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

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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 monzomite to gabbroic rocks whereas syenogranite dominates the latter pluton. The syenitic rocks are characterized by an extended composition of lower SiO₂ (46 to 66 %) compared to the Perhentian granite (>70.9 % SiO₂) and have significantly high Al₂O₃, TiO₂, Fe²⁺, MnO, MgO, CaO, P₂O₅, Sr, Ba and V compared to the granitic rocks. Petrology and geochemical data indicate that both rocks are individual melt probably derived from a different source. 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 SiO₂ rich source or may represent a minimum melt, the first melt produced from a solid containing plagioclase-K-feldspar-quartz.

INTRODUCTION

The magmatism of the Eastern Belt is dominated by High-K calc-alkaline granite (SiO₂ 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 Peninsular 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
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, sphe, 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.

<table>
<thead>
<tr>
<th>Rock types</th>
<th>PERHENTIAN KECIL SYENITE</th>
<th>PERHENTIAN GRANITE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Syenite (90%) ±</td>
<td>Syenogranite ±</td>
</tr>
<tr>
<td></td>
<td>microcline ± Gabbro</td>
<td>Monzogranite ±</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Porphyritic types</td>
</tr>
<tr>
<td>Mineral assemblage</td>
<td>K-feldspar (~ 40-70%),</td>
<td>K-feldspar (~ 30 -</td>
</tr>
<tr>
<td></td>
<td>plagioclase (~ 10-30%),</td>
<td>35%), plagioclase</td>
</tr>
<tr>
<td></td>
<td>hornblende (~ 10%),</td>
<td>(~ 30 - 35%),</td>
</tr>
<tr>
<td></td>
<td>quartz (~ 5%),</td>
<td>biotite (~ 5-10%),</td>
</tr>
<tr>
<td></td>
<td>biotite, biotite,</td>
<td>hornblende, allanite,</td>
</tr>
<tr>
<td></td>
<td>sphene, epidote,</td>
<td>zircon, epidote</td>
</tr>
<tr>
<td></td>
<td>apatite, zircon</td>
<td>and magnetite</td>
</tr>
<tr>
<td>Main mafic phases</td>
<td>Hornblende, augite and</td>
<td>Biotite ± hornblende</td>
</tr>
<tr>
<td></td>
<td>biotite</td>
<td></td>
</tr>
<tr>
<td>Accessory phases</td>
<td>5 % of total rock</td>
<td>&lt; 1 % of total rock</td>
</tr>
<tr>
<td></td>
<td>Sphere, apatite</td>
<td>Apatite, epidote,</td>
</tr>
<tr>
<td></td>
<td>magnetite and</td>
<td>zircon and</td>
</tr>
<tr>
<td></td>
<td>epidote</td>
<td>allanite</td>
</tr>
<tr>
<td>Secondary phases</td>
<td>Sericite (K-feldspar)</td>
<td>Sericite (K-feldspar),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>chlorite (biotite)</td>
</tr>
</tbody>
</table>

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 platters. 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 + 10 ml 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 SiO₂, for each of the Perhentian Kecil syenite and Perhentian granite are 46.8 to 65.9% and 70.96 to 75.35% respectively.

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The Harker diagrams also show that there is a gap between Perhentian Kecil syenite and Perhentian granite at SiO₂ 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 Al₂O₃, TiO₂, FeOtal, MnO, MgO, CaO and P₂O₅ contents compared to the Perhentian granite rocks. Both plutons however overlap in the Na₂O and K₂O contents.

All rocks from both units generally have high alkali content, with Na₂O + K₂O 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 K₂O vs SiO₂ diagram (Pecceirillo and Taylor, 1976) (Fig. 4), the two gabbroic samples plot in the calc-alkali field at low SiO₂ the Perhentian granite samples plot in the high-K calc-alkaline 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...
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$_2$O + K$_2$O) 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 pluont in which the CaO and (Na$_2$O + K$_2$O) curves do not intersect. This is due to the lower CaO and higher (Na$_2$O + K$_2$O) 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 along two separate 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 4.** K$_2$O 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.

**Figure 6.** Combined plot Na$_2$O + K$_2$O 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 LaN/LuN 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 LaN/LuN, 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% SiO2 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.
syenite. They form a reversely zoned complex where the younger 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 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 SiO₂ contents with all samples analysed giving more than 70.9 % SiO₂. On the hand the syenitic pluton is characterized by an extended composition of lower SiO₂ compared to the Perhentian granite, from 46 to 66 % SiO₂. Thus the two plutons are separated by a compositional gap of about 5 % SiO₂. The granitic rocks have significantly low Al₂O₃, TiO₂, FeO, MnO, MgO, CaO and P₂O₅, Sr, Ba and V compared to the syenitic rocks. They also have restricted but high alkali content (Na₂O vs K₂O: 8.16 – 9.93%) compared to the average syenitic and monzonitic rocks in the Perhentian Kecil syenite (Na₂O vs. K₂O: 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 K₂O vs SiO₂ 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 K₂O content of the Perhentian Kecil syenite samples increase whereas the granitic samples decrease with increasing SiO₂. The former also grades from high-K calc alkal 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.


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

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La\textsubscript{N}/Lu\textsubscript{N} ratios (30.7 - 218.5). The decrease of the Eu anomaly with increasing SiO\textsubscript{2} (Fig. 10) indicates plagioclase fractionation. A decrease of Sr concentration with increasing SiO\textsubscript{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\textsubscript{2} values suggests that hornblende fractionation is not responsible for the LREE 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 syenitic dykes which show evidence of mixing and mingling processes (Azman, 2000b), local hybridization between basic and syenitic magmas may occur. Two analyses of gabbroic rocks associated with the Perhentian Kecil syenite show a primary mantle-derived signature. The rock has low K\textsubscript{2}O (< 2%) and Rb (< 100 ppm) and high MgO (> 6 %) content. Thus the gabbroic rock along with the mafic syenitic 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\textsubscript{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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