Geol. Soc. Malaysia, Bulletin 44, July 2000; pp. 165-171

K:Ar ages and geochemistry of the Sabah Cenozoic volcanic rocks

[1]STEVEN C. BERGMAN, [2]CHARLES S. HUTCHISON, [1]DAVID A. SWAUGER AND [1]JOHN E. GRAVES

[1]Arco International Oil & Gas Company and Arco Exploration and Production Technology
2300 W. Plano Pkwy., Plano
Texas, U.S.A. 75075-8499

[2]10 Lorong 5/19A
46000 Petaling Jaya
Selangor, Malaysia

Abstract: K-Ar dates for volcanic rocks of the southern Dent Peninsula confirm a Middle Miocene age, and K-Ar dates on the Semporna Peninsula also indicate a similar Middle Miocene age, older than previously held.

The Pliocene rift-related subaerial basalts of the Mostyn Estate of the Kunak area are of the low-K tholeiite series and also display MORB characteristics, indicating a rift-related magma genesis resulting in partial melting of an identical source to the Mesozoic ophiolite of the Segama area.

The Miocene volcanic rocks of the Semporna and southern Dent Peninsulas, by contrast, have calc-alkaline affinities and their trace element geochemistry indicates a subduction related genesis with typical enrichment in the light rare earth elements.

INTRODUCTION

A reconnaissance field transect was made across Sabah in May 1994. A Magellan GPS satellite device was used to accurately position the outcrop sampling localities (Fig. 1).

The southern part of the Dent Peninsula is dominated by Miocene volcanic rocks, and volcanic rocks have been incorporated into the Miocene Ayer Formation mélange. The Semporna Peninsula is also characterized by Miocene andesitic volcanic rocks, many of which preserve a volcanic geomorphology (Kirk, 1968; Hutchison, 1989). The Pliocene rift-related basalts of the Mostyn Estate represent the youngest volcanic event.

LOCALITIES AND PETROGRAPHY

The specimens were collected at the following localities: **1** = andesitic tuff which immediately underlies the basal Sandakan Formation, on the coast beneath the mosque (poorly sorted coarse tuff composed of 0.5 to 2 mm plagioclase crystals and < 1 to 2 mm andesite clasts in a smectite- and chlorite-rich muddy matrix), 5.8433°N, 118.1267°E. **2** = basaltic-andesite tuff breccia, Lahad Datu–Tungku road (poorly sorted crystal-rich; composed of euhedral feldspar, hornblende and pyroxene grains < 2 mm and together forming 30% of the rock, with rare vitric andesite fragments in a devitrified glass matrix of smectite and zeolites), 4.9817°N, 118.6100°E. **3** = dacite clast in tuff breccia, Lahad Datu–Tungku road (hornblende andesite lava or intrusive fragment, composed of < 2 mm euhedral feldspar, hornblende, and pyroxene grains totalling 60% of rock in a devitrified glass matrix of smectite and zeolites), 4.9817°N, 118.6100°E. **4** = basaltic andesite tuff breccia, Membatu Road, Tungku (poorly sorted crystal rich, composed of < 2 mm euhedral feldspar, hornblende and pyroxene grains totalling 40% of rock, with rare 2–10 mm vitric andesite fragments in devitrified matrix of smectite and zeolites), 4.9817°N 118.7883°E. **5** = tholeiitic vesicular basaltic-andesite, Mostyn estate, Kunak (fine grained porphyritic vesicular, with euhedral 1–3 mm plagioclase and augite phenocrysts in a < 0.2 mm matrix of plagioclase, augite and altered glass. Irregular vesicles are 1–3 mm across), 4.6617°N 118.1950°E. **6** = basaltic-andesite tuff, Mostyn estate, Kunak (poorly sorted with angular to sub-rounded clasts dominantly of volcanic fragments, including basalt, andesite and tuff fragments, and subordinate quartz, plagioclase, chert, shale, calcite and hornblende, in a clay matrix), 4.6717°N 118.0733°E. **7** = andesite tuff breccia, Kukusan main quarry, Tawau (hornblende andesite tuff breccia composed of 1–3 mm andesite and diorite clasts, < 2 mm euhedral feldspar, altered hornblende and pyroxene grains in a devitrified glass matrix of smectite and zeolites), 4.3100°N,

117.8717°E. **8** = grey vitric andesite lava flow, Batu Payong (hornblende porphyry composed of < 3 mm euhedral feldspar, altered hornblende and pyroxene grains, totalling 40% of rock, in a vitric matrix of plagioclase microlites), 4.2233°N, 117.9983°E. **9** = grey diorite porphyry dome, Kobal quarry, Semporna Peninsula (hornblende andesite porphyry composed of < 4 mm euhedral feldspar, altered hornblende and pyroxene grains, totalling 30% of rock, in a vitric glass matrix with plagioclase microlites), 4.2883°N, 117.9733°E. **10** = rhyolite lava, mile 52 quarry, Mount Pock (andesite porphyry composed of < 2 mm euhedral feldspar phenocrysts, forming 10% of rock, in a devitrified glass matrix with plagioclase microlites), 4.4050°N, 118.3417°E.

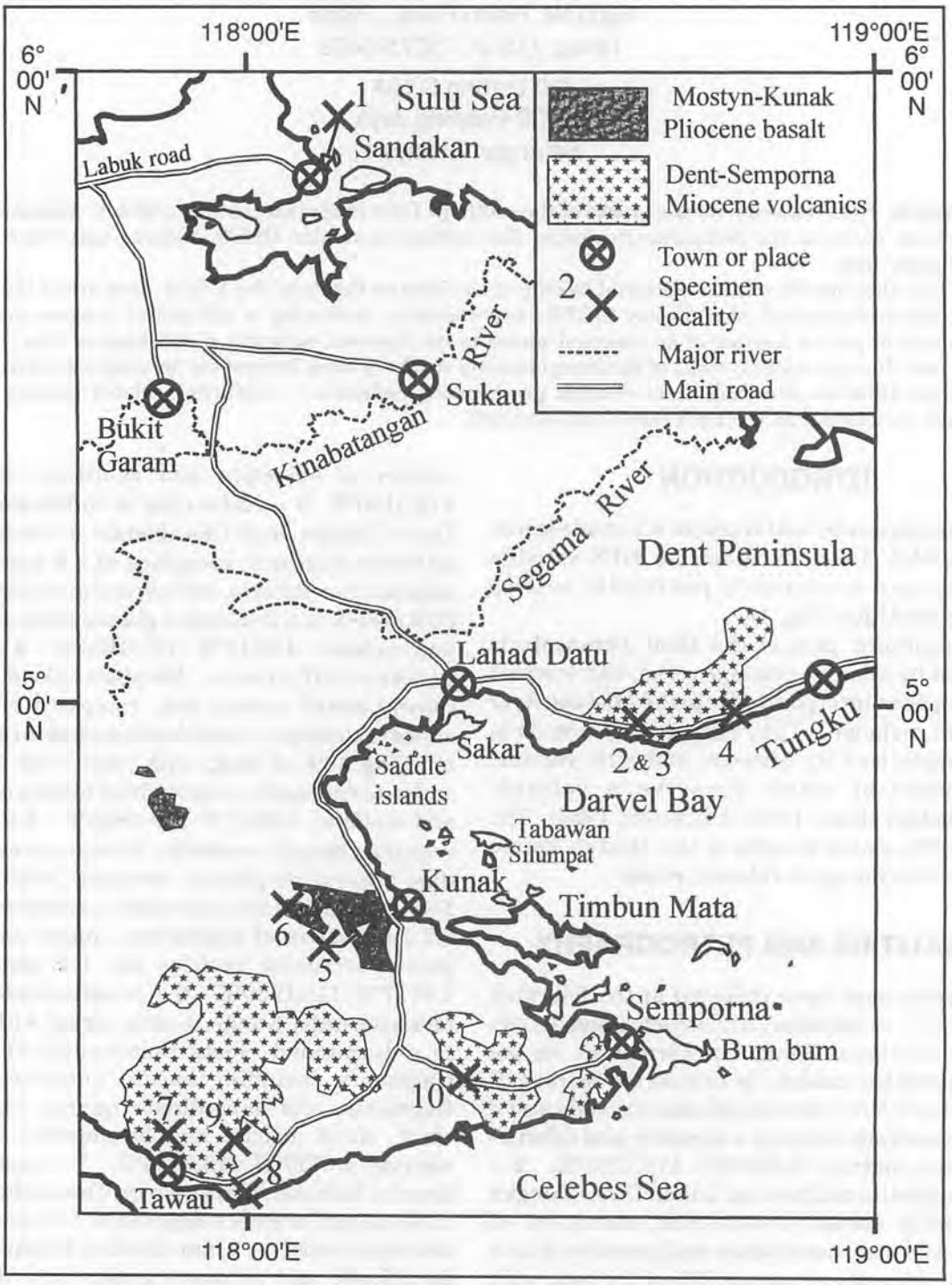

Figure 1. Sketch map showing the sample localities included in this study. Road alignments are only approximate.

Table 1. K-Ar dating of volcanic rocks (Dent and Semporna Peninsulas).

Kunak rift-related basalt	2.79 ± 0.42 Ma, 3.11 ± 0.93 Ma
Porphyritic andesite south of Kunak	11.8 ± 0.59 Ma, 12.92 ± 0.65 Ma
Tungku Formation (andesite), Membatu Bridge	11.69 ± 0.58 Ma
Tungku Formation (aphanitic), Membatu Bridge	16.65 ± 0.83 Ma
Tungku Fm., andesite-dacite clasts, Cape Membatu	12.58 ± 0.63, 11.53 ± 0.58 Ma
Andesite plug in Tawau (Semporna)	9.01 ± 0.45 Ma
Massive andesite in Tawau (Semporna)	11.61 ± 0.58 Ma
	(Rangin *et al.*, 1990)

Locality	Specimen	Age
2	Plagioclase (0.31 wt% K) in Tungku dacite tuff breccia	17.9 ± 1.2 Ma
2	K-feldspar (2.26 wt%) in Tungku dacite tuff breccia	18.8 ± 0.6 Ma
7	Plagioclase (0.43 wt%) in andesite porphyry, Kukusan, Tawau	14.4 ± 0.9 Ma
8	Plagioclase (0.36 wt%) in vitric andesite, Batu Payong	16.3 ± 1.1 Ma
10	Plagioclase (0.37 wt%) from flow-banded lava, Mount Pock	18.2 ± 1.2 Ma
1	Plagioclase (K % = 0.10 wt%), andesite tuff, Sandakan Mosque	76.6 ± 4.1 Ma
	Apatite Fission Track Age	
1	Andesite tuff beneath Sandakan mosque	33.9 ± 7.7 Ma
		(Swauger *et al.*, 1995)

K:AR DATING

The K:Ar dates obtained in this study, and previously reported by other authors, are given in Table 1. The K-Ar analyses were carried out by Tom Bills of Geochron Inc., Cambridge, Mass.

VOLCANIC ROCKS, DENT AND SEMPORNA PENINSULAS

Sandakan Mosque (Loc. 1, Fig. 1)

The andesite tuff which outcrops on the coast beneath the mosque belongs to a formation which is unconformably overlain by the Sandakan Formation. Lee (1970) ascribed the andesite tuff to the Garinono Formation, because outcrops on the nearby islands are composed of mélange. However, Rangin *et al.* (1990) identified Oligocene fossils from the tuff. Plagioclase extracted from the tuff yielded a Cretaceous K-Ar age, which may be anomalous because of the very low potassium content and possible excess ^{40}Ar content (Table 1). Separated apatite crystals yielded an Oligocene fission track age, which like the overlying Sandakan Formation has not been reset and may indicate an Oligocene igneous age. The andesitic material in Sandakan is on line with the Cagayan Ridge of the Sulu Sea, and may be the landward continuation of this volcanic arc, which was rifted during the Miocene spreading of the Southeast Sulu Sea marginal basin.

Dent Peninsula

Andesite and dacite of the Tungku Formation (Haile *et al.*, 1965) have yielded K-Ar dates ranging from 11 to 16 Ma (Middle to Upper Miocene) (Rangin *et al.*, 1990). Our data (Table 1) have yielded a confirmatory Middle Miocene age (Locality 2, Fig. 1). Details of the offshore drilling of the Dent Peninsula have never been published. The wells drilled into a basement of volcanic rocks, which unfortunately have never been studied. The Dent Miocene volcanic province is likely to be more extensive than shown on the outcrop maps.

Semporna Peninsula

K-Ar ages for volcanic and plutonic rocks, sampled at Tawau (loc. 7) and as far east as Mount Pock (loc. 10) confirm a general Middle Miocene age, somewhat older than the age assumed by Kirk (1962) for the Semporna Volcanic Arc. Clearly the Semporna Volcanic Arc is synchronous with volcanism in the Dent Peninsula, described by Haile *et al.* (1965). Offshore wells drilled into these volcanics, but details have never been published.

The Kunak rift-related basalts at Mostyn Estate are confirmed to have been extruded in the Pliocene (Rangin *et al.*, 1990).

The Middle and Upper Miocene volcanism of the Dent and Semporna peninsulas was synchronous with deposition of the Tanjong and Sandakan Formations, and this has implications for possible degradation of reservoir porosity quality.

GEOCHEMISTRY

Major element contents were determined by conventional X-ray fluorescence spectroscopy, minor and trace elements using a variety of wet chemistry, ICP-MS, DCP, XRF and other techniques in X-ray Assay Laboratories, Toronto. Analytical uncertainties are < 1–5 relative % for major elements (present in concentrations > 10 wt%) and 5–20 relative % for minor and trace elements (Tables 2 and 3). The details are contained in an unpublished ARCO report (Swauger *et al.*, 1995).

The two samples from the Pliocene Kunak rift-related volcanics (5 and 6) plot in the tholeiitic basaltic-andesite field (Fig. 2). The Dent and Semporna peninsulas Miocene volcanic rocks range from basaltic-andesite to dacite of the calc-alkaline series, while the rhyolite sample from Mount Pock

Table 2. Major element geochemistry (wt%) of selected Sabah volcanic rocks.

Oxide	Locality								
	2	3	4	5	6	7	8	9	10
SiO_2	55.00	64.90	54.50	53.00	52.70	60.70	61.80	60.00	70.70
TiO_2	0.63	0.61	0.69	2.12	0.76	0.54	0.57	0.59	0.40
Al_2O_3	17.10	15.40	17.10	14.00	15.50	16.00	16.40	16.30	13.30
Fe_2O_3	4.68	2.68	5.30	2.71	4.28	2.69	2.36	2.62	1.88
FeO	1.60	1.10	1.40	8.90	3.70	3.00	2.90	2.80	1.30
MnO	0.13	0.07	0.11	0.16	0.18	0.14	0.13	0.14	0.09
MgO	3.58	1.44	3.12	5.53	3.75	3.20	3.02	3.07	0.61
CaO	6.70	6.04	6.33	7.35	8.09	5.72	6.34	6.25	1.43
Na_2O	2.58	2.86	2.31	2.84	3.56	2.29	2.77	2.53	3.73
K_2O	1.09	2.10	1.54	0.35	0.30	2.25	1.85	1.99	3.82
P_2O_5	0.21	0.16	0.21	0.18	0.10	0.14	0.17	0.19	0.08
S	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00
H_2O^+	2.90	1.00	2.70	0.80	2.50	1.80	0.40	1.50	0.80
H_2O^-	3.70	1.20	3.90	0.40	0.90	1.20	0.40	1.10	0.30
CO_2	< 0.01	< 0.01	< 0.01	< 0.01	2.58	0.20	< 0.01	0.07	0.21
Total:	99.90	99.56	99.21	98.34	99.00	99.87	99.01	99.15	98.65

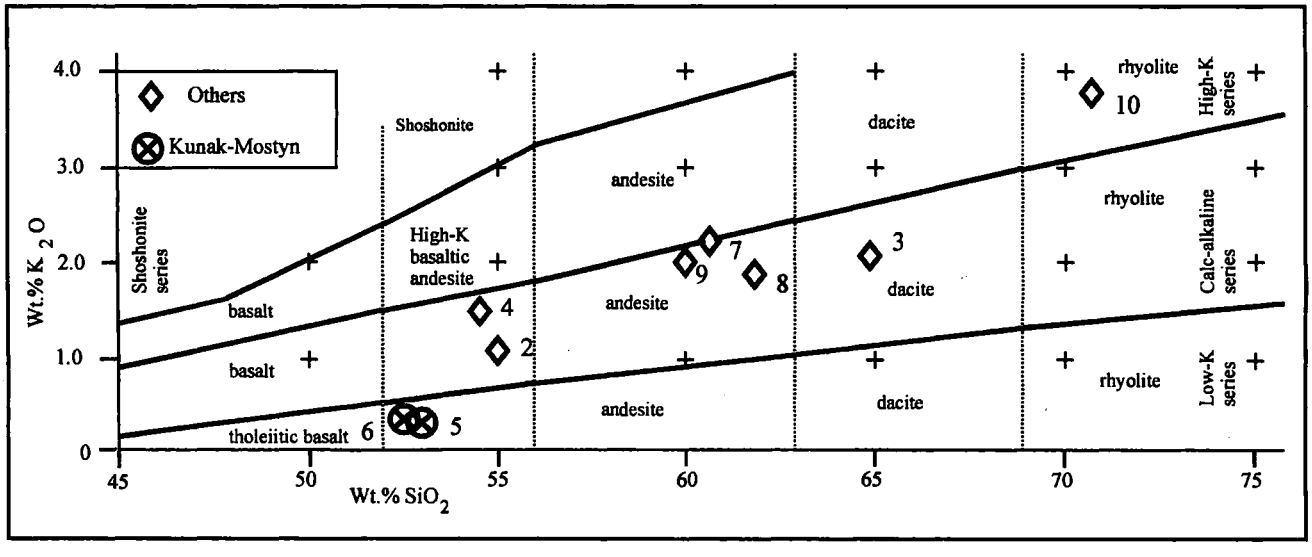

Figure 2. Plot of weight % K_2O versus SiO_2 for the analysed Sabah volcanic rocks. The fields of subdivision are after Ewart (1982).

Table 3. Trace element contents (in ppm). Dent and Semporna volcanic rocks.

Element	Locality								
	2	3	4	5	6	7	8	9	10
F	290	200	310	140	240	240	200	120	210
Cl	212	96	143	101	67	169	459	241	62
Sc	17	17	13	20	26	15	17	16	10
V	131	132	133	117	131	91	87	80	5
Cr	43	63	32	190	29	14	31	44	6
Co	14	18	10	34	18	13	15	13	2
Ni	8	13	3	102	9	5	12	13	2
Cu	29.4	28.3	31.4	39.1	26.0	29.3	27.3	24.6	4.3
Zn	66.5	66.5	45.9	116.0	63.6	49.9	66.4	48.5	45.0
Mo	3	5	3	1	3	2	2	2	3
Ag	1.3	0.3	0.9	0.6	0.8	0.2	0.3	0.3	1.1
Rb	48	70	52	12	7	74	53	86	71
Li	13	7	5	8	20	17	11	6	7
Cs	3.7	5.0	4.2	1.6	1.5	5.4	2.6	4.5	1.3
In	< 0.5	< 0.5	0.7	< 0.5	< 0.5	0.8	< 0.5	< 0.5	< 0.5
Sn	15	16	10	12	16	15	5	5	21
Sb	0.2	0.4	0.5	< 0.1	< 0.1	0.3	0.3	0.4	0.2
Sr	469	456	448	162	245	244	273	314	77
Ba	363	459	336	128	164	362	335	356	538
La	19.4	15.2	18.1	7.0	10.0	15.4	18.1	16.9	26.4
Ce	38.0	32.6	37.6	14.9	17.4	32.0	35.8	34.1	57.3
Pr	4.8	4.1	4.8	2.5	2.9	3.9	4.4	4.1	7.3
Nd	19.6	16.5	20.1	14.2	13.5	15.7	17.8	16.3	31.1
Sm	4.6	4.1	4.8	6.1	4.5	4.0	4.2	3.7	8.5
Eu	1.33	1.21	1.26	2.04	1.34	0.99	1.31	1.13	1.76
Gd	4.4	3.3	4.3	6.6	5.2	3.3	4.6	3.4	8.3
Tb	0.5	0.5	0.6	1.1	0.9	0.5	0.7	0.5	1.4
Dy	3.3	2.7	3.6	6.2	5.6	3.1	4.2	3.0	8.8
Ho	0.66	0.52	0.69	1.27	1.29	0.62	0.85	0.56	1.92
Er	1.9	1.6	2.0	3.2	3.5	1.9	2.5	1.9	5.8
Tm	0.3	0.2	0.3	0.5	0.5	0.3	0.4	0.3	0.9
Yb	1.9	1.6	2.1	2.7	3.1	1.9	2.3	1.8	6.1
Lu	0.27	0.25	0.33	0.41	0.5	0.3	0.38	0.28	0.92
Th	8.2	7.5	8.3	1.6	2.4	6.5	5.7	6.3	8.9
U	1.9	2.1	1.9	0.4	0.7	1.7	1.3	1.9	2.3
Y	16	13	17	29	35	16	21	15	48
Zr	91	88	83	122	78	90	96	98	225
Nb	7	7	5	12	4	6	6	7	12
Hf	2.6	2.2	2.9	3.9	2.2	2.4	2.8	3	6.9
Ta	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	0.6	< 0.5	< 0.5
W	3	4	2	< 1	< 1	2	2	2	4
Hg	< 5	< 5	< 5	< 5	24	< 5	< 5	< 5	< 5
Tl	0.4	0.5	0.4	0.3	0.1	0.6	0.4	0.6	0.4
Pb	3	3	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ga	21	18	21	23	16	18	19	18	17
Ge	< 10	15	< 10	20	< 10	< 10	< 10	< 10	20
As	2.6	3.5	2.2	0.8	6.0	1.8	2.9	3.6	2.4
Br	2	2	2	2	1	1	2	2	3

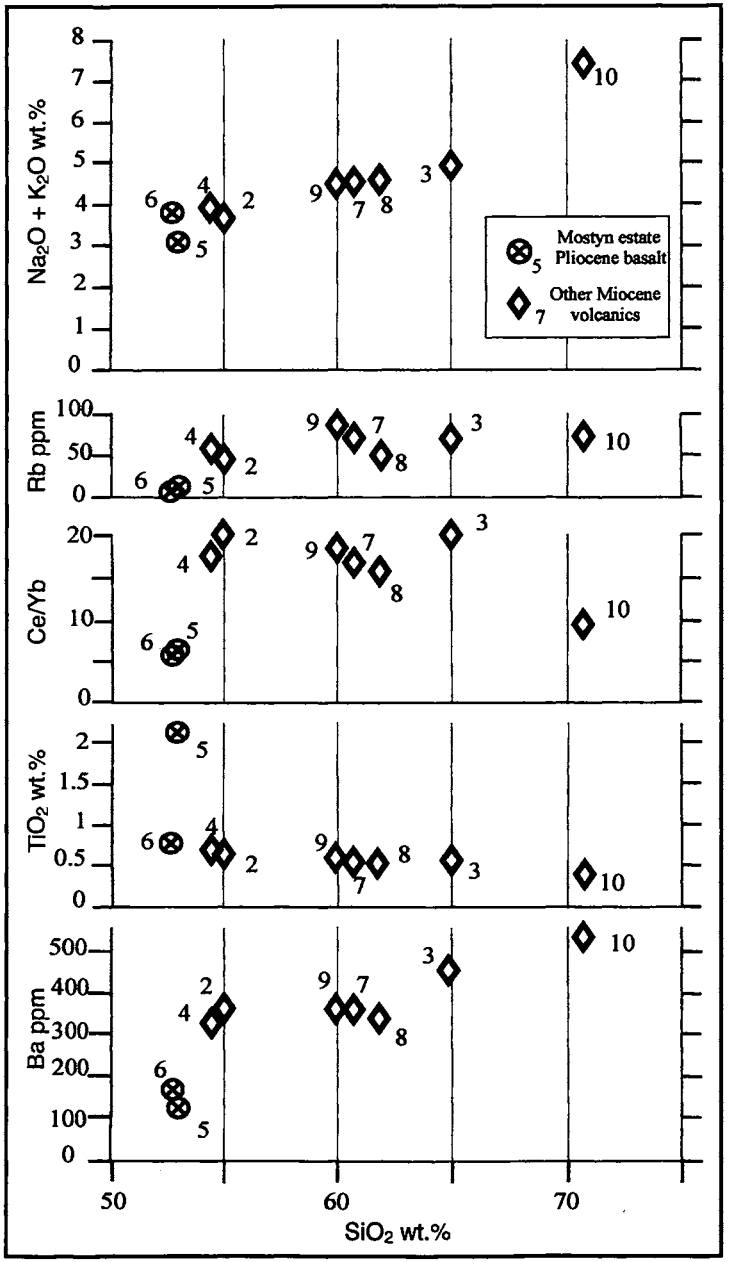

Figure 3. Various chemical parameters plotted against SiO_2 for the selected Sabah volcanic rocks. Samples 5 and 6 are of tholeiitic Mostyn Estate Pliocene basalt.

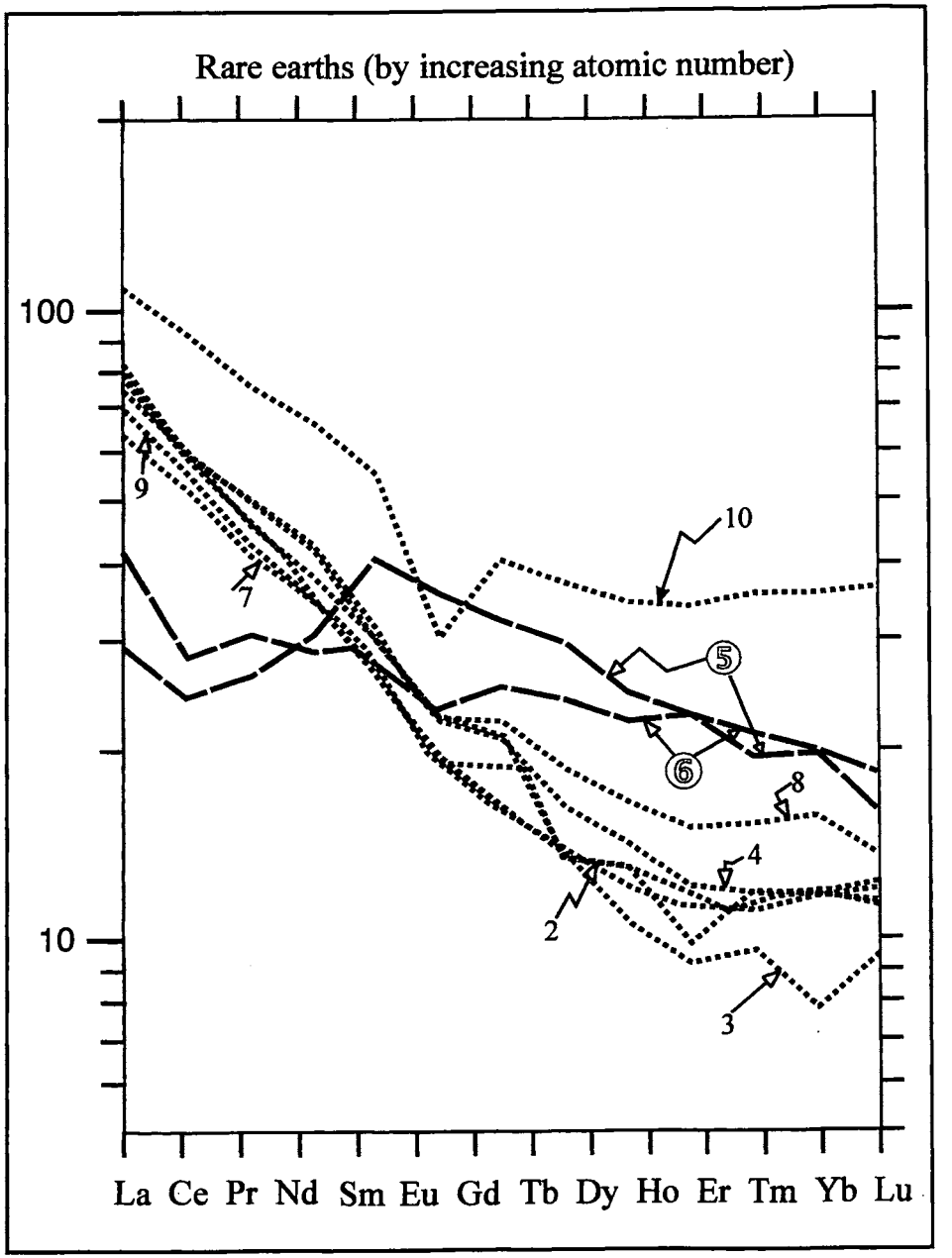

Figure 4. A rare earth chondrite normalized diagram of the Pliocene Mostyn Estate basalt.

fits into the High-K series. Although quite distinct on Figure 2, a convention Harker plot of (Na_2O + K_2O) versus SiO_2 fails to show the distinction, because of the compensating higher Na_2O contents (Fig. 3).

Plots of Ba (ppm), Rb (ppm) and Ce/Yb, versus SiO_2 clearly show that the Pliocene tholeiitic lavas of the Kunak area are tholeiitic (Fig. 3) and have geochemical similarities to the ophiolite suite and were derived from the same composition mantle as the Mesozoic ophiolite of the nearby Darvel Bay and Segama areas.

The Pliocene Mostyn Estate basalt is shown on a rare earth chondrite normalized diagram (Fig. 4), and it displays a remarkably similar signature to the ophiolite basement, indicating that the basalt is rift-related and derived from the same mantle as the Mesozoic ophiolite. Indeed the Pliocene rift-related basalts are indistinguishable from the ophiolitic basalts (Graves *et al.*, 2000) and have MORB type signatures. By contrast, the Dent and Semporna Miocene volcanic rocks display normal calc-alkaline signatures.

TECTONIC SETTING

The tectonic setting of the Miocene volcanic arc is by no means clear. It is impossible to relate its origin wholly to subduction from the Northwest Borneo Trough, which became extinct in the Lower Miocene (Hutchison, 1989). Hutchison (1992) modelled the arc as being related to subduction from the Celebes Sea, combined with intra-arc rifting to form the Southeast Sulu Sea marginal Basin, in which Middle Miocene mélange was deposited. One of the mélange formations (Ayer Formation) contains rifted clasts of the volcanic rocks in the southern Dent Peninsula. Solving the regression equations of Hutchison (1976) of the chemical data to calculate the Benioff zone depth is inconclusive, giving depths commonly in the range 145 to 155 km. The Pliocene Kunak-Mostyn Estate basalts are not subduction-related and their distinctive nature is emphasized by a calculated depth of 130 km. Sketch tectonic cross sections are presented in Hutchison *et al.* (in preparation).

ACKNOWLEDGEMENTS

ARCO International Oil and Gas Co. paid all expenses for field and laboratory work and gave permission to publish this paper. We are extremely grateful for this support and encouragement. CSH participated with the permission of ESRI, the University of South Carolina. We gratefully acknowledge the field help provided by the Kota Kinabalu branch of the Geological Survey of Malaysia, and we especially thank Mohd. Pauzi b. Abdullah and Tungah b. Surat for accompanying us in the field.

REFERENCES

EWART, A., 1982. The mineralogy and petrology of Tertiary–Recent orogenic volcanic rocks: with special reference to the andesitic–basaltic compositional range. *In:* Thorpe, R.S. (Ed.), *Andesites. Orogenic andesites and related rocks.* John Wiley, Chichester, 25–95.

GRAVES, J.E., HUTCHISON, C.S., BERGMAN, S.C. AND SWAUGER, D.A., 2000. Age and MORB geochemistry of the Sabah ophiolite basement. *Bull. Geol. Soc. Malaysia, 44,* 151–158 (this issue).

HAILE, N.S., WONG, N.P.Y. AND NUTTALL, C.P., 1965. The geology and mineral resources of Dent Peninsula, Sabah. *Geological Survey of the Borneo Region, Malaysia, Memoir 16.*

HUTCHISON, C.S., 1976. Indonesian active volcanic arc: K, Sr and Rb variation with depth to the Benioff zone. *Geology, 4,* 407–408.

HUTCHISON, C.S., 1989. *Geological evolution of South-East Asia.* Oxford University Press.

HUTCHISON, C.S., 1992. The southeast Sulu Sea, a Neogene marginal basin with outcropping extensions in Sabah. *Bull. Geol. Soc. Malaysia, 32,* 89–108.

HUTCHISON, C.S., BERGMAN, S.C., SWAUGER, D.A. AND GRAVES, J.E. (in prep.). Fission track dating and tectonic evolution of Sabah (north Borneo). *Journal of the Geol. Soc. of London.*

KIRK, H.J.C., 1962. The geology and mineral resources of the Semporna Peninsula, North Borneo. *Geological Survey Dept., British Territories in Borneo, Memoir 14.*

KIRK, H.J.C., 1968. The igneous rocks of Sarawak and Sabah. *Geol. Survey Borneo Region, Malaysia, Bull. 5,* Kuching.

LEE, D.T.C., 1970. Sandakan Peninsula, Eastern Sabah, Eastern Malaysia. *Geol. Survey of Malaysia Borneo Region, Report 6.*

RANGIN, C., BELLON, H., BENARD, F., LETOUZEY, J., MULLER, C. AND SANUDIN, T., 1990. Neogene arc-continent collision in Sabah, northern Borneo (Malaysia). *Tectonophysics, 183,* 305–319.

SWAUGER, D., BERGMAN, S.C., GRAVES, J., HUTCHISON, C.S., SURAT, T., MORILLO, A.P., BENAVIDEZ, J.J. AND PAGADO, E.S., 1995. Tertiary stratigraphic, tectonic, and thermal history of Sabah, Malaysia: results of a 10 day reconnaissance field study and laboratory analyses. *ARCO International Oil and Gas Co. unpublished report TRS 95-0036.*

Manuscript received 30 September 1999