Permian ultrafelsic A-type granite from Besar Islands group, Johor, peninsular Malaysia

AZMAN A GHANI^{1*}, FATIN IZZANI HAZAD¹, AZMIAH JAMIL¹, QUEK LONG XIANG¹,
WAN NUR ATIQA WAN ISMAIL², SUN-LIN CHUNG³, YU-MING LAI³, MUHAMMAD
HATTA ROSELEE¹, NUR ISLAMI¹, KYAW KYAW NYEIN¹, MEOR HAKIF AMIR HASSAN¹,
MOHD FARID ABU BAKAR⁴ and MOHD ROZI UMOR⁵

¹*Department of Geology, University of Malaya, 50603, Kuala Lumpur, Malaysia.*

²*J Resources Sdn. Bhd. P.O. Box 49, 27207 Kuala Lipis Pahang, Malaysia.*

³*Department of Geosciences, National Taiwan University, Taipei, Taiwan.*

⁴*SapuraKencana Petroleum Bhd, Kuala Lumpur, Malaysia.*

⁵*Science & Technology Faculty, University Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia.*

**Corresponding author. e-mail: azmangeo@yahoo.com*

The granitic rocks of the peninsula have traditionally been divided into two provinces, i.e., Western and Eastern provinces, corresponding to S- and I-type granite respectively. The Western Province granite is characterised by megacrystic and coarse-grained biotite, tin-mineralised, continental collision granite, whereas, the Eastern Province granite is bimodal I-type dominated by granodiorite and associated gabbroic of arc type granite. This paper reports the occurrence of an A-type granite from peninsular Malaysia. The rocks occur in the Besar, Tengah, and Hujung islands located in the south-eastern part of the peninsula. The granite is highly felsic with SiO₂ ranging from 75.70% to 77.90% (differentiation index = 94.2–97.04). It is weakly peraluminous (average ACNK=1.02), has normative hypersthene (0.09–2.19%) and high alkali content (8.32–8.60%). The granites have many A-type characteristics, among them are shallow level of emplacement, high Ga, Fe_T/MgO and low P, Sr, Ti, CaO and Nb. Calculated zircon saturation temperatures for the Besar magma ranging from 793° to 806°C is consistent with high temperature partial melting of a felsic infracrustal source which is taken as one of the mechanisms to produce A-type magma. The occurrence of the A-type granite can be related to the extensional back arc basin in the Indo-China terrane during the earliest Permian.

1. Introduction

A-type granites were first distinguished by Loiselle and Wones (1979) as granite with alkaline and anhydrous affinities and generated in an ‘anorogenic’ setting. With respect to I- and S-type granitoids, the A-types are characterised by their relatively high alkali and low CaO contents (at

SiO₂=70%: Na₂O+K₂O=7–11%, CaO<1.8%) and high FeO_T/MgO=8–80. It often has elevated halogen, particularly F contents (F = 0.05–1.7%), can contain water up to a few % and is characterised by low water and oxygen fugacity (Loiselle and Wones 1979). It can be met aluminous or even peraluminous (Collins *et al.* 1982). Several petrogenetic models for A-type granites have

Keywords. Ultrafelsic granite; A-type granite; peninsular Malaysia; Johor island; eastern belt.

been proposed as summarised by Bonin (2007), including:

- extensive fractional crystallization from mantle-derived mafic magmas (Turner *et al.* 1992);
- interaction of mantle-derived magmas and overlying crustal rocks (Kerr and Fryer 1993);
- anatexis of middle or lower crustal source rocks (Collins *et al.* 1982; Creaser *et al.* 1991); and
- metasomatism of granitic magmas (Taylor *et al.* 1981).

Studies show that A-type granite occurs in a wide variety of tectonic settings which include transcurrent shear zones (Nironen *et al.* 2000; Lauri *et al.* 2006); extensional regime (Smith *et al.* 1977; Mahood and Hildreth 1986; Capaldi *et al.* 1987; Johnson *et al.* 1989; Key 1989); reactivation of transcurrent shear zones within uplifts and swells (Bonin *et al.* 1987, 1998; Rämö and Haapala 1995; Christiansen *et al.* 2002), and within-plate (Gagnevin *et al.* 2003; Bonin *et al.* 2004; Tucker *et al.* 2001) settings.

Granitic rocks form about 60% of the total land area of peninsular Malaysia. They can be divided into two contrasting granite types based on mineralogy and geochemistry. They are: (1) S-type Western Belt and (2) Eastern Belt composed mainly of I-type (with minor S-type). Both granite provinces are separated by a paleo-suture known as the Bentong–Raub–Suture which represents the closure of the Tethys ocean during the Late Permian to Early Triassic. The Western Belt granite is tin-bearing, monzo- to syenogranite±granodiorite with SiO₂ content ranging from 66 to 75%. The Eastern Belt granite is bimodal and consists of granodioritic (+ monzogranite) and associated with minor gabbroic-dioritic intrusions with SiO₂ contents 68–73% and 55–60%, respectively. This paper reports the occurrence of A-type granite from the Besar island off the southeastern coast of peninsular Malaysia. We will discuss the implications of the A-type granite to the tectonism of peninsular Malaysia.

2. General geology and tectonic setting

The granitoids of southeast Asia have been grouped into north–south elongate provinces: (i) Western (southwest Thailand–east Myanmar) granite provinces, (ii) Eastern provinces (east Malaya), (iii) Main Range provinces (south Thailand–west of peninsular Malaysia and (iv) Northern provinces (N Thailand) (Hutchison 1973, 1977; Mitchell 1977; Cobbing *et al.* 1992) (figure 1). Two of the provinces exposed in peninsular Malaysia are the Eastern and Main Range provinces, also known as Eastern and Western Belt

granites, respectively (figure 2). They are separated by the Bentong–Raub suture (Metcalf 2000) and show very contrasting petrological, age, and geochemical characteristics. The Main Range granite is generally younger, i.e., 198–220 Ma (Liew and McCulloch 1985; Liew and Page 1985; Searle *et al.* 2012; Ghani *et al.* 2013a) and has been regarded as collisional granite. The Eastern granite province consists of Triassic to Permian granitoids (220–280 Ma) intruded by swarms of basaltic dykes (Haile *et al.* 1983; Ghani 2000a, b; Ghani *et al.* 2013b). The granitoids occur contemporaneous with volcanic rocks of the same age (Ghani *et al.* 2013c, 2014). The age generally becomes older eastward from the Bentong–Raub suture, with the oldest ages recorded from the eastern coastal granite outcrops such as the Maras Jong, Kuantan, and Bari granites (Liew 1983; Oliver *et al.* 2013). High SiO₂ granites for both provinces are usually restricted to veins and high-level pods or dykes. However, in unusual cases, the high SiO₂ granite can occur as small plutons characterised by homogeneous, enclave-free, and leucocratic rock. One example of a pluton sized high SiO₂ granite is the Besar granite. The granite is exposed in three islands, i.e., Besar, Tengah, and Hujung islands. The islands (referred to as the Besar Island Group in this paper) are part of Johore state, in the southern part of peninsular Malaysia. The islands are situated about 13 km off the peninsular Malaysia mainland (figure 3). The total area of granitic rocks in the three islands is about 4 km². The granite is ultrafelsic with an average SiO₂ content of ~76.5% and high K-feldspar + quartz content ~>70%.

Regionally, the Johore islands expose the eastern most plutonic and volcanic rocks of peninsular Malaysia (figure 3). The archipelago is gazetted as a National Park which consists of beautiful islands such as Tioman, Aur, Pemanggil, Tinggi, and Sibul (Khoo 1974; Ghani *et al.* 1999; Mohd Basri 2002; Ghani and Mohd Farid 2004; Ghani 2006, 2008, 2009; Ghani and Azmi 2008). A variety of igneous rocks are exposed on these islands, ranging from basic to felsic plutonic rock and pyroclastic to felsic and intermediate volcanic lava. Both Sibul and Tinggi islands are made up of pyroclastic volcanic types whereas intermediate to basic plutonic rocks (dioritic to gabbroic in composition) dominate the Pemanggil and Aur islands. The age of the plutonic and volcanic rocks in the islands is poorly known. Biotite feldspar granites from Tioman Island off the east coast of Malaysia yield a zircon age of 80±1 Ma (Searle *et al.* 2012). Ar–Ar age of biotite of the dioritic rocks from Pemanggil Island (Ghani *et al.* 2014) gives about 78±2 Ma. Both ages suggest that the Cretaceous magmatism is common within this area. Ar–Ar ages from Sibul volcanoclastic and Tinggi volcanic lavas give ages of ~300 Ma

Figure 1. Subdivision of granitoids from the southeast Asia Tin Belt (modified from Cobbing *et al.* 1992).

and ~100 Ma, respectively (Oliver *et al.* 2013; Ghani *et al.* 2014). U–Pb zircon dated Sibuluff or volcanoclastic conglomerate at 274.8 ± 5.2 Ma.

Ghani *et al.* (1999) reported evidence for an older garnet-bearing granite series in the eastern part of the Tioman Island.

Figure 2. Subdivision of granites from peninsular Malaysia showing the Eastern and Western Belts. Small box is the study area.

The Besar Island Group is made up of biotite granite, leucogranite, mafic dykes, and metasedimentary rocks (figure 4). The granitic rock is homogeneous, medium to coarse-grained, equigranular and is devoid of xenoliths and other enclaves. The metasedimentary rocks consist of an interbedded sequence of phyllite and quartzite, both varying in thickness from 0.5 to 5 cm. The granite intrudes the metasedimentary formation and this is evident from a large metasedimentary raft that occurs to the south of Tengah Island, and is intruded by a swarm of granitic veins and mafic

dykes (figure 5a and b). The veins show an irregular thickness from 5 mm to 5 cm (figure 5a). The granites have been intruded by a series of northeast-southwest trending mafic dykes with average thicknesses ranging from 0.5 to 2 m (figure 5c). A leucogranitic xenolith is found in the pyroclastic volcanic ash Sibu Island, 2 km south of the study area (figure 3d). The xenolith has a similar texture and mineralogy when compared to the Besar granite. If the granite represents part of the Besar Granite Group, then it appears that the granite is possibly older than Permian.

Figure 3. Geological map of the south Johor islands. Location map showing the southern part of peninsular Malaysia and the geology of the Johor islands.

3. Petrology

The main granite from the three islands (with average %) consists of K-feldspar (40%), plagioclase (20%), quartz (35%), biotite (<5%), amphibole (trace), apatite (trace), zircon (trace), sericite, and chlorite. Some of the leucogranites exhibit a porphyritic texture with K-feldspar, plagioclase, and quartz as the main phenocrystic phases. The phenocrysts always have irregular outlines bordered by micro-granophyric texture. Quartz sometimes displays embayed texture and resorbed outline resulting in skeletal shape.

Plagioclase (An_{4-12}) is equigranular, subhedral to anhedral and usually occurs as clusters and may represent early plagioclase, which crystallised from the melt. Some plagioclases have cracked and

corroded cores and these crystals are usually accompanied by zoned crystals. No cores with higher anorthite contents have been identified. Sericite is present mainly at the centre of the mineral. The main alkali feldspar type is perthitic orthoclase sometimes exhibit simple twinning. The crystals are usually bigger in size compared to quartz and plagioclase.

Granophyric intergrowths can be seen extensively in the Tengah and Hujung granite samples (figure 6). Quartz in the granophyric texture displays various shapes from rounded elongate to square to worm-like to tiny rounded shapes (figure 6b and d). The texture sometimes radiates from plagioclase and alkali feldspar. There are two types of quartz present: (i) large anhedral quartz grains displaying shadowy extinction indicating

Figure 4. Detailed geological map of the Besar Island. The Besar Island is the biggest island among the three islands. Other two islands, Tengah and Hujung also have the same geology.

strain (figure 6a and c) and (ii) smaller anhedral quartz associated with granophyric intergrowth. Sometimes, they form a zone of quartz blebs at the margins of plagioclase (figure 6e). The type (i) quartz usually has embayed texture especially if the crystal occurs adjacent to the intergrowth (figure 6a, c and d). Muscovite occurs as small or tiny crystals (0.1 mm-wide and up to 0.4 mm-long) associated with heavily sericitised parts of plagioclase. Sometimes, the tiny flakes are well-oriented at the centre of plagioclase, suggesting that the minerals were developed along the cracks. These textural relationships suggest that the muscovite is not primary but altered from plagioclase.

The main mafic phase is biotite and occurs less than 5% in the rock. The pleochroic scheme is X = dark brown and Y = straw yellow. The texture suggests that the mineral was early in origin because it occurs as inclusions in other essential minerals. Alteration of biotite to chlorite is common and developed mainly along the biotite cleavage. Occasionally, secondary muscovite crystals can be seen developed in the biotite cleavage. The Besar granite does not contain any amphibole as in many A-type granites reported elsewhere (King *et al.* 1997). However, there are traces of a greenish mineral, which appears similar to the green amphibole, but this needs to be confirmed using EPMA as the crystals are too small to be identified using

Figure 5. Various field photos of Besar, Tengah and Hujung islands. (a) Swarms of parallel granitic dykes and veins intruded into the metasediments raft at Tengah island; (b) contact between granite (left) and metasediments block at the Tengah island; (c) enclave of mafic dyke in the leucogranite of Hujung Island. Below the enclave is the contact between the dyke proper and the leucogranite; (d) leucogranite block found in the nearby Ash tuff formation of the Sibu Island (south of Besar Island). The tuff dated as 296–299 Ma (Ghani *et al.* 2014).

ordinary light microscope (figure 6d). The crystal occurs either interstitially or as individual anhedral shapes.

4. Geochronology

Two samples, one each from Besar (sample BES5) and Tengah (sample TG4) islands have been selected for U–Pb zircon dating. The analyses have been done at the Department of Geoscience, National Taiwan University, Taiwan. Zircons were separated from rock samples (up to 5 kg per sample) using conventional heavy-liquid and magnetic separation techniques. The zircons were cast with zircon standards in epoxy mounts that were polished to section the crystals for analysis. Cathodo luminescence images were taken for examining the internal structures of individual zircon grains and selecting suitable positions for U–Pb isotope analyses, which were performed using a New Wave

UP213 laser ablation system combined with an Agilent 7500s quadrupole ICPMS (inductively coupled plasma mass spectrometer).

The zircons from both samples were euhedral to subhedral and mostly showed long to short prismatic forms. However, the zircon crystals from TG4 sample were larger compared to the zircons from BES 5 (figure 7). Majority of the zircons were transparent, colourless to pale brown and showed oscillatory zoning indicative of magmatic growth. Thus, the interpretation of zircon U–Pb isotope data is simple and the obtained ages are interpreted as representing the crystallization time of the zircons or the emplacement age of the host rocks.

The U–Pb age results for both samples are shown in figure 8 and table 1, all the mean $^{206}\text{Pb}/^{238}\text{U}$ ages are given at 95% confidence level for both samples. All of the analyses are concordant, and the $^{206}\text{Pb}/^{238}\text{U}$ ages for BES 5 scatter between 264 and 336 Ma giving a weighted mean age of

Figure 6. Photomicrograph of the granitic rocks from the Besar, Tengah and Hujung islands. (a) Euhedral shape of quartz crystal. Coarse grained biotite granite; (b) coarse wormy K-feldspar and quartz intergrowth. Coarse grained biotite granite; (c) Quartz gleuomercrysts showing embayed texture. Coarse grained biotite granite; (d) coarse wormy K-feldspar and quartz intergrowth. Coarse grained biotite granite; (e) plagioclase gleuomercryst in leucogranite surrounded by microgranophyric intergrowth. Note the margin of the plagioclase show irregular margin invade by granophyric intergrowth; (f) plagioclase and clinopyroxene occur as a phenocrystic phase in dolerite sample. Plagioclase gleuomercryst (2 or more plagioclase phenocryst crystal cluster together) is quite common in the dyke.

281.7 ± 2.1 Ma. For TG4 sample, the $^{206}\text{Pb}/^{238}\text{U}$ ages plot between 274 and 294 Ma (mean age of 280.1 ± 2.4 Ma), with one spot giving extremely high age (1141 Ma).

5. Geochemistry

5.1 Methods

Nine representative granite samples were collected from the Hujung (2), Tengah (2) and Besar (5)

islands. All samples were crushed to a fine powder at the Department of Geology, University of Malaya, Kuala Lumpur, Malaysia. The whole-rock compositions were determined at Acme Analytical Laboratories in Vancouver, Canada. Major elements were determined by X-ray fluorescence (XRF) using a Philips PW 1404/10 X-ray spectrometer by fusing the samples with lithium tetraborate and casting into glass discs. Precision was of 2–5% for major elements, except for Mn and P (2.5–5%). Calibration was done with international standards PM-S and WS-E (Govindaraju

Figure 7. Representative of CL image of zircons for samples BES5 and TG4.

et al. 1994). Trace and rare earth elements were also analysed at the same Lab using ICP–MS. Trace and rare earth and refractory elements were determined by ICP mass spectrometry following a Lithium metaborate/etraborate fusion and nitric acid digestion of a 0.2 g sample. Precision for all trace elements ranged between 2 and 4%.

5.2 Results

All granite samples from the Besar granite are high in silica and alkalis, with SiO_2 ranging from 75.70 to 77.90 wt% and total $\text{K}_2\text{O}+\text{Na}_2\text{O}$ varying from 8.32 to 8.6 wt% (table 2). The granite is weakly peraluminous, with A/CNK value ranging from 1 to 1.16 (average 1.02). Interestingly, all the samples have normative hypersthene, ranging from 0.09 to 2.3%. Differentiation index for all granite samples ranges from 94.2 to 97.04. The granite has low Al_2O_3 and K_2O compared with the Main Range S-type granite of peninsular Malaysia. On Rb *vs.* Y+Nb and Rb *vs.* Ta+Yb diagrams (Pearce *et al.* 1984), all samples plot in within plate granite field (figure 9). All rock samples plot in the A-type field in FeOt/MgO *vs.* Zr+Nb+Ce+Y, (b) $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$ *vs.* Zr+Nb+Ce+Y, (c) $\text{K}_2\text{O}/\text{MgO}$ *vs.* $10000 \times \text{Ga}/\text{Al}$, (d) FeOt/MgO *vs.* $10000 \times \text{Ga}/\text{Al}$, (e) Ce *vs.* $10000 \times \text{Ga}/\text{Al}$, and (f)

Y *vs.* $10000 \times \text{Ga}/\text{Al}$ diagrams (figure 10) (Collins *et al.* 1982; Whalen *et al.* 1987). The Besar samples also plot in the field of ferroan granites (figure 11) following the classification of Frost *et al.* (2001). In the modified alkali lime index $(\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO})$ *vs.* SiO_2 diagram (figure 12), the Besar granites straddle between alkali calcic and calc alkali fields similar to the A-type Kaffo Valley albiteriebeckite granite, northern Nigeria (Orajaka 1986).

REE profile for the Besar granite is shown in figure 13. A majority of the rocks analysed display a striking uniformity in their REE patterns. Chondrite-normalized REE patterns show enrichment of LREE relative to heavy rare earth elements (HREE) and significant negative Eu anomalies. The total REE for the granite ranges from 268 to 615 ppm which is characteristic of high to highly felsic granite. Another interesting feature of the REE profile is that, although all the analysed samples have very high SiO_2 , the profile does not show a tetrad effect profile as shown by many other high SiO_2 granites elsewhere (Kawabe 1995; Irber 1999; Jahn *et al.* 2001; Wu *et al.* 2004; Monecke *et al.* 2007). This is also evidenced from calculated $\text{TE}_{1,3}$ for all the samples which give the value of <1.1 (Irber 1999). The $\text{TE}_{1,3}$ value of the Besar granites range from 1.0–1.09. Compared to the typical A-type granite

Figure 8. Zircon U–Pb concordia and weighted average diagram for sample (a) TG4 and (b) BES5 from the Besar granites.

(figure 13), the rocks from the study area show slightly higher total REE content and less negative Eu anomaly.

In the spider diagram (figure 14), all the granitic rocks show the characteristic negative anomalies for Ba, Nb, Sr, P, Zr, Eu, and Ti, and positive anomalies for Th, Ce, U, K, Pb, La, Nd, and Sm consistent with the patterns for A-type granites (Collins *et al.* 1982; Whalen *et al.* 1987). The troughs at Sr and Ti could be related either to the plagioclase and Fe–Ti oxides residual or to the early extraction of the Fe–Ti phases.

Figure 15 shows Zr *vs.* M diagram for the calculated temperature (M whole-rock cationic ratios $[(100\text{Na} + \text{K} + 2\text{Ca})/(\text{Al} + \text{Si})]$) for the Besar granites. All the samples from the three islands clustered at curve approximately $T = 800^\circ\text{C}$ and $M = 1.3$ to 1.4 . Calculated zircon saturation temperatures from bulk rock compositions yield a

temperature range for the Besar magma from 793° to 806°C (Watson and Harrison 1983).

6. Discussion

Geochemical study of the Besar granite indicates that the rocks have higher SiO_2 compared with other peninsular Malaysia granites and more importantly, they occur in pluton size. In other Malaysian granites, highly felsic plutonic rock ($\text{SiO}_2 > 75\%$) usually occurs as veins or aplogmatite complexes, small stocks, high-level and secondary variant two-phase granite pods within a granitic pluton or batholith. These types of granite represent a highly evolved residual magma typically associated with tin-tungsten mineralisation, greisen vein systems and are usually associated with high concentrations of U and Th and are different from the presently studied granite

Table 1. (Continued.)

U (ppm)	Th/U	Age (Ma)										Inferred age (Ma)						
		$^{207}\text{Pb}/^{235}\text{U}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	rho	$^{207}\text{Pb}/^{206}\text{Pb}$	1σ	$^{206}\text{Pb}/^{238}\text{U}$	1σ	$^{207}\text{Pb}/^{235}\text{U}$		1σ	$^{208}\text{Pb}/^{232}\text{Th}$	1σ			
BES5																		
1146	0.590	0.32330	0.00782	0.04491	0.00099	0.9002876	0.05222	0.00055	283	6	295	24	284	6	257	8	283	6
559	0.698	0.32311	0.00718	0.04350	0.00090	0.901218	0.05387	0.00052	274	6	366	22	284	6	263	7	274	6
692	0.845	0.31914	0.00703	0.04347	0.00089	0.9009832	0.05325	0.00051	274	5	339	22	281	5	261	7	274	5
640	0.546	0.32058	0.00776	0.04450	0.00096	0.9005455	0.05225	0.00055	281	6	296	24	282	6	270	8	281	6
279	0.745	0.33556	0.00802	0.04446	0.00092	0.9007823	0.05474	0.00057	280	6	402	23	294	6	274	8	280	6
491	0.562	0.32582	0.00740	0.04519	0.00092	0.8990903	0.05230	0.00052	285	6	299	22	286	6	284	9	285	6
478	0.737	0.32443	0.00917	0.04471	0.00102	0.9011481	0.05264	0.00066	282	6	313	28	285	7	252	10	282	6
478	0.526	0.32026	0.00907	0.04429	0.00101	0.9009724	0.05245	0.00066	279	6	305	28	282	7	234	9	279	6
588	0.543	0.34938	0.00848	0.04567	0.00097	0.8992685	0.05549	0.00059	288	6	432	23	304	6	300	11	288	6
454	0.539	0.32880	0.00779	0.04540	0.00090	0.8992264	0.05253	0.00055	286	6	309	24	289	6	288	11	286	6
559	0.551	0.32564	0.00761	0.04517	0.00095	0.9010079	0.05228	0.00053	285	6	298	23	286	6	282	8	285	6
620	0.539	0.32990	0.00745	0.04473	0.00092	0.8986846	0.05349	0.00053	282	6	350	22	289	6	296	8	282	6
760	0.793	0.32375	0.00724	0.04449	0.00092	0.8981164	0.05278	0.00052	281	6	319	22	285	6	278	8	281	6
989	0.657	0.31421	0.00782	0.04410	0.00097	0.9003535	0.05167	0.00056	278	6	271	25	277	6	269	9	278	6
331	0.417	0.32903	0.00836	0.04527	0.00094	0.9017411	0.05272	0.00059	285	6	317	25	289	6	294	10	285	6
344	0.428	0.32107	0.00824	0.04445	0.00095	0.9011364	0.05238	0.00059	280	6	302	26	283	6	286	9	280	6
821	0.896	0.32501	0.00734	0.04464	0.00092	0.9000333	0.05281	0.00052	282	6	321	22	286	6	279	9	282	6
638	0.562	0.32252	0.00752	0.04501	0.00094	0.8992825	0.05197	0.00053	284	6	284	23	284	6	275	9	284	6
444	0.521	0.31087	0.00743	0.04343	0.00091	0.9006727	0.05192	0.00054	274	6	282	24	275	6	269	9	274	6
226	0.319	0.35165	0.01121	0.04611	0.00096	0.9014943	0.05532	0.00088	291	6	425	35	306	8	318	17	291	6
1306	0.532	0.33290	0.00856	0.04574	0.00103	0.9009516	0.05279	0.00059	288	6	320	23	292	7	273	9	288	6
778	0.658	0.32058	0.00710	0.04446	0.00092	0.8985635	0.05230	0.00051	280	6	299	20	282	5	269	7	280	6
440	0.453	0.33092	0.00858	0.04582	0.00098	0.900321	0.05239	0.00060	289	6	302	24	290	7	297	10	289	6
334	0.577	0.33941	0.00917	0.04662	0.00103	0.9010999	0.05281	0.00063	294	6	321	25	297	7	287	9	294	6
478	0.326	0.31335	0.00721	0.04341	0.00090	0.8980025	0.05235	0.00053	274	6	301	21	277	6	265	7	274	6

Figure 9. Rb vs. Y+Nb and Rb vs. Ta+Yb for the Besar, Hujung and Tengah granites. In both plots, all samples fall in the within plate (WAG) field. VAG: Volcanic arc granite; Syn-COLG: Syn collision granite; ORG: Orogenic granite (Pearce *et al.* 1984).

which represents a pluton-sized body of highly felsic magma. Liew (1983) modelled the evolution of the main range granite and suggested that 50–70% fractionation of parental granodioritic magma is required to achieve the trace element signatures ($Rb > 500$ ppm, Ba and Sr < 50 ppm) of many of the highly felsic plutonic rock from the Western Belt of peninsular Malaysia.

The Besar granitic rock is characterized by homogeneous, equigranular, medium grained granite and is generally devoid of xenoliths and other enclaves. The granites have many A-type characteristics, among them are high Ga/Al, Fe_T/MgO , low P, Sr, Ti, CaO, and Nb, shallow level of emplacement (see discussion on textural evidence below) and high temperature magma. More importantly all the samples plot in the A-type field in Whalen *et al.* (1987) plot (figure 10). The A-type granite from the study area is much more iron enriched (figure 11) and plots in the ferroan

alkali-calcic and ferroan alkali fields of Frost *et al.* (2001). Calculated zircon saturation temperatures for the Besar magma range from 793° to 806°C which suggest that these granites represent high-temperature partial melts. The temperature is consistent with high temperature partial melting of a felsic infracrustal source which is considered as one of the mechanisms to produce A-type magma (Jung *et al.* 1998; Chappell 1999). The temperature of the Besar magma was higher compared with the haplogranitic magma (Chappell 1999), which represents a low temperature hydrous silicate melt in equilibrium with quartz and feldspar (Tuttle and Bowen 1958). It is generally accepted that the high temperature of the magma may suggest that the A-type magma originated from partial melting of tonalitic sources, which could be one of the candidates for the Besar granite source rock (Clemens *et al.* 1986; Creaser *et al.* 1991; Patino Douce 1997).

The Besar granite texture shows an abundance of graphic intergrowth, especially in thin section, which indicates the shallow level emplacement of the magma (figure 6). Micrographic intergrowths of quartz and alkali feldspars are common in the A-type magma, which is supported by experimental work by Clemens *et al.* (1986). The work suggested that most A-type granites formed from relatively high temperature, water-undersaturated, completely molten (i.e., restite-free) magmas. The quartz and feldspar proportions that form the intergrowth texture are close to near minimum-temperature melt compositions for pressures of 100–200 MPa (Whalen *et al.* 1987). Granophyric intergrowths involve quartz and alkali feldspar, intergrown on scales from submicroscopic to 1 or 2 mm. Approximately equal amounts of SiO_2 , $NaAlSi_3O_8$ and $KAlSi_3O_8$ participate in most of these intergrowths, which have a truly granitic composition. Granophyric intergrowths occur as mesostasis, ground mass, and megacrysts, and result from relatively rapid simultaneous growth of quartz and alkali feldspar from a melt, vapour, or devitrified glass.

In general, compared with the I-type granites, the A-type granites have higher HFSE, $Na_2O + K_2O$, Ge/Mg and Ga/Al, and lower Eu, CaO, and Sr (Loiselle and Wones 1979; Collins *et al.* 1982; Whalen *et al.* 1987). Highly felsic rocks of I-, S- and A-types often overlap in geochemical character as they converge towards the minimum temperature composition (e.g., Tuttle and Bowen 1958; Chappell 1999). Such rocks are very siliceous with 73–77% SiO_2 , low Al_2O_3 , MgO, CaO and high Na_2O , K_2O , SiO_2 , Al_2O_3 . Na_2O and K_2O do not vary greatly in amount. This makes it difficult to discriminate most of the A-type granites consisting of highly felsic rocks. Several attempts have

Figure 10. Various plot of the Besar granite samples (a) FeOt/MgO vs. Zr+Nb+Ce+Y ; (b) $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{CaO}$ vs. Zr+Nb+Ce+Y ; (c) $\text{K}_2\text{O}/\text{MgO}$ vs. $10000*\text{Ga}/\text{Al}$; (d) FeOt/MgO vs. $10000*\text{Ga}/\text{Al}$; (e) Ce vs. $10000*\text{Ga}/\text{Al}$ and (f) Y vs. $10000*\text{Ga}/\text{Al}$ (Collins *et al.* 1982; Whalen *et al.* 1987). I: I-type, S: S-type, A: A-type; blue field: peninsular Malaysia I-type granite field; red field: peninsular Malaysia S-type field.

Figure 11. Fe index vs. SiO_2 (%) of the Besar group granites (Frost *et al.* 2011), boundary between ferroan and magnesian rocks from Frost and Frost (2008).

Figure 12. Modified alkali lime index $(\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO})$ vs. SiO_2 (%) of the Besar group granites (Frost *et al.* 2011). Boundaries between calcic, calc-alkalic, alkali-calcic and alkali granitoids from Frost *et al.* (2001).

Figure 13. Primitive-mantle normalized spidergrams for the Besar granite. Elements are arranged in the order of decreasing incompatibility from left to right. The primitive-mantle values are from Sun and McDonough (1989).

Table 2. Major, trace element and REE data for the Besar, Tengah and Hujung granites and associated dykes.

	BH2	BH4	BT6	BT10	BES1	BES2	BES3	BES4	BES6
Rock type	Gra	Gra	Gra	Gra	Gra	Gra	Gra	Gra	Gra
Location	Hujung	Hujung	Tengah	Tengah	Besar	Besar	Besar	Besar	Besar
%									
SiO ₂	75.7	76.6	77.4	77.9	77.39	77.45	77.35	76.87	77.31
TiO ₂	0.14	0.17	0.21	0.16	0.09	0.09	0.09	0.11	0.08
Al ₂ O ₃	12.08	12.1	11.72	12.21	12.14	11.98	12.01	12.44	12.05
Fe ₂ O ₃ (T)	1.54	1.34	0.89	0.68	1.67	1.57	1.52	1.74	1.42
MnO	0.03	0.17	0.02	0.01	0.02	0.02	0.03	0.02	0.02
MgO	0.05	0.04	0.08	0.03	0.02	0.02	0.02	0.03	0.03
CaO	0.46	0.38	0.42	0.22	0.34	0.39	0.44	0.43	0.44
NaO ₂	3.54	3.45	4.69	3.56	3.96	3.76	3.52	3.48	3.52
K ₂ O	4.9	4.88	2.97	4.97	4.57	4.73	4.99	5.12	4.8
P ₂ O ₅	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
LOI	0.58	0.63	0.6	0.52	0.49	0.49	0.64	0.66	0.60
Total	99.03	99.77	99.02	100.1	100.8	100.6	100.7	100.5	100.3
ppm									
Ba	585	630	630	534	472	500	509	661	548
Co	1.4	0.4	0.4	0.3	0.6	0.6	0.6	1	0.4
Cs	4.4	3.2	1.6	2.6	3.8	3.7	4.2	4.3	3.5
Ga	18.6	17.7	15.2	19.1	19.9	18.8	21.3	19.8	19.3
Hf	6.6	6.2	5.9	7	7	6.7	6.8	6.7	7.1
Nb	14.7	17.3	16	17.9	18.6	17.8	17.9	16.7	17
Rb	212	208	115	196	210	222	246	223	225

Table 2. (Continued.)

	BH2	BH4	BT6	BT10	BES1	BES2	BES3	BES4	BES6
Rock type	Gra	Gra	Gra	Gra	Gra	Gra	Gra	Gra	Gra
Location	Hujung	Hujung	Tengah	Tengah	Besar	Besar	Besar	Besar	Besar
Sn	5	11	4	3	9	7	6	3	5
Sr	34	30	53	27	26	23.5	25.1	36.1	26.6
Ta	1.1	1.3	1	1.4	1.4	1.4	1.7	1.4	1.5
Th	22	24	25	25	24	23	22	22	22
U	5.6	5.8	3.7	6.1	6.6	6.4	5.9	6.4	7
W	2.5	1.4	1.3	1.2	1.9	1.8	1.8	0.9	0.7
Zr	171	162	172	186	181	181	176	190	181
Y	179	83	55	54	81	75	76	148	95
Mo	1.3	1.9	0.4	0.2	1.8	1.6	1.5	1.4	0.8
Cu	7.1	9.5	4.4	2.1	6	3.8	5.5	5.3	3.4
Pb	15.5	16.9	5.8	7.9	26.1	25	15.9	18.6	29
Zn	150	93	37	37	79	51	58	40	57
Ni	2.2	2.7	2.7	1.2	2.8	1.9	2.6	4.1	1.8
La	121	73.1	86.7	48	55.3	59	59	85	70
Ce	215	150	191	110	115	124	118	160	140
Pr	28	17.4	21	12.2	13.6	14	14	19	16
Nd	122	68.4	83	49.5	51	53	52	78	59
Sm	26.4	13.7	14.5	9.9	12	11	11	18	13
Eu	2.2	1.1	1.1	0.7	0.77	0.71	0.71	1.25	0.84
Gd	29	14.1	12.8	9.54	12.6	12	12	24	14
Tb	5.6	2.7	2.3	1.85	2	2	2	4	2
Dy	31.1	16.1	12.7	10.8	14	13	13	26	15
Ho	4.9	2.8	2.2	1.9	2.9	2.8	2.8	5	3
Er	15	8.8	6.6	6.4	8.9	8.3	8.2	14.6	9.6
Tm	1.9	1.2	0.9	0.9	1.3	1.3	1.2	1.9	1.5
Yb	11.6	7.5	5.7	5.7	8.6	8	8	11.6	9.34
Lu	1.6	1	0.9	0.9	1.2	1.2	1.2	1.6	1.4
DF	94.2	95.01	94.89	97.04	95.64	95.47	95.16	94.74	94.78
A/CNK	1.01	1.04	1	1.05	1.01	1	1	1.03	1.02
Hy	0.12	0.09	0.44	0.27	2.19	2.02	2.01	2.3	1.89
Mt	1.3	1.13	0.58	0.42	0.28	0.25	0.25	0.28	0.23
Ilm	0.26	0.32	0.39	0.3	0.17	0.17	0.17	0.20	0.15
N+K	8.37	8.32	8.53	8.59	8.53	8.49	8.51	8.6	8.32
F/F+M	0.99	0.95	1	0.98	0.99	0.99	0.99	0.98	0.98
N+K-C	8.19	8.32	8.49	8.55	8.19	8.10	8.07	8.17	7.88
TE _{1,3}	1.05	1.09	1.09	1.05	1.03	1.03	1.0	1.0	1.02

DF: Differentiation index; A/CNK: Mol $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}+\text{K}_2\text{O}+\text{CaO}$; Hy: Hypersthene normative; Mt: Magnetite normative; Ilm: Ilmenite normative; n.d: not determined; LOI: Loss on ignition; Na+K : $\text{Na}_2\text{O}+\text{K}_2\text{O}$; F/F+M: $\text{FeO}/(\text{FeO}+\text{MgO})$; N+K-C: $\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO}$, TE_{1,3}: degree of tetrad effect.

been made to discriminate A-types from the others (e.g., Collins *et al.* 1982; Whalen *et al.* 1987; Sylvester 1989; Eby 1990, 1992; Frost and Frost 2011). The SiO_2 content of the Besar granite is generally similar to the haplogranite from the Lachlan Fold Belt (Chappell 1999). The major element content of the Lachlan Fold Belt is characterized by 73 to 77% SiO_2 , low Al_2O_3 (<13%), low MgO (0.04 to 0.79%), CaO (0.32 to 1.68%), and transition elements (see table 2

in Chappell 1999). Interestingly, Al_2O_3 , MgO, and CaO contents of the Besar granite are much lower compared with the haplogranite from the Lachlan Fold belt, i.e., Al_2O_3 (<12.5%), MgO (0.0–0.08%), CaO (0.0–0.46%) respectively. This large amount of high SiO_2 granite may imply that the source rock was relatively homogeneous and not highly variable in composition; otherwise, the anatexis would have produced large heterogeneities.

Figure 14. Rock chondrite REE profile of the Besar granite. Sample and its SiO₂ content are shown in the legend.

Figure 15. Zr (ppm) vs. M [(100Na+K+2Ca)/(Al.Si)] for the granite from Besar Island Group.

It is generally accepted that the subduction of Paleo-Tethys oceanic floor beneath Indo-China

terranes started in Early Permian (Metcalf 2000; Sone and Metcalfe 2008) (figure 17). The subduction caused an early magmatism along the eastern margin of the Indo-China terrane which resulted in the development of the Sukhotai island arc system (Sone and Metcalfe 2008; Metcalfe 2013). At the same time (most earliest Permian), convection asthenosphere driven by the downward drag of the down going oceanic slab caused a spreading and produced the back arc basin behind the magmatic arc (Sukhotai Arc) (figure 16). Regional extension occurs when continental lithosphere breaks in response to long-lived mantle perturbations, when hot mantle rises and erodes continental lithosphere, leading to full-scale rifting (e.g., Santosh *et al.* 2010). Sone and Metcalfe (2008) and Metcalfe (2013) suggested that these back arc basins now represent Nan suture and Sra Kaeo suture of central and southern Thailand, respectively (see figure 17 for the location of both sutures). According to Sone and Metcalfe (2008), these two sutures (Nan and Sra Kaeo) contain Permian melanges and ophiolites (e.g., Hada *et al.* 1999). Metcalfe (2013) suggested that these back arc sutures can be traced southward to the eastern offshore Malay

Figure 16. Diagram showing the tectonic evolution of Sundaland (Thailand–Malay peninsula) and evolution of the Sukhothai Arc System during Late Carboniferous–Early Jurassic times. Note also the formation of back arc basin in the early to Middle Permian – Jinghong-Nan-Sra Kaeo Back arc basin. Diagram taken from Metcalfe (2013).

peninsular, where the study area is located. Evidence of highly deformed carboniferous continental margin sequences along the eastern part of Malay peninsular may be the expression of orogenic deformation related to the closure of the back arc basin (Metcalfe 2013). The extension

causes the hot asthenosphere rises, undergoes decompression melting, and induces melting in the overlying continental crust. Both regional extensional regimes have been proposed as likely tectonic regimes for A-type granites and related rocks.

Figure 17. Tectonic subdivision of mainland SE Asia Sundaland showing the Sukhothai Arc terranes and bounding Palaeo-Tethys and back-arc suture zones. Diagram taken from Metcalfe (2013).

7. Conclusion

This paper reports the first possible occurrence of A-type granite from peninsular Malaysia. The granite occurs in the Besar, Tengah, and Hujung islands off the southeastern part of peninsular Malaysia. The granite is characterized by high SiO_2 (>76%) and a texture dominated by

granophyric intergrowth. The granite is mildly peraluminous, with a high calculated zircon temperature, high Ga, Fe_T/MgO , low P, Sr, Ti, CaO, and Nb and can be classified as A-type granite. The granite is characterized by shallow-level emplacement texture such as abundant granophyric intergrowth, which is common in A-type granite elsewhere.

Geochemical data showed that the granite is highly felsic A-type granitic rock with SiO₂ ranging from 76.24% to 77.90% (differentiation index=94.2–97.84). The granite has normative hypersthene (0.09–0.44%) and high alkali content (7.88–8.59 wt%). Calculated zircon saturation temperatures for the Besar magma ranging from 793° to 806°C is consistent with high temperature partial melting of a felsic infracrustal source, which is taken as one of the mechanisms to produce A-type magma. REE and spidergram patterns are consistent with an A-type magma. The granite is characterized by shallow level emplacement texture such as abundant granophyric intergrowth. The occurrence of A-type granite can be related to the extensional back arc basin in the Indo-China terrane during the earliest Permian.

Acknowledgements

This work presents a preliminary study of the Johor Island, southeast of peninsular Malaysia. The field work on these islands was done by AAG with the help from FI, WAWI, QLX, KKN, AJ, MHR, and MFAB. The geochemical work sponsored by University Malaya Research Grant No. RG041/09AFR and University Malaya PPP Grant No. PV087/2012A. Geochronological analyses were done in Department of Geosciences, National Taiwan University (under the supervision of SLC and YML) and partly sponsored by High Impact Research Grant UM/MOHE No. (UMC/HIR/MOHE/SC/27) and Post Graduate Research Grant PG095-2012B. AAG acknowledge NSC Grant No. 101-2811-M-002-133 (Republic of China) for fellowship in the Department of Geoscience, National Taiwan University, where most of the manuscript was written. The manuscript benefited from comments and suggestions by Dr N A Majid and the two reviewers are greatly acknowledged.

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MS received 27 February 2014; revised 7 July 2014; accepted 11 July 2014