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# Petrology and geochemistry of igneous rocks from southern Tioman Island, Pahang, Peninsular Malaysia

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**Abstract:** This study reports on the petrology and geochemistry of the plutonic and volcanic on southern part of the Tioman Island. Tioman lies about 50km east of Rompin district, Pahang. The island is dominated by plutonic and volcanic rocks with minor occurrences of metamorphic rock. The plutonic rocks consist of hornblende diorite and biotite granite. The hornblende diorite shows differences in mineralogy and geochemistry when compared to the main diorite body. The volcanics are mostly rhyolite and dacite with exception of andesite on other part of the island. Metamorphic rocks include the andalusite hornfels, quartz pyroxene hornfels, quartzite and amphibolite. Field relationships and published geochronological results indicates that the granite rock intruded both volcanic and diorite rocks during the Late Cretaceous (~80 Ma).The biotite granite post-dates the volcanic rocks by about 8.8Ma. Biotite granite shows slightly older age than the main Tioman diorite by about 1.5 Ma. The geochemistry of the igneous rocks from southern Tioman Island shows that they have a high-calc alkaline affinity which suggests that they are related to arc magmatism.

**Keywords:** Tioman Island, hornblende diorite, biotite granite, rhyolite, dacite, arc magmatism, Late Cretaceous

## INTRODUCTION

Tioman Island is located about 50km east coast of Rompin district, Pahang, Peninsular Malaysia (Figure 1a). Tioman Island is located on the Eastern Granitoid Province of Peninsular Malaysia along with other islands such as Pemanggil Island, Besar Island, Aur Island and Tinggi Island forming the NW – SE trend island chains.The Eastern Granitoid Province consists of predominant I-type granitoid with subordinate S-type and A-type granitoid (Cobbing *et al*., 1992; Liew, 1983; Ghani, 2009b; Ghani *et al*., 2014; Oliver *et al*., 2014; Ng *et al*., 2015a). Tioman Island is made up of 90% igneous rocks with minor occurrences of contact metamorphosed sediments. The igneous rock consists of both plutonic and volcanic rocks with compositions varying from felsic to basic (Bean, 1972; Khoo, 1974). The metamorphic rocks are composed mostly of hornfels and minor amphibolite which are believed to predate the igneous rocks (Bean, 1972). The occurrences of volcanic rocks of eastern Tioman Island have been described by Anuar Ismail (2003) in terms of field relations, petrography and geochemistry. However, the igneous rocks on southern part of Tioman have not been studied in detail.

This paper will discuss the field relations, petrology and geochemistry of the plutonic and volcanic rocks from southern part of Tioman Island. In addition, the discovery of hornblende diorite boulders will be reported.

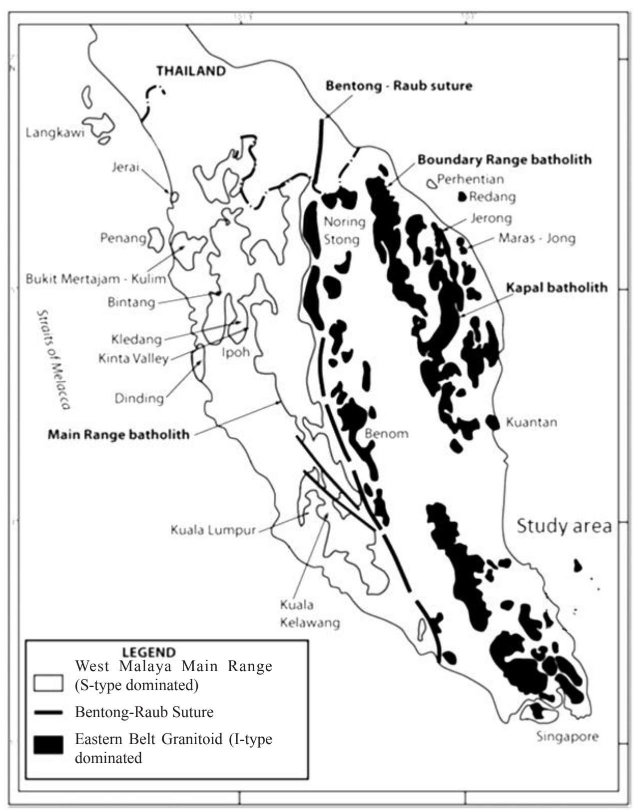


**Figure 1a:** Subdivision of the granitoid province in Peninsular Malaysia (Cobbing *et al*., 1986).

## REGIONAL GEOLOGY AND GEOLOGY OF TIOMAN ISLAND

The igneous rocks of Tioman Island are located within the Eastern Granitoid Province which is dominated by Permo-Triassic I-type arc magmatism where the composition varies from felsic to less common mafic (Cobbing *et al*., 1986; Cobbing *et al*., 1992; Ghani, 2009b; Hutchison, 2014; Ng *et al*., 2015a).The Eastern Granitoid province is actually the western margin of the Indochina terrane which is presently known as Indochina-East Malaya Block or the Sukhotai Arc (Metcalfe, 2013; Hutchison, 2014; Ng *et al*., 2015a). A geological map of Tioman Island is shown in Figure 1b.

Tioman Island mainly consists of plutonic and volcanic rocks with minor meta-sedimentary rocks. The plutonic rocks consist of granitoids that have compositional range from granitic to gabbroic while the volcanic rocks consist mainly of tuff and lava flow that have composition ranging from rhyolitic to dacitic (Bean, 1972; Anuar Ismail *et al*., 2003). The igneous rocks cover approximately 90% of the island where granitic predominates on the western side and volcanics predominate on the eastern side of the island. Intrusive rocks of diorite composition form an elongated body which is located in the east-central part of Tioman Island. The diorite made a contact to the granitic, volcanic and also meta-sedimentary rocks. Apart from the main diorite bodies, there are also occurrence of small bodies of gabbro in Tanjung Temendor and Tanjung Saing which is located on the eastern part of the island (Bean, 1972). The gabbroic is believed to have intruded into the lava and tuffaceous volcanic. The volcanic rocks cover about 40% of the island, outcropping on the eastern side. Metamorphic rocks occur as minor isolated bodies located on the north and eastern part of the island. Andalusite hornfels, quartz pyroxene hornfels, quartzite and amphibolites probably originated from sedimentary and igneous rocks. XRF analysis of major elements shows that andalusite hornfels, quartz pyroxene hornfels and quartzite are of sedimentary origin while amphibolite formed from mafic igneous rocks (Bean, 1972). The hornfels and quartzite show high contents of $SiO_2$ compared to the amphibolite which is reflected in their mineralogy. There are no presence of undeformed sedimentary rock on Tioman Island. There are several intrusions of aplite and dolerite dykes which are the youngest rocks on Tioman Island. These dykes cut through both volcanic and plutonic rocks (Bean, 1972).

## GENERAL GEOLOGY OF MUKUT AREA, SOUTH TIOMAN ISLAND

The igneous rocks of the Mukut area in the southern part of Tioman Island (refer to geology map) can be divided into biotite granite, hornblende diorite, rhyolite and dacite. These rocks can be found as in-situ bodies or as boulders to smaller pebbles.The diorite occurs as boulders with diameter of approximately 1 meter to 2 meter (Figure 2). Volcanic rocks

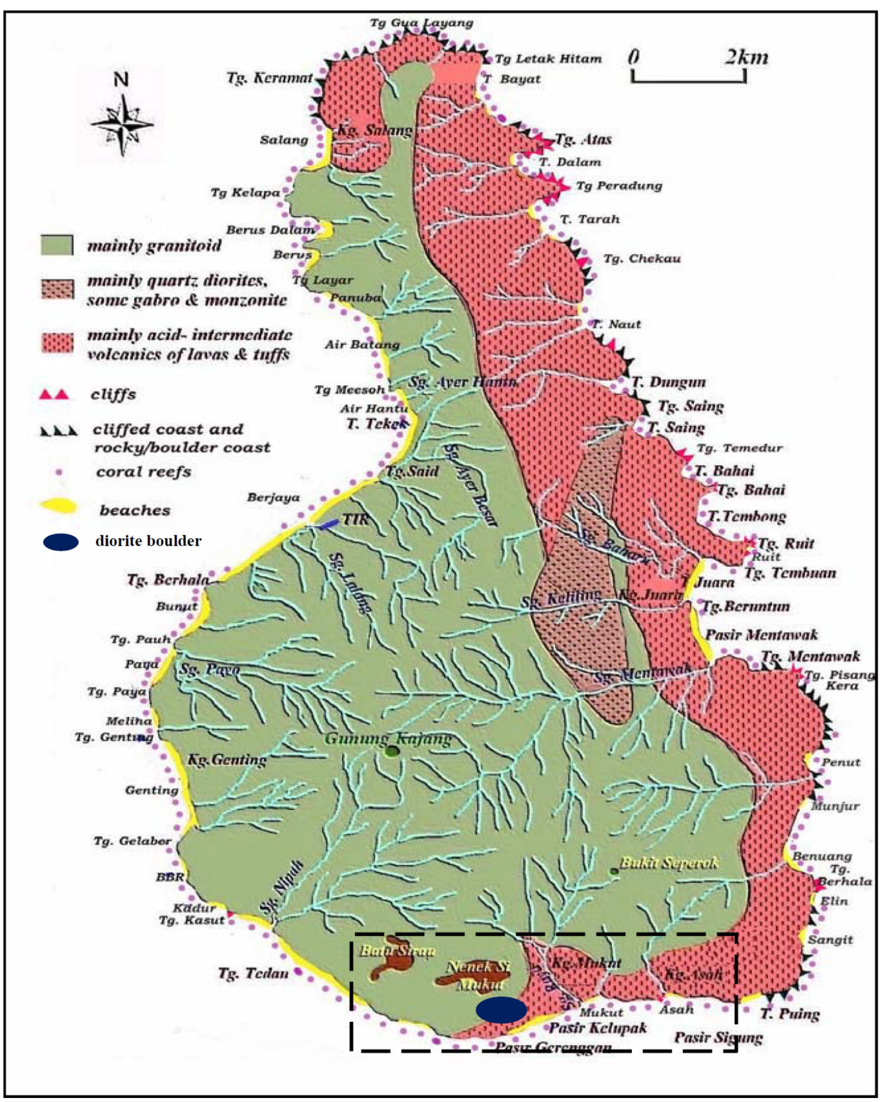


**Figure 1b:** Geological Map of Tioman Island (modified after Bean, 1972).

occur as blocky xenoliths varying from several centimeters up to 5 meters in size (Ghani *et al*., 1999) (Figure 3). Small volcanic xenoliths within biotite granite are metamorphosed to biotite bearing metavolcanic or biotite hornfels. The xenoliths range from 1.5 cm to 15 cm in diameter and are sub-angular to angular. Evidence of magma mixing and mingling between dacitic and rhyolitic melts can be found within the study area. The dark grey aphanitic rhyolite melt and light grey porphyritic dacite melt are blending together to form the mingling texture prior to cooling (Figure 4). However the field evidence as seen in Figure 4 shows that the rhyolitic and dacitic melt does not completely mixing together as no evidence of hybrid rock found on the study area. The development of most of joints in the study area are NW – SE to WNW- ESE trending joints with 70°– 75° dips toward north show the same structural trend as in the eastern part of Penyu Basin which is located at the north of Tioman Island and east of the Pahang Platform (Tjia, 1998b). There are also presence of Cretaceous volcanics at the basement of the Penyu Basin with may be related to the volcanic in Tioman island (Tjia, 1999b). Microgranite or aplite dyke has been found intruded into the granitic body at Western part of Pasir Kelupak (Figure 5**)**. Heavy minerals such as magnetite, zircons and apatite which derived from both granitic and volcanic rocks are concentrated in local beach sands (Figure 6).

**Figure 2:** Photograph of hornblende diorite from south of Tioman Island. The mafic minerals (dark) are dominated by hornblende and biotite.

**Figure 3:** Photograph shows the evidence of fine grained volcanic rock (dark) has experienced cracked which latter infilled by hornblende granite during stopping. Occurences of volcanic xenoliths are quite common in Tioman Island.

**Figure 4:** Photograph shows evidence of magma mixing and mingling between rhyolite (dark grey) and dacite (light grey).

**Figure 5:** Photograph shows the aplite dyke intrude into the volcanic rocks body. Note the aplilte formed as sharp contact with the volcanic rocks. No chilled margin is seen.

**Figure 6:** The dark layers are dominated by ilmentite, magnetite and zircon. The lighter brown colour is dominated by quartz-feldspatic minerals.

## METHODOLOGY

A total of fresh 19 rock samples were selected for thin section petrographic study and geochemical analysis. The geochemical analysis was conducted using X-ray Fluorescence in the Department of Mineral & Geoscience, Ipoh. Samples were prepared into fuse bead and pressed pellet for major and trace elements analysis respectively. Standard reference materials from USGS were used for standard calibration for igneous rocks.The results are given in Table 1. Accuracies and precision of the XRF analysis are estimated to be better than 2% for all major oxides and 5% for trace elements.

## PETROGRAPHY OF GRANITIC ROCK

The granitic rock within the study area can be classified as biotite granite. The dominant minerals in the biotite granite are K- feldspar (orthoclase), plagioclase, quartz, biotite with traces of hornblende. Biotite granite from the Mukut area is mostly medium grained with grain size between 0.6mm to 1.2mm. The microscopic textures are poikilitic hypidiomorphic equigranular to allotriomorphic equigranular. Plagioclase makes up about 37% of total rock composition and is mostly euhedral to subhedral crystal shape with sizes from 0.2 mm to 0.8 mm in diameter. Plagioclase (oligoclase) commonly shows oscillatory zoning and albite twinning. It is partly altered to sericite due to hydrothermal fluid alteration. There is also a presence of anti-rapakivi texture (plagioclase enclosed within K-feldspar) which indicates that the magma has undergone mixing process (Aslan & Aslaner, 1998). However the presence of anti-rapkivi texture is very minor which indicate the mixing process is involve to only small extend.

K-feldspar makes up about 35% of total rock. The crystals are subhedral to anhedral with some sericite alteration. Quartz formed during late crystallization and makes up about 23% of the total rock. Quartz formed as both individual and interstitial grains in between the earlier formed minerals. Most of the quartz crystals are anhedral with rare occurrences of sub-hedral shapes. Biotite (with rare hornblende) makes up about 3% to 5% of the rock. The biotite minerals pleochroic scheme varies from light brown to brown and are rarely altered to chlorite. Accessory minerals (< 1%) commonly seen in biotite granite are zircon, sphene and hornblende. This suggests that the late magma evolution is titanium-rich although the magma has already become more acidic. A microphotograph of hornblende granite is shown in Figure 7 (A – B).

### Petrography of hornblende diorite

The dominant minerals in decreasing abundance are plagioclase, hornblende, biotite, quartz, opaque, apatite and sphene. Secondary minerals include chlorite and sericite. Plagioclase (~andesine) constitutes about 60% of the total rock and is characterised by euhedral to subhedral shapes with albite twinning and oscillatory zoning. Plagioclase appears to be the earliest mineral to have crystallized. Some of the plagioclase shows corroded and cracked cores. Mason (1985) in explaining the same plagioclase texture from granitic rocks of the Coastal Batholiths, Peru, suggested that this probably represents and early or pre-emplacement plagioclase which was resorbed during the ascent of the magma. Hornblende and biotite makes up to 20% and ~5% respectively. Hornblende frequently occurs with biotite in mafic clots with accessories sphene, opaque and apatite. The hornblende ranges from individual subhedral crystals to anhedral poikilitic to ophitic textured crystals. The later enclosed numerous euhedral small plagioclase crystals which suggests that the latter commenced to crystallise earlier than biotite. The pleochroic scheme is X = Y = dark green to pale greenish yellow and Z = dark bluish green colour. Biotite makes up 10% of the rock and is subhedral to anhedral and the same size as hornblende. The pleochroic scheme is X = dark brown and Y = pale brown. Apatite occurs mainly as inclusions in biotite and less commonly in hornblende, magnetite and plagioclase. Five percent quartz occurs interstitially with plagioclase. Microphotographs of hornblende diorite are shown in Figure 7 (C – D).

### Petrography of volcanic rocks

Most of the volcanic rocks are hypocrystalline with porphyritic to aphanitic textures. Rhyolite are commonly aphanitic, daciteis commonly porphyritic. Rhyolite consists of quartz (55% – 60%), K-feldspar (15% – 20%) and plagioclase (10% – 15%) of total rock composition. Dacite

**Table 1:** Major elements and trace elements concentration of granite, diorite and volcanic rocks from study area.

| Rock Type | Granite | Granite | Granite | Granite | Granite | Granite | Granite | Granite | Granite | Granite |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample ID | 10G | 6G | CG | GRP | P18 | PT1 | PT21 | PT24 | DYK | GR |
| Symbol | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 | 16 |
| Colour | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $SiO_2$ | 75.39 | 65.35 | 64.5 | 74.71 | 72.56 | 63.07 | 63.35 | 64.61 | 63.8 | 62.8 |
| $Al_2O_3$ | 12.85 | 15.63 | 11.55 | 12.74 | 14.45 | 14.7 | 14.87 | 14.81 | 18.7 | 15.12 |
| $Fe_2O_3$ | 0.99 | 4.10 | 5.46 | 1.30 | 2.79 | 3.83 | 4.03 | 3.50 | 5.11 | 4.15 |
| $TiO_2$ | 0.17 | 0.87 | 1.58 | 0.19 | 0.19 | 0.77 | 0.80 | 0.76 | 0.72 | 0.82 |
| $Na_2O$ | 4.32 | 4.34 | 4.25 | 3.82 | 3.63 | 5.04 | 4.99 | 5.13 | 2.54 | 5.20 |
| $K_2O$ | 5.26 | 4.30 | 4.03 | 5.33 | 5.23 | 4.10 | 4.18 | 4.39 | 3.85 | 4.10 |
| CaO | 0.25 | 2.99 | 4.88 | 0.22 | 0.23 | 3.17 | 3.09 | 3.08 | 2.25 | 3.62 |
| MgO | 0.11 | 1.54 | 2.11 | 0.10 | 0.17 | 1.40 | 1.26 | 1.36 | 0.90 | 1.53 |
| MnO | 0.03 | 0.08 | 0.03 | 0.02 | 0.04 | 0.07 | 0.07 | 0.06 | 0.08 | 0.07 |
| $P_2O_5$ | 0.09 | 0.30 | 0.25 | 0.02 | 0.04 | 0.04 | 0.38 | 0.39 | 0.10 | 0.50 |
| Total (%) | 99.4 | 99.5 | 98.6 | 98.4 | 99.3 | 96.2 | 97.0 | 98.1 | 98.1 | 97.9 |
| Sr | 14 | 128 | 212 | 15 | 71 | 1195 | 1098 | 987 | 127 | 1194 |
| Ba | 102 | 76 | 22 | 85 | 1091 | 752 | 693 | 728 | 112 | 720 |
| Rb | 175 | 851 | 105 | 158 | 218 | 93 | 86 | 95 | 99 | 79 |
| Cr | 95 | 111 | 25 | 85 | 221 | 189 | 80 | 70 | 124 | 120 |
| Co | 5 | 2 | 1 | 5 | 1 | 0 | 0 | 0 | 3 | 4 |
| Ni | 2 | 0 | 0 | 2 | 5 | 6 | 9 | 10 | 8 | 1 |
| Cu | 10 | 12 | 2 | 8 | 5 | 12 | 5 | 14 | 3 | 12 |
| Zn | 8 | 2 | 15 | 14 | 5 | 5 | 18 | 12 | 19 | 5 |
| Th | 28 | 5 | 4 | 21 | 18 | 16 | 15 | 13 | 32 | 22 |
| U | 7 | 6 | 0 | 2 | 1 | 2 | 1 | 2 | 13 | 5 |
| A/CNK | 0.97 | 0.91 | 0.57 | 1.02 | 1.20 | 0.79 | 0.81 | 0.79 | 1.50 | 0.77 |
| $K_2O/Na_2O$ | 1.22 | 0.99 | 0.95 | 1.39 | 1.44 | 0.81 | 0.84 | 0.86 | 1.52 | 0.79 |

| Rock Type | Diorite | Diorite | Volk | Volk | Volk | Volk | Volk | Volk | Volk |
|---|---|---|---|---|---|---|---|---|---|
| Sample ID | D2 | D3 | PT10 | PT13 | PT16 | PT3 | PT8 | Volk | TMN |
| Symbol | 15 | 15 | 17 | 17 | 17 | 17 | 17 | 17 | 17 |
| Colour | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| $SiO_2$ | 52.04 | 55.23 | 71.39 | 73.28 | 72.78 | 63.56 | 63.78 | 66.11 | 60.28 |
| $Al_2O_3$ | 7.94 | 6.61 | 15.49 | 14.63 | 14.39 | 15.19 | 14.85 | 18.16 | 17.72 |
| $Fe_2O_3$ | 9.90 | 8.20 | 2.86 | 1.95 | 2.45 | 3.72 | 5.59 | 7.52 | 7.47 |
| $TiO_2$ | 1.41 | 1.38 | 0.36 | 0.34 | 0.33 | 0.79 | 0.95 | 0.80 | 0.80 |
| $Na_2O$ | 6.49 | 5.74 | 4.57 | 3.09 | 2.71 | 5.13 | 4.42 | 0.97 | 1.06 |
| $K_2O$ | 1.72 | 1.99 | 2.81 | 3.38 | 3.65 | 4.37 | 2.22 | 3.06 | 2.79 |
| CaO | 10.00 | 11.12 | 2.38 | 2.00 | 1.29 | 3.29 | 4.71 | 2.26 | 8.11 |
| MgO | 6.35 | 7.29 | 0.44 | 0.24 | 0.32 | 1.35 | 1.75 | 0.82 | 1.54 |
| MnO | 0.12 | 0.14 | 0.05 | 0.05 | 0.06 | 0.07 | 0.15 | 0.09 | 0.13 |
| $P_2O_5$ | 2.17 | 1.36 | 0.11 | 0.09 | 0.10 | 0.45 | 0.34 | 0.17 | 0.16 |
| Total (%) | 98.1 | 99.1 | 100.5 | 99.0 | 98.1 | 97.9 | 98.7 | 100.0 | 100.1 |
| Sr | 1679 | 2150 | 154 | 149 | 123 | 1088 | 358 | 225 | 200 |
| Ba | 305 | 489 | 188 | 268 | 289 | 761 | 526 | 122 | 479 |
| Rb | 17 | 23 | 67 | 95 | 105 | 86 | 44 | 153 | 174 |
| Cr | 85 | 111 | 251 | 259 | 210 | 150 | 80 | 15 | 120 |
| Co | 0 | 1 | 0 | 0 | 0 | 6 | 0 | 2 | 2 |
| Ni | 5 | 6 | 10 | 6 | 5 | 12 | 2 | 5 | 0 |
| Cu | 2 | 4 | 5 | 8 | 6 | 16 | 10 | 2 | 11 |
| Zn | 5 | 10 | 6 | 27 | 15 | 58 | 14 | 2 | 2 |
| Th | 12 | 10 | 19 | 15 | 22 | 28 | 22 | 45 | 2 |
| U | 2 | 2 | 1 | 5 | 5 | 2 | 2 | 5 | 5 |
| A/CNK | 0.26 | 0.21 | 1.04 | 1.18 | 1.34 | 0.79 | 0.81 | 2.01 | 0.91 |
| $K_2O/Na_2O$ | 0.27 | 0.35 | 0.62 | 1.09 | 1.35 | 0.85 | 0.50 | 3.14 | 2.63 |

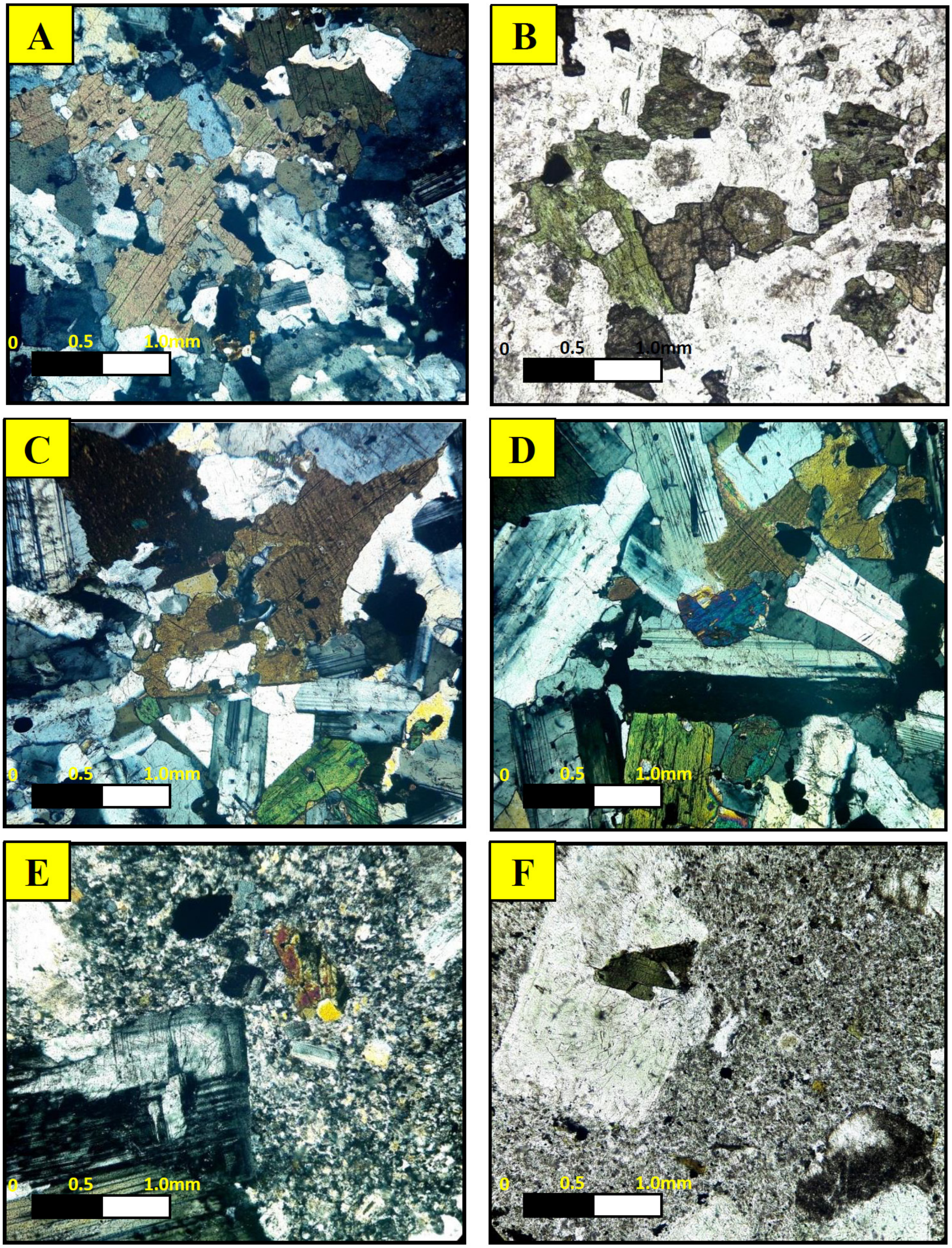


**Figure 7:** Figure shows the photomicrographs of igneous rocks from South of Tioman Island. **A:** Photomicrograph shows sample of granite which consists of quartz, plagioclase, K-feldspar, biotite and hornblende as main minerals constituent. **B:** Photomicrograph taken under plane polarized light which shows the occurrence of biotite, hornblende and sphene and less common apatite. Biotite shows light brown in colour with one set of cleavage develop parallel to its length. Hornblende shows dark brown to greenish pleochroic colour and sometimes shows 2 sets of cleavages (124$^{O}$/56$^{O}$). Sphene clearly shows high relief and formed as half diamond shape. **C:** Photomicrograph of hornblende diorite which shows the rock is dominated by plagioclase, hornblende, biotite and less common quartz and K-feldspar. Note the biotite shows dark brown colour while hornblende shows green colour. Albite twinning is very commonly seen on plagioclase grains. **D:** Photomicrograph of diorite shows the occurrence of bluish hornblende (center) and greenish hornblende grains (center bottom). Note the plagioclase also formed Carlsbad-Albite twinning. **E:** Photomicrograph of volcanic rock of dacitic composition which clearly shows porphyritic texture. The phenocrysts are composed of mainly quartz and lesser occurrence of plagiolcase and K-feldspar. Note the phenocrysts are surrounded by quartzo feldspatic groundmass. Biotite also sometimes can be found within dacite rock. **F:** Photomicrograph shows the occurrence of biotite as inclusion within feldspar mineral. This photomicrograph is taken under plane polarized light.

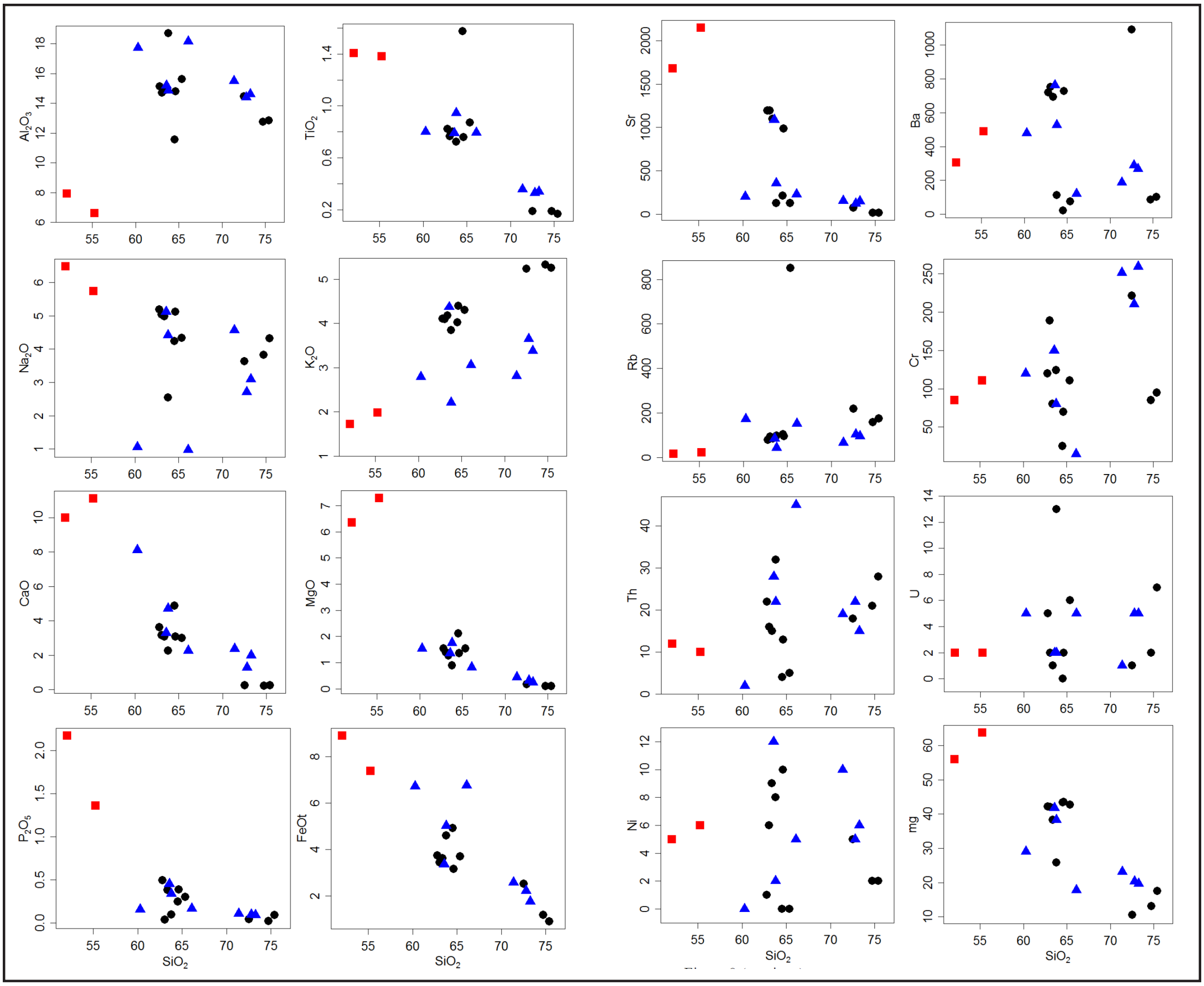


**Figure 8:** Harker diagrams for major and trace elements of hornblende granite, hornblende diorite and volcanics.

composed of quartz (40% – 50%), K-feldspar (25-30%) and plagioclase (20% – 25%). The accessories minerals that formed within rhyolite and dacite are biotite, zircon, apatite and opaque minerals. The phenocryst consists of K-feldspar, plagioclase and quartz enclosed in aquartzo-feldspatic matrix. Quartz commonly shows crystal embayment while feldspar shows evidence of resorption. Quartz mostly formed as anhedral crystals and show wavy extinction. Plagioclase formed in lath shapes and commonly shows zoning extinction and albite twinning. K-feldspar formed as subhedral crystals and shows simple twinning. Some of the feldspar grains have been partially altered to sericite due to hydrothermal effects. Biotite formed as platy mineral and is sometimes altered to chlorite. Zircon is found as inclusions within biotite and feldspar grains. Apatite formed as small tabular crystal. Opaque minerals occur as clots and as individual grains. Microphotographs of volcanic rocks are shown in Figure 7 (E – F).

## GEOCHEMISTRY

Nineteen representative rock samples (dacite, rhyolite, hornblende diorite and biotite granite) were analysed for major and trace elements (Table 1). Major and trace element Harker variation diagrams have been plotted for all the rock samples and are shown in Figure 8. The range of $SiO_2$ for each of the biotite granite, hornblende diorite, volcanic rocks are 62.8% to 75.39%, 52.04% to 55.23%, 60.28% - 73.28% respectively. In general, the plots show good trends of decreasing $Fe_2O_3$, $TiO_2$, $Na_2O$, CaO, MgO, $P_2O_5$, Mg# (Mg number) and Sr with increasing $SiO_2$. All the rock samples generally have moderate to high alkali content i.e. 6.39% to 9.57% (biotite granite), 7.73% to 8.21% (hornblende diorite), 3.85%- 9.497% (volcanics). The $K_2O$ versus $SiO_2$ plot on biotite granite, diorite and volcanics shows predominant high-K calc alkaline characteristic (Figure 9). Hornblende diorite has A/CNK value less than 1.0 which shows metaluminous characteristics while the volcanic and granite were metaluminous to peraluminous with A/CNK value between 0.5 and 2.0. Both plutonic and volcanic rocks show chemical trends compatible with liquid evolution by extraction of K- Feldspar or K- feldspar + biotite or K-feldspar + plagioclase or all these three minerals. Rb/Sr versus $SiO_2$ (Figure 10) shows a J-like shape trend that suggests the importance of feldspar crystal fractionation

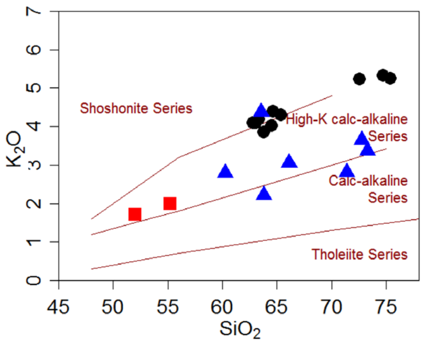


**Figure 9:** Discrimination diagram $K_2O$ versus $SiO_2$ of Peccerillo and Taylor (1976). Note most of the rock samples are plotted into high-K calc alkaline field.

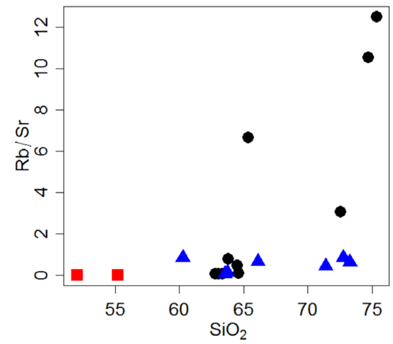


**Figure 10:** Binary diagram of Rb/Sr againsts $SiO_2$. Note the development of J-shape pattern which indicate imporatance of feldspar during magmatic fractionation.

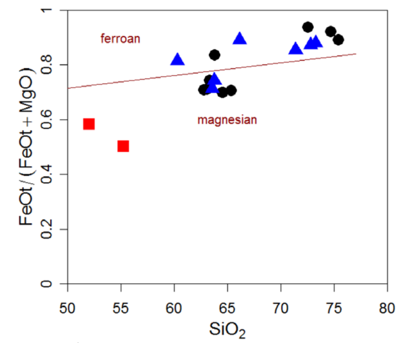


**Figure 11:** Discrimination diagram of Frost *et al.* (2001). Granite and diorite are plotted into both Ferroan and Magnesian field except for diorite samples which only plotted into magnesian field.

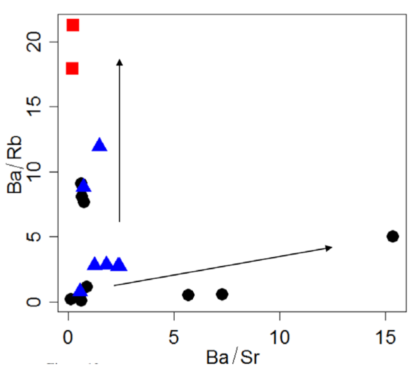


**Figure 12:** Diagram of Ba/Rb against Ba/Sr. Note that the granite samples shows 2 different pattern which reflects the different variation during magmatic evolution. Most of the rocks samples are controlled by barium and rubidium during crystal fractionation.

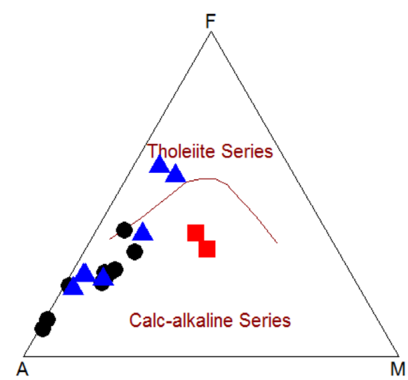


**Figure 13a:** Ternary AFM discrimination diagram after Irvine and Baragar (1971). Most rock samples are plotted within Calc-Alkaline series. A = ($Na_2O$+$K_2O$) F = (Total Fe) M = (MgO) in percentage.

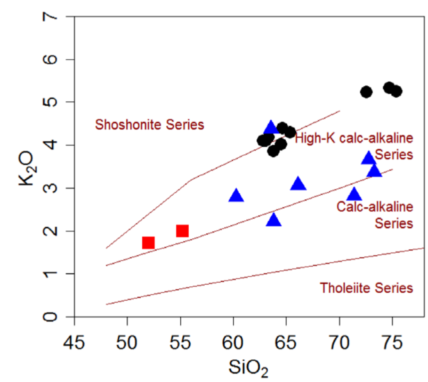


**Figure 13b:** Discrimination binary diagram of $K_2O$ against $SiO_2$ (after Peccerillo and Taylor, 1976). Note most of the hornblende diorite, biotite granite and volcanic were plot into high- K calc-alkaline field.

during magma evolution (Atherton, 1993, Ahmad *et al.*, 2002).When plotted on the discrimination diagram of Frost *et al.* (2001), granite and volcanic rock from Tioman shows both ferroan and magnesian characteristics whilst hornblende diorite only shows magnesian characteristics (Figure 11). The plot of Ba/Rb against Ba/Sr shows most of the rocks from study area are controlled by barium and rubidium magma fractionation (Figure 12). The average ratio of $K_2O/Na_2O$ for biotite granite, hornblende diorite and volcanic rocks are 1.08, 0.31 and 1.45 respectively. The average of the volcanic is quite high due to two of the volcanic sample having high values of $K_2O/Na_2O$ (i.e. 2.6 and 3.1 respectively). The ternary AFM diagram and $K_2O$ against $SiO_2$ shows that most of the rock samples plot in the calk-alkaline series (Figure 13a and Figure 13b).

## GEOCHRONOLOGY OF TIOMAN ISLAND

The igneous rocks of Tioman Island were originally thought to be of Triassic to Jurassic age based on the radiometric ages of the neighbouring Eastern Belt granites (Bean, 1972). Ghani *et al.* (1999) found field evidence for magma mixing and mingling indicating that the volcanics and granitic formed contemporaneously. U-Pb zircon and whole rock Ar-Ar radiometric dating have subsequently been carried out on both granitic and volcanic rocks from Tioman Island. Although the Ar-Ar radiometric dating is not accurate due to argon lost or gained subsequent to initial crystallization, it is the only available data of volcanic rocks from Tioman island and other adjacent island such as Pemanggil Island and Tinggi Island.

Volcanic rocks (rhyolite) from Tioman Island give a Late Cretaceous age of 88.9 $\pm$ 0.2 Ma based on whole rock Ar-Ar dating (Ghani, 2009a). Granitic rocks from Tioman give a younger age of 80.1$\pm$0.8Ma based on zircon U-Pb dating (Ng *et al.*, 2015a). Assuming that the rhyolite has not lost or gained Ar since its crystallisation, the results shown apparent difference of 9 Ma and confirm that the plutonic rocks in Tioman are younger than and intrude the older volcanics. ThePemanggil pyroxene hornblende diorite gives the same age (81.5$\pm$ 0.6 Ma) within statistical error, (Ng *et al.*, 2015a) as the granitic despite the fact that the geological map (Figure 2) shows that the hypersthene diorite intrudes and cross-cuts the granite/volcanic contact and must be younger. However, Bean (1972) has found outcrop that shows the biotite granite contained numerous inclusion diorite in Keliling river which therefore support the given zircon geochronology age. The 9 Ma difference in rock ages between the Late Cretaceous volcanic and plutonic rocks from Tioman Island indicate that both volcanics and plutonic were very probably formed within the same tectonic setting.

## DISCUSSION

Based on the geochemical data, the biotite granite and volcanic rocks show overlapping compositions and the decreasing/increasing trends on Harker diagrams that indicate that they both are petrogenetically related. However most of the biotite granites yield higher $K_2O$ contents compared to volcanics of the same silica content. This may result from a different magmatic pulse although their source rocks are related where the former has undergone higher crustal contamination. The magmatic pulse that formed the bitoite granite may have higher degree of crustal contamination where the contry rock has been assimilated with the magma during magma ascending. Again the range in aluminium saturation index from strong metaluminous to strongly peraluminous suggests that there was crustal contamination during magma ascent or heterogenous signature of the crustal (Chappell & White, 2001; Meade *et al*., 2009). The occurrences of metasedimentary rocks on Tioman Island support the hypothesis that there was (some) sedimentary input during magmatic evolution.

The hornblende diorite reported in this study is different to the quartz hypersthene diorite found in the centre of Tioman, where quartz, biotite and hornblende are notably in lesser amounts in the latter (Bean, 1972). Major elements analysis of 4 main hyperstene diorites by Bean (1972) shows that the total alkali content ($Na_2O + K_2O$) of hyperstene diorite ranging from 6.48% to 6.81% while the total alkali content of 2 samples of hornblende diorite are 7.73% and 8.21%. Other than that the CaO content of the hyperstene diorite is less than 7.5% compared to the hornblende diorite with more than 10%. When plotting all diorite samples from study area, main body hyperstene diorite and pyroxene hornblende bearing diorite from Pemanggil Island into A/CNK and $Al_2O_3$ against $SiO_2$ (Figure 14a and Figure 14b), the trend for hornblende diorite does not follow the trend of main Tioman quartz hyperstene diorite and also pyroxene diorite from Pemanggil Island which clearly shows that the hornblende diorite does not genetically related with the main pyroxene diorite from main diorite body from Tioman and Pemanggil diorite. Furthermore, hornblende diorite does not follow the Tioman granite and volcanic chemical trends on Harker diagrams and has a metaluminous characteristic with very low value of Alkali saturation Index (0.21 -0.26), again suggesting that it may be not genetically related to the biotite granite and volcanics. This is despite the fact that they have the same radiometric age. It may be the hypersthene diorite is a sample of (slightly differentiated) basalt underplated that heated, melted and mobilised the lower crustal to make the volcanics and granite.

It is hypothesised that Tioman Island was formed in a calc-alkaline volcanic arc setting. This conclusion is supported by the calc-alkaline geochemical trends and field evidence. The nearest place that has undergone extensional processes is the Penyu Basin, about 30 km north of Tioman Island. The whole rock Ar–Ar and zircon U-Pb age dates reveals that igneous rocks from Tioman Island were formed during the Late Cretaceous whereas the Penyu Basin is a Tertiary basin (Tan, 2009).

It is possible that Tioman Island formed by the far-field subduction effects of the Neo-Tethys oceanic lithosphere underneath Eastern Malaysia (Searle *et al*., 2012 and Ng *et al*, 2015b). The partial melting of subducted oceanic crust and overlying mantle could have formed the islands of

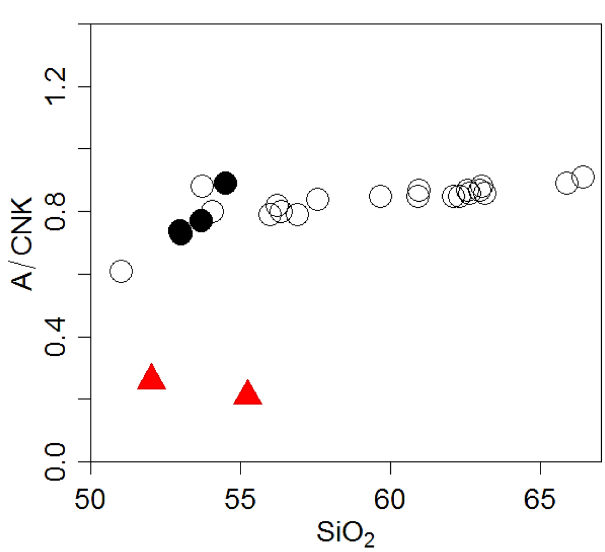


**Figure 14a:** Binary plot of A/CNK against $SiO_2$ shows that hornblende diorite from this study yield low A/CNK value compared to Tioman main hyperstene diorite and Pemanggil Pyroxene diorite.

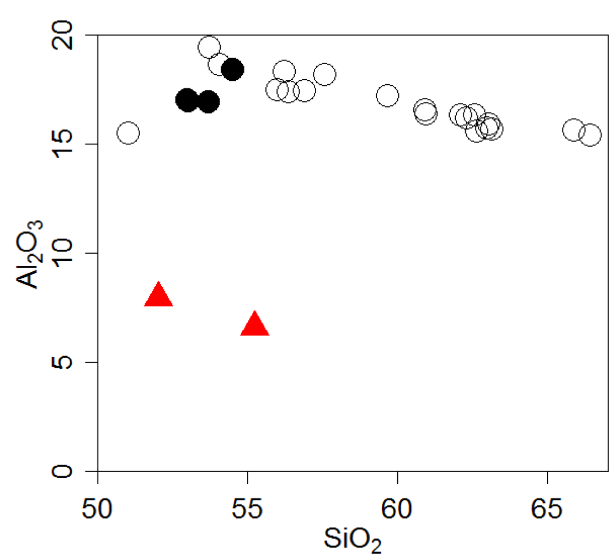


**Figure 14b:** Binary plot of $Al_2O_3$ against $SiO_2$ shows very low aluminium content compared to Tioman main hyperstene diorite and Pemanggil Pyroxene diorite.

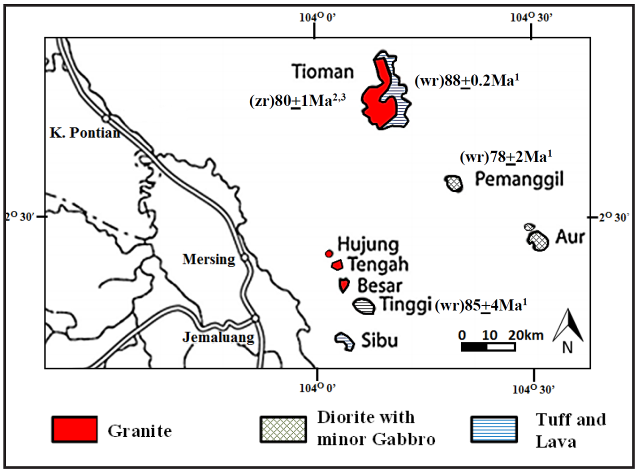


**Figure 15:** Age compilation map of Tioman, Pemanggil, and Tinggi Island. (zr = zircon U/Pb age, wr = whole rock Ar-Ar age) 1. Age data taken from Ghani, 2009a; Ghani *et al*., 2014, 2. Age data taken from Searle *et al*., 2012, 3. Age data taken from Ng *et al*., 2015b.

Tioman granite (zircon U/Pb = 80± 1 Ma), Tioman volcanic (88.9 ± 0.2 Ma), Tinggi (85 ± 4 Ma) and Pemanggil Diorite (78 ±2 Ma) (Zircon U/Pb age data in Searle *et al*., 2012, Ng *et al*., 2015b, Ar-Ar whole rock age data in Ghani, 2009a, Ghani *et al*., 2014). The compilation age of Late Cretaceous igneous rocks are shown in Figure 15. In any case, further study of the trace and REE geochemistry, and isotope chemistry of the Tioman Island rocks is needed in order to test this hypothesis.

## CONCLUSIONS

Based on geochemistry, the Tioman granite and associated volcanic rocks are cogenetic and plot in the high-calc-alkaline field which in present-day tectonic environments is related to arc magmatism.

Calk-alkaline hornblende diorite from the southern part of Tioman Island is different from calk-alkaline hypersthene diorite from central Tioman and diorite from Pemanggil, both in mineralogy and geochemistry. Hornblende diorite from this study contains higher contents of alkali ($Na_2O$ + $K_2O$), CaO, much lower aluminium saturation index (A/CNK), $Al_2O_3$ compared to main Tioman hypersthene diorite and Pemanggil pyroxene hornblende diorite. The two diorites may not be related to each other by fractionation despite their identical ages.

Published Ar-Ar whole rock and zircon U-Pb results show that the high-calc-alkaline igneous rocks from Tioman Island were formed in the Late Cretaceous. They may been formed by the far-field effect of subduction of the Neotethys oceanic plate underneath Eastern Malaysia.

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