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Petrogenesis of Perhentian granite and Perhentian Kecil syenite from the Perhentian Island, northeastern Peninsular Malaysia: Evolution of two contrasting magmas

AZMAN A. GHANI

Department of Geology, University of Malaya,
50603 Kuala Lumpur

Abstract: The Perhentian complex consists of two plutons, the younger Perhentian granite and the older Perhentian Kecil syenite. They form a reversely zoned complex where the syenitic rock is rimmed by the granitic rock. The former ranges in composition from syenite to monzonite to gabbroic rocks whereas syenogranite dominates the latter pluton.. The syenitic rocks are characterized by an extended composition of lower SiO_2 (46 to 66 %) compared to the Perhentian granite (>70.9 % SiO_2) and have significantly high Al_2O_3, TiO_2, Fe^{tot}, MnO, MgO, CaO, P_2O_5, Sr, Ba and V compared to the granitic rocks. Petrology and geochemical datas indicate that both rocks are individual melt probably derived from a different sources. It is suggested that the syenitic magmas formed by hydrous melting of lower crust probably as a result of underplating by, or intrusion of mantle derived basaltic magma. The strong enrichment of large ion lithophile elements (Sr and Ba) is probably related to transfer of enriched (hydrous?) fluids from the mantle into the lower crust, and possibly initiated melting to form the syenites. In contrast to the Perhentian Kecil syenite, the Perhentian granite has no mafic association. The felsic nature of the Perhentian granite suggests that it may be derived from an SiO_2 rich source or may represent a minimum melt, the first melt produced from a solid containing plagioclase-K-feldspar-quartz.

Abstrak: Komplek Perhentian terdiri daripada dua pluton iaitu granite Perhentian yang lebih muda dan syenit Perhentian Kecil yang lebih tua. Mereka membentuk zon terbalik dimana batuan syenitik di kelilingi oleh batuan granitik. Pluton syenitik terdiri daripada batuan yang berkomposisi syenit ke monzonit ke gabro manakala pluton granitik didominasikan oleh batuan syenogranit. Batuan syenitik dicirikan oleh julat SiO_2 yang luas (46 – 66% SiO_2) berbanding dengan granit Perhentian (> 70.9 SiO_2) dan mempunyai Al_2O_3, TiO_2, Fe^{tot}, MnO, MgO, CaO, P_2O_5, Sr, Ba dan V yang tinggi berbanding dengan batuan granitik. Data petrologi dan geokimia menunjukkan kedua-dua batuan ini adalah cecair individu dan terhasil dari punca yang berbeza. Ini mencadangkan bahawa magma syenitik terbentuk dari perleburan hidrous kerak bawah kemungkinan terhasil daripada 'underplating' oleh atau pernerobosan magma basaltik mantel. Perkayaan yang tinggi unsur-unsur ion litofil besar (Sr dan Ba) adalah berkemungkinan berkaitan dengan pemindahan perkayaan bendalir (hidrous?) dari mantel ke kerak bawah dan kemungkinan memulakan peleburan untuk membentuk magma syenit. Berlawanan dengan syenit Perhentian Kecil, granit Pernehtian tidak mempunyai asosiasi mafik. Keadaan semulajadi felsik granit Perhentian mungkin diterbitkan oleh punca yang kaya SiO_2 atau mungkin mewakili cecair minima, cecair pertama yang terbentuk dari pepejal yang mengandungi plagioclas-K-feldspar-kuarza.

INTRODUCTION

The magmatism of the Eastern Belt is dominated by High-K calc-alkaline granite (SiO_2 between 60 to 74%) with subordinate gabbro. It is in contrast to the Western Belt magmatism, no gabbro and is compositionally more evolved compared to the Eastern Belt. While much has been written on the petrography and regional geochemistry of the Eastern belt granites (e.g. Cobbing *et al.*, 1992) there has been relatively little systematic study of their intra-pluton geochemistry. The study can provide detailed magmatic and geochemical processes that operate in a smaller scale. To date, with help from previous work (e.g. Cobbing *et al.*, 1992; Azman and Khoo, 1998) we are able to distinguish different components in the granitic bodies. The Perhentian intrusion is a reversely zoned complex exposed over several islands off the east coast of Peninsular Malaysia. The intrusion is the easternmost of the igneous bodies of the Eastern Belt intruded into Upper Paleozoic metasedimentary rocks. One of the most intriguing features of the Perhentian complex, different from other Eastern Belt igneous rocks, is the coexistence of syenitic and granitic rocks which are rarely found in the Eastern Belt. The aim of this paper is to report the geochemical variation of the syenite and granite and to establish the difference between these rocks in term of the evolution, textures and petrogenesis.

GENERAL GEOLOGY AND TECTONIC SETTING

The study area is a group of islands situated about 15 km off the northeast coast of Terengganu (Fig. 1). They consist of six main islands: Perhentian Besar, Perhentian Kecil, Rawa, Serenggeh, Susu Dara Besar and Susu Dara Kecil. Geologically, the Perhentian group is located in the Eastern Belt of Peninsula Malaysia. The Eastern Belt igneous rocks are distributed as linear masses parallel to the medial suture of Peninsular Malaysia. The province extends for a distance of approximately 600 km and has a

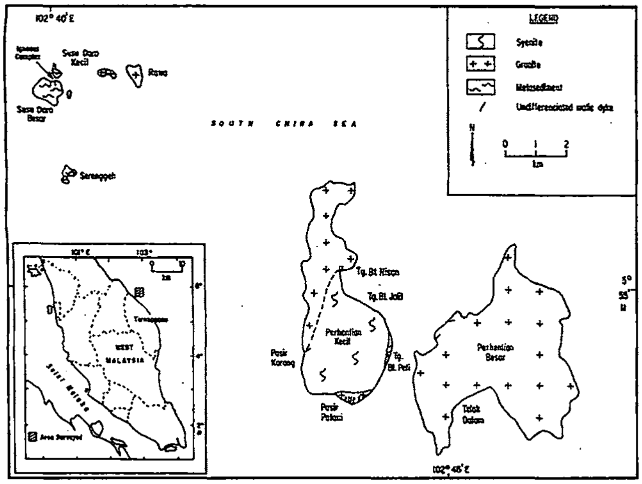

Figure 1. Geological map of the Perhentian island and its surrounding area.

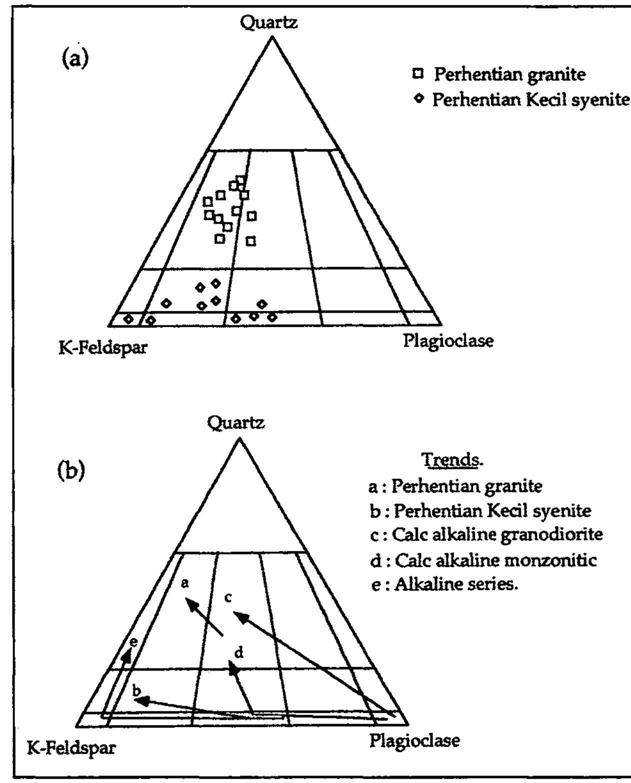

Figure 2. (a) Q-A-P classification of the Perhentian granite and Perhentian Kecil Syenite. (b) General trend of both syenite and granite and comparison with other rock series elsewhere.

typical exposed width of 80 km. A biotite ± hornblende granodiorite to syenogranite of variable texture is the common rock type but a single intrusive complex may consist of rocks ranging from gabbro to syenogranite. Mafic dyke swarms of doleritic in composition are common (Azman *et al.*, 1998; Azman, 2000a). The igneous rocks of the Perhentian area lies to the north of the Kapal batholith and have been considered geographically an extension of the batholith which has geological and geochemical affinities to the Eastern belt of Peninsula Malaysia (Cobbing and Mallick, 1987). The contacts between the Perhentian granite and Perhentian Kecil syenite plutons and the host rock in the study area are nowhere exposed, but at Susu Dara Besar island, the metasedimentary rocks are intruded by granite porphyry, microgranite, dolerite and other igneous rocks forming an Igneous Complex (Fig. 1) (Azman, 1992; Kamal and Azman, 1999).

The contacts between the Perhentian Kecil syenite and the Perhentian granite are sharp and can be found at Pasir Karang, Pasir Patani, Tanjung Batu Nisan and along Tanjung Batu Peti to Tanjung Sireh. The relationship of the contacts suggests that the Perhentian granite is younger than Perhentian Kecil syenite (Azman and Khoo, 1998).

The Perhentian granite made up the whole of Perhentian Besar, Rawa, Tengku Burung islands and the northern and southern parts of Perhentian Kecil Island. The Perhentian granite has been divided into 2 varieties by Cobbing and Mallick (1987), namely hornblende-bearing and hornblende-free granite. The main body of Perhentian granite consists of medium to coarse grained biotite granite (hornblende-free granite) exposed along the coast of Perhentian Besar island, north and south part of Pulau Perhentian island and the whole of Rawa island (Fig. 1). Microgranite and granite porphyry are found at the contact with Perhentian Kecil syenite at Pasir Patani, Pasir Karang and Tanjung Batu Nisan. Occasionally the microgranite contains pegmatitic patches characterized by large plates of muscovite, biotite and K-feldspar (Loc: Tanjung Batu Nisan).

The Perhentian Kecil syenite forms a circular outcrop at the central part of Perhentian Kecil Island and consists of a variety of igneous rocks ranging in composition from syenitic to monzonitic and even gabbroic. The monzonitic rocks can be found at Tanjung Batu Nisan about 10 m from the contact between Perhentian Kecil syenite and Perhentian granite. In terms of percentage, the syenitic rock totals almost 90% of the pluton. Epidote nodules and veins (thickness from 2 to 5 cm) can be seen throughout the pluton. The gabbroic rocks are found as boulders mainly at Kampung Pasir Hantu and Pasir Patani and they usually contain hornblende as a main mafic phase.

PETROGRAPHY

Modes were determined for medium and coarse grained rocks by point counting. The data were collected using a Swift Model E point counter fitted with an automated stage. All Perhentian granite samples plot in the syenogranite field on a Q-A-P diagram (Streckeisen, 1976) whereas the Perhentian Kecil syenite samples grade from monzonite to syenite (Fig. 2). Both plutons show different trends, thus the Perhentian Kecil syenite samples show a similar trend to the rocks from alkaline province (e.g. Bowden and Turner, 1974) whereas the Perhentian granite samples plot in the field of a granitoid formed by crustal fusion. The essential minerals in the Perhentian Kecil syenite are K-feldspar, plagioclase, hornblende, pyroxene, quartz, biotite, sphene, epidote, apatite, zircon and magnetite. The main mineral assemblages are K-feldspar, plagioclase, quartz, biotite, hornblende, allanite, zircon, epidote and opaque

Table 1. Summary of petrographic features of the Perhentian Kecil syenite and Perhentian granite.

	PERHENTIAN KECIL SYENITE	PERHENTIAN GRANITE
Rock types	Syenite (90%) ± monzonite ± Gabbro	Syenogranite ± Monzogranite ± Porphyritic types at the contact
Mineral assemblage	K-feldspar (~40-70%), plagioclase (~10 – 30%), hornblende (~10%), augite (~3-5%), quartz, biotite, sphene, epidote, apatite, zircon and magnetite	K-feldspar (~30 – 35%), plagioclase (~30 – 35%), quartz (~30 – 35%), biotite (~5-10%),, hornblende, allanite, zircon. epidote and magnetite
Main mafic phases	Hornblende, augite and biotite	Biotite ± hornblende
Accessory phases	5% of total rock Sphene, apatite, magnetite and epidote	< 1% of total rock Apatite, epidote, zircon ± allanite
Secondary phases	Sericite (K-feldspar)	Sericite (K-feldspar), chlorite (biotite)

phase. Petrographic characteristics of both Perhentian Kecil Syenite and perhentian granite are summarized in Table 1.

GEOCHEMISTRY

30 samples, 15 each from Perhentian Kecil syenite and Perhentian granite, were analyzed for major and trace elements. 10 samples (4 Perhentian granite and 6 Perhentian Kecil syenite) were analyzed for rare earth elements (Table 2). In addition, 7 samples (4 Perhentian granite and 3 Perhentian Kecil syenite) are taken from Cobbing *et al.* (1992). The syenitic rock includes two gabbroic samples found as an insitu block in the western part of the pluton.

Analytical method

Major oxide elements and trace elements were analyzed by x-ray fluorescence at the Department of Earth Sciences, University of Liverpool. Accuracy in major element analysis was checked by routine analysis of the USGS standard G2. Glass fusion discs were used in the analysis of major elements. Each disc was prepared by using a mixture of approximately 0.62 g (weighed to 4 decimal places) of 153 microns of rock powder with 3.3 g of lithium borate flux in a ratio of 5.4321:1 flux: rock, at 1000°C and casting the melt onto 4 cm diameter aluminium platterns. Powder pellets used in trace elements analysis were prepared by mixing 7 g of 53 microns powder with 12 to 15 drops moviol binder solution (4 g Moviol + 10ml ethanol + 50 ml distilled water). The resultant mixture was pressed into a 4 cm disc under 5 tons pressure and left to dry before analysis.

Major elements chemistry

Selected major elements Harker variation diagrams have been plotted for the Perhentian Kecil syenite and Perhentian granite and are shown in Figure 3. The range of SiO_2 for each of the Perhentian Kecil syenite and Perhentian granite are 46.8 to 65.9% and 70.96 to 75.35% respectively. The Harker diagrams also show that there is a gap between Perhentian Kecil syenite and Perhentian granite at SiO_2 of 65.9 to 70.9 %. This gap probably represents a true compositional difference between the two plutons and not because of under-sampling. The syenitic rocks have higher Al_2O_3, TiO_2, Fe^{tot}, MnO, MgO, CaO and P_2O_5 contents compared to the Perhentian granite rocks. Both plutons however overlap in the Na_2O and K_2O contents.

All rocks from both units generally have high alkali content, with $Na_2O + K_2O$ ranging between 8.16 to 9.93 % for Perhentian granite, 6.34-12.08 % for Perhentian Kecil syenite. However the gabbroic rocks associated with the Perhentian Kecil syenite have low alkali contents i.e. 3.82 to 3.85 %. This is clearly shown in the K_2O vs SiO_2 diagram (Peccerillo and Taylor, 1976) (Fig. 4), the two gabbroic samples plot in the calc-alkali field at low SiO_2 the Perhentian granite samples plot in the high-K calc-alkali whereas those from Perhentian Kecil syenite plot in both high-K calc-alkali and shoshonite fields. Classification by alumina saturation index (ASI) of Zen (1986) indicates that the Perhentian granite has higher ACNK values ranging from 0.92 - 1.03 (mildly peraluminous to metaluminous), compared to the Perhentian Kecil syenite which ranges from 0.63 - 0.97 (metaluminous) (Fig. 5). Both units also

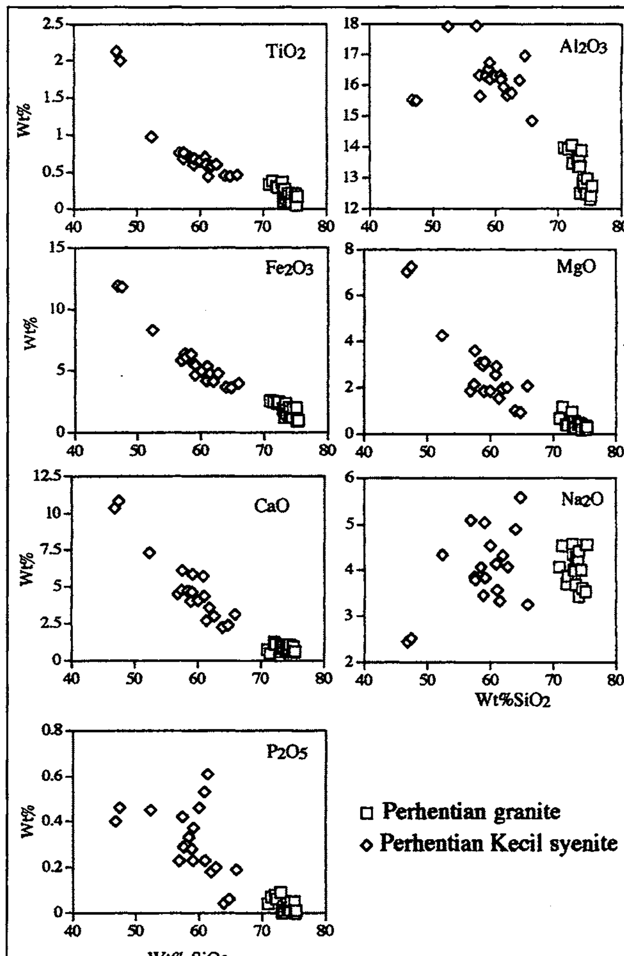

Figure 3. Major elements Harker diagram of the syenitic and granitic rocks from the Perhentian island.

show a different ACNK trend with SiO_2, thus the ACNK trend of the syenitic rocks increase whereas those from the granitic rock decrease with increasing SiO_2.

Plots of CaO and (Na_2O + K_2O) vs SiO_2 (Fig. 6) emphasise the alkali calcic character of the syenitic rocks: that is alkali-lime index of 54.5 (Peacock, 1931), as well as very different character, in alkali term, of the Perhentian granite pluton in which the CaO and (Na_2O + K_2O) curves do not intersect. This is due to the lower CaO and higher (Na_2O + K_2O) contents which are constant over the SiO_2 ranges (71 - 75 %) of the granitic rocks.

Trace elements geochemistry

Harker diagrams of trace elements are shown in Figure 7. In general samples from the two plutons clearly fall

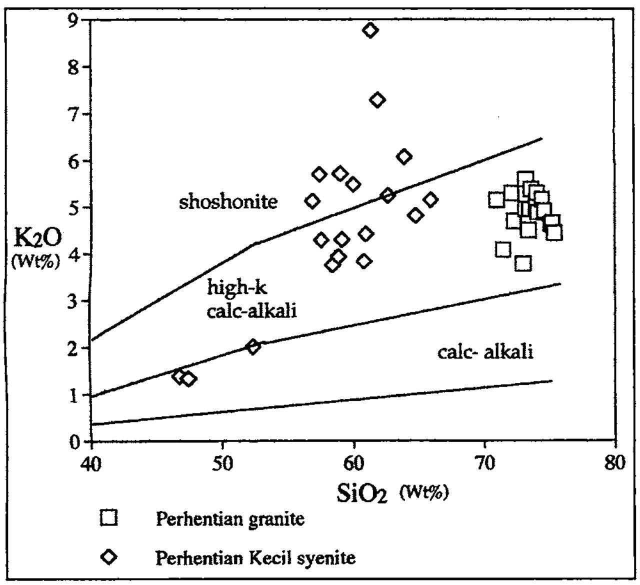

Figure 4. K_2O vs. SiO_2 diagram of the Perhentian granite and Perhentian Kecil Syenite. Note that the different trends shown by both rocks. Compositional field after Peccerillo and Taylor (1976).

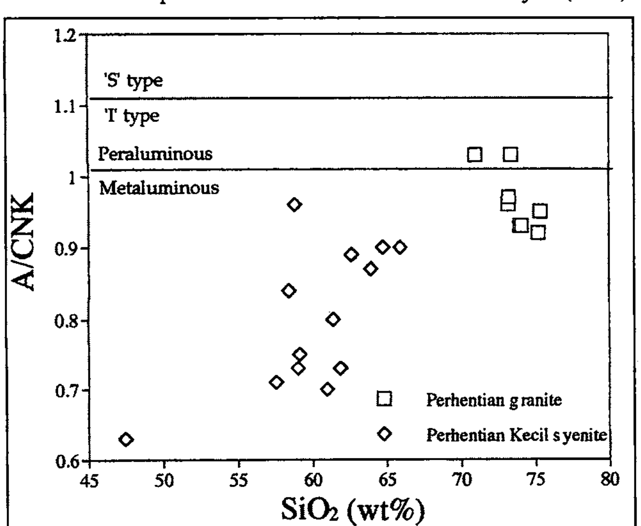

Figure 5. ACNK vs SiO_2 plot of the syenitic and granitic rocks. Line at ACNK = 1 divides peraluminous and metaluminous field and line at ACNK = 1.1 divides 'I' and 'S' type granite field. Note that the different trends shown by both rocks.

along two saperate and somewhat distinct trends. Many of the elements overlap, particularly Ce, La, Co, Nb, Nd, Rb, Sc, Zn and Zr. A clear decreasing trend is shown by Sc, V and Sr with increasing SiO_2. However, in detail, each pluton shows a different behaviour with SiO_2. In rocks from the Perhentian Kecil syenite, Ba, Ce, La, Rb,Th increase and Sc, V, Sr, Pb, Y, Zn and possibly Zr decreases with increasing SiO_2.Trace elements in the Perhentian granite show some odd trends, thus Ce, Co, La, Nd, Pb, Th, Rb and Y neither increase nor decrease but produce steeply vertical trends. Ba, Sr, V and Zr decrease with increasing SiO_2.

The TiO_2 vs Zr plot (Fig. 8) shows the different crystallising options in the Perhentian Kecil syenite and Perhentian granite. General trends of the syenitic and the granitic rocks seem to be controlled by some combination of the crystallisation of zircon + sphene, zircon + hornblende, zircon + magnetite, zircon + biotite + hornblende and zircon + hornblende + sphene + magnetite. However the granitic trend seems to have been controlled by more proportions of sphene and magnetite compared to the syenitic trend.

Rocks from Perhentian Kecil syenite have high Sr and Ba compared to the Perhentian granite. All the Perhentian can be considered as low Ba-Sr granite according to Tarney

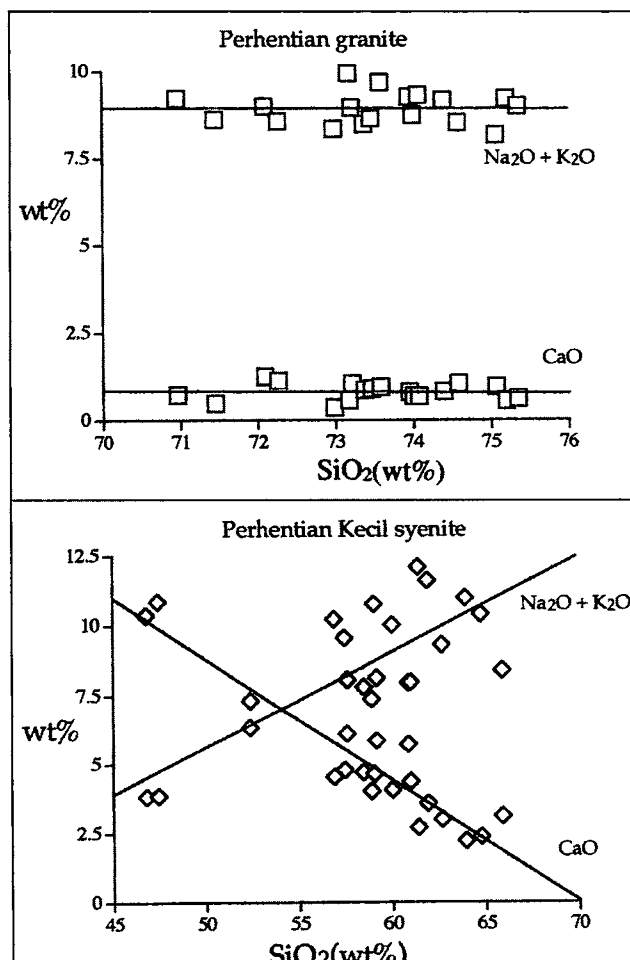

Figure 6. Combined plot Na_2O + K_2O and CaO vs SiO_2 for the (a) Perhentian granite and (b) Perhentian Kecil syenite.

and Jones (1994). This is in contrast to the syenitic rocks in which the majority of the samples contain > 1000 ppm Sr and Ba. The spider diagrams for the Perhentian Kecil syenite and Perhentian granite are shown in Figure 9. The lack of Ba enrichment and major depletion in Nb, Ce, Sr, P and Ti in the Perhentian granite is in contrast to the syenitic rocks from the Perhentian Kecil. Sr, P and Ti depletion in the granitic rocks is probably due to plagioclase, apatite and Fe-Ti oxide phases.

Rare earth elements geochemistry

REE analyses of the Perhentian intrusion are plotted on a chondrite-normalized diagram in Figure 10. All samples are generally enriched in light rare earth elements (LREE) and depleted in heavy rare earth elements (HREE). The Perhentian granite has low total REE (106-382 ppm) contents compared to the Perhentian Kecil syenite (224-450 ppm). The Perhentian granite has La_N/Lu_N ratios ranging from 0.96 - 58.8 whereas the Perhentian Kecil syenite has more wider ratios, 30.7 - 218.5. Steep REE patterns of the latter, with large La_N/Lu_N, suggest the presence of residual garnet during the partial melting event. Furthermore, some of the Perhentian Kecil syenite samples also show a slight concave upward REE pattern which may be the result of minerals such as garnet, clinopyroxene and amphibole having remained residual in their source (Williamson *et al*., 1992). The chondrite normalized pattern of the syenitic rocks are also characterized by the absence of Eu anomalies. The absence of the prominent Eu anomaly in the syenitic rocks indicates that plagioclase fractionation is not a necessary requirement in the development of this syenite intrusion (e.g Liggett, 1990).

On the other hand, the REE pattern of Perhentian granite has a pronounced Eu anomaly indicating plagioclase fractionation. One of the granite sample (sample TKG) show a typical 'seagull' shape profile with large Eu anomaly which is similar to REE profiles of other highly evolved granites and pegmatites elsewhere (e.g. Ludington, 1981; Whalen, 1983; Thorpe *et al.*, 1990; Azman, 1997). The sample generally has flat chondrite normalised patterns from LREE to HREE (except Eu anomaly). Thorpe *et al.* (1990) suggested that the low REE abundance, accompanied by negative Eu anomalies in pegmatite from the Lundy granite (cf. sample TKG), is consistent with variation resulting from fractional crystallisation of minor REE-bearing phases (e.g. apatite, xenotime, monazite and zircon) together with plagioclase and K-feldspar (e.g. Ludington, 1981; Whalen, 1983). The differing REE abundance for two samples at 73% SiO_2 indicates the presence of two discrete population in the Perhentian granite probably suggests that the granitic pluton was made up by several magmatic pulses.

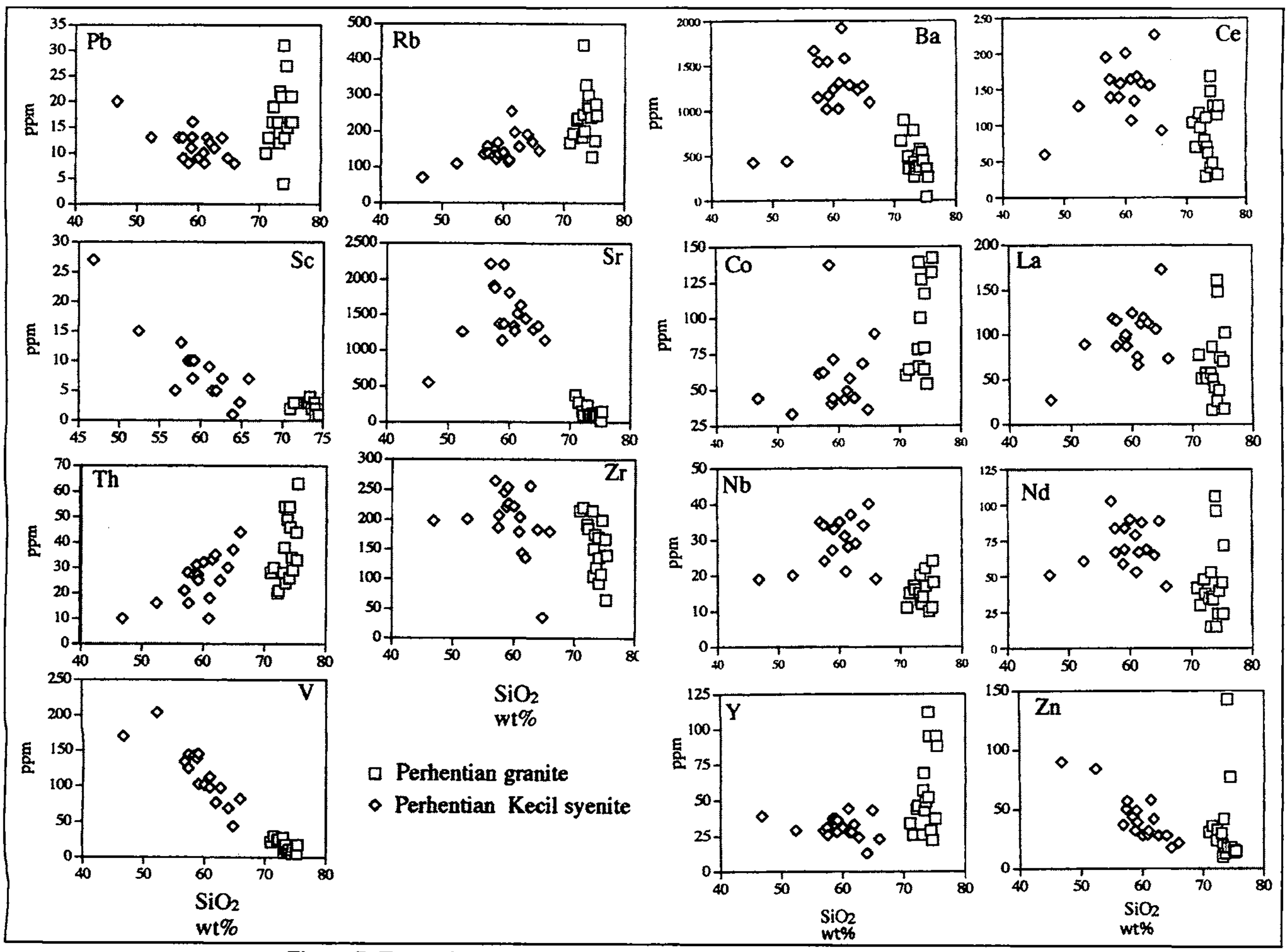

Figure 7. Trace elements Harker diagram of the syenitic and granitic rocks.

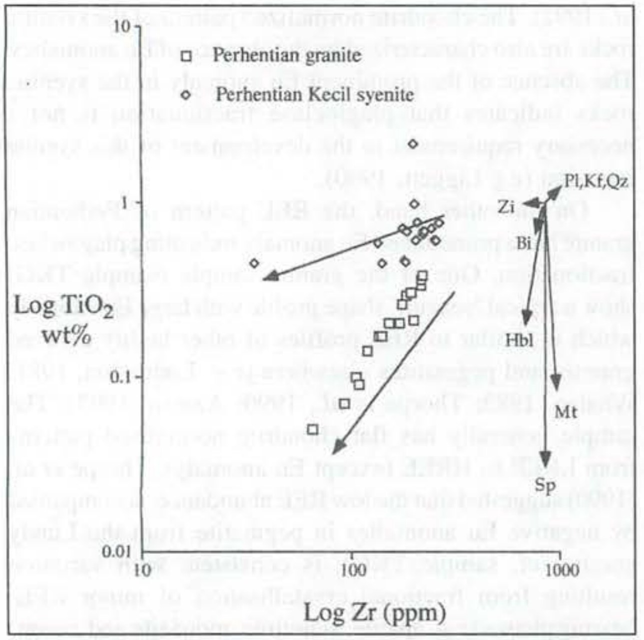

Figure 8. TiO_2 vs. Zr plot of the syenitic and granitic rocks from the Perhentian area. Mineral vectors indicate path evolved liquids for 15% of a mineral precipating: Pl = plagioclase: Kf = K-feldspar, Qz = quartz; Mt = magnetite, Sp = sphene ; Hbl = hornblende ; Bi = biotite ; Zi = zircon

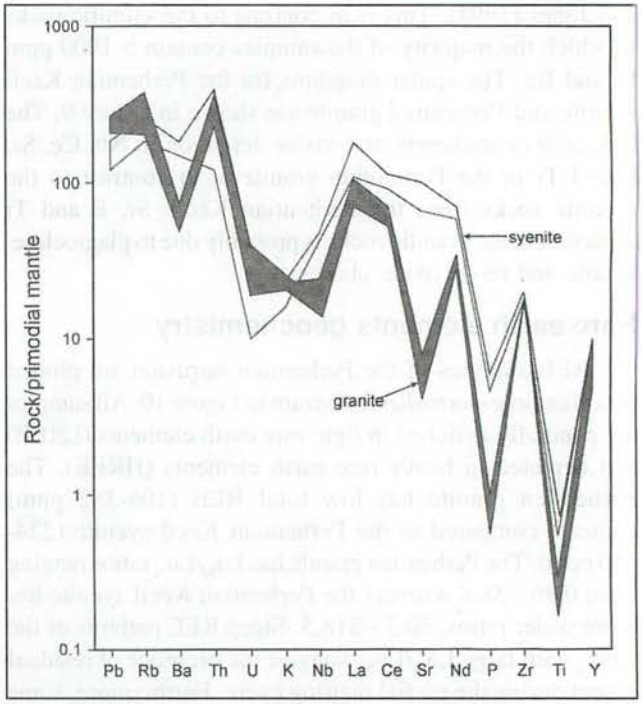

Figure 9. Multi-elements variation diagram illustrating geochemical characteristics of average Perhentian granites and Perhentian Kecil syenite. Elements are arranged with increasing incompatibility, right to left, for spinel-lherzolite mantle assemblage. Normalizing values after Sun and Mc Donough (1989). Note that the granite profile is more evolved compared to the syenitic profile.

DISCUSSION

The Perhentian complex consists of two plutons, the younger Perhentian granite and the older Perhentian Kecil syenite. They form a reversely zoned complex where the syenitic rock is rimmed by the granitic rock. The former ranges in composition from syenite to monzonite to gabbroic rocks whereas syenogranite dominates the latter pluton. The exposed contacts suggest that the syenitic rock is relatively older which is contrary to the interpretation of Dawson (in MacDonald, 1967). The angular character of the contacts strongly suggest that the granite magma intruded along early joints or fractures of the syenitic pluton. Occurrence of syenitic blocks adjacent to the contacts suggests that the granitic magma forced its way up into fractures in its roof and probably helped to detach lumps of overlying syenite. This mechanism is known as stoping (e.g. Pitcher and Berger, 1972). However, no large syenitic blocks are found, so direct evidence of large scale stoping is presently unavailable. The emplacement of the Perhentian granite magma was probably late enough to chill against the contacts (cf. Pitcher and Berger, 1972). This is evidence from the occurrence of microgranite and porphyry granite at all places where the contacts are found in the study area.

The Perhentian granite is marked by high SiO_2 contents with all samples analysed giving more than 70.9 % SiO_2. On the hand the syenitic pluton is characterized by an extended composition of lower SiO_2 compared to the Perhentian granite, from 46 to 66 % SiO_2. Thus the two plutons are separated by a compositional gap of about 5% SiO_2. The granitic rocks have significantly low Al_2O_3, TiO_2, Fe^{tot}, MnO, MgO, CaO and P_2O_5, Sr, Ba and V compared to the syenitic rocks. They also have restricted but high alkali content (Na_2O vs K_2O: 8.16 – 9.93%) compared to the average syenitic and monzonitic rocks in the Perhentian Kecil syenite (Na_2O vs. K_2O: 6.34 – 12%) (not including the gabbroic rock).

Petrographic evidence does not show any continuous lineage between the syenite and granite to suggests that they are co-magmatic. On a QAP plot, the granitic samples fall in a separate field from those of the syenitic rocks. Furthermore, the rocks from both plutons are not represented in a single lineage on a QAP diagram. The granitic samples tend to cluster in the middle of the QAP diagram, the field of granitoids formed by crustal fusion. On the other hand, the syenitic samples show a trend similar to the rocks from alkaline provinces (e.g. Bowden and Turner, 1974). The fact that both plutons are not co-magmatic is also supported by the major element geochemistry. On a K_2O vs SiO_2 diagram, rocks from both plutons show different trends, which may suggest that they evolved differently. In this diagram, the Perhentian Kecil syenite trends which cross different field boundaries do not suggest simple crystal-liquid fractionation as a main process that operated in the magma chamber. The K_2O content of the Perhentian Kecil syenite samples increase whereas the granitic samples decrease with increasing SiO_2. The former also grades from high-K calc alkali to shoshonite fields, a trend which is not compatible to a simple fractionation. Other processes that might produce the observed Perhentian Kecil syenite

Table 2. Representative chemical composition of major and trace elements for the Perhentian Kecil syenite (PKS) and Perhentian granite (PG). Rock types based on the modal analyses.

Pluton	PG	PG	PG	PG	PG	PG	PG	PG	PG	PKS	PKS	PKS	PKS	PKS	PKS
Rock types	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Granite	Syenite	Gabbro	Mz dio	Syenite	Syenite	Syenite
Sample	RTBN	BPP	TBP30	PPU1	TKG	TBP31	PKRG	PRB	PTR	MB6	G30	TBN8	TBN7	PP10	PK1
Major element oxides (wt%)															
SiO_2	70.96	75.35	74.07	73.58	75.2	73.95	73.17	73.37	73.21	61.88	46.81	52.37	59.14	58.86	62.65
TiO_2	0.33	0.17	0.17	0.14	0.05	0.21	0.11	0.26	0.21	0.58	2.13	0.97	0.68	0.68	0.60
Al_2O_3	13.97	12.74	12.74	13.89	12.42	12.84	13.61	13.37	13.37	15.66	15.52	17.91	16.2	16.53	15.75
Fe_2O_3	2.59	0.98	1.69	1.50	0.90	2.04	1.23	2.31	1.99	4.13	11.9	8.28	5.41	5.53	4.74
MnO	0.03	0.00	0.02	0.01	0.01	0.02	0.02	0.01	0.03	0.06	0.13	0.09	0.06	0.04	0.04
MgO	0.68	0.31	0.49	0.27	0.36	0.5	0.29	0.55	0.54	1.93	7.03	4.25	3.11	2.97	2.01
CaO	0.72	0.61	0.66	0.93	0.54	0.78	0.56	0.85	1.03	3.57	10.35	7.33	5.85	4.01	2.99
Na_2O	4.07	4.56	4.42	4.29	4.55	4.25	4.34	3.89	4.01	4.31	2.44	4.33	3.83	3.45	4.06
K_2O	5.14	4.44	4.88	5.38	4.66	5.01	5.59	4.51	4.95	7.28	1.38	2.01	4.30	3.93	5.24
P_2O_5	0.04	0.01	0.02	0.01	0.01	0.04	0.00	0.01	0.02	0.18	0.40	0.45	0.37	0.28	0.20
LOI	0.99	0.52	0.40	0.42	0.95	0.30	0.62	0.36	0.56	1.10	1.68	1.70	0.90	2.90	0.90
Total	99.52	99.69	99.56	100.42	99.65	99.94	99.54	99.49	99.92	100.68	99.77	99.69	99.85	99.18	99.18
Trace elements (ppm)															
Ba	662	257	365	340	36	377	261	362	423	1576	419	434	1158	1010	1275
Ce	104	127	147	62	32	168	29	70	111	168	60	127	158	139	159
Co	60	142	117	127	132	64	66	100	136	58	44	33	71	40	44
La	77	102	148	41	17	161	16	50	86	119	17	89	87	96	113
Nb	11	18	17	14	24	22	20	12	13	37	19	20	33	27	29
Nd	42	72	96	34	24	106	15	36	53	88	51	61	84	59	69
Pb	10	16	13	21	21	4	12	22	14	12	20	13	16	11	11
Rb	168	244	265	329	276	274	441	201	247	198	71	110	137	123	157
Sr	378	150	131	100	20	132	108	112	107	1634	552	1263	1372	1139	1443
Th	28	63	46	49	33	54	38	24	54	35	10	16	25	31	25
V	22	18	11	5	10	10	7	18	13	77	170	204	145	139	97
Y	34	88	95	49	95	112	57	43	69	33	39	29	36	37	24
Zn	31	15	18	13	14	18	10	42	20	42	90	84	39	32	28
Zr	215	140	136	119	65	170	105	175	151	135	198	201	227	221	256

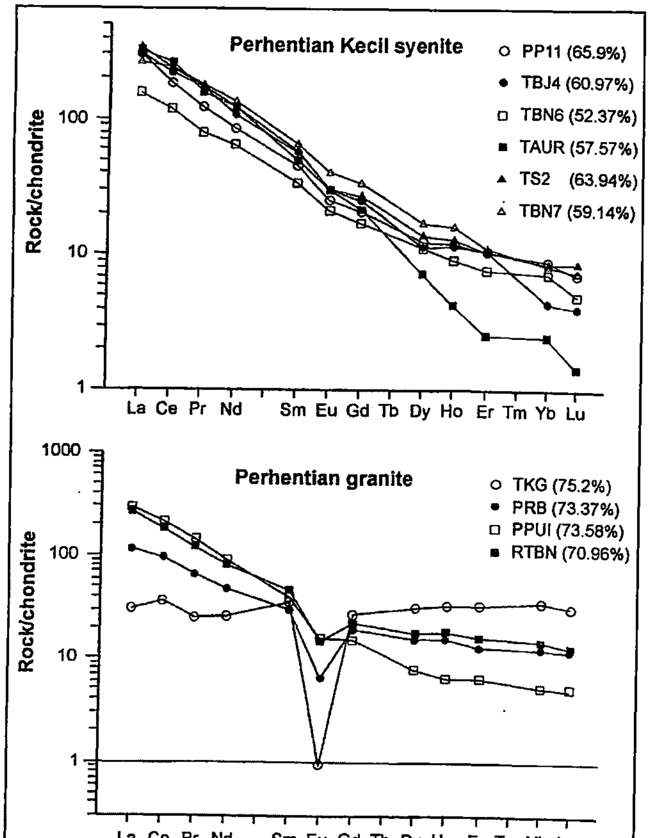

Figure 10. REE profiles for the syenitic and granitic rocks from Perhentian area.

trend is magma mixing (Roberts and Clemens, 1993).

A different trend of the plutons is also shown by the ACNK vs SiO_2 plot. The increasing trends as shown by the Perhentian Kecil Syenite pluton have been ascribed by Cawthorn and Brown (1976) to be due to the precipitation of metaluminous hornblende from the magma. On the other hand, the continuous decrease of ACNK values with increasing SiO_2 (Fig. 5) of the Perhentian granite samples shows that they evolved from peraluminous to the metaluminous fields. If one assumes that the lowest SiO_2 samples represent a composition near their source, then the source of the Perhentian granite is relatively more peraluminous (Chappell and White 1992). The difference between the syenite and granite is also shown by some of the trace element ratios, for example the Perhentian Kecil syenite has a very high Sr/Y ratio compared to the Perhentian granite. On a Sr/Y vs Y plot, syenitic samples have a similar ratio as Archean high-Al trondhjemite tonalite dacite rocks, whereas the granite samples are similar to the andesite-dacite-rhyolite rocks. Other evidence such as the high Rb/Sr in the granitic (average: 2.63) compared with $<$ 0.11 in the syenitic rocks, which is constant with SiO_2 content is not consistent with an origin by crystal fractionation between the two rocks (Fig. 11).

The Perhentian granite has low total REE (106-382) compared to the Perhentian Kecil syenite (224-450). The granite also has more restricted La_N/Lu_N ratios (0.96 - 58.8) compared to the syenitic rock which has more wider

La_N/Lu_N ratios (30.7 - 218.5). The decrease of the Eu anomaly with increasing SiO_2 (Fig. 10) indicates plagioclase fractionation. A decrease of Sr concentration with increasing SiO_2 indicates that plagioclase fractionation seems to play an important role in the evolution of the granitic magmas. Furthermore, the depletions of Sr, P and Ti mantle normalized ratios towards the more evolved facies imply a fractionation of plagioclase, apatite and Fe-Ti oxides in the magma. The steep fractionation with variable positive Eu anomalies, shown by the REE data from the Perhentian Kecil syenite indicates the presence of garnet in the source. The presence of garnet constrains the mafic source to be within the lower crust (deeper than 25 km) or upper mantle (Rudnick and Taylor, 1986). Fluctuation of REE profiles from Eu to Lu with SiO_2 values suggests that hornblende fractionation is not responsible for the HREE depletion.

The distinctive chemical characteristics for both the syenitic and granitic rocks presented above suggest that they are evolved from different sources. The association of the syenitic rocks with the gabbroic and mafic synplutonic dykes suggests that the magmas are closely related to the basic magmatism. At least in the case of the synplutonic dykes which show evidence of mixing and mingling processes (Azman, 2000b), local hybridation between basic and syenitic magmas may occur. Two analyses of gabbroic rocks associated with the Perhentian Kecil syenite show a primary mantle-derived signiture. The rock has low K_2O (< 2%) and Rb (< 100 ppm) and high MgO (> 6 %) content. Thus the gabbroic rock along with the mafic synplutonic dykes may represent a mafic association that provided heat that might initiate partial melting of overlying upper mantle or upper crust and presumably give rise to the syenitic magmas. It is suggested that the syenitic magmas formed by hydrous melting of lower crust probably as a result of underplating by, or intrusion of mantle derived basaltic magmas (cf. Johnson *et al.*,1997). The strong enrichment of large ion lithophile elements (Sr and Ba) is probably related to transfer of enriched (hydrous ?) fluids from the mantle into the lower crust, and possibly initiated melting to form the syenites (Stephens and Halliday, 1984). In contrast to the Perhentian Kecil syenite, the Perhentian granite has no mafic association. The felsic nature of the Perhentian granite suggests that it may be derived from an SiO_2 rich source or may represent a minimum melt, the first melt produced from a solid containing plagioclase-K-feldspar-quartz (Atherton, 1988).

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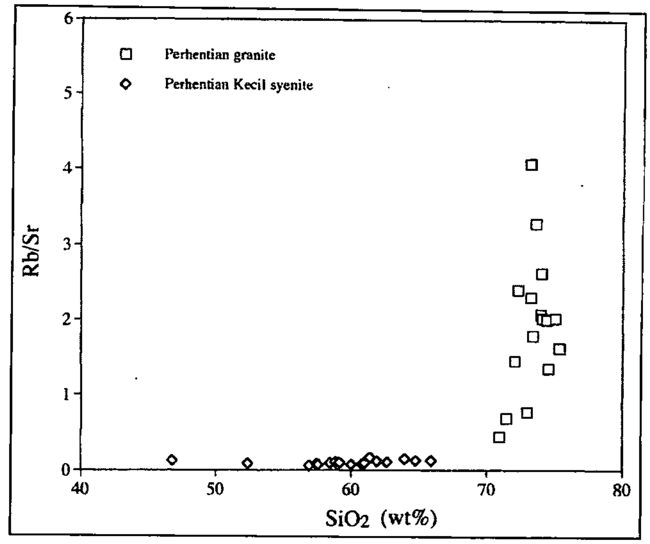

Figure 11. Rb/Sr vs. SiO_2 plot of the syenitic and granitic rocks from the Perhentian area. Note that the granitic rocks have high Rb/Sr ratio compared to the syenitic rock.

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