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Chemical variation of Biotite and Hornblende in some Malaysian and Sumatran Granitoids

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Abstract: Electron probe microanalyses of biotite and hornblende are presented for a variety of granitoids from Peninsular Malaysia and Sumatra. Most biotites from the Main Range have Fe/(Fe+Mn+Mg) mole ratios greater than 0.62, with exceptions at Sg. Sok and the Cameron Highlands, which have I-type characteristics.

The Eastern Belt granitoids commonly contain hornblende and biotite. The biotite shows a wide range of Fe/(Fe+Mn+Mg), with higher values from the known tin mineralized areas of Jemaluang and Kuantan. Hornblendes and co-existing biotites generally exhibit equilibrium partitioning of Fe/Mg proving a magmatic origin for both. The total aluminium in the amphiboles prove an epizonal environment of emplacement for the Eastern Belt granitoids and an even higher sub-volcanic environment for the SE province.

The known occurrences of amphibole in the Main Range are few (Sg. Sok in Kedah and Bk. Berapit in Perak). They are of actinolitic hornblende and exhibit a non-equilibrium partitioning of Fe/Mg with the biotite. They are probably of hydrothermal origin.

An unusually green coexisting biotite and hornblende in the Gunung Benom area of the Central Belt appears to represent a deeper level of emplacement than the Main Range or Eastern Belt. The biotite-hornblende assemblage is not in equilibrium and the biotite is unusually enriched in magnesium.

INTRODUCTION

A reconnaissance overview of the chemical variation of biotites and hornblendes of Malaysian and Sumatran granitoids is presented. The samples analysed in the present study are listed in Table 1. The majority of the samples are from Peninsular Malaysia, with three granitoids from Sumatra and one trondhjemite from the gabbro layer of the Sabah ophiolite included for comparison. Brief reference is also made to feldspar, chlorite and muscovite analysis made during the course of the study. All analyses were carried out on carbon-coated polished thin sections in an electron probe microanalyser using a computer-controlled energy dispersive spectrometer for all elements except fluorine, for which a wavelength spectrometer was used. The preliminary results of this study were presented at the GEOSEA IV Conference in Manila in November 1981, but were not compiled for publication in the proceedings.

Liew (1983) carried out a considerable number of microprobe analyses of such minerals as feldspar, biotite, muscovite, tourmaline, rare garnet, horn-

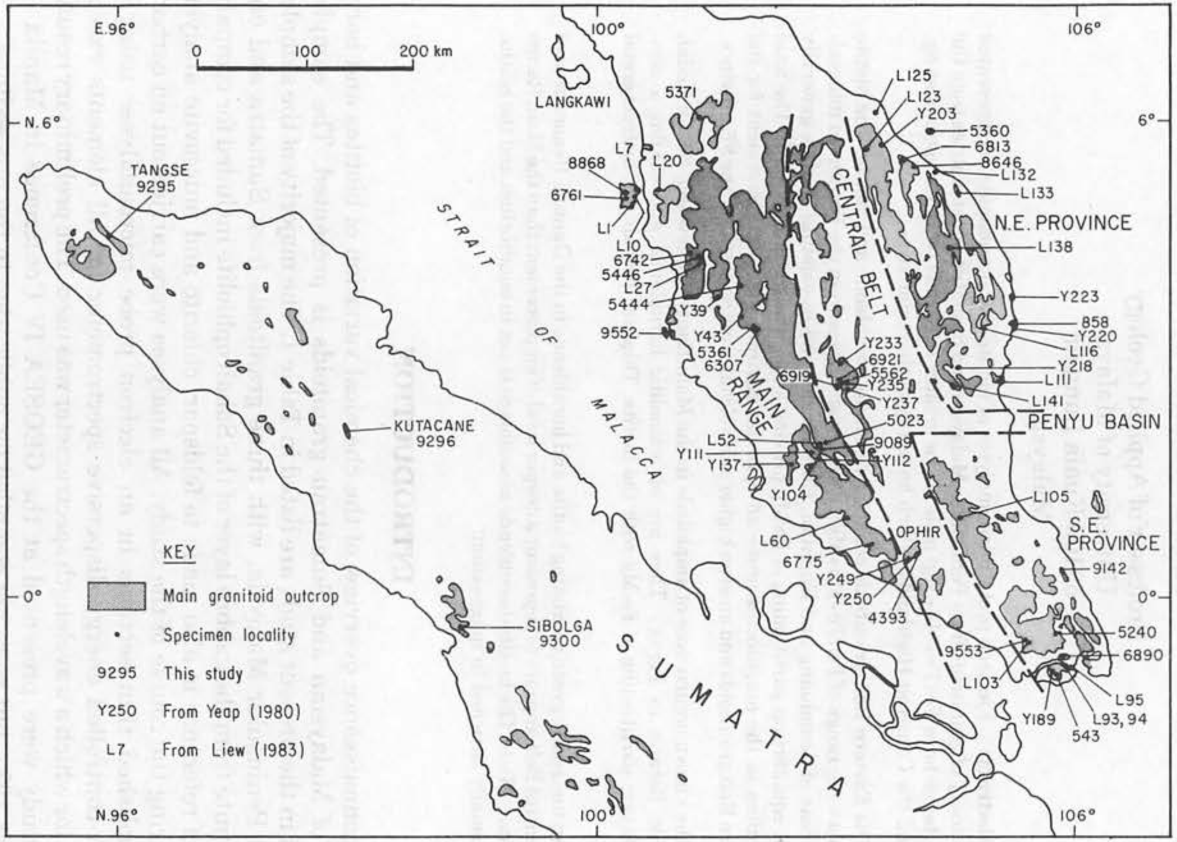

Figure 1 : Specimen locality map for granitoids whose biotites and hornblendes were analysed. L and Y localities are from Liew (1983) and Yeap (1980) respectively. Samples with no prefix are from this study.

blende and ilmenite in Peninsular Malaysian granitoids. As far as I know, these analyses have remained unpublished. I have incorporated his biotite and hornblende results for comparison in the mineral plots of the present paper.

Yeap (1980) reported chemical analyses of such minerals as alkali feldspar, biotite, ilmenite and zircon, separated from crushed Malaysian granitoids and analysed by X-ray fluorescence and other chemical methods. His work has remained unpublished. His biotite analyses compare well with the results of the present study, so have been incorporated in the mineral plots of this paper. The sample localities of all three studies are shown on Fig. 1.

SUMMARY OF THE GRANITOID BELTS

Eastern calc-alkaline plutonic arc

The granitoids form a compositionally expanded calc-alkaline series. They are mainly I-type, but S-type also occurs (Hutchison, 1983), and the province has mixed magnetite and ilmenite series characteristics (Ishihara *et al.*, 1979). The rocks range from gabbro to monzogranite, with the latter predominating (Cobbing *et al.*, 1986). The dominant lithologies are biotite granite and hornblende-biotite granite. The rocks have Andino-type characteristics, interpreted as representing an ensialic arc overlying an eastward-dipping Permo-Triassic Benioff zone (Mitchell, 1977). Using Rb vs (Nb + Y) discriminant plots, Cobbing *et al.* (1986) have shown that the great majority of Eastern Belt granitoids plot in the volcanic arc field of Pearce *et al.* (1984), with some overlap onto the within-plate field. The plutonic suite is closely associated with contemporaneous volcanic rocks, which are predominantly rhyolite-ignimbritic but also include andesite. The plutonic rocks show sub-volcanic characteristics. Their epizonal nature is illustrated by well developed cordierite-andalusite hornfels aureoles and the granitoids contain alkali feldspars ranging from orthoclase to intermediate microcline structural state (Hutchison, 1977, 1978).

There are two distinct sub-provinces (Fig. 1). The SE province of eastern Johore and Singapore has I-type characteristics and a Nd-Sr isotopic age of 230 Ma. The NE province is of mixed I and S affinities and Nd-Sr and U-Pb zircon ages ranging from as old as 265 down to 230 Ma (Early Permian to Late Triassic)(Liew and McCulloch, 1985). However, F. Darbyshire (pers. comm.) has not been able to substantiate the older ages and her radiometric data suggest a range of 197 to 240 Ma (Middle Triassic to Liassic) for the whole eastern belt.

Central Belt

The central Carnian-Norian Semantan-Gemas basin contains a narrow belt of granitoids through Gunung Benom to the Stong Complex of Kelantan. This belt lies parallel to and east of the Bentong-Raub suture zone (Hutchison, 1987). The plutonic suite is distinct from the Main Range but appears to be contemporaneous with it.

The granitic batholith of Benom has been dated by Bignell and Snelling (1977) and revised by F. Darbyshire (pers. comm.). The Rb:Sr isochron gave an age of 207 ± 7 Ma (Early Jurassic) with an initial Sr isotope ratio of 0.7079, significantly lower than the granitoids of the eastern part of the Main Range. The Benom granite is a coarse grained non-porphyritic biotite granite which intrudes an older series of alkali-rich rocks that range from gabbro to quartz syenite, some of which are distinctly gneissic and metamorphic, while others have an igneous texture (Hutchison, 1971). This suite, which has been intruded and hybridized by the Benom Granite, may be interpreted as the deeper differentiated levels of a pre-granite volcanic arc.

Late Cretaceous rift-related pink granites occur at Mount Ophir (Gunung Ledang) and Gunung Pulai in Johore. They may be broadly equated to the widespread Late Yenshanian granites of south China. K:Ar ages range from 52 to 72 Ma. The Rb:Sr date of the Mount Ophir granite is 78 ± 2 Ma and from Gunung Pulai 80 ± 12 Ma, but the data from the latter are less convincing. The rocks are characterized by low initial $^{87}Sr/^{86}Sr$ ratios of 0.7075 to 0.7082 (Bignell and Snelling, 1977). These granites are characterized by a medium grained equigranular hypersolvus texture. The alkali feldspar is pink and lacks the cross hatched twinning of the Main Range and Eastern Belt granites. Usually it ranges from orthoclase to intermediate microcline (Hutchison, 1977). The Mount Ophir granite is characterized by a well developed thermal aureole containing cordierite and andalusite, and corundum in restricted localities on its northern side.

A close comparison of the Gunung Pulai with the Bukit Lunchoo granite of east Johore shows that the rocks are closely similar, including the tendency for pink hydrothermally modified alkali feldspar. However the Bukit Lunchoo granite gives a good Rb:Sr isochron of 217 ± 6 Ma with an initial Sr isotope ratio of 0.7122, and K:Ar ages of 214 and 205 Ma. The Bukit Lunchoo pluton is therefore closely similar to the Singapore granite, but its petrographic similarity with the Gunung Pulai granite suggests that more work needs to be performed before the Late Cretaceous age is confirmed. The pink feldspars and other post-solidus hydrothermal alteration may be related to hydrothermal activity focused along NW-SE trending fault zones which lie parallel to the Straits of Malacca coastline and run through the Kuala Lumpur and Bukit Tinggi regions of the Main Range (Hutchison, 1987). The question must remain that the Late Cretaceous dates may represent hydrothermal modification adjacent to major fault zones and not the actual granite emplacement age.

In northern Kelantan, the igneous belt lying immediately east of the Bentong-Raub suture zone is known as the Stong Complex. The granite is generally fine grained and non-porphyritic, but there are coarser varieties. The whole complex is migmatitic with biotite gneiss and psammitic nebulite engulfing a variety of amphibolite facies schist, gneiss and phlogopite and diopside marble, in blocks varying from a few metres to several km long (Hutchison, 1973).

Although the high grade metamorphic rocks of the Stong Complex may be of Paleozoic age, similar to the Taku Schist, the granitic part has young mineral ages suggesting a Late Cretaceous tectonic and/or igneous event. A muscovite granite from nearby Batu Melintang gave a whole rock Rb:Sr age of 76 Ma (Bignell and Snelling, 1977). New Rb:Sr isochron dating by F. Darbyshire (pers. comm.) gave an age of 79 ± 3 Ma for the Kenerong granite, with an initial Sr isotope ratio of 0.7080. The nearby Noring granite gave a Rb:Sr isochron age of 90 ± 30 Ma (initial $^{87}Sr/^{86}Sr$ ratio 0.7087) and K:Ar dates of 64 to 67 Ma. These new results confirm a Late Cretaceous igneous event in the northern part of the Central Belt.

Main Range

The eastern half of the Main Range batholith system has been intruded into an envelope of deep water strata known as the Hawthornden Schist in the Kuala Lumpur area, the Schist Series near Bentong and the Pilah Schist farther south. Along its western half, it has been intruded into platform carbonates and other shelf strata as far west as Kedah and Langkawi. The central and eastern parts of the Main Range have been interpreted by Hutchison (1977) to show mesozonal characteristics. Contacts with the Lower Paleozoic greenschist facies schists are sharp and a thermal aureole is conspicuously absent. Westwards the batholith system displays more epizonal characteristics. In the Ipoh area and in Langkawi and Kedah the granites have caused extensive skarn formation and have produced chiastolite hornfels aureoles in the Paleozoic Singa Formation (Hutchison, 1983).

The Main Range granites are commonly coarse to very coarse grained and contain large phenocrysts up to 5 cm length in the Gap pluton. The megacrysts are of maximum microcline. Predominantly the batholith is of biotite granite and hornblende is conspicuously absent except for a very few localities (Table 1). There are also local areas of fine grained tourmaline-rich leucogranite and two-phase hydrothermally modified granites are common in the Kuala Lumpur pluton (Cobbing *et al.*, 1986).

Chemically the Main Range is strictly confined to the granite field, exclusively of S-type and of the ilmenite series. The peraluminous (S type) nature is indicated by a few regions of two-mica granite, notably near Seremban and in the Sungei Ara pluton of Penang, where andalusite is also contained (Chakraborty and Amerizal, 1984). Elsewhere the common occurrence of muscovite is of greisenization and hydrothermal origin.

U-Pb zircon dating yields precise and unambiguous ages of 198 to 220 Ma (Late Triassic to Early Jurassic) (Liew and Page, 1985). Initial $^{87}Sr/^{86}Sr$ ratios are high and range from 0.7159 to 0.7512 (Liew and McCulloch, 1985), clearly indicating derivation from a continental crustal infrastructure. The Rb vs (Nb + Y) plots of the Main Range granite lie on Pearce *et al.* (1984) discrimant diagrams

Table 1 : Specimen localities and analysed minerals

			Biotite	Hblende	Feldspar
a)	**Sumatra**				
	9295	Late Cretaceous granite, TANYSE (G 714)	X	X	
	9296	Middle Miocene porphyritic microdiorite 50 km NNW of Kotacane (GA/JI/RII)	X	X	$Or_2Ab_{46}An_{52}$
					$Or_2Ab_{48}An_{50}$
	9300	Main phase Sibolga granite (KD/JI/R26)	X		$Or_1Ab_{57}An_{42}$
b)	**Main Range**				
	5371	Sungei Sok, Kedah	X	X	$Or_{86}Ab_{14}$
	8868	Soon Gin quarry, Penang	X		$Ab_{87}An_{13}$
	6761	District quarry, Sg. Penang, Penang	X		$Or_2Ab_{87}An_{11}$
	6742	J.K.R. quarry, Taiping	X		$Or_{80}Ab_{20}$
	5446	Kuala Kangsar-Taiping road 41.5 milestone.	X		$Ab_{64}An_{36}$
	5444	Kuala Dipang quarry, Perak	X		$Or_{80}Ab_{20}$
	9552	Pangkor island, Perak	X		$Or_{86}Ab_{14}$
	5361	Tapah-Cameron Highlands road, 19 milestone	X		$Or_1Ab_{62}An_{37}$
	6307	Tapah-Cameron Highlands road, 7 milestone	X		$Or_1Ab_{59}An_{40}$
					$Or_2Ab_{57}An_{41}$
					Or_{100}
	5023	Gunung Ulu Kali, Genting Highlands	X		$Or_{52}Ab_{48}$
					$Or_{95}Ab_5$
	9089	Karak-Kuala Lumpur highway	X		$Or_{85}Ab_{15}$
	6775	Seremban-Tampin main road, 10.75 miles	X		$Ab_{92}An_8$
c)	**Central Belt**				
	6921	Sungei Pertang, Gunung Benom area	X		$Or_3Ab_{82}An_{15}$
					$Or_3Ab_{79}An_{18}$
	5562	Sungei Ruan, Gunung Benom area	X		$Or_{93}Ab_6An_1$
				(contains muscovite)	
	6919	Kg. Dong, Gunung Benom area	X	X	$Or_1Ab_{74}An_{25}$
				(biotite is dark green)	
d)	**Mount Ophir Late Cretaceous**				
	4393	Gunung Ledang (Mount Ophir)	X		$Or_{89}Ab_{11}$
					$Or_3Ab_{84}An_{13}$
e)	**N.E. Province of Eastern Belt**				
	5360	Kg. Pasir, Perhentian Kechil, Trengganu	X	X	$Or_1Ab_{70}An_{29}$
					$Or_1Ab_{61}An_{38}$
	6813	Besut, Trengganu	X	X	$Or_1Ab_{40}An_{59}$
	8646	Sg. Bintang, Trengganu	X		$Or_2Ab_{69}An_{29}$
					$Or_2Ab_{72}An_{26}$
	858	Kuantan-Kemaman road	X	X	
f)	**S.E. Province of Eastern Belt**				
	9142	Bukit Batu Besar, Jemaluang, Johore	X	X	
	9553	Kulai, Johore	X	X	
	5240	Gunung Panti West, Johore	X	X	$Or_{86}Ab_{14}$
	6890	J.K.R. quarry, Lunchoo, Johore	X		$Or_{96}Ab_4$
	543	Bukit Mandai, Singapore	X		
g)	**Sabah**				
	9412	Trondhjemite from gabbro zone of ophiolite, Lower Bole River, Ulu Segama.	X		$Or_1Ab_{80}An_{19}$

in the syn-collisional origin field (Cobbing *et al.*, 1986). Recent Rb:Sr dating by F. Darbyshire (pers. comm.) confirms the earlier work. Her determined ages lie within the range 207 to 230 Ma and initial Sr isotope ratios lie within the range 0.711 to 0.731.

Sumatra

Small granitoid plutons are widely scattered through the Barisan Mountains of Sumatra (Fig. 1). A compilation of their ages (Hehuwat, 1976) shows that some are Triassic, and a few as old as Permian, such as at Sibolga (Fig. 1), which gave a Rb:Sr age of 257 ± 24 Ma., though most of their K:Ar dates are around 215 Ma (Late Triassic). These ages suggest that Sumatra may be part of the Main Range block. The Sibolga granite is representative. It is an epizonal hypersolvus-textured granite containing biotite and pink orthoclase.

In north Sumatra, stocks and small batholiths of mainly granitic to dioritic composition are known (Page *et al.*, 1979; Stephenson and Aspden, 1982). They range from Late Cretaceous to Miocene. The northernmost stock at Pulau Brueuh gives a Rb:Sr age of 24 Ma with a low Sr isotope ratio of 0.7043.

Most northern Sumatran granitoids are equigranular medium grained and coarsely megacrystic granite is rare. Biotite granite and granodiorite are more common in the north and hornblende-biotite granitoids are more common in the west and south. Most occurrences belong to the magnetite series and have I-type characteristics but there are a few local occurrences of S-type granite (Wikarno *et al.*, 1987). The Cretaceous-Cenozoic Sumatran granitoids exhibit an expanded calc-alkaline spectrum belonging to a subduction-related Andino-type setting. However the Permian (?) and Triassic granites may represent the epizonal western margins of the Main Range of Peninsular Malaysia.

BIOTITE CHEMISTRY

Main Range and Sumatra

The biotite electron probe microanalyses of the Main Range are summarized in Table 2. The biotite crystals show no systematic variation from core to rim. However, when the rim is chloritized (9), the analysis is distinguished by a dramatic drop in SiO_2 and K_2O and an increase in Al_2O_3 and MgO. Chloritized samples were therefore avoided. All samples were analysed for chlorine, but only a few for fluorine content, which ranges from 0.78 to 1.42 wt. %.

The analyses, together with those of Liew (1983) and the analyses of separates by Yeap (1980) were recalculated as mineral formulae and plotted on a standard diagram using the end members:

Siderophyllite $K_2Fe_5Al[Si_5Al_3O_{20}](OH)_4$

Annite $K_2Fe_6[Si_6Al_2O_{20}](OH)_4$

Table 2: Chemical analyses (wt. %) of biotite in Main Range Granite

Specimen	SiO_2	TiO_2	Al_2O_3	FeO^T	MnO	MgO	K_2O	Cl	Total
(1). 5371	38.27	3.48	14.00	18.46	0.30	11.86	9.41	0.09	95.87
(2) C. 6761	35.51	3.12	19.55	24.95	0.61	3.63	9.47	0.15	96.99
(3) R. 6761	35.67	2.99	18.89	25.38	0.61	3.81	9.24	–	96.59
(4) C. 8868	34.85	3.46	17.06	25.97	0.46	3.91	9.63	–	95.34
(5) R. 8868	35.77	2.83	18.27	25.31	0.54	3.82	9.63	–	96.17
(6) C. 6742	35.31	3.93	13.78	27.16	0.54	5.49	9.38	0.68	96.27
(7) R. 6742	35.82	3.54	13.97	26.83	0.46	5.49	9.24	0.99	96.34
(8) C 5446	36.99	2.89	14.39	20.68	0.43	10.57	9.58	0.12	95.65
(9) R 5446 @	25.69	–	19.77	26.57	0.47	13.76	0.40	–	86.65
(10) C. 6307	37.68	3.68	16.53	19.74	0.32	9.60	9.83	0.12	97.88
(11) R. 6307	37.54	2.71	17.65	19.53	0.26	9.58	9.77	0.02	97.45
(12) C. 5361	37.14	3.73	17.34	20.36	0.29	9.05	9.61	0.13	97.65
(13) R. 5361	37.48	3.48	17.41	20.72	–	8.52	9.65	0.22	97.48
(14) C. 9552	35.68	4.64	14.38	27.26	0.31	5.44	9.23	0.28	98.15
(15) R. 9552	35.00	3.29	15.46	26.87	0.31	5.26	8.91	0.17	96.40
(16) C. 5444	35.57	3.93	13.64	27.16	0.26	6.10	9.58	0.32	97.98
(17) R. 5444	35.57	3.31	13.52	26.95	0.32	5.78	9.62	0.23	96.63
(18) C 5023	37.02	2.79	14.78	26.35	0.32	5.81	9.45	0.10	96.76
(19) R. 5023	36.59	1.72	14.62	27.65	0.37	6.04	9.21	0.04	96.26
(20) C. 9089	36.49	3.46	17.24	21.13	0.38	8.22	9.54	0.33	96.79
(21) R. 9089	36.45	3.18	17.22	21.71	0.37	8.05	9.74	0.36	97.08
(22). 6775	36.88	2.16	18.62	23.56	0.54	4.21	9.69	0.13	95.79

FeO^T = Total iron as FeO. C = core R = rim of crystal @ = Chlorite

[1] = (average of 2 analyses) (contains CaO 0.08, Na_2O 0.21. [2] = core (1 analysis, [3] = rim (1 analysis),. [4] = core (1 analysis), [5] = rim (1 analysis). [6]= core (1 analysis). [7] = rim (1 analysis). [8] = core (1 analysis). [9]CHLORITE rim (average of 2). [10] = core (average of 2) (contains Fluorine 0.78%), [11] = rim (average of 2) (contains Fluorine 0.81%). [12] = core (1 analysis), [13] = rim (1 analysis). [14] = core (1 analysis) (contains Fluorine 0.93%), [15] = rim (1 analysis) (contains Fluorine 1.13%). [16] = core (1 analysis) (contains Fluorine 1.42%), [17] = rim (1 analysis) (contains Na_2O 0.10, CaO 0.04), [19] = rim (average of 3) (contains CaO 0.02) (strongly foliated). [20] = core (1 analysis), [21] = rim (1 analysis). [22] (average of 2).

Phlogopite $K_2Mg_6[Si_6Al_2O_{20}](OH)_4$

Eastonite $K_2Mg_6Al[Si_5Al_3O_{20}](OH)_4$

Figure 2 shows a plot of the Main Range granite biotites together with those from Sumatra for comparison. The Sumatran samples from Tanyse (9295) and Kotacane (9296) define the biotite field expected for I-type granitoids, with Fe/(Fe + Mn + Mg) atomic ratios less than 0.6.

The Main Range granite samples which fall in this field are known to be unusual. The Sungei Sok granitoid carries abundant hornblende. The samples from the Tapah-Cameron Highlands road also have biotites characterized by low Fe/(Fe + Mn + Mg) ratios, as also does the gneissic sample (9089) from the Karak-Kuala Lumpur Highway.

All other Main Range granite biotites have atomic ratios of Fe/(Fe + Mn + Mg)

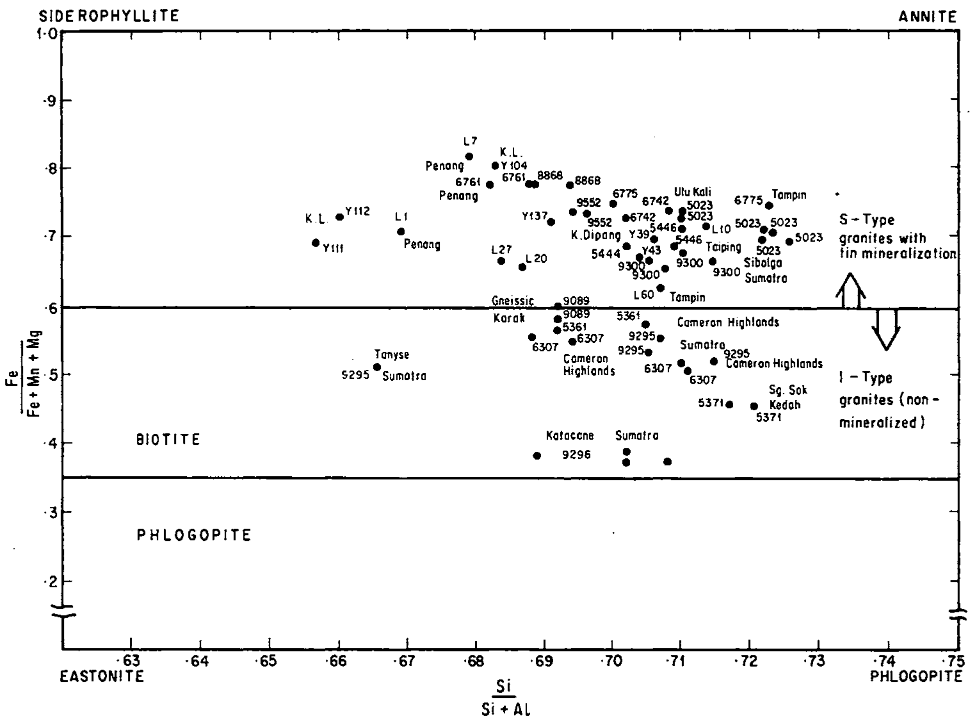

Figure 2 : Biotite mineral compositions plotted on a formula element ratio diagram. Specimens 9295, 9296 and 9300 are from Sumatra. All others are from the Main Range Belt of Peninsular Malaysia. The division into S-type and I-type granitoid fields is empirical.

greater than 0.62, within the S-type granite field. These are the granites which can be shown or are expected to be associated with tin mineralization. It is interesting that the Permo-Triassic granite from Sibolga, Sumatra (9300) also lies in this field, though it has no known tin association.

Central and Eastern Belts

The electron probe microanalyses of biotites from the Eastern Belt are given in Table 3 and of the Central Belt and Sumatra in Table 4, with one sample (9412) from a plagiogranite from the gabbro zone of the Ulu Segama ophiolite of Sabah for reference.

The elemental variation in the mineral formulae is illustrated in figure 3, together with the analyses of Liew (1983) and Yeap (1980). More of the samples lie in the field of Fe/(Fe + Mn + Mg) less than 0.62 than was the case for the Main

Table 3: Chemical analyses (wt. %) of biotite in Eastern Belt granitoids

Specimen		SiO_2	TiO_2	Al_2O_3	FeO^T	MnO	MgO	K_2O	Cl	Total
(1)	5360	37.25	4.47	13.64	17.37	0.13	12.52	9.11	0.50	95.14
(2)	8646	35.39	3.42	13.52	31.23	0.74	3.57	9.10	0.32	98.95
(3)	8646	35.98	2.96	13.79	30.57	0.60	3.90	9.15	0.30	98.73
(4)	6813	36.75	4.99	13.65	22.20	0.19	9.53	9.39	0.60	97.29
(5)	6813	36.60	2.98	13.78	21.94	–	9.83	9.09	0.64	94.85
(6)	858	35.01	4.12	13.20	28.99	0.32	4.40	9.11	0.58	95.79
(7)	9142	36.29	2.59	15.02	27.58	0.59	2.93	8.72	0.49	94.38
(8)	9553	32.07	1.02	18.52	26.97	0.29	7.97	7.15	0.29	94.90
(9)	5240	36.14	5.11	13.45	24.13	0.24	7.97	9.18	0.41	96.63
(10)	5240	36.72	3.17	14.26	23.93	0.24	9.28	9.54	0.50	97.64
(11)	6890	36.81	3.76	16.91	19.58	0.36	9.88	10.11	–	97.42
(12)	6890	37.26	2.54	16.94	19.64	0.24	9.85	10.04	–	96.64
(13)	543	35.65	4.51	13.64	25.29	0.37	7.70	8.97	0.33	97.00

FeO^T = Total iron as FeO

[1] = (average of 2 analyses) (contains CaO 0.10, Na_2O 0.05). [2] = (core) (average of 2) (contains CaO 0.04, Fluorine 1.62), [3] = (rim) (average of 2) (contains CaO 0.02, Fluorine 1.46). [4] = (core) (1 analysis), [5] = rim (1 analysis). [6] = (average of 2) (contains CaO 0.06). [7] = (average of 2) (contains CaO 0.01, Na_2O 0.16). [8] = (average of 4) (contains CaO 0.27, Na_2O 0.35). [9] = (core) (1 analysis), [10] = (rim). [13] = (average of 2) (contains Fluorine 0.54).

Table 4: Chemical analyses (wt. %) of biotite in Central Belt of Peninsular Malaysia, Sabah and Sumatra

Specimen		SiO_2	TiO_2	Al_2O_3	FeO^T	MnO	MgO	K_2O	Cl	Total
(1)	6919	40.64	0.96	14.25	16.34	0.41	14.74	9.99	-	97.48
(2)	6919	40.17	0.81	14.23	16.25	0.35	15.13	10.18	-	97.12
(3)	6921	37.02	4.02	12.6	24.46	0.53	7.31	8.97	0.11	95.29
(4)	5562	36.72	2.80	17.02	22.52	0.43	7.77	9.57	0.07	97.24
M (5)	5562	47.08	0.61	30.69	4.81	0.05	1.13	10.43	0.03	95.00
(6)	4393	38.47	2.89	14.22	17.24	0.86	11.53	9.41	0.03	97.15
(7)	9412	36.87	2.45	17.65	18.63	0.53	11.24	9.08	0.05	96.72
(8)	9300	36.23	3.87	13.72	25.44	0.50	6.86	8.97	0.16	95.95
(9)	9295	35.82	3.66	13.4	121.77	0.62	10.63	8.22	0.12	94.59
(10)	9296	36.73	4.56	13.67	15.38	0.35	13.90	8.55	0.31	93.72

FeO^T = Total iron as FeO M = Muscovite

[1] = (core) (average of 2 analyses) (contains CaO 0.15), [2] = (rim) (average of 2). [3] = (average of 2) (contains CaO 0.11, Na_2O 0.09). [4] = (average of 2) (contains Na_2O 0.34), [5] = MUSCOVITE (average of 2) (contains CaO 0.04, Na_2O 0.13). [6] = (average of 6) (contains CaO 0.03, Na_2O 0.19, Fluorine 2.28). [7] = (average of 4) (contains CaO 0.11. Na_20 0.11). [8] = (average of 4) (contains CaO 0.07, Na_2O 0.13). [9] = (average of 4) (contains CaO 0.07, Na_2O 0.27). [10] = (average of 4) (contains CaO 0.13, Na_2O 0.14).

Range. This is in keeping with the predominantly I-type characteristics of the granitoids. The plagiogranite (4912) clearly defines the I-type field. Also to be found in this field are the Late Cretaceous granites of Gunung Ledang (4393) and the Perhentian islands (5360). The distinctly green biotites from Kampong Dong (6919) have the lowest Fe/(Fe + Mn + Mg) ratios of all analyses, and they almost lie in the phlogopite field (Fig. 2). These biotites are as green as the accompanying hornblende.

Biotites from the S.E. Province of eastern Johore and Singapore are characterized by low Fe/(Fe + Mn + Mg) values less than 0.65 with the exception of the specimens from Jemaluang (9142) from the formerly important tin mining region, and the high iron values reflect this. The low values of Singapore and south Johore reflect the general absence of mineralization and the I-type nature of the granites. The single high value of Liew (1983) from Pulau Ubin (L94) is a curious anomaly. However the other Fe-rich values from Kuantan reflect the important tin mineralized region.

The specimens from Kulai (9553) have consistently low Si/(Si + Al) values, clearly demonstrated in the unusually high Al_20_3 values of around 18.52 % and

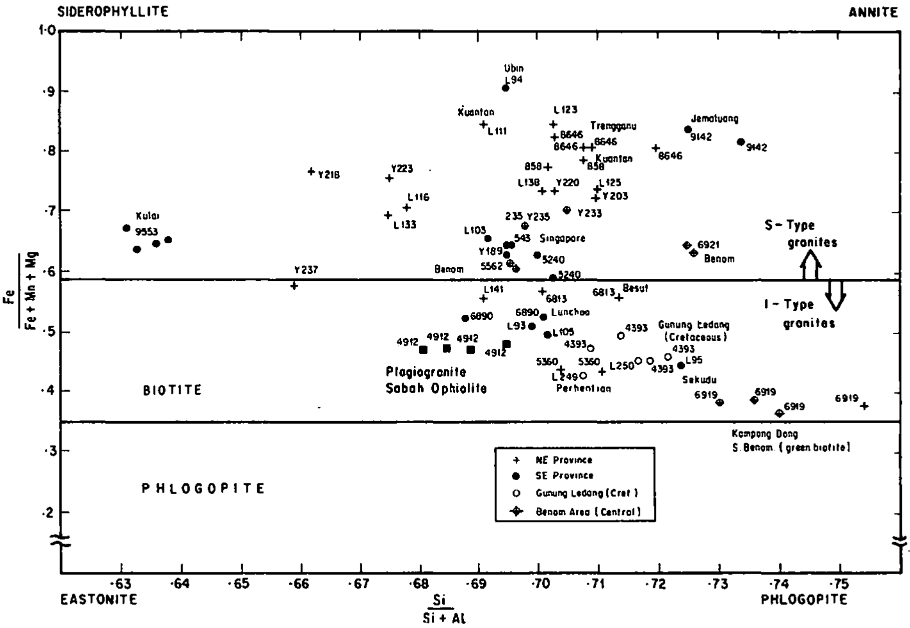

Figure 3 : Biotite mineral compositions plotted on a formula element ratio diagram. Specimen 4912 is from the Sabah ophiolite. The others are from the Eastern and Central belts and are distinguished by the symbols.

low SiO_2 of 32.07 % contents (Table 3). These values are consistent and accurate. The geological significance of this anomaly is unclear but worthy of further investigation.

HORNBLENDE CHEMISTRY

The electron probe microanalyses of this study are given in Table 5. They were recalculated to mineral formulae using the method of Hutchison (1974) and plotted along with the microanalyses of Liew (1983) on Figure 4. In figure 4(A) the calciferous amphibole end members are:

Edenite	$NaCa_2Mg_5Si_7AlO_{22}(OH)_2$
Pargasite	$NaCa_2Mg_4AlSi_6Al_2O_{22}(OH)_2$
Tschermakmite	$Ca_2Mg_3Al_2Si_6Al_2O_{22}(OH)_2$
Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$

The iron content systematically increases with Al increase in the Z_8 structural position (Fig. 4B). The analyses show the common range from actinolite through actinolitic hornblende to common Fe-hornblende.

The specimens from Gunung Panti West (5240), Besut (6813), Sungei Sok (5371), Bukit Berapit (L27) and Kotacane, Sumatra (9296) occupy the actinolitic

Si-rich end of the spectrum, which is characterized by low sodium and iron contents. There is a distinct possibility that most of these actinolitic varieties are

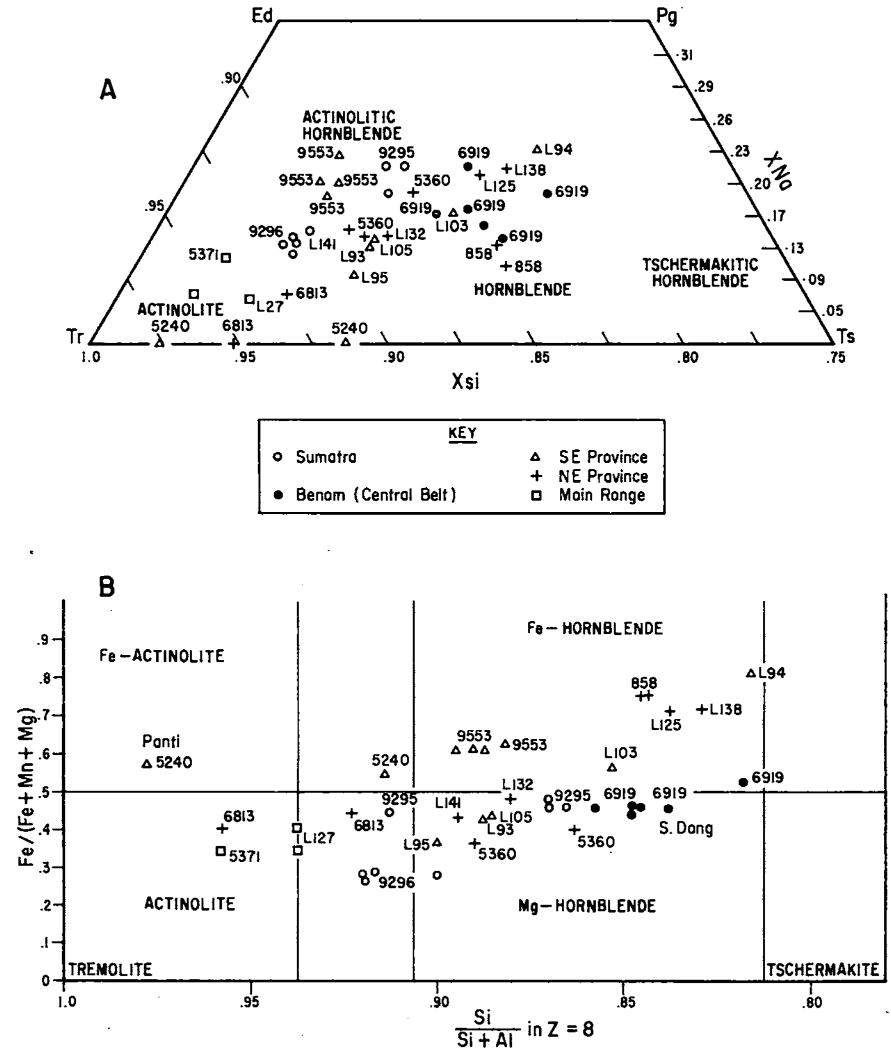

Figure 4 : Hornblende mineral compositions plotted on formula element ratio diagrams. The prefix L means from Liew (1983). Analyses without a prefix are from this study. In A the parameters are X_{Na} = Na/ (Na+Ca+K) in the formula. X_{Si} = Si/ (Si+Al) in structural position Z_8.

Table 5 : Chemical analyses (wt.%) hornblende in Peninsular Malaysia and Sumatra granitoids

Specimen	SiO_2	TiO_2	Al_2O_3	FeO^T	MnO	MgO	CaO	Na_2O	K_2O	Cl	Total
(1) 9295	47.15	1.28	6.28	18.14	0.83	11.25	11.19	1.61	0.67	0.18	98.58
(2) 9296	50.45	1.14	5.03	11.22	0.60	15.87	11.43	1.07	0.46	0.11	97.38
(3) 537	52.89	0.45	3.52	14.50	0.46	14.24	12.15	0.78	0.38	0.07	99.44
(5) 5360	47.46	1.25	6.93	14.82	0.34	12.82	11.91	1.50	0.90	0.34	98.27
(6) 6813	49.79	0.37	5.08	18.04	0.37	11.97	10.99	0.50	0.50	0.39	98.00
(7) 6813	52.07	0.29	3.34	16.67	0.40	12.59	11.88	–	0.24	0.21	97.69
(8) 858	42.68	2.03	8.26	26.62	0.44	4.63	10.32	0.89	1.13	0.62	97.62
(9) 5240	48.46	0.16	5.55	22.47	0.62	9.98	10.24	–	0.23	0.19	97.90
(10) 5240	52.06	–	1.79	26.44	1.39	10.35	6.58	–	0.09	–	98.72
(11) 9553	46.39	0.93	6.02	23.98	0.53	8.02	10.07	1.55	0.60	0.24	98.33

FeO^T = Total iron as FeO

(1) = (average of 4 analyses). (2) = (average of 4 analyses) (3) = (average of 2 analyses)

(4) = (average of 6 analyses) (5) = (average of 2 analyses) (6) = (core) (1 analysis)

(7) = (rim) (1 analysis) (8) = (average of 2 analyses) (9) = (core) (1 analysis)

(10) = (rim) (1 analysis) (11) = (average of 4 analyses)

not primary magmatic amphibole. With these exceptions, the analyses represent normal magmatic amphiboles, and the great majority are from the eastern belt of Peninsular Malaysia.

FE-MG PARTITIONING BETWEEN BIOTITE AND HORNBLENDE

The partitioning of iron and magnesium between coexisting biotite and hornblende is shown in figure 5 as a plot of X_{Fe} (hornblende) versus X_{Fe} (biotite).

The majority of the eastern belt granitoids contain co-existing hornblende and biotite which have KD_{Fe} (biotite-hornblende) values close to unity (Fig. 5) representing an equilibrium assemblage resulting from magmatic crystallization of both phases.

The specimens L27, 5371 and 9296 have KD_{Fe} (biotite-hornblende) values in excess of 2.0 and therefore these co-existing compositions are far from equilibrium assemblages. Since L27 and 5371 are the only known amphiboles from the Main Range province, doubt is cast on the existence of primary amphibole in Main Range granitoids.

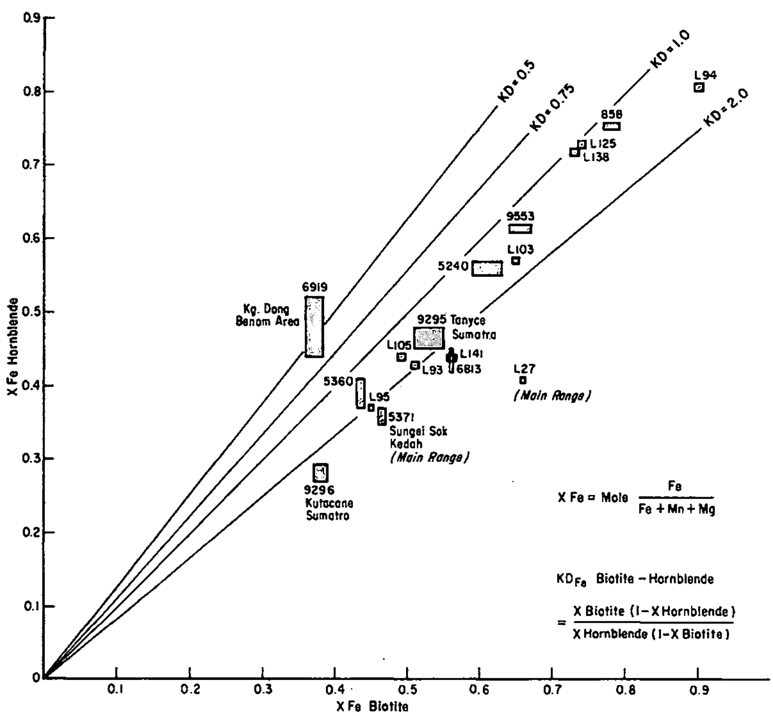

Figure 5 : Partition of Fe between co-existing biotite and hornblende in the granitoids.

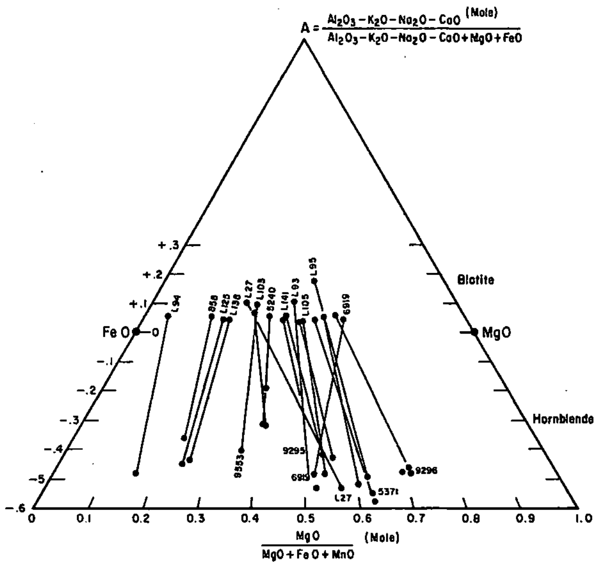

Figure 6 : Tie lines between co-existing biotite and hornblende in granitoids. Lack of equilibrium is particularly noted for the crossing tie of 6919 with biotite considerably richer in MgO and L27 with biotite considerably poorer in MgO than the co-existing amphibole.

At the other end of the spectrum, the Kampong Dong specimen (6919), which is characterized by dark green biotite resembling the amphibole, shows KD_{Fe} values around 0.5, representing a non-equilibrium assemblage.

The general equilibrium between the biotite and hornblende compositions is illustrated by a common plot of both mineral compositions (Fig. 6). Most of the tie lines between coexisting minerals lie along lines of approximately similar MgO/(MgO + FeO + MnO) (mole) values. The non equilibrium assemblages are shown by crossing tie lines, the outstanding example being 6919. Its biotite is very MgO rich in comparison with its hornblende, implying a complex recrystallization history for rocks in the Benom area.

L27 shows the opposite trend. The tie line slopes towards the FeO rich side for biotite in comparison with the high MgO value of the hornblende (Fig. 6).

HORNBLENDE GEOBAROMETRY

Hammarstrom and E-an Zen (1986) showed that the aluminium content of amphiboles may be empirically related to the pressure under which the granitoids crystallized:

$P = -3.92 + 5.03Al^T$ where P is the pressure (in kilobars) and Al^T is the total aluminium in the amphibole formulae calculated on the basis of 23 oxygens (Hutchison, 1974). Hornblendes from shallow level intrusions have Al^T less than

Table 6: Total Al in amphiboles and calculated pressure (kilobars)

Spec	Al^T	Pres.	Spec	Al^T	Pres.	Spec	Al^T	Pres.
Sumatra								
9295	1.26	2.42	9295	0.86	0.41	9295	1.15	1.86
9295	1.18	2.02	9296	0.83	0.25	9296	0.92	0.71
9296	0.82	0.20	9296	0.87	0.46			
Main Range								
5371	0.70	-0.40	5371	0.49	-1.46	L27	0.68	-0.50
Central								
6919	1.49	3.57	6919	1.42	3.22	6919	1.31	2.67
6919	1.48	3.52	6919	1.77	4.98	6919	1.39	3.07
Eastern (NE Province)								
858	1.52	3.73	858	1.57	3.98	5360	1.33	2.77
5360	1.09	1.56	6813C	0.89	0.56	6813R	0.58	-1.00
Eastern (SE Province)								
5240C	0.99	1.06	5240R	0.32	-2.31	9553	1.03	1.26
9553	1.12	1.71	9553	1.16	1.91	9553	1.07	1.46

C = core, R = rim. Al^T = total iron in formula based on 23 oxygens.

2.0. All the amphiboles analysed in this study belong to this category (Table 6).

The following general observations may be made:

a) The Sumatran plutons represent shallow emplacements with pressures of crystallization less than about 2.4 kilobars, and ranging to much lower values.

b) The amphiboles of both known examples of Main Range granitoids (5371: Sungei Sok, and L27: Bukit Berapit) are unlikely to be primary magmatic. The extremely low Al^T values of less than 0.70 lead to negative calculated pressures. I interpret these actinolitic hornblendes to have resulted from hydrothermal replacement. There is therefore no proven example of Main Range granitoids which contain authenticated primary hornblende.

c) The Kg. Dong specimen (6919) contains Al^T within the range 1.31 to 1.77, representing pressures of crystallization of nearly up to 5 kilobars. This suite of rocks has the deepest level of emplacement of the whole analysed set of samples.

d) The NE province of the Eastern Belt appears to have crystallized at deeper epizonal levels than the SE province. Calculated pressures may be as high as nearly 4 kilobars. The analysed rim of specimen 6813 is likely to be of hydrothermal origin.

e) The SE province of the Eastern Belt appears to have crystallized at much shallower epizonal levels than the NE province. The common occurrence of ignimbrite in this region shows that the associated granites are sub-volcanic. This is in keeping with the low calculated pressures less than 1.7 kilobars. The negative value of the rim of 5240 indicates a hydrothermal origin.

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