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Hornblende Chemistry and its Application to Geobarometry of the Noring Pluton, Stong Complex, Kelantan

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Abstract

One of the main mafic silicates in the Noring pluton is hornblende. It is euhedral to subhedral with grain size ranging from 1 to 4 mm across. Electron microprobe results show that the hornblende from the Noring granite have high MgO contents compared to other calc alkaline plutons and can be classified as magnesio-hornblende. The deduced magmatic crystallisation interval for the hornblende using the T-sensitive cations Ti and Al^{4+} gave values from 660 to 780 °C (± 70°C). The pressure of crystallisation of hornblende was estimated using the Al^{tot} pressure calibrations to give a mean value ranging from 1.89 to 3.08 kbar.

Kimia Hornblend dan Aplikasi Terhadap Geobarometri Pluton Noring, Kompleks Stong

Abstrak

Salah satu mineral silikat mafik utama dalam batuan pluton granit Noring ialah hornblend. Berdasarkan mikroprob elektron, hornblend daripada granit Noring ini mempunyai kandungan MgO yang tinggi berbanding dengan pluton kalk-alkali yang lain dan boleh dikelaskan sebagai hornblend-magnesio. Sela pengkristalan magma bagi hornblend mengunakan T-sensitif kation Ti dan Al^{4+} memberikan nilai daripada 660 hingga 780°C(±70°C). Tekanan pengkristalan hornblend dianggarkan menggunakan kalibrasi tekanan yang memberikan nilai berjulat dari 1.89 hingga 3.08 kbar.

INTRODUCTION

Empirical geobarometers based on the Al^{tot} content of hornblende for a rock containing the mineral assemblage : quartz + plagioclase + alkali feldspar + hornblende + biotite + titanite + an oxide phase (magnetite and ilmenite) have been proposed by Hammarstorm and Zen (1986) and Hollister *et al.* (1987). Johnson and Rutherford (1989) presented an experimental calibration, which confirms a linear correlation of Al^{tot} versus total pressure in igneous amphibole as suggested by the previous empirical calibrations of Hammarstrom and Zen (1986) and Hollister *et al.* (1987). The experimental calibration is based on the rim compositions, which are thought to have equilibrated with silicate melt (Johnson and Rutherford, 1989; Schmidt, 1992). This empirical geobarometer has not been tested on the granitic rocks from Peninsular Malaysia except in a brief work by Hutchison (1989). The aim of this paper is to present the chemistry of the hornblende from the Noring pluton of the Stong complex and to calculate the geobarometry using total Al in the hornblende.

GENERAL GEOLOGY

The Stong complex is located in the northern part of Peninsular Malaysia and consists of three components i.e. Berengkat tonalite, Kenerong microgranite and Noring pluton (Fig. 1). The complex was dated as Cretaceous (Cobbing *et al.*, 1992) and was emplaced into metasedimentary rocks comprising of sillimanite gneisses and calc silicate gneisses. Singh *et al.* (1984) grouped the complex as part of the Eastern Granitic Belt of Peninsular Malaysia. They showed that on the grounds of textural and mineralogical compositions, the Berengkat tonalite and Noring granite are similar to those from the Eastern Belt.

PETROGRAPHY

Azman (2000, in press) presented a detailed textural and petrographical study of the Noring granodiorite. In this rock, the major mineral phases present are alkali feldspar, plagioclase, quartz, biotite and hornblende. Sphene, apatite, allanite, epidote, zircon, magnetite, pyrite and ilmenite are the accessory phases. Plagioclase crystals are euhedral to subhedral and are generally 1 to 8 mm in size. It has a compositional range between An_{20} to An_{35}. Inclusions of small biotite, sphene and quartz blebs are present in the plagioclase. Regular zoning, both normal and oscillatory, and simple and polysynthetic twinning are common. In some places plagioclase has been replaced by microcline. This indicates that the plagioclase crystallised earlier than microcline. It often occurs as glomerocrysts of three to five crystals, which according to Vance (1969) can only be produced in a magmatic environment.

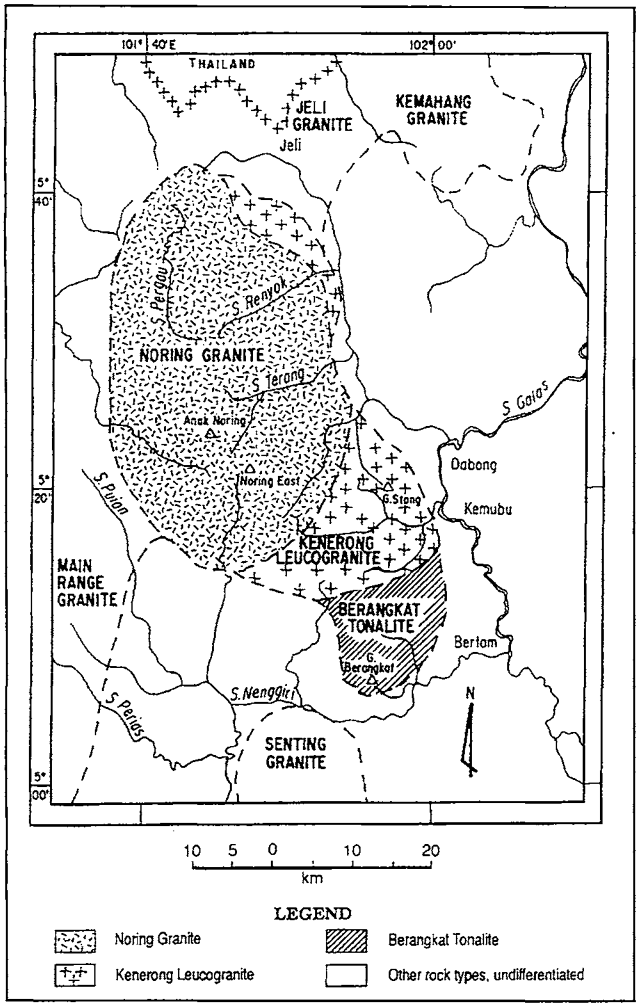

Figure 1: Regional geological map of the Stong Complex. The complex comprises the Noring granite, Kenerong leucogranite and Berengkat tonalite.

Large alkali feldspars, up to 3 cm across, often give the rock a distinctly porphyritic appearance in hand specimen. The main types are perthitic orthoclase and they often show a euhedral outline in hand specimen but sometimes appear to be very irregular in thin section. Simple twinning of the alkali feldspar and the presence of small oriented euhedral inclusions usually of plagioclase, oriented subparallel to the crystal faces of the host alkali feldspar, suggests that the minerals are magmatic.

Mantled feldspar formed by mantling of plagioclase over orthoclase are common (Azman, 1998). Mymerkite and granophyric intergrowths are sometimes found included in the plagioclase and orthoclase respectively. Quartz is mostly anhedral and sometimes occurs as subgrains. It is generally interstitial to all other minerals, especially to plagioclase and to the orthoclase. Hornblende is euhedral to subhedral with a grain size usually 1 to 4 mm across. It often shows simple twinning. Pleochroism is X = blue green, Y = brown green and Z = blue green. The mineral usually form multi granular aggregates associated with biotite, sphene, apatite and magnetite resulting in a clotted appearance. The occurrence of euhedral hornblende included in the cores of all other major phases indicates that the mineral is the earliest essential mineral to crystallise. Biotite is the main constituent of mafic aggregates ; its pleochroic scheme is X = dark brown and Y = brown. Sometimes the mineral is altered to chlorite at the margins. It occurs as anhedral plates up to 5 mm long, which are usually clotted together in-groups along with hornblende, sphene, apatite and magnetite. Sometimes the plates are weakly aligned resulting in a poor foliation in the rocks. Biotite commonly encloses numerous small crystals of apatite, zircon and magnetite.

Sphene is the most abundant accessory mineral of the Noring granite. Two types of sphene are present. The first type is euhedral to subhedral in form that is either found scattered or associated with the hornblende-biotite clots. It shows a faint pleochroism from brown to very pale brown and is mostly from 0.5 to 1 mm in length. Sometimes this type can be seen in hand specimen. The second type, generally subordinate to the first, is usually anhedral and occurs in biotite. Apatite occurs as small, colourless, subhedral to euhedral crystals with shapes varying from stumpy to elongated hexagonal prisms. Zircon is less common than apatite and is found as subrounded crystals probably due to magmatic corrosion. The main opaque phase in the Noring granite is magnetite.

HORNBLENDE CHEMISTRY

The compositions of the hornblende have been determined by using an electron microprobe located at the University of Manchester. The instrument (modified Cambridge Instruments Geoscan) was running under the following conditions: EDS analysis, 15 kv beam accelerating potential, 3nA specimen current on cobalt metal with a count time of 40 liveseconds. The results are presented in Table 1. Overall compositional range for the hornblende analyses are: SiO_2: 45.2 to 48.6 ; TiO_2: 0.25 to 1.5 ; Al_2O_3: 5.9 to 7.6; FeO: 14.8 to 16.5; MgO: 11.3 to 13.4; Na_2O: 1.16 to 1.83; CaO: 11.1 to 11.9 and K_2O: 0.65 to 1.2. The results also show that the hornblende from the Noring granite have a high MgO content compared to other calc alkaline plutons (e.g. Ardara and Thorr plutons, Donegal (8.85 - 10.17% and 8.83 - 10.8% respectively, Azman, 1997). A plot of Mg/(Mg + Fe_{tot}) vs Si (Fig. 2) (Leake, 1978; Barnes, 1987) shows that the majority of hornblendes found in the Noring granites are magnesio-hornblende. Hornblendes from the Noring plutons are often slightly zoned from core to rim but there is no consistent pattern.

The plot of Al^{4+} vs Al^{tot} in hornblende's from the Noring granite is shown in Figure 3. In this plot all hornblende samples from the Noring granite show a good correlation of Al^{4+} and Al^{tot}. All plots fall in the hornblende composition of low pressure (< than 2 kbar) granitic rocks (Mount Princeton and Pioneer batholiths of North America) (Hammarstrom and Zen, 1986).The hornblendes from the Noring granite also have comparable MgO content to the

Table 1: Analytical results of hornblende from the Noring granite.

Sample Location	PER1 core/1	PER1 rim/1	PER21 core/2	PER21 rim/2	PER2 Core/3	PER2 Rim/3	PER2 core/4	PER2 rim/4	PER2 Core/5	PER2 Rim/5	PER2 CoreJ6	PER2 Rim/6	PERTRA Core/1	PERTRA Rim/1
SiO_2	45.22	48.67	46.31	45.73	48.81	48.74	48.59	48.53	47.85	47.01	47.33	46.95	46.07	45.99
TiO_2	1.38	0.25	1.03	0.80	1.06	1.20	0.99	1.33	1.06	1.21	1.28	0.99	1.50	1.32
Al_2O_3	7.57	5.91	6.96	6.53	6.85	6.77	6.41	6.97	6.85	6.78	6.86	6.95	7.24	7.27
Cr_2O_3	0.08	0.02	0.08	0.16	0.15	0.00	0.15	0.16	0.14	0.24	0.00	0.03	0.13	0.17
FeO	16.53	16.32	16.55	15.83	14.74	15.01	14.30	14.82	15.21	15.74	15.17	15.52	15.49	15.16
MnO	0.38	0.39	0.24	0.45	0.02	0.10	0.10	0.09	0.15	0.00	0.03	0.20	0.08	0.27
MgO	11.31	12.56	11.83	12.09	13.29	13.13	13.39	13.01	12.54	12.61	12.41	12.21	12.02	12.18
CaO	11.50	11.94	11.45	11.12	11.48	11.88	11.75	11.6Z	11.62	11.60	11.71	11.54	11.55	11.70
Na_2O	1.83	1.39	1.55	1.63	1.51	1.37	1.17	1.19	1.25	1.26	1.48	1.24	1.44	1.42
K_2O	1.02	0.65	0.86	0.80	0.87	0.87	0.84	0.90	0.89	O.91	0.83	0.89	1.19	1.02
BaO	0.18	0.20	0.00	0.10	0.48	0.32	0.30	0.24	0.29	0.43	0.23	0.49	0.47	0.57
P_2O_5	0.12	0.05	0.19	0.00	0.42	0.45	0.31	0.43	0.50	0.49	0.37	0.42	0.50	0.33
Total	97.11	98.34	96.89	95.18	99.41	99.76	98.29	99.29	98.36	98.27	97.65	97.42	97.72	97.46
Structural formula based on 23 oxygen														
Si	6.84	7.19	6.97	7.01	7.08	7.05	7.11	7.04	7.03	6.95	7.01	7.00	6.87	6.89
Ti	0.16	0.03	0.12	0.09	0.12	0.13	0.11	0.15	0.12	0.13	0.14	0.11	0.11	0.15
Al	1.35	1.03	1.23	1.18	1.13	1.15	1.11	1.19	1.19	1.18	1.20	1.2Z	1.22	1.28
AlIV	1.16	0.81	1.04	0.99	0.92	0.95	0.89	0.96	0.97	1.05	0.99	1.00	1.13	1.11
AlVI	0.19	0.22	0.20	0.19	0.21	0.20	0.21	0.23	0.2Z	0.13	0.21	0.22	0.09	0.17
Cr	0.01	0.00	0.01	0.02	0.02	0.00	0.02	0.02	O.OZ	0.03	0.00	0.00	0.00	0.21
Fe	2.09	2.02	2.08	2.03	1.79	1.82	1.75	1.80	1.87	1.95	1.88	1.94	1.94	1.90
Mn	0.05	0.05	0.03	0.06	0.00	0.01	0.01	0.01	0.02	0.00	0.00	0.03	0.25	0.04
Mg	2.55	2.77	2.65	2.76	2.87	2.83	2.92	2.81	2.75	2.78	2.74	2.71	2.71	2.72
Ca	1.86	1.89	1.85	1.83	1.79	1.84	1.84	1.81	1.83	1.84	1.86	1.84	1.84	1.88
Na	0.54	0.40	0.45	0.48	0.42	0.39	0.33	0.34	0.36	0.36	0.42	0.36	0.36	0.41
K	0.20	0.12	0.17	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.16	0.17	0.17	0.19
Ba	0.01	0.01	0.00	0.01	0.03	0.02	0.02	0.01	0.02	0.03	0.01	0.03	0.03	0.03
P	0.02	0.01	0.02	0.00	0.05	0.06	0 04	0.05	0.06	0.06	0.05	0.05	0.05	0.04

hornblendes from north American batholiths (see p.1301 in Hammarstrom and Zen, 1986).

HORNBLENDE GEOTHERMOMETER

The thermal stability of the amphiboles from the Noring granites was estimated in a plot of the T-sensitive cations Ti and Al^{4+} (Weiss and Troll, 1988) (Fig. 4). The largely empirical T scale is based on the correlation of Al^{4+} vs Ti (Hammarstrom & Zen, 1986), which is largely independent of pressure (Nabelek & Lindsley, 1985). Generally, there is a positive correlation of Ti and Al^{4+} cations with temperature. The deduced magmatic crystallisation interval for the hornblendes is in the range from 660 to 780 °C (± 70°C).

HORNBLENDE GEOBAROMETER

Theoretical Background

The pressure of crystallisation of hornblende was estimated using the Al^{tot} pressure calibrations of Hammarstrom and Zen (1986), Hollister *et al.* (1987), Johnson and Rutherford (1988). The equations for the hornblende geobarometer based on the Al^{tot} content are :

$P = 5.03\ Al^{tot} - 3.92$ (Hammarstorm and Zen, 1986)

$P = 5.64\ Al^{tot} - 4.76$ (Hollister *et al.*, 1987)

$P = 4.28\ Al^{tot} - 3.54$ (Johnson and Rutherford, 1988)

$P = 4.76\ Al^{tot} - 3.01$ (Schmidt, 1992)

In this paper, the hornblende geobarometer of the Noring pluton will be calculated using all the four equations. Hollister *et al.*(1987) suggested that in order to apply an emperical geobarometer based on hornblende composition, the following conditions must be met :

(1) the phases quartz, plagioclase, hornblende, biotite, orthoclase, sphene and magnetite must have crystallised together from a melt.

(2) only the rim compositions of the hornblende should be used because these are the only parts of the hornblende crystals that have crystallised with the last remaining melt of the rock, so that the final temperature of crystallisation may be limited to a small range.

(3) although hornblende can crystallise between 950°C to 650°C in calc alkaline magma (Heltz, 1982) the temperature range is thought to be relatively narrow compared to the total range over which amphibole is stable in the crust and upper mantle (Hollister *et al.*, 1987). Hollister *et al.* (1987) indicated that the pressure should be more than 2 kb as the temperature of crystallisation increases rapidly with a drop of pressure. They based this on the findings of Clemens and Wall (1981) who noted a considerable increase in temperature with a drop in pressure.

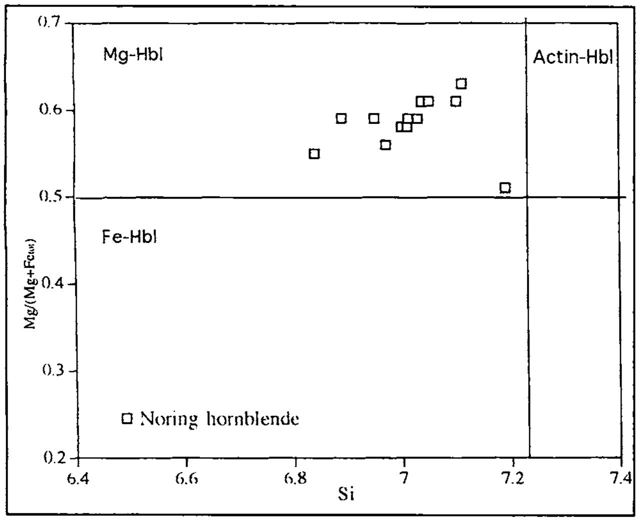

Figure 2: Classification of hornblendes from the Noring granite. All samples plot in the Mg-Hbl field.

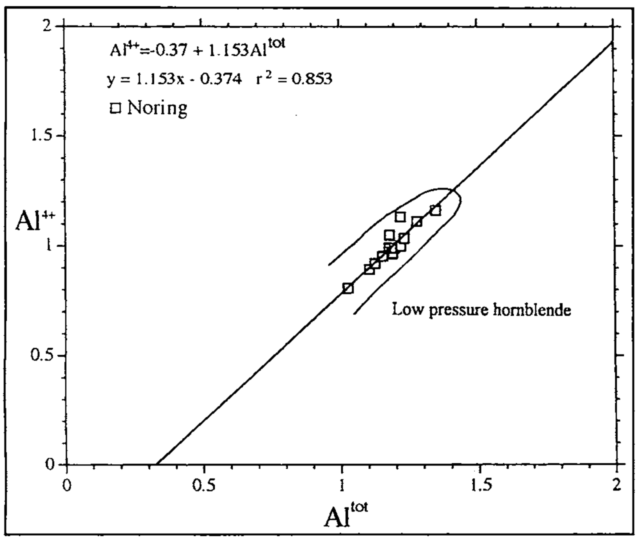

Figure 3: Al^{4+} vs Al^{tot} diagram for hornblendes from the Noring granite.

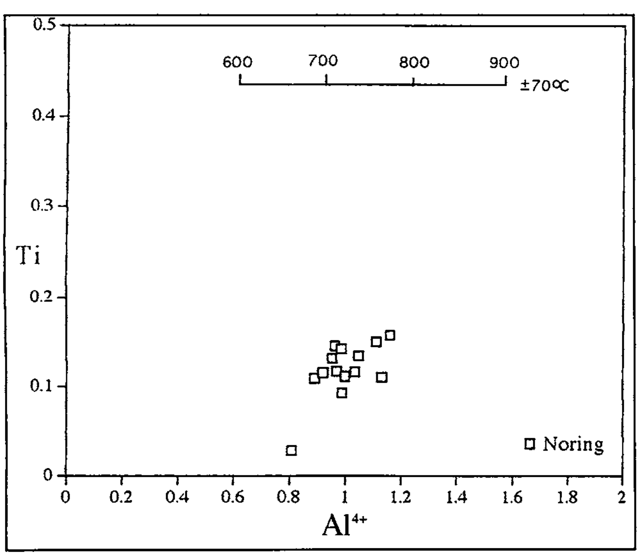

Figure 4: Ti vs Al^{4+} diagram for hornblendes from the Noring granite.

(4) the rim plagioclase composition should be within a well-defined range, which ideally should be between ~ An_{25} and An_{35}.

RESULTS

Pressure calculated using all four equations is shown in Table 2. All four equations used gave different pressures, with the equation from Schmidt (1992) giving the highest calculated pressure. The lowest calculated value is 0.86 kbar and the highest is 3.08 kbar. Mean calculated pressure for all the four equations range from 1.89 to 3.08 kbar.

DISCUSSION AND CONCLUSION

One of the main findings of this paper is that the hornblendes from the Noring granite have high MgO contents compared to hornblende from other low pressure plutons (Hammarstrom & Zen, 1986 ; Vyhnal *et al.*, 1991) (Table 3). Table 3 shows the calculated hornblende geobarometer and MgO content of hornblende from various granitic bodies along with those of the Noring granite. The low pressure plutons such as Noring, Pioneer (Colorado) and Mount Princeton (Montana) batholiths, Indian Brook granodiorite from Southern Applachians (Vyhnal *et al.*, 1991) have hornblendes with more than 11.3% MgO. Calculated geobarometer values for the Noring pluton range from 1.89 to 3.08 kbar. The result is consistent with the result obtained from Al^{4+} vs Al^{tot} plot where all samples fall in the low-pressure hornblende field (Fig. 3). This is consistent with the findings of Hammarstrom and Zen (1986), that the hornblende from shallow level intrusions predominate for Al^{tot} less than 2.0 pfu (Al^{tot} for the hornblende from Noring granite is less than 1.5 pfu).

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Table 2: Calculated hornblende geobarometry results (in kbar). NOTE: H & Z: Hammarstrom and Zen,1986; H *et al.*: Hollister *et al.*, 1987; J & R: Johnsoll and Rutherford, 1988; Sch: Schmidt, 1992

SAMPLE	Al_{tot}	Si	Pressure (kbar)				Mean
			H&Z	H *et al.*	J&R	Sch	
PER1	1.03	7.19	1.26	1.04	0.86	1.89	1.26
PER21	1.18	7.01	2.01	1.89	1.51	2.60	2.00
PER2	1.15	7.05	1.88	1.72	1.39	2.48	1.87
PER2	1.19	7.04	2.07	1.96	1.56	2.66	2.06
PER2	1.18	6.95	2.01	1.90	1.51	2.61	2.01
PER2	1.22	7.00	2.22	2.13	1.66	2.80	2.20
PERTRA	1.28	6.89	2.52	2.46	1.94	3.08	2.49

Table 3: Calculated hornblende geobarometry and MgO content in hornblende from various granitic bodies.

Granite body	MgO content in hornblende (%)	Calculated hornblende geobarometer	References
Noring pluton	11.3 - 13.4	2 kbar	This study
Pioneer & Mount Princeton batholiths	12.74 - 13.58	1 - 2 kbar	Hammarstrom & Zen 1986
Indian Brook granodiorite	12.49 - 13.63	2 kbar	Hammarstrom & Zen 1986
Butterword Creek, Southern Applachian	11.3 (average)	2.1±0.5 kbar	Vyhnal *et al.* (1991)
Kathy Road diorite, Southern Applachian	9.6-9.8	6.8 kbar	Vyhnal *et al.* (1991)
Dort pluton, Southern Applachian	7.37 (average)	5.1±0.5 kbar	Vyhnal *et al.* (1991)

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