

'Mantle plume' type magmatism in the Central Belt of Peninsular Malaysia and its tectonic implications

MUSTAFFA KAMAL SHUIB AND AZMAN A. GHANI

Geology Department, University of Malaya
50603 Kuala Lumpur

Abstract: None of the existing tectonic models of Peninsular Malaysia fully explains the spatial, age or geochemical characteristics of the Central Belt intermediate to basic igneous rocks. The Central Belt granitoids, which lie critically close to the Bentong-Raub Line, have distinct geochemical characteristics. They have very high LIL elements, i.e. Ba and Sr are nearly 1,000 times rock/mantle. The high Ba and Sr values may result from the penetration of the lower lithosphere by a small volume of mantle material that is enriched in those elements attributed to 'mantle plume' type magmatism. Other supporting evidences include the presence of bimodal magmatism, the presence of mafic enclaves of older granitoids in younger granitoids and the new age data indicated that there is a significant time interval (up to between 30 Ma) between the first mafic magmatism and the later felsic magmatism; the Central Belt plutons are post-orogenic and pencontemporaneous with rapid post-orogenic uplift, and erosion with the development of the Jurassic-Cretaceous continental deposits of the Central Basin; the presence of thin continental crust beneath the Central Belt; the Benom granite has yielded an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7079, which points to an origin in highly enriched lithospheric mantle; and the presence of mafic enclaves is consistent with a mafic lower crust beneath central belt formed by underplating. A model have been proposed that involved the oblique convergence of the two tectonic provinces of Peninsular Malaysia where slab breakoff which is the natural consequence of the attempted subduction of the continental crust is invoked to account for the 'mantle-plume' type magmatism of the Central Belt. The outcome of the slab breakoff is the long linear belt of single plutons characterized by high-K, shoshonitic granitoids with characteristic trace element signatures, specifically high Ba and Sr, which lie critically close to the Bentong-Raub Line. Other features include the bimodal association of mafic and felsic rocks, the low grade regional metamorphism, thinned continental crust, rapid uplift and erosion with the development of extensional/transensional basins.

INTRODUCTION

The granitoid and other igneous rocks of the Central Belt of Peninsular Malaysia form a long, narrow, and a well defined chain of plutons. These complex suites of igneous rocks intruded into low grade Permo-Triassic sediments which lies adjacent to the Bentong-Raub Line. The Central Belt intermediate to basic igneous rocks have been studied by several workers (Scrivenor, 1931; Richardson, 1939; Khoo, 1968; Hutchison, 1971; Jaafar, 1979; Khoo and Tan, 1983; Tan and Khoo, 1993; Mohd Rozi Umor and Syed Sheikh Almashoor, 2000; Azman A. Ghani and Mustafa, 2002).

These plutons which lie critically close to the boundary between the Western and Eastern Provinces of Peninsular Malaysia have distinct geochemical characteristics. New trace element data from these plutonic rocks shows that they have very high LIL elements, i.e. Ba and Sr are nearly 1,000 times rock/mantle. The high Ba and Sr values may result from the penetration of the lower lithosphere by a small volume of mantle material that is enriched in those elements (Azman A. Ghani and Mustafa, 2002)

None of the existing tectonic models of Peninsular Malaysia fully explains their spatial, age or geochemical characteristics. In this presentation we will relate the distinct geochemical signature of the Central Belt granitoids to

'mantle plume' type magmatism and discuss their implications on the geotectonic development of Peninsular Malaysia.

THE CENTRAL BELT GRANITOIDS

The Central Belt granitoids and other igneous rocks (Fig. 1) includes from north to south, the Kemahang Granite, the Senting pluton, the Benta plutonic complex and the Benom pluton, the Teris, Tapah, Palong, Manchis, Ma'Okil and Batu Pahat plutons. They were emplaced into low grade Permo-Triassic sediments with the exception of the Kemahang Pluton which intruded into low grade greenschist to amphibolite facies metasediments of the Taku Schist. Some of the plutons showed strong deformation but others are relatively undeformed (Cobbing *et al.*, 1992).

Among the Central Belt plutons the most well studied are the Benta plutonic complex and the Benom pluton (Fig. 2, Scrivenor, 1931; Richardson, 1939; Khoo, 1968; Hutchison, 1971; Jaafar, 1979; Khoo and Tan, 1983; Tan and Khoo, 1993; Mohd Rozi Umor and Syed Sheikh Almashoor, 2000; Azman A. Ghani and Mustafa, 2002). This complex suite of igneous rocks consists of (from the oldest to the youngest) strongly foliated K-feldspar megacrystic gabbro or diorite, unfoliated K-feldspar megacrystic gabbro or diorites, K-feldspar megacrystic

syenite, monzonite with lesser amount of dolerite dykes and mafic microgranular enclaves (Mohd Rozi Umor and Syed Sheikh Almashoor, 2000). Mafic magmatic enclaves are ubiquitous in the complex. They occur as isolated inclusions in the silicic plutons and as packed masses in the intermingled zones of the gabbro-diorite unit. The mafic enclaves typically display round and pillow-like shapes, igneous textures, and chilled margins, and thus denote the mingling of mafic and felsic magmas. They were emplaced into low grade Permo-Triassic metasediments which include calc-silicates, pelitic hornfels and lesser amount of quartzites. These characteristics suggest that the intrusive complex represent a deeply eroded, shallow level plutonic complex.

The K/Ar ages for the rocks yield an age from Jurassic to Lower Cretaceous (Hutchison, 1977; Mohd Rozi Umor and Syed Sheikh Almashoor, 2000). According to Mohd Rozi Umor and Syed Sheikh Almashoor (2000), the K/Ar ages for the syenite is 127 Ma, diorite is 157 Ma and Monzonite 163 Ma. They attribute the old age of the monzonite which should be the youngest to the contamination by diorite. But the more reliable Rb/Sr age of the Benom Pluton yield an age of 207 Ma (earliest Jurassic, Cobbing *et al.*, 1992), and Triassic (Hutchison, 1977).

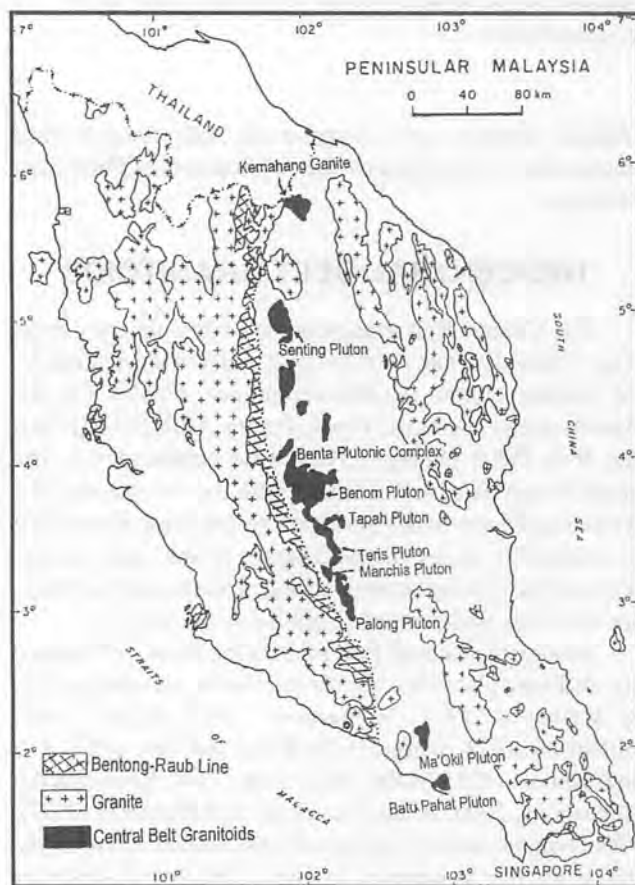


Figure 1. The granites of Peninsular Malaysia showing the long line of the Central Belt plutons in relation to the Bentong-Raub Line.

GEOCHEMICAL CHARACTERISTICS

The Benta plutonic complex are predominantly high-K, shoshonitic (Fig. 3) with I type characteristics. On the K_2O vs SiO_2 plot the whole dataset lies in the shoshonite field. On the Rb vs (Nb + Y) diagram, all the Benta pluton lies in the syn-collisional field (Fig. 4). New trace element data from these granitoids shows that they have very high LIL elements. The igneous rocks near Raub contain barium from 2,401 to 10,744 ppm with a mean of 4,590 ppm and Sr from 578 to 2,340 ppm with a mean of 1,000 ppm (Table 1). Mohd Rozi Umor and Syed Sheikh Almashoor, 2000 found that the igneous rocks near Benta contain barium from 2,826 to 4,333 ppm with a mean of 4,342 ppm and Sr from 644 to 958 ppm with a mean of 829 ppm. Cobbing *et al.*, 1992, recorded a sample from the Boundary Range batholith near Kuala Krai with 9836 ppm Ba and 344 ppm Sr.



Figure 2. Map showing the relationship between the Central Belt plutons near Raub (modified from Tjia and Zaitun Harun, 1985) in relation to the structural elements of the Central Belt, illustrating the underlying structural control on their emplacement.

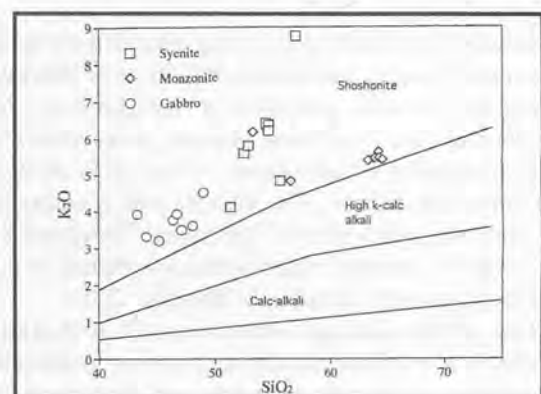


Figure 3. K_2O vs SiO_2 plot which shows that the whole dataset lies in the shoshonite field.

The trace elements of the Central Belt rocks are presented in a multi-element spider diagram (Fig. 5). The representative samples from Central Belt were plotted with increasing SiO₂. The pattern in these rocks is hard to match to other rocks elsewhere. The profile does not show any systematic trend with decreasing SiO₂. There is depletion in Rb, Ba, U, K, Nb, P and Ti or negative anomalies against mantle composition. Gabbroic rocks have higher Ce, La, P, and Y and lower K compared to syenitic and monzonitic rocks.

The Ba and Sr content in these rocks are very high compared to other rocks elsewhere, i.e. Ba and Sr contents are nearly 1,000 times rock/mantle.

IMPLICATION OF HIGH BA AND SR: MANTLE PLUME TYPE MAGMATISM

The extremely high Ba-Sr plutons of Central Belt have no comparison with other granitoids elsewhere in the world. Figure 6 compares the Ba content of the Central belt rocks

Table 1. Representative chemical composition of major and minor trace elements of the igneous rocks near Raub (from Azman A Ghani and Mustafa, 2002).

Sample Rock Type	1sy Syenite	6sy Syenite	10syd Syenodiorite	B21sy Syenite	P1sy Syenite	24Mz Monzonite	28Mz Monzonite	B2Mz Monzonite	MJ2Mz Monzonite	B1Mz Monzonite	GrMz Monzonite	2G Gabbro	15G Gabbro	16G Gabbro	G1G Gabbro
wt%															
SiO ₂	54.41	54.64	54.64	56.97	52.90	63.97	64.37	63.41	64.67	56.55	64.29	54.40	46.82	46.50	49.05
TiO ₂	0.88	0.86	0.77	0.58	0.93	0.61	0.61	0.67	0.60	0.72	0.56	0.87	1.68	1.70	1.36
Al ₂ O ₃	16.48	16.52	20.18	18.34	16.61	15.61	15.58	15.40	15.23	20.59	16.20	16.18	12.81	12.16	14.88
Fe ₂ O ₃	6.50	6.46	4.56	5.42	6.94	4.33	4.21	4.60	4.27	4.43	3.54	6.80	9.55	9.66	9.26
MnO	0.11	0.11	0.04	0.08	0.11	0.07	0.06	0.07	0.07	0.06	0.05	0.12	0.14	0.15	0.14
MgO	4.13	4.05	2.90	1.93	4.81	2.13	2.08	2.41	2.06	2.38	1.79	4.39	9.17	9.58	6.96
CaO	6.78	6.65	5.86	4.36	7.55	3.54	3.53	3.85	3.44	4.34	3.24	6.94	12.10	12.62	9.67
Na ₂ O	2.58	2.73	2.98	2.33	2.27	2.85	2.85	2.88	2.75	4.90	3.22	2.53	1.37	1.19	2.04
K ₂ O	6.42	6.37	6.21	8.76	5.80	5.45	5.46	5.39	5.41	4.82	5.63	6.32	3.93	3.76	4.51
P ₂ O ₅	0.65	0.65	0.69	0.32	0.72	0.35	0.35	0.38	0.33	0.36	0.27	0.64	1.26	1.32	1.00
LOI	1.29	1.21	1.41	1.41	1.65	0.88	0.87	1.33	1.34	1.31	1.08	1.18	1.59	1.61	1.68
Total	100.23	100.25	100.24	100.50	100.29	99.79	99.97	100.39	100.17	100.46	99.87	100.37	100.42	100.25	100.55
ppm															
Ba	4394	4175	10744	6289	6334	2577	2354	3019	2761	2401	2420	4200	6085	6290	4639
Ce	295	313	239	142	247	210	216	213	219	274	206	305	248	256	305
La	124	135	93	55	103	92	93	88	90	118	84	134	96	102	128
Nb	30	31	12	12	28	24	21	23	22	29	23	53	20	18	38
Ni	48	47	49	18	51	25	26	28	26	32	23	51	138	137	75
Pb	145	157	82	130	139	88	85	103	95	50	74	139	61	43	99
Rb	389	370	289	371	326	268	258	256	262	290	257	434	420	387	317
Sr	1018	996	2340	1547	1145	667	664	635	578	1068	682	984	919	890	854
Th	74	80	88	27	93	83	84	80	91	113	84	75	31	32	42
V	191	195	121	96	183	110	115	103	87	122	95	186	352	372	285
Y	50	50	25	27	48	38	35	38	35	44	34	54	82	65	56
Zn	71	73	41	57	65	56	54	59	50	80	95	77	80	80	86
Zr	412	471	231	156	402	310	302	302	317	396	600	530	220	246	713

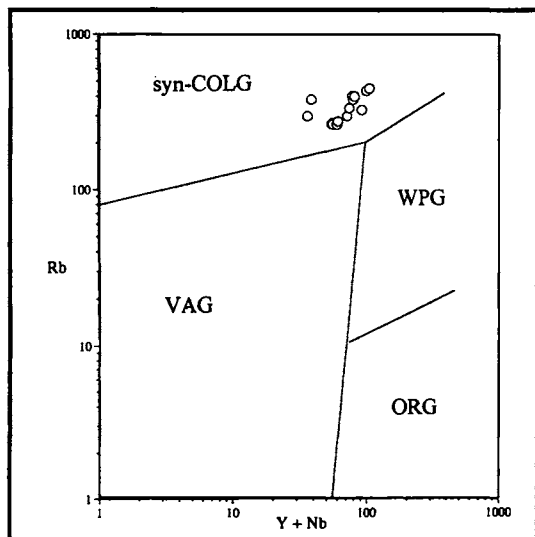


Figure 4. Rb vs (Y + Nb) diagram shows that all the Benta pluton lies in the syn-collisional field.

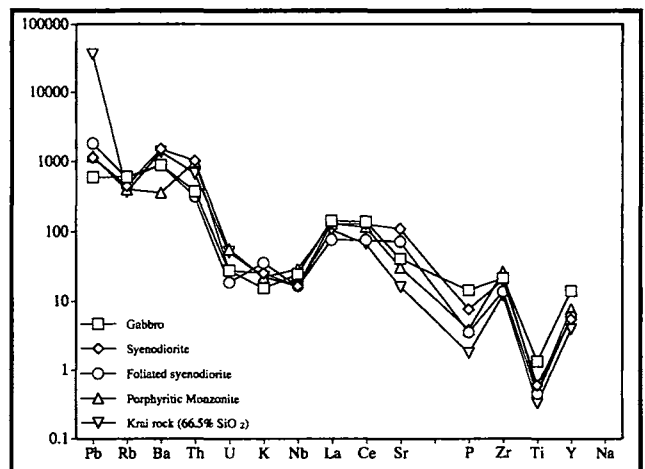


Figure 5. Multi-element variation diagram of the granitoids from Raub area (Azman A. Ghani and Mustafa, 2002).

with the rocks from the North Atlantic craton and Oceanic Island basalt. The North Atlantic craton and Oceanic Island basalt has up to 2,500 ppm Ba and 1,800 ppm Sr only (Tarney and Jones, 1994). Other high Ba-Sr rocks are the late Archaean Syenitic Murdock Creek pluton, Ontario (Ba 227-2881 ppm and Sr 1,660-4,302 ppm) which is related to extensional tectonic setting (Rowins *et al.*, 1993). The rocks with Ba-Sr content that come closest to the Central Belt rocks is the monzodiorite from the Fanad Pluton, Donegal with Ba content up to 4367 ppm and Sr content up to 2,094 ppm (Azman A. Ghani, 1997; Atherton and Azman A. Ghani, 2002). The high Ba and Sr trace elements characteristics of the Caledonian Late Granites were suggested to be derived from the mantle and not the continental crust (Fowler and Henney, 1996). These Caledonian Granites have been attributed to 'mantle plume' type magmatism related to slab breakoff (Atherton and Azman A. Ghani, 2002).

Azman A. Ghani and Mustafa (2002) considered that the high Ba and Sr values may result from the penetration of the lower lithosphere by a small volume of mantle material that is enriched in those elements. Mohd Rozi Umor and Syed Sheikh Almashoor (2000) considered that the granitoid were derived from the melting of eclogite from the mantle and could not have derived from the continental crust. The interaction with mantle material is supported by the occurrences of mafic enclaves and synplutonic dykes in the granitoids (Azman A. Ghani and Mustafa, 2002).

The Benom Granite has yielded an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7079 (Cobbing *et al.*, 1992), which points to an origin in highly enriched lithospheric mantle.

The long line of Central Belt plutons and the geochemical data are consistent with 'mantle plume' type magmatism (Davies and von Blanckenburg, 1995; Atherton and Azman A. Ghani, 2002). The granitoids were derived from the melting of cooler, thickened, metasomatized mantle

lithosphere when a hot plume-like asthenospheric linear diapir impinged against a mafic lower crust. Some of this magma stalled and crystallized at the base of the crust and subsequently partial melting formed the granitic magma as the asthenospheric upwelling increased. A similar scenario had been used to explain the genesis of the Late Granites of Scotland (Atherton and Azman A. Ghani, 2002). However compared to Late Granites of Scotland, the Central belt granitoids lack picrites.

OTHER SUPPORTING EVIDENCES

Other supporting evidences for 'mantle plume' type magmatism for the Central belt include:

1. The presence of bimodal magmatism, the occurrences of mafic enclaves of older granitoids in younger granitoids and the new age data from Mohd Rozi Umor and Syed Sheikh Almashoor (2000) indicated that there is a significant time interval (up to 30 Ma) between the first mafic magmatism and the later felsic magmatism. This data suggest that the melting of the lower crust were due to the conduction of heat upward from the top of a hot basaltic region and not due to advective processes. Chakraborty (1990) also came to the same conclusion based on different line of evidences.
2. The geochemical and the new age data also shows that the Central Belt granitoids are syn-collisional to post-orogenic and penecontemporaneous with rapid post-orogenic uplift, followed by erosion and coeval extensional/strike-slip deformation with the development of the Jurassic-Cretaceous continental deposits of Central Basin (extensional, Khoo and Tan, 1983 or transtensional/transpressional, Mustafa Kamal and Abdul Hadi, 2000a, b; Mustafa Kamal, 2000; Tjia, 2000).
3. Gravity data suggest that there is a thin continental crust beneath the Central Belt (Ryall, 1982; Loke *et al.*, 1983) as compared to the Western and Eastern Belt. This indicated that the Continental crust beneath the Central belt undergone crustal extension.
4. The presence of mafic enclaves is consistent with a mafic lower crust beneath the Central Belt formed by underplating. The large volume of granitoid, some rich in mafic enclaves others rich in older continental crust is a strong argument for enhanced partial melting throughout the whole Central Belt thinned crust, and not just the young mafic lower crust during the magmatic event.

Therefore the magmas could not have been derived from a subducting slab; it fundamentally resulted from the melting of lithospheric mantle. The bimodal nature of the complex suggests that igneous activity occurred during crustal extension and thinning phase which accompanied strike-slip tectonic motion in the Central Belt. Consequently the 'mantle plume' type magmatism is a plausible explanation for the Central Belt magmatism.

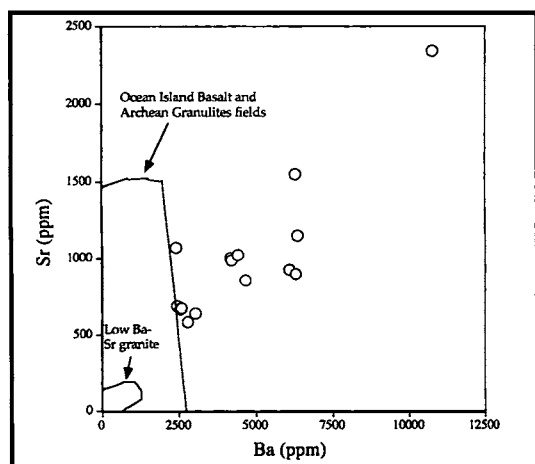


Figure 6. Ba vs Sr of the igneous rocks from Raub area (from Azman A. Ghani and Mustafa, 2002).

IMPLICATION ON THE GEOTECTONIC DEVELOPMENT OF PENINSULAR MALAYSIA

None of the existing tectonic models of Peninsular Malaysia fully explains the spatial, age or geochemical characteristics of the Central Belt granitoids. A consistent model must involve the oblique convergence of the two tectonic provinces of Peninsular Malaysia where 'mantle-plume' type magmatism is the natural consequence of the attempted subduction of the continental crust.

The extensional models

The aborted rift model (Khoo and Tan, 1983) implicitly or explicitly assumed that the magmatism beneath the Central Belt were due to mantle plume processes. The scale, basaltic followed by felsic magmatism with a time gap in between each magmatism, associated with rapid uplift and erosion and genesis by partial melting of the underplated lower older continental crust is similar to magmatism in Archaean Karro and Yilgarn Plutons, inferred to be due to mantle plume processes (Hill *et al.*, 1992).

However the inequant and linear form of the Central Belt Plutons differ from the plume formed magmatic provinces (e.g. Deccan). The disposition of the Central belt Plutons adjacent to the Bentong-Raub Line, characterized by numerous reactivated faults and shear zones (Fig. 2) ranging from reversed to strike-slip and normal faults and their emplacement associated with rapid uplift to give rise to the strike-slip controlled (Mustaffa Kamal and Abdul Hadi, 2000b; Mustaffa Kamal, 2000; Tjia, 2000) continental Mesozoic Central Belt basin may suggest an underlying structural control on their emplacement. In addition, the subvertical contacts between the granitoids and against the country rocks, the presence of foliation in older igneous rocks, igneous xenoliths in younger rocks and synplutonic dykes and other major protrusions from the main body, lack of associated structures in the country rocks which are only weakly deformed and the low grade metamorphism of the country rocks suggest high level block-like emplacement partly controlled by the regional tectonic trend. Thus, the elongated and linear geometry of the plutons can be explained by fault-controlled emplacement. This lead Chakraborty (1990) to proposed a combined mantle plume-strike-slip model to explain the granite magmatism of the Eastern Province.

The recognition of the mantle plume type magmatism of the Central Belt, support the extensional models. However, carbonatites, typical of mantle plume magmatism have not been documented and how does the extensional models account for the regional transpressional (Mustaffa Kamal, 2000, this volume) event prior to granite emplacement in the Central belt is unclear.

Subduction-collision models

In subduction-collision models, the Eastern Province (which includes the Central Belt Plutons (Cobbing *et al.*,

1992)) has long been regarded as an ensialic volcano-plutonic arc, overlying a Permo-Triassic Benioff Zone (Hutchison, 1989). However, Chakraborty (1990) pointed out that the evidence for typical subduction related magmatism is lacking. He stressed that the plutonic suites in this province are bimodal with abundance of acidic rocks; there are no space-time composition relationship across the province, and high potassic rocks (Central Belt plutons) occur nearer to the postulated trench (Bentong-Raub Line). Moreover, the evidence that collision commenced around the Permian-Triassic boundary (Metcalf, 2000) suggest that the Permian to Triassic magmatism could not have been related to oceanic subduction processes as it would have ceased upon collision.

For example, our data indicated that all the Benta Complex rocks here are shoshonitic, which should occur furthest away from a trench, but found very close to the Bentong-Raub Line. The evolutionary trend in time from tholeiitic to calc-alkaline and shoshonitic rocks are not recognizable in the Benta complex. The oldest rock, gabbro, have the highest K₂O values and the youngest rock, monzonite have the lowest values.

The Jurassic age for the Benta plutonic complex add further problem to the subduction model. It indicates that this plutonic suite is post-orogenic and could not have been associated with oceanic crust subduction as it would have been ended by the Latest Permian-Triassic collision. The Benta complex are different from the extensive I type Cordilleran Batholiths of the Pacific Rim. Thus on the Rb vs (Nb + Y) diagram all the Benta pluton lie in the syn-collisional field, while the Cordilleran Batholiths plot in the volcanic arc granite field as might be expected from the Andean continental margin subduction setting (Pitcher *et al.*, 1985).

During the Late Permian-Triassic convergent, low grade greenschist to amphibolite facies metamorphism accompanied deformation (thrusting and strike-slip faulting) and plutonism. These events will almost certainly result in significant crustal thickening. Yet today the Central Belt is characterized by thin crust (Ryall, 1982; Loke *et al.*, 1983), evidence of lithospheric extension, and magmatism, typical of passive hot spots, or continental extension.

TOWARDS A GEOTECTONIC MODEL

The recognition of 'mantle plume' type magmatism in the Central Belt may help resolve some of the problems related to subduction-collision and extensional models. The aspects of 'mantle plume' type magmatism, and their supporting evidences as discussed above, together with the outcrop shape and the long linear arrangements of the plutons in the Central Belt (Figs. 1 and 2), could relate specifically to a linear, hot, asthenospheric upsurge onto lithospheric mantle on slab breakoff producing post-convergent basaltic/granitic magmatism as suggested by von Blanckenburg and Davies (1995) for the Tertiary magmatism in the Alps and Atherton and Azman A. Ghani

(2002) for the Scottish Caledonides magmatism. The high Ba and Sr plutons of the Central belt form a linear belt closely associated with the Bentong-Raub Line. This association might well mark the position of the slab breakoff at the surface.

Probably during oblique convergent, a thickened crustal segment descended, slab rollback can caused horizontal extension in both the asthenosphere and mantle lithosphere causing lithospheric thinning beneath the Central Belt. Then, the descending crustal slab breaks off (Fig. 7). The denser slab then, sinks into the deeper asthenospheric mantle. A likely consequence of slab breakoff is the rise of hot asthenosphere through the break to impinge on the thick lithosphere in the overlying mantle wedge (von Blanckenburg and Davies, 1995). The overlying lithosphere is heated by conduction as the asthenosphere impinge on its base leading to melting of metasomatized, veined and hydrated layers. This magma will rise to the crust, pass through and induce crustal melting to produce granitic magmas. Expected melts could be alkaline to ultrapotassic or calc-alkaline depending on degree of melting of the hydrated peridotite layers (von Blanckenburg and Davies, 1995). Breakoff will lead to heating of the overriding lithospheric mantle by upwelling asthenosphere, melting of its enriched layers, and thus to bimodal magmatism.

CONCLUSION

A consistent model have been proposed that involved the oblique convergence of the two tectonic provinces of Peninsular Malaysia where slab breakoff which is the natural consequence of the attempted subduction of the continental crust, is invoked to account for the 'mantle-plume' type magmatism of the Central Belt.

The outcome of the slab breakoff is the long linear belt of single plutons characterized by high-K, shoshonitic granitoids with characteristics trace element signatures, specifically high Ba and Sr, which lie critically close to the Bentong-Raub Line. Other features include the bimodal association of mafic and felsic rocks, the low grade regional metamorphism, thinned continental crust, rapid uplift and erosion with the development of extensional/transensional basins.

REFERENCES

- ATHERTON, M.P. AND AZMAN A. GHANI, 2002. Slab breakoff: a model for Caledonian, Late Granite syn-collisional magmatism in the orthotectonic (metamorphic) zone of Scotland and Donegal, Ireland, 65-85.
- AZMAN A. GHANI AND MUSTAFFA KAMAL, 2002. Towards a geodynamic model of Peninsular Malaysia: Evidence from high Ba-Sr rocks from Central Belt of Peninsular Malaysia (abstract). *Programme and Abstract, Petroleum Geology Conference and Exhibition 2002*, 109.
- AZMAN A. GHANI, 1997. *Petrology and Geochemistry of the Donegal granites*. Unpubl. PhD. thesis, Univ. of Liverpool.
- CHAKRABORTY, K.R., 1990. Early Mesozoic tectonism in Peninsular Malaysia: a combined strike-slip-plume model (abstract). *In: GSM Annual Geological Conference, Ipoh, Perak, 7 & 8 May 1990, Warta Geologi*, 16(3), 139.
- COBBING, E.J., PITFIELD, P.E.J., DARBYSHIRE, D.P.F. AND MALLICK, D.I.J., 1992. The granites of the South-East Asian tin belt. *Overseas Memoir 10*, British Geol. Surv.
- DAVIES, J.H. AND VON BLANCKENBURG, F., 1995. Slab breakoff, a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth Planet. Sci. Lett.*, 129, 85-102.
- FOWLER, M.B. AND HENNEY, P.J., 1996. Mixed Caledonian appinite magmas: implications for lamprophyre fractionation and high Ba-Sr granite genesis. *Contrib. Mineral. Petrol.* 126, 199-215.
- GREEN, D.H. AND WALLACE, M.E., 1988. Mantle metasomatism by ephemeral carbonatite melts. *Nature*, 336, 459-462.
- HALLIDAY, A.N. AND STEPHEN, W.E., 1984. Crustal controls on the genesis of the 400 Ma old Caledonian granites. *Phys. Earth Planet. Int.*, 35, 89-104.
- HILL, R.I., CAMPBELL, I.H., DAVIES, G.F. AND GRIFFITH, R.W., 1992. Mantle plumes and continental tectonics. *Sciences*, 256, 186-193.
- HUTCHISON, C.S., 1971. The Benta migmatite complex: Petrology of two important localities. *Bull. Geol. Soc. Malaysia*, 4, 49-70.
- HUTCHISON, C.S., 1989. *Geological evolution of South-East Asia*. Oxford Monography on Geology and Geophysics, 13, 376p.
- JAAFAR AHMAD, 1979. The petrology of the Benom igneous complex. *Geol. Surv. Malaysia Spec. Paper 2*, 141p.
- KERRICK, R. AND WATSON, G.P., 1984. The Macassa mine Archean lode gold deposit, Kirkland Lake, Ontario: geology, pattern of alteration and hydrothermal regimes. *Econ. Geol.*, 79, 1104-1130.
- KHOO, T.T. AND TAN, B.K., 1983. Geological evolution of the Peninsular Malaysia. *Proceedings of a workshop on*

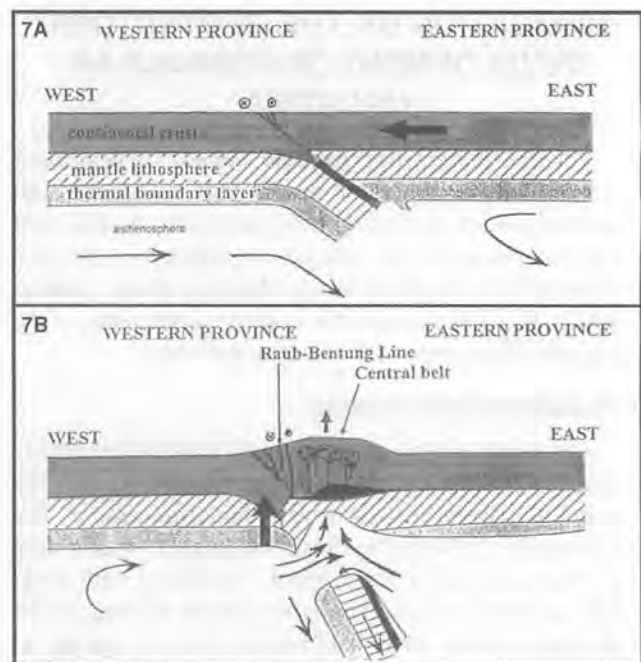


Figure 7. Cartoons showing the sequence of events leading to the slab breakoff and Central Belt magmatism.

- stratigraphic correlation of Thailand and Malaysia, vol 1, 253-283.*
- KHOO, T.T., 1968. *A Petrological study of Sungai Ruan area.* Unpubl. BSc. Thesis Univ. of Malaya.
- LOKE, M.H., LEE, C.Y. AND VAN KLINKEN, G., 1983. Interpretation of regional gravity, and magnetic data in Peninsular Malaysia. *Bull. Geol. Soc. Malaysia, 16, 1-21.*
- MCDONOUGH, W.F., SUN, S., RINGWOOD, A.E., JAGOUTS, E. AND HOFMANN, A.W., 1991. K, Rb and Cs in the earth and moon and the evolution of the earth's mantle. *Geochim. Cosmochim. Acta.* Ross Taylor Symposium volume.
- MOHD ROZI UMOR AND SYED SHEIKH ALMASHOOR, 2000. Tren unsur-unsur surih dan nadir bumi batuan kompleks Benta, Pahang berdasarkan kepada petunjuk kepada proses pembentukan dan evolusi batuan. *Proceeding Annual Geological Conference Geological Society of Malaysia, Penang, 87-95.*
- MUSTAFA KAMAL SHUIB, 2000. The Mesozoic tectonics of Peninsular Malaysia. Peninsular Malaysia. *Proceedings Third Seminar of the Mesozoic of Peninsular Malaysia - Dynamic Stratigraphy & Tectonics of Peninsular Malaysia, Kuala Lumpur, 13 May, 2000, 1-29.*
- MUSTAFA KAMAL SHUIB AND ABDUL HADI A.R., 2000a. The Mesozoic of the Central Belt of the Malay Peninsular-Part II: Basin Configuration and Tectonism, *Proceedings Third Seminar of the Mesozoic of Peninsular Malaysia — Dynamic Stratigraphy & Tectonics of Peninsular Malaysia, Kuala Lumpur, 13 May, 2000, 74-95.*
- MUSTAFA KAMAL SHUIB AND ABDUL HADI, A.R., 2000b. A strike-slip basin model for the Mesozoic of the Central Belt of Peninsular Malaysia. *In: The 29th IAGI Annual Convention, Bandung, Indonesia, 21-22 November 2000, (Abstract), 99.*
- PITCHER, W.S., ATHERTON, M.P., COBBING, E.J. AND BECKINSALE, R.D., 1985. Magmatism at a plate edge: the Peruvian andes. Blackie Halstead Press, Glasgow, 328p.
- RICHARDSON, J.A., 1939. The geology and mineral resources of the neighbourhood of Raub, Pahang, Federation Malay States. *Memoir Geological Survey Department 13, 166p.*
- ROWINS, S. M., CAMERON, E. M., LALONDE, A.E. AND ERNST, R. E., 1993. Petrogenesis of the late Archean syenitic Murdock Creek pluton, Kirkland, Ontario: Evidence for an extensional tectonic setting. *Can. Mineral., 31, 219-244.*
- RYALL, P.J.C., 1982. Some thoughts on the crustal structure of Peninsular Malaysia: results of a gravity traverse. *Bull. Geol. Soc. Malaysia, 15, 9-18.*
- SCRIVENOR, J.B., 1931. *The geology of Malaya.* Macmillan London.
- TAN, B.K. AND KHOO, T.T., 1993. Clinopyroxene composition and tectonic setting of the Bentong Raub belt, Peninsular Malaysia. *Jour. Southeast Asian Earth Sciences, 8, 539-545.*
- TARNEY, J. AND JONES, C.E., 1994. Trace element geochemistry of orogenic igneous rocks and crustal growth models. *J. Geol. Soc. 151, 855-868.*
- TJIA, H.D. AND ZAITUN HARUN, 1985. Regional structures of Peninsular Malaysia. *Sains Malaysiana, 14(1), 95-107.*
- TJIA, H.D., 2000. Tectonics of deformed and undeformed Jurassic-Cretaceous strata of Peninsular Malaysia. *Proceedings Third Seminar of the Mesozoic of Peninsular Malaysia — Dynamic Stratigraphy & Tectonics of Peninsular Malaysia, Kuala Lumpur, 13 May, 2000, 1-29.*
- VON BLANCKENBURG, F. AND DAVIES, J.H., 1995. Slab breakoff: a model for syncollisional magmatism and tectonics in the Alps. *Tectonics, 14, 120-131.*
- VON BLANCKENBURG, F. AND DAVIES, J.H., 1996. Feasibility of double slab breakoff (Cretaceous and Tertiary) during Alpine convergence. *Eclogae Geol. Helv., 89, 111-127.*

Manuscript received 21 February 2003