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Cretaceous and Neogene lavas of Sabah — origin and tectonic significance

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Abstract: A combination of field and geochemical investigations of the Cretaceous and Neogene lavas of Sabah (CNLS) allow some control on the relative timing of events in its tectono-magmatic history. The low-K tholeiitic lava (Telupid basalt of Cretaceous age) or so-called 'boninitic suite', interpreted as a product of partial melting of hydrated oceanic lithosphere in the mantle wedge, suggesting that the first magma formed in response to intra-oceanic subduction. As subduction proceeded, the magma composition changed to the calc-alkaline suite (high-K calc-alkaline lavas of Neogene Tungku and Tanjung Batu andesites), probably because of the hydrated asthenosphere of the mantle wedge confirming an oceanic, supra-subduction zone origin for this volcanic arc assemblage.

An evolutionary sequence can be envisaged for the CNLS which begins with the establishment of an oceanic island arc where supra-subduction zone extension led to the genesis of tholeiitic lava and/or boninitic (Telupid basalt) and followed by formation of the volcanic arc (Tungku andesite). Next, followed by Tungku arc-splitting, as extension continued, a marginal basin (Sulu Sea) developed. Later, incomplete closing of the Sulu Sea caused the southwards subduction beneath the older arc and formation of the Tanjung Batu andesite.

INTRODUCTION

Sabah is a state of Malaysia located in the northern part of Borneo island, bounded by the Eurasion plate to the northwest, by the Pacific plate to the east and by the Indo-Australian plate to the south (Fig. 1). The tectonic evolution of Sabah and its surrounding area has widely been discussed by a number of researchers (e.g. Bol and van Hoorn, 1980; Taylor and Hayes, 1983; Hutchison, 1988, 1989; Letouzey *et al.*, 1988; Hinz *et al.*, 1989, 1991; Rangin *et al.*, 1990; Tjia, 1988; Tongkul, 1990, 1991; Clennell, 1991). Various models have been proposed, they differ in their interpretations, but all seek to explain the geological evolution of Sabah within the framework of the marginal basin system. Neogene lavas of Sabah (NVLS) were mainly exposed in the Dent and Tawau-Semporna Peninsulas (Fig. 1), produced by arc-type volcanic activity from Middle Miocene to Quaternary time. In the Telupid area, a large volumes of basaltic lavas of Cretaceous age are exposed. So far, no detailed petrologic and geochemical studies have been carried out on these rocks. Therefore, this paper presents a short account on their petrographic and geochemical aspects and explain their tectonic significance.

FIELD AND PETROGRAPHIC DESCRIPTIONS

Telupid Basalt

These rocks are mainly exposed along the Telupid river and along Jalan Ranau-Telupid at km 85 (R85/T12; Fig. 1). These basalts are probably of Cretaceous age. These rocks are characterised by a well developed pillow structure, where the geometry of the pillows indicate younging upwards. These pillows are usually brownish in colour but sometimes greenish and bluish. Amygdaloidal and/or vesicular textures are well preserved. Calcite veins of a few centimeters thickness are commonly associated with the rocks.

In thin section, the pillow basalt is fine grained, showing interstitial and amygdaloidal textures. Most of the vesicles have been filled by quartz and sometimes by carbonate. Petrographically, this rock is characterised by two pyroxenes, suggesting arc tholeiite affinity or of boninitic affinity. The

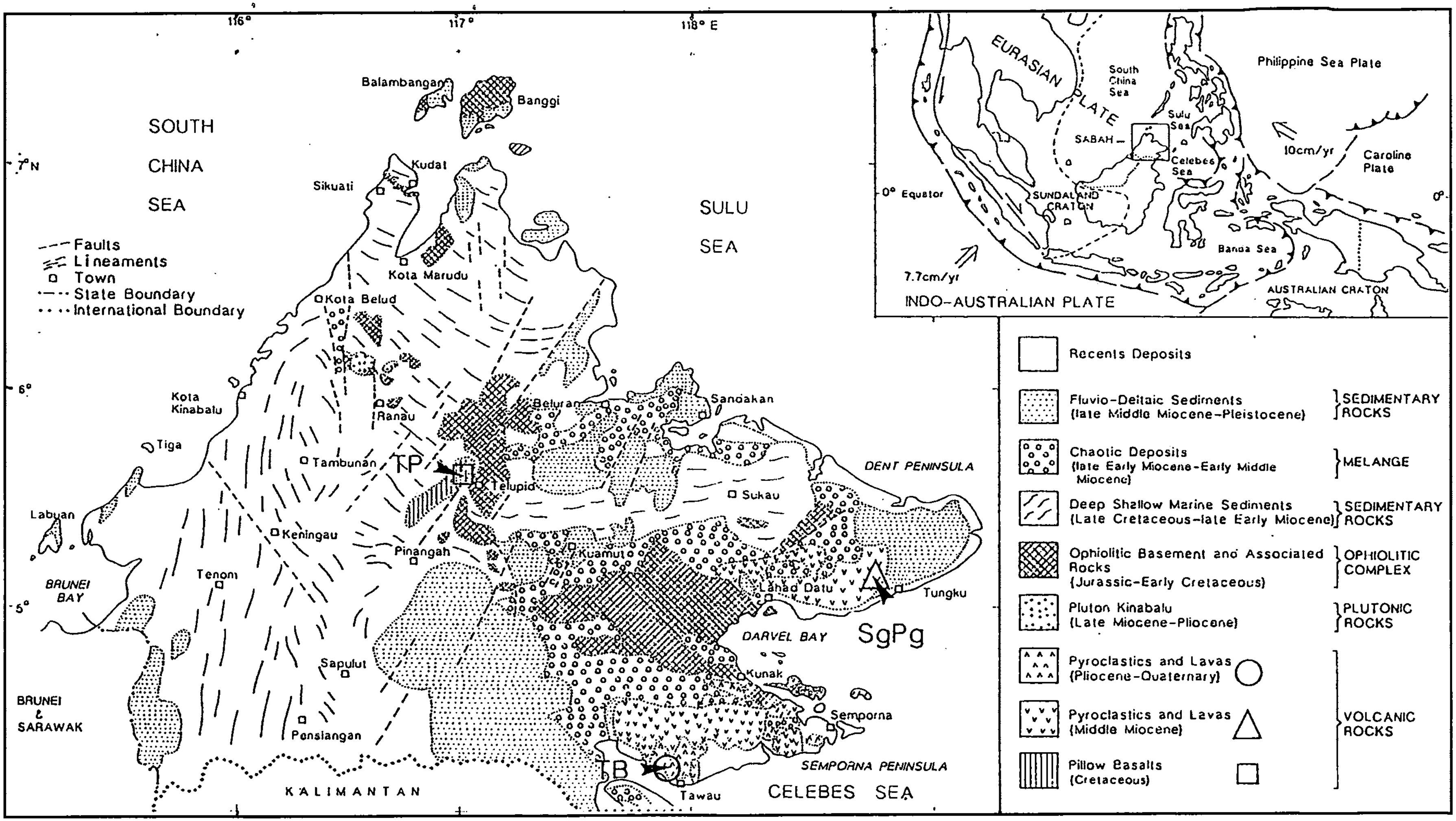

Figure 1. Simplified geological map of Sabah (modified from Yin, 1985).

Table 1. Chemical analyses of some lavas of Sabah compared to average compositions of the volcanic rocks from different tectonic setting. Total iron as Fe_2O_3* (Fe_2O_3* = Fe_2O_3 + FeO x 1.111). Modal percentage of phenocrysts/microphenocrysts are listed in approximate abundance. Source data: Island arc andesite, Back-arc basin tholeiite and N-MORB of Wilson (1989); Boninite and Arc tholeiite of Ballantyne (1991, 1992). *Abbreviations:* SgPg — Sungai Pungulupi, TB — Tanjung Batu (Tawau), TP — Telupid and mt — Titanomagnetite.

	TP	SgPgD	SgPgP	TB	Boninite	Arc tholeiite	Island-arc andesite	Back-arc basin tholeiite	N-MORB
Oxides (wt.%)									
SiO_2	58.39	60.16	56.89	62.79	54.40	48.58	58.58	51.00	48.77
TiO_2	0.62	0.69	0.71	0.53	0.42	0.68	0.72	1.02	1.2
Al_2O_3	14.63	17.50	17.95	16.64	15.69	14.20	17.52	17.90	15.90
Fe_2O_3*	7.32	6.36	7.66	5.82	3.25	2.15	7.10	7.54	1.33
MgO	6.42	2.31	3.68	3.07	6.26	7.74	3.43	7.37	9.67
MnO	0.12	0.22	0.18	0.11	0.12	0.08	0.14	0.44	0.17
CaO	10.06	7.10	7.87	5.62	11.93	13.96	7.55	10.70	11.16
Na_2O	2.36	3.35	3.09	2.77	3.72	2.20	3.11	2.72	2.43
K_2O	0.06	2.13	1.81	2.37	0.17	1.10	0.92	0.57	0.08
P_2O_5	0.06	0.24	0.25	0.14	0.10	0.14	0.19	0.15	0.09
TOTAL:	100.04	100.06	100.07	99.86	99.06	99.39	–	–	–
LOI	3.96	0.77	0.46	1.74	–	–	–	–	–
Al_2O_3/TiO_2	23.71	25.33	25.46	31.22	37.36	20.88	24.33	17.55	13.83
CaO/TiO_2	16.31	10.28	11.63	10.55	28.40	20.53	10.49	10.49	9.70
CaO/Al_2O_3	0.69	0.41	0.44	0.37	0.76	0.98	0.43	0.59	0.70
Trace Elements (ppm)									
Ni	70	13	15	10	66	180	7	66	214
Cr	193	27	17	13	197	268	40	196	528
V	244	184	199	136	222	158	–	–	262
Sc	38	24	20	18	39	24	–	–	40
Pb	1.1	15.4	17.8	13.6	0.80	1.9	–	–	–
Sr	44	385	434	301	45	1037	204	212	88.7
Rb	2	69	65	91	3	16	21	6	0.56
Ba	8	377	415	316	6	90	200	77	4
Th	0.4	5.2	6.2	8.0	–	0.6	–	–	0.2
Zr	31	89	81	101	28	88	91	130	85
Nb	0.1	2.2	2.7	3.4	0.3	1	–	8	3.1
Y	18	23	21	16	15	16	24	30	29
La	0.4	12	13	15	0.3	6	6	8	3
Ce	3	22	27	28	4	19	17	19	9
Nd	3	16	18	13	3	12	10	13	8
Modal percentage (%)									
Olivine	1–2	–	–	–					
Orthopyroxene	~2	–	–	–					
Clinopyroxene	5–7	~10	7–10	~7					
Hornblende	–	–	–	~5					
Biotite	–	–	–	~1					
Plagioclase	20–25	~35	30–35	30–40					
Quartz	–	–	–	~7					
mt	~20	5–7	~5	3–5					

rock contains microphenocrysts of plagioclase (20–25%), clinopyroxene (5–7%), orthopyroxene (~2%), olivine (1–2%) and Fe-Ti oxides (~10%) (Table 1).

Tungku Andesitic Lava

These lavas are exposed in the Sungai Pungulupi, approximately 50 miles east of Lahad Datu town (Fig. 1). They occur as megablocks in a chaotic deposit of Middle-Late Miocene age. These rocks are also associated with other igneous, metamorphic and sedimentary rocks in this area. The rocks are banded, angular and sub-angular suggested that they were derived from a nearby source. However, Aralas (*pers. comm.*) has found and studied the andesitic lavas which crop out to the east of the Sungai Pungulupi. In thin section, the Tungku andesitic lavas are fine to medium grained and commonly show porphyritic and flow textures. Petrographically, they are pyroxene andesite and consist mainly of plagioclase, clinopyroxene and Fe-Ti oxides. Plagioclase constitutes from 30–35% of the total phenocrysts and microphenocrysts and forms the largest mineral grains. Most of the plagioclase fall in the range of oligoclase (An_{15-20}). The size of the plagioclase phenocrysts ranges from 0.1 to 3.0 mm. Plagioclases are fresh, euhedral and subhedral, elongated and prismatic in shape, showing albite and Carlsbad twinning, and are slightly zoned. Clinopyroxene forms less than 10% of the total phenocrysts, is commonly euhedral and subhedral, and ranges from 0.1 to 2 mm across. Fe-Ti oxides are the most common accessory phase in the Tungku andesite and occur as microphenocrysts. Fe-Ti oxides constitute less than 7% of the total phenocrysts. Fe-Ti oxides can be seen as small inclusions in pyroxene.

Tanjung Batu Andesitic Lava

These rocks have been observed in Tanjung Batu Quarry, about 10 miles north of Tawau town (Fig. 1). Tanjung Batu andesitic lavas are medium to coarse grained and show slightly phorphyritic texture. Petrographically, this lava is a hornblende-pyroxene andesite and consists mainly of plagioclase, clinopyroxene, hornblende and accessory minerals (Fe-Ti oxides, biotite, quartz). Plagioclase constitutes from 30–40% of the total phenocrysts and microphenocrysts and forms the largest mineral grains. Most of plagioclases fall in the range of oligoclase (An_{15-20}). The size of plagioclase phenocrysts ranges from 0.2 to 4.0 mm, euhedral and subhedral, elongated and prismatic in shape, showing albite and Carlsbad twinning, and slightly zoning. Some of the plagioclase grains are partially altered and replaced by epidote and sericite. Clinopyroxene forms less than 10% of the total phenocrysts, is commonly euhedral and subhedral, and ranges from 0.1 to 3 mm across. Some clinopyroxenes are partially replaced by hornblende and opaque oxides, especially in the core of clinopyroxene grains. Hornblende phenocrysts constitute less than 7% of the total phenocrysts, are brownish in colour, range from 1.0 to 4.0 mm in length, and euhedral and subhedral in shape. Some hornblendes are partially replaced by opaque oxides and biotite, especially in the core of the hornblende grains. Quartz (< 7%), biotite (< 1%) and Fe-Ti oxides (3–5%) occur as microphenocrysts and in the groundmass. They occur as small grains. Fe-Ti oxides can be seen as small inclusions in pyroxene and hornblende.

ANALYTICAL METHOD

One sample of the Telupid basalt (sample TP), two samples of Tungku andesitic lavas (samples SgPgD, SgPgP) and one sample of Tanjung Batu andesitic lava (sample TB) were analysed for major and trace elements using the Philips PW1480 XRF spectrometer at Royal Holloway and Bedford New College, University of London. Analytical techniques, precision and accuracy were the same as those of Thirlwall and Marriner (1986). Concentrations of major and trace elements for these lavas of Sabah are given in Table 1. Sample localities are given in Figure 1.

BULK-ROCK GEOCHEMISTRY

Major and trace element concentrations for the CNLS are presented in Table 1. Geochemical data from the other volcanic rocks of different tectonic environments are also given in Table 1, for comparison.

Major Element Geochemistry

Major element compositions of the Telupid basalt (sample TP) are quite different from the Tungku andesite (sample SgPg) and Tanjung Batu andesite (sample TB). On the SiO_2 versus K_2O diagram (Fig. 2) the Tungku and Tanjung Batu andesites fall into the high-K calc-alkaline field. Whereas, Telupid basalt falls into the low-K tholeiite field. In terms of major element compositions (Table 1) and the Neogene Lava of Sabah are typical of orogenic volcanics, which are characterised by low TiO_2 (< 1 wt.%), high in Al_2O_3 (15–18 wt.%) and SiO_2 (57–63 wt.%), and low in MgO (2–6 wt.%). However, concentrations of major element such as SiO_2, Al_2O_3, CaO, Na_2O, K_2O and P_2O_5 are low in the sample TP (Telupid basalt) relative to the other

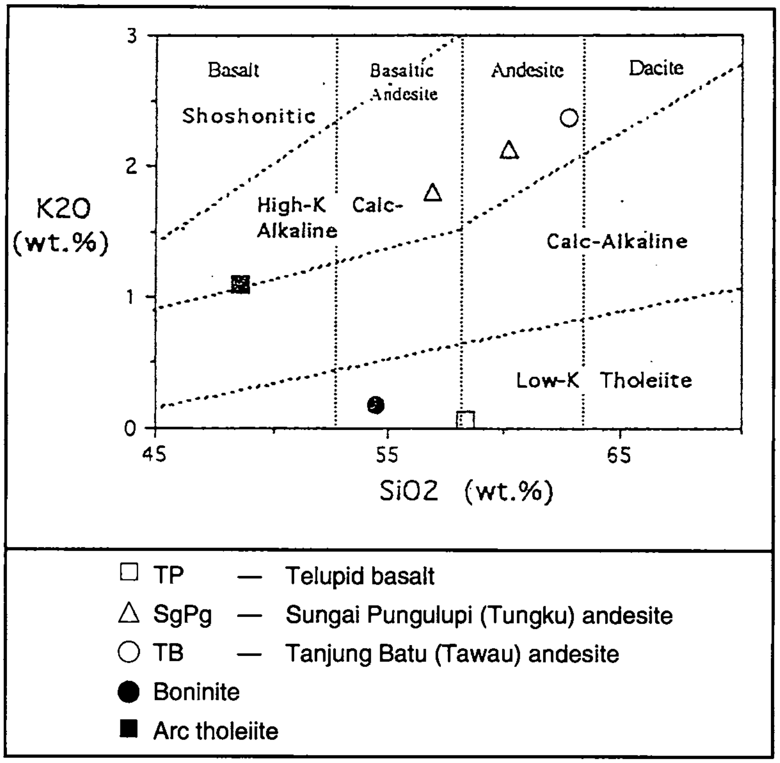

Figure 2. SiO_2 (wt.%) versus K_2O (wt.%) plot for lavas of Sabah. Data from boninite and arc tholeiite for comparison. Boundaries from Peccerillo and Taylor (1976).

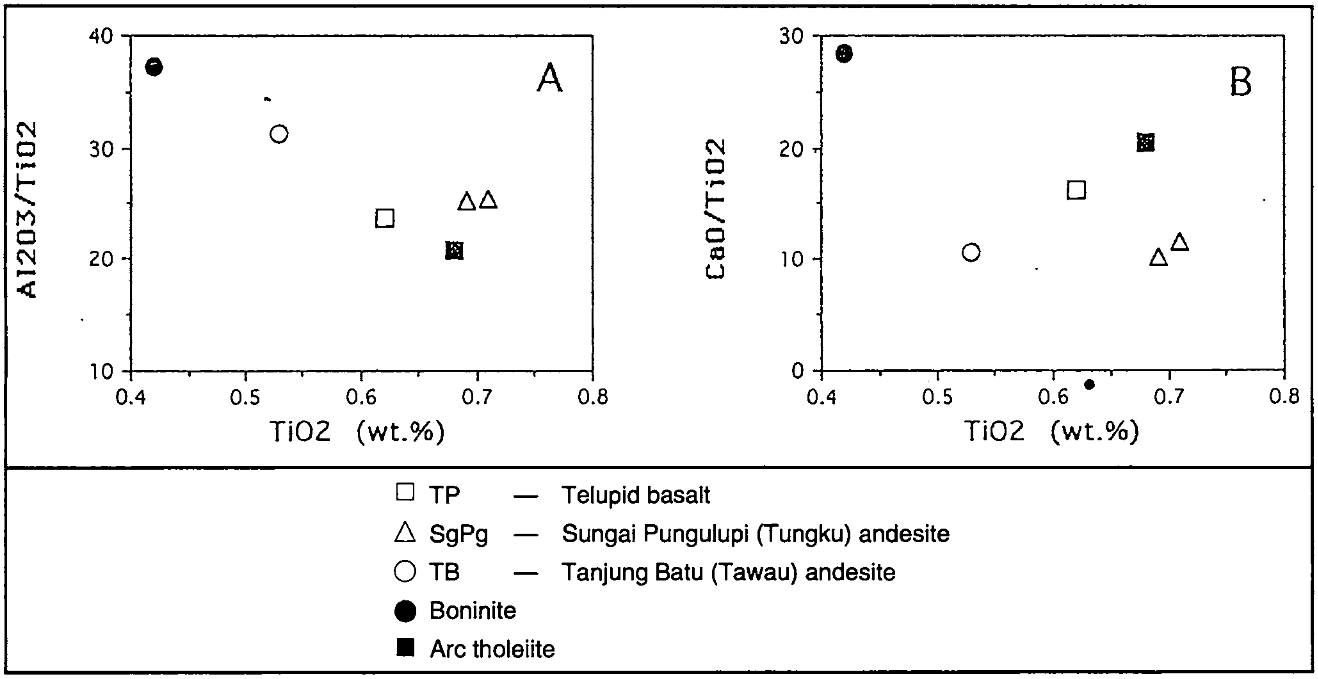

Figure 3. Plots of (A) TiO_2 versus Al_2O_3/TiO_2, (B) TiO_2 versus CaO/TiO_2 for the lavas. Data from boninite and arc tholeiite for comparison.

two andesites. But concentrations of MgO in sample TP are higher compared to the andesitic samples. Major element concentrations of the Telupid basalt are almost similar to the boninite and/or arc tholeiite whereas the Tungku and Tanjung Batu samples are the same as island-arc andesite (Table 1). The TiO_2 versus Al_2O_3/TiO_2 and CaO/TiO_2 plots (Fig. 3) may reflect the plagioclase (Fig. 3A) and clinopyroxene (Fig. 3B) accumulations in the rocks, suggesting that the Tungku andesite and Tanjung Batu andesite are derived from different tectonic events and suggesting that the degree of partial melting in the source region to produce the NLS is more than 25%.

Trace Element Geochemistry

Large-ion lithophile element (LILE: Pb, Sr, Rb, Ba, Th, K), light rare earth element (LREE: La, Ce, Nd) and high-field strength element (HFSE: Zr, Nb, P) concentrations are low in the Telupid basalt compared to Tungku and Tanjung Batu andesites (Table 1). In contrast, compatible element (Ni, Cr, V, Sc) concentrations are higher than in the Tungku and Tanjung Batu andesites.

Plots of trace element contents normalised to chondrite show the principal features of the CNLS (Fig. 4). All show a strong negative Nb anomaly, reflect a typical character of arc volcanic rocks (e.g. Saunders and Tarney, 1984; Saunders *et al.*, 1988; Wilson, 1989). Tungku andesite (samples SgPgD, SgPgP) and Tanjung Batu andesite (sample TB) show the humped and sloping patterns compared to the Telupid basalt (sample TP), suggests that the Telupid sample may be derived from a different source. However, all samples have marked positive 'anomalies' in Pb, Rb, Ba, K and Sr (hydrophile elements), reflecting that these elements are believed to be preferentially added to the mantle source of arc magmas through their much greater solubility in hydrous fluids released from subducted oceanic crust (e.g. Hawkesworth and Powell, 1980), or through their relative enrichment by weathering in subducted oceanic sediments (e.g. Thirlwall and Bluck, 1983). The plot of trace element discriminant diagrams (Fig. 5) indicates that all samples fall within the IAT field (Fig. 5A). On the Zr-Ti-Y diagram (Fig. 5B) the Telupid basalt falls within the MORB/IAT boundary and the Tungku and Tanjung Batu andesites fall in the CAB field, suggesting an arc affinity. Low incompatible element (Cr, Ni) contents of the Tungku and Tanjung Batu samples (Fig. 5A) clearly indicate that these group of rocks are typical island-arc suites.

DISCUSSIONS

Origin of the CNLS

Despite probable ocean floor alteration, spilitization and burial metamorphism (e.g. Oliver *et al.*, 1984), the composition of the single Telupid basalt (Table 1) is comparable to modern oceanic arc tholeiite (may be similar to the boninite series) in several key parameters (Beccaluva and Serri, 1988; Murton, 1989): low Al_2O_3, extremely low abundances of incompatible elements (Zr, Nb, Ti, P, Y and the light rare earth elements), high CaO/Al_2O_3 ratio (~ 0.7: Boninite low – Ca Type – 3) and high Cr, Ni, V, Sc, MgO and CaO contents. Arc tholeiite and/or boninites are primitive subduction-related lavas found only in modern island arcs of the SW Pacific and some ophiolites, derived by partial melting of hydrated oceanic lithosphere in the 'mantle wedge' (e.g. Taylor *et al.*, 1992). To generate such refractory magmas probably requires unusual thermal conditions, which may occur during the earliest stages of arc formation (including pre-arc spreading; cf. Pearce *et al.*, 1984b) and/or subsequent arc-splitting (e.g. Beccaluva and Serri, 1988). The observation that arc tholeiite (IAT) lavas are interbeded with boninite in several modern island arcs (e.g. Meijer, 1980), indicates that IAT magmas may already have existed prior to the eruption of at least some boninites. This is consistent with the suggestion of Beccaluva and Serri (1988) that the depleted mantle source responsible for arc tholeiite and/or boninite magmas had already undergone extraction from mid-ocean ridge basalts (MORB). A general association with supra-subduction zone extension is apparent and inferred for the Telupid Complex. Arc tholeiite and/or boninite eruption followed by a major phase of arc-building activity (the Tungku and Tanjung Batu andesites). The Telupid basalts therefore seem likely to be the product of pre-arc spreading during the initiation of subduction as may be the case in some West Pacific examples (e.g. Taylor *et al.*, 1992). However, whether the extension involved at Telupid occurred in the 'mature' forearc (e.g. Crawford *et al.*, 1989) or as the intra-arc initiation of arc splitting and marginal basin development (e.g. Beccaluva and Serri, 1988) or in response to supra-subduction zone transtension (e.g. Murton, 1989) cannot be determined from consideration of the arc tholeiite and/or boninites alone. Only from their integration with other aspects, may be with the Labuk Ophiolite Complex, can the evolution be worked out.

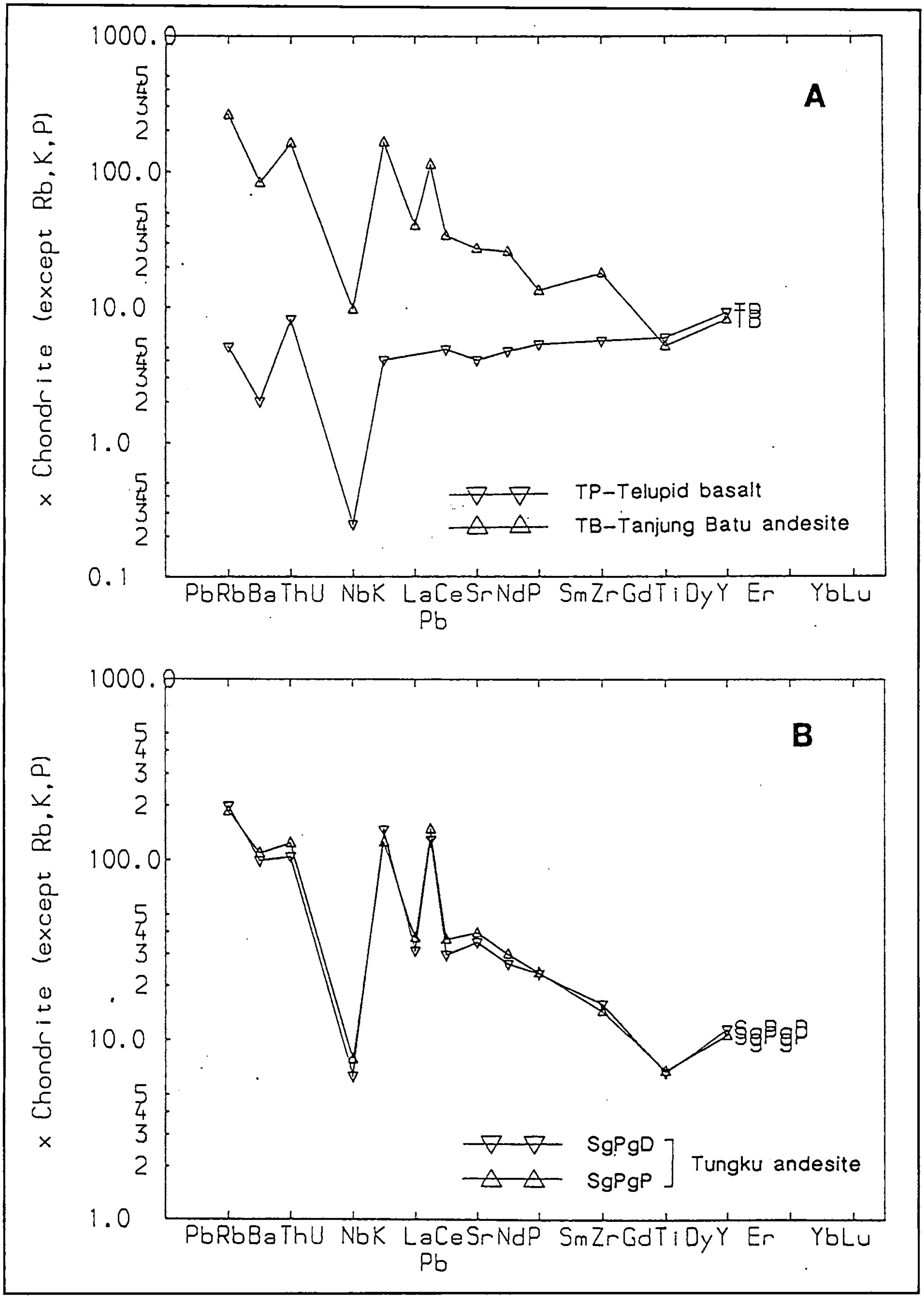

Figure 4. Spider diagram of Cretaceous and Neogene lavas of Sabah. Sample/Chondrite (except Rb, K, P) normalization and element arrangement are according to Sun (1980).

Tectonic significance of the CNLS

It is not so easy to assess plate tectonic models in the light of data, however, geochemical data of CNLS suggest that the tectonic setting of Sabah during the Cretaceous started from pre-arc spreading/supra-subduction zone extension (forearc basin to major island-arc setting. However, the following likely sequence of events of CNLS is deduced and shown diagramatically in Figure 6. In the Cretaceous time, Telupid basalt (arc tholeiite and/or boninite affinity) was produced in the forearc basin (pre-arc spreading) (Fig. 6A), due to southward subduction of the oceanic crust (proto South China Sea). As subduction proceeds, the magma composition changes to calc-alkaline (because the hydrated asthenosphere of the mantle wedge) produced the high-K calc-alkaline Tungku andesite (Fig. 6B). Next, followed by Tungku arc-splitting, as extension continued, a marginal basin (Sulu Sea) developed (Fig. 6C). Later, incomplete closing of the Sulu Sea caused the southwards subduction beneath the older Tungku arc and the formation of the Tanjung Batu andesite (Fig. 6D). However, Hutchison (1988) favour the northward subduction of the Celebes Sea.

CONCLUSIONS

1. The Telupid basalt represents a magma (low-K are tholeiite/or boninite suites) to be form in response to supra-subduction extension zone (intra-oceanic subduction/forearc basin).
2. The Tungku and Tanjung Batu andesites represent a major phase of arc-building activity, however, the Tanjung Batu andesite is much later develop and related to the southwards subduction of the Sulu Sea and/or northward subduction of the Celebes Sea.
3. More petrologic and geochemical data, or even the radiogenic isotope analysis to work out, to get a more precise interpretations for the Cretaceous and Neogene volcanic rocks (CNLS) of Sabah.

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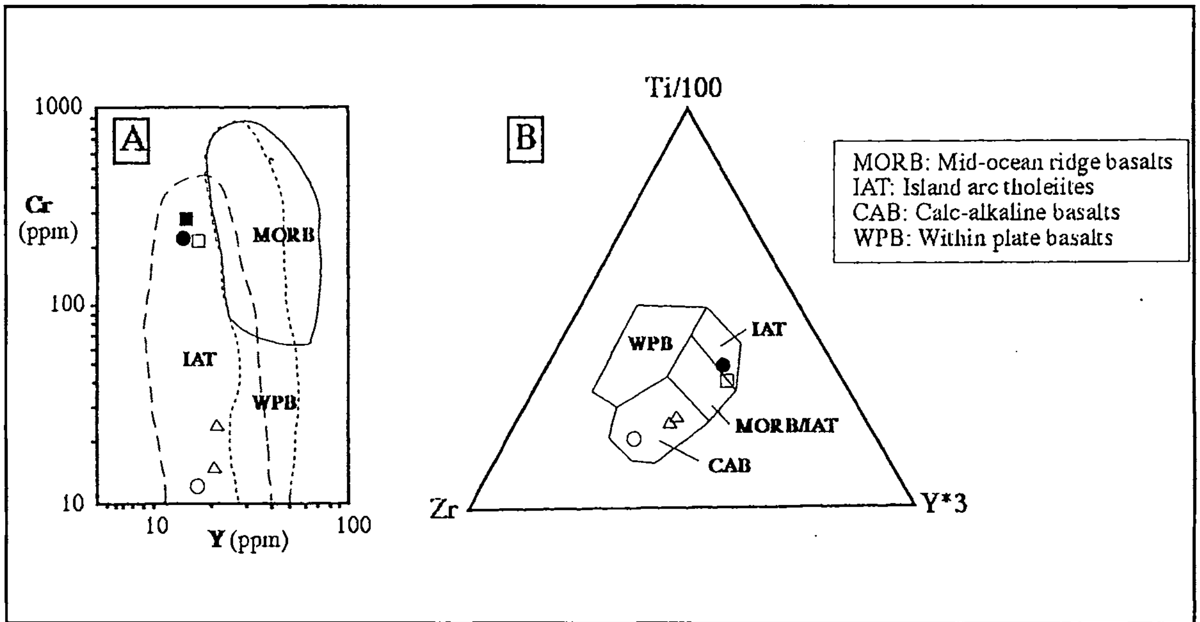

□ TP — Telupid basalt
△ SgPg — Sungai Pungulupi, Tungku
○ TB — Tanjung Batu, Tawau
● Boninite
■ Arc tholeiite

MORB: Mid-ocean ridge basalts
IAT: Island arc tholeiites
CAB: Calc-alkaline basalts
WPB: Within plate basalts

Figure 5. Tectonic discriminant diagrams of lavas of Sabah. Boninite and arc tholeiite data for comparison.
[A] Y-Cr diagram of Pearce *et al.* (1984a)
[B] Zr-Ti/100-Y*3 diagram of Pearce & Cann (1973).

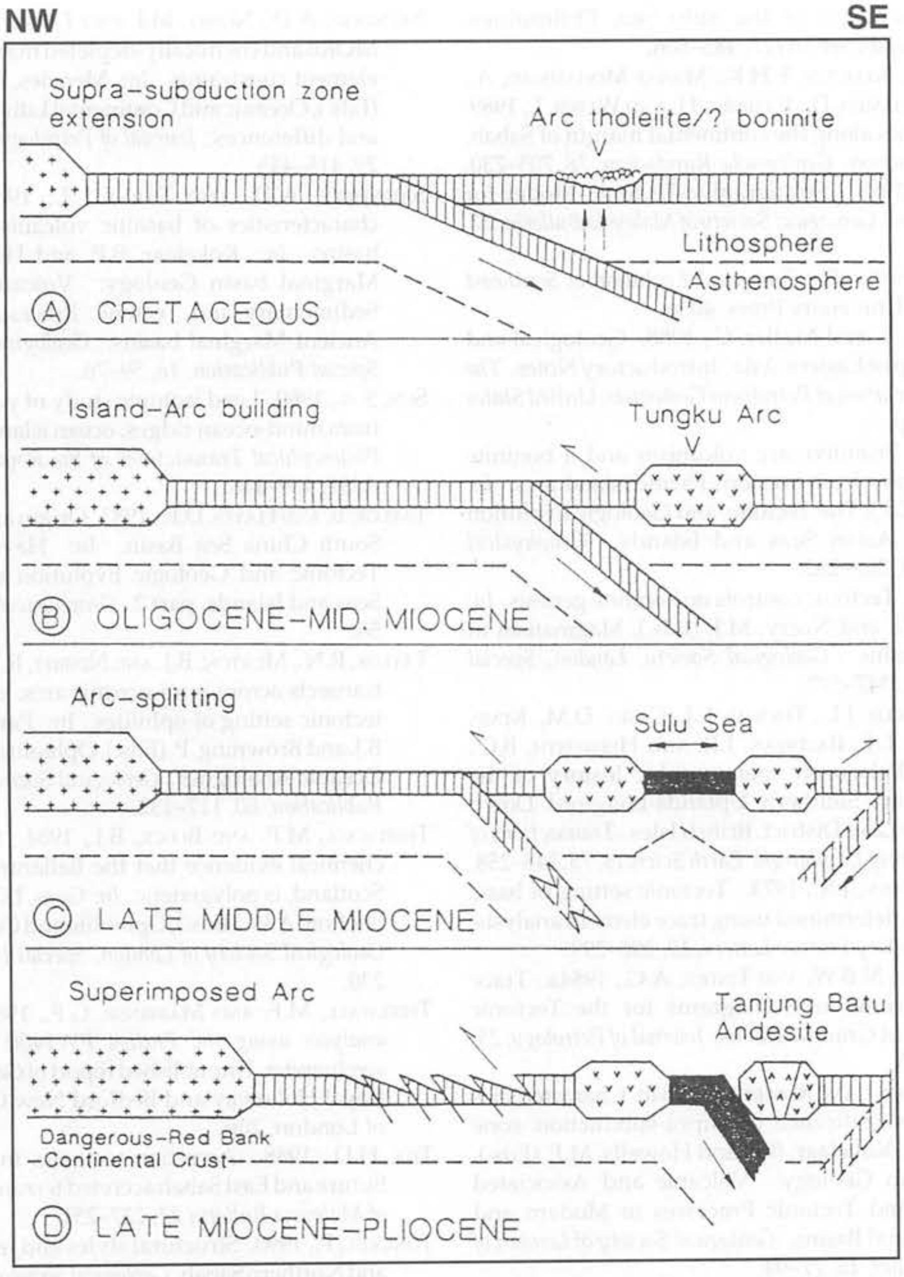

Figure 6. Possible tectonic evolution related to the formation of the CNLS.

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