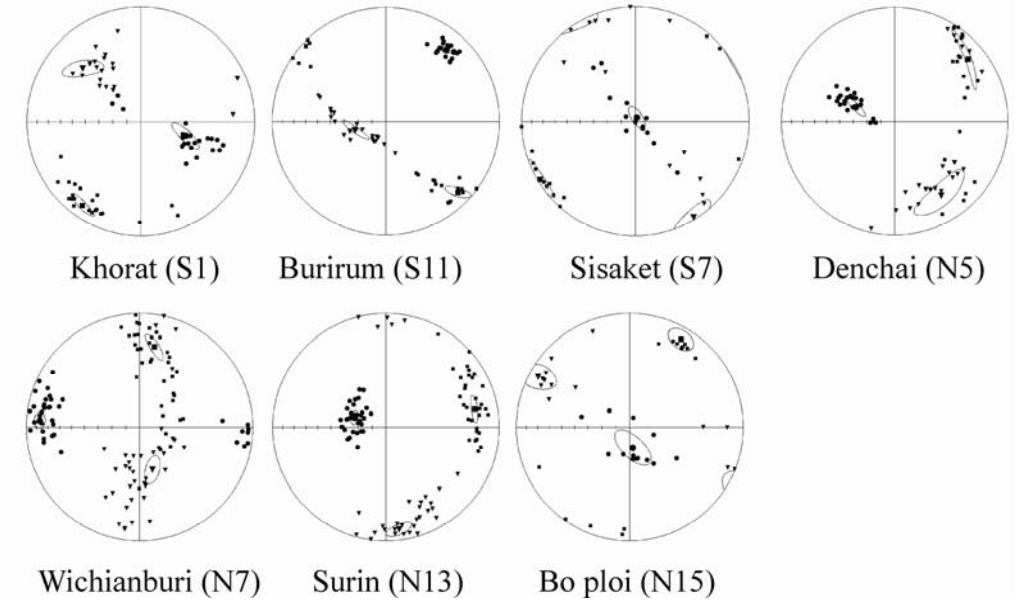


Figure 4. Stereographic projections, lower hemisphere, of the principal susceptibility axes of the basaltic rocks from selected sites. Squares indicate maximum susceptibility direction, triangles indicate intermediate susceptibility direction, circles indicate minimum susceptibility direction. The mean axes are marked with larger symbols encircled with 95 percent confidence ovals.

Denchai

The degrees of anisotropy of the samples were 1.052, 1.036, 1.016, 1.014, and 1.024. The T factors of the samples were 0.042, 0.173, 0.148, and 0.452 from sites N1, N2, N3, and N5 and indicate an oblate shape (Figure 3c). The T factors of the samples from site N4 were -0.169, indicating a prolate shape. The natural remnant magnetism intensity values are 1136.7 to 5372.0 milliampere per meter for sites N1, N2, N3, N4, and N5. The measured magnetic susceptibility of the samples was 2063×10^{-6} to 20110×10^{-6} (SI). The sample shape from site N5 indicates an oblate shape, with the minimum susceptibility axes oriented northwest and with the maximum and intermediate susceptibility axes scattered, or defining a girdle pattern (Figure 4).

Wichianburi

The measured magnetic susceptibility of the samples was 3850×10^{-6} to 27810×10^{-6} SI. The natural remnant magnetism intensity values were 633.0 to 3605.1 milliampere per meter for sites N6, N7, and N8. The degrees of anisotropy of the samples were 1.029, 1.036, and 1.057. The T factors of the N6 and N7 site samples were 0.181 and 0.129, indicating an oblate shape. The T factors of site N8 samples were -0.046, indicating a prolate shape (Figure 3e). The shape of site N7 sample is oblate, with the minimum susceptibility axes oriented west and the maximum and intermediate susceptibility axes scattered, or defining a girdle pattern (Figure 4).

Surin

The measured magnetic susceptibility of the samples was $16260\text{x}10^{-6}$ to $29500\text{x}10^{-6}$ (SI). The natural remnant magnetism intensity values were 444.6 to 1170.5 milliampere per meter for sites N11, N12, and N13. The degrees of anisotropy of the samples were 1.022, 1.031, and 1.035. Sample T factors were 0.531, 0.608, and 0.802 for sites N11, N12, and N13, respectively. All samples have a T value greater than zero, indicating an oblate shape (Figure 3b). The sample shape from site N13 indicates an oblate shape, with the minimum susceptibility axes vertical and the maximum and intermediate susceptibility axes scattered, or defining a girdle pattern (Figure 4).

Bo Ploi

The measured magnetic susceptibility of the samples was $46540\text{x}10^{-6}$ to $52960\text{x}10^{-6}$ (SI). The natural remnant magnetism intensity values were 6703.6 to 12572.2 milliampere per meter for sites N14 and N15. The degrees of anisotropy of the samples were 1.032 and 1.064 and the T factors were -0.076 and -0.264. All samples T values were less than zero, indicating a prolate shape (Figure 3f). The shape of the site N15 sample is prolate, with the maximum susceptibility axes oriented northeast (Figure 4).

PROPERTIES OF TEMPERATURE DEPENDENCE OF MAGNETIC SUSCEPTIBILITIES

Temperature dependence of low-field magnetic susceptibility was measured up to 700°C on a Kappabridge at room temperature. Thermomagnetic curves, which show the Curie point temperature of magnetic minerals, are useful for determining the composition of mineral phases in rocks. Magnetic susceptibility versus temperature curves from Surin site N13-08 show that the magnetic susceptibility decreases at 550 ^{o}C. This suggests that the mineralogical phase of the rock corresponds to magnetite (Figure 5a). After heating in air, an unstable magnetic phase was destroyed, resulting in a final decrease in susceptibility of the initial value. The heating curves from Burirum site S12-05 show stable thermomagnetic behavior. The magnetic susceptibility decreases at 550^{o}C. The Curie temperature indicates magnetite as the only ferromagnetic mineral. The absence of the hump and the stability of the magnetic susceptibility after the heating–cooling cycle indicate that an unstable phase is not present (Figure 5b). Samples from Denchai site N4-04 show that the magnetic susceptibility decreases at 200 to 300^{o}C (Figure 5c), suggesting that the mineralogical phase of this rock corresponds to titanium-magnetite with variable titanium content, while the content of titanium in titanomagnetite decreases the Curie temperature. A Curie point of about 200 to 300°C is characteristic for stoichiometric $Fe_{2.45}$ $Ti_{0.55}$ O_4 (Dunlop and Ozdemir, 1997). The sample from Bo Ploi site N14-02 shows that magnetic susceptibility decreases at 150 to 200°C (Figure 5d), suggesting that the mineralogical phase of the rock corresponds to titanomagnetite, $Fe_{2.4}$ $Ti_{0.6}$ O_4.

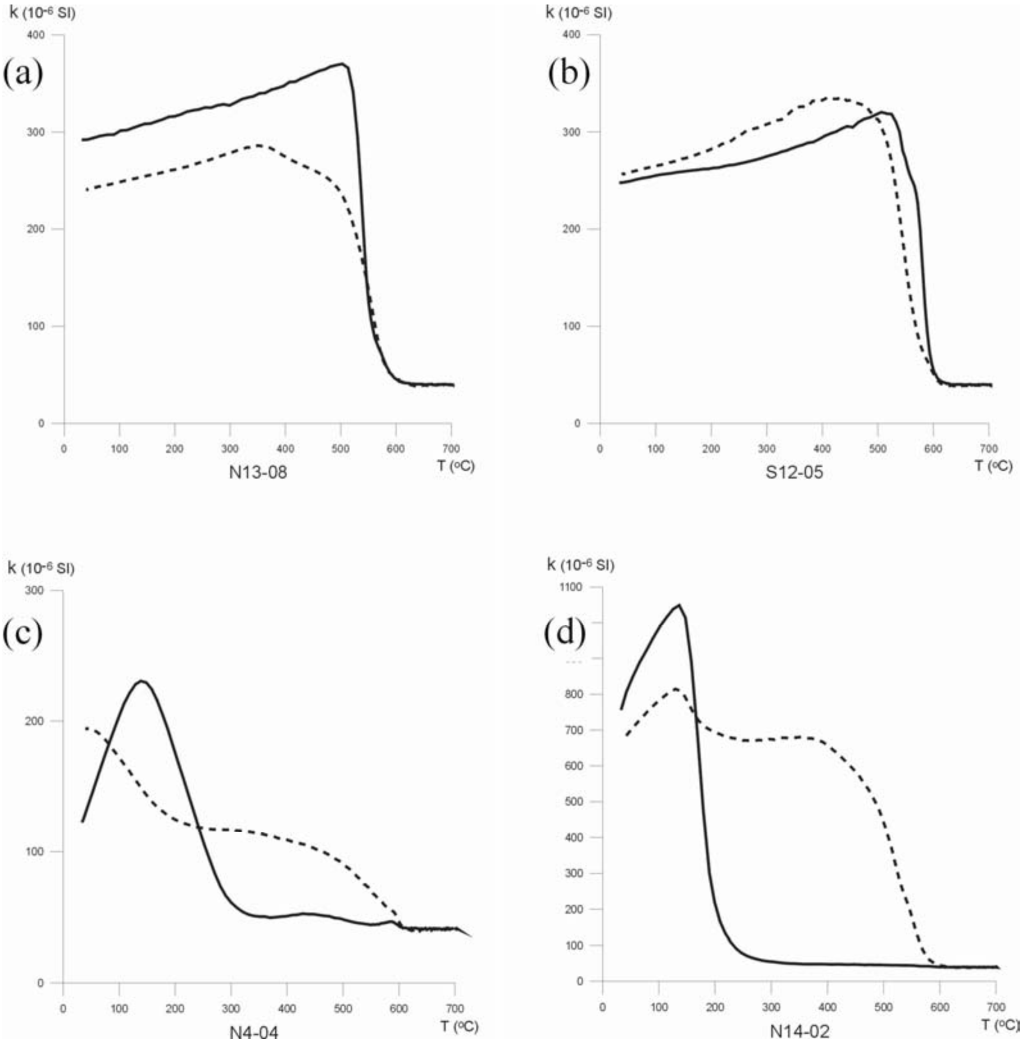


Figure 5. Curves for the temperature dependence of magnetic susceptibilities of rock samples from (a) Surin, (b) Burirum, (c) Denchai, and (d) Bo Ploi. Solid and dashed lines are heating and cooling curves, respectively.

CONCLUSIONS

Magnetic susceptibility anisotropy measurements indicate that the shape of the ellipsoid is prolate for alkali olivine and nepheline type basalt and is oblate for Hawaiite type basalt. Thermomagnetic analysis showed that the Curie temperature of titanomagnetite varied between 200 and 300°C for alkali olivine and nepheline basalt. The curie temperature of magnetite varied between 550 and 600°C for Hawaiite basalt. Alkali olivine and nepheline basalt are corundum-bearing basalts.

ACKNOWLEDGEMENTS

The authors thank the Graduate School, Prince of Songkla University, for a scholarship to carry out this study and for partial financial support. They also thank the IPPS, Uppsala University, Sweden, for supporting the rock magnetic instrumentation of the Prince of Songkla University's Department of Physics. The authors further thank all of Prince of Songkla University's geophysics graduate students for their support during the fieldwork campaign.

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