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Petrology and geochemistry of the volcanic rocks associated with the Darvel Bay Ophiolite, Lahad Datu, eastern Sabah, Malaysia

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Abstract: Field observation, petrographic description and bulk rock geochemistry investigation suggest the presence of at least three, genetically unrelated, volcanic rock groups in the ophiolitic terrain of the Darvel Bay area. Group I Darvel Bay volcanic rocks are of the ocean island alkali basalt (OIB_A) origin, characterised by LREE enrichment and abundance in HFSE (Zr, Ti). Group II Darvel Bay volcanic rocks have a chemistry similar to those of N-MORB on the basis of depleted LREE and abundance of compatible elements (Ni, Cr, Sc). Group III Darvel Bay volcanic rocks are characterised by LILE and LREE enrichment, and have a depletion in compatible elements (Ni, Cr) and HFSE (Nb, Ti), indicating that they may have originally been erupted in an island arc setting.

Group I and II Darvel Bay volcanic rocks may be related to the volcanic activity during formation of the oceanic crust. Group III Darvel Bay volcanic rocks may be related to the Middle Miocene volcanic arc activity of the Dent Peninsula, SE Sabah.

INTRODUCTION

Volcanic rocks associated with the Darvel Bay Ophiolite named the Darvel Bay volcanic rock (DBVR) consist mainly of massive basalts, with minor of pillow lava, layered basalt, volcanic breccia and tuff. DBVR is only sparsely distributed and cover approximately 20% of the Darvel Bay Complex (Fig. 1). These rocks mainly crop out along road sections in the southern part of the complex. Some of the volcanic rocks are associated with the mélange outcrop and occur as a loose blocks and sometimes are associated pelagic sedimentary rocks. The DBVR can also be observed in several islands around the Darvel Bay.

The Darvel Bay Ophiolite Complex has been well described in the publications of the Geological Survey of Malaysia (Reinhard and Wenk, 1955; Fitch, 1955; Dhonau and Hutchison, 1966; Koopmans, 1967). The complex has been interpreted as a segment of ocean floor, either of a Proto-South China Sea (Holloway, 1981; Rangin *et al.*, 1990) or of the Celebes Sea (Hutchison, 1988). A wide range of K/Ar age dates have been obtained from the rocks of the Darvel Bay Ophiolite Complex from 210 Ma, Early Jurassic (Leong, 1971, 1974) to 168 Ma, 150 Ma Late Jurassic and 137 Ma Early Cretaceous (Rangin *et al.*, 1990). Cherts from the Chert-Spilite Formation have yielded radiolaria of the Early Cretaceous age (Rangin *et al.*, 1990; Aitchison, 1994).

This paper gives an account of the field observation, petrographic descriptions and geochemistry of the DBVR and discusses their origin and significance in the tectonic evolution of Sabah.

ANALYTICAL METHODS

Bulk rock geochemistry of the DBVR used in this study was analysed in the geochemistry laboratories at Royal Holloway, University of London using Philips, PW1480 XRF Spectrometer.

FIELD AND PETROGRAPHIC DESCRIPTIONS

Based on the field observation, petrography and geochemistry the DBVR are divided into three main groups: (1) Group I Darvel Bay volcanic rocks, (2) Group II Darvel Bay volcanic rocks and (3) Group III Darvel Bay volcanic rocks.

Group I

Group I DBVR occur mainly as loose blocks in the mélange outcrop. To the south of the study area, they occur along the road section at km 101 of Jalan Silam and to the north of the study area near Kampong Sepagaya, about 6 miles west of Lahad Datu town. Group I DBVR crop out in the Kampong Sepagaya shows pillow structures, where the geometry of the pillow structures indicates that the pillow lava youngs downwards, indicating

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overturning. These pillows are always brownish in colour and sometimes greenish. Amygdaloidal or vesicular textures are well preserved. Each pillow structure is between 50–70 cm long. Calcite veins a few centimetres thickness are commonly associated with the pillow lava, basaltic dykes with size range between 5–10 cm also occur within the pillow basalt outcrop.

In thin section, the pillow basalt is fine grained, showing microphenocrysts and/or microcrystalline textures (Fig. 2). Most of the vesicles have been filled by carbonate and quartz. This rock contains microphenocrysts of plagioclase, clinopyroxene, olivine and Fe-Ti oxides. The plagioclase is prismatic in shape and with grades up to 1 mm long. Some clinopyroxenes are partially and

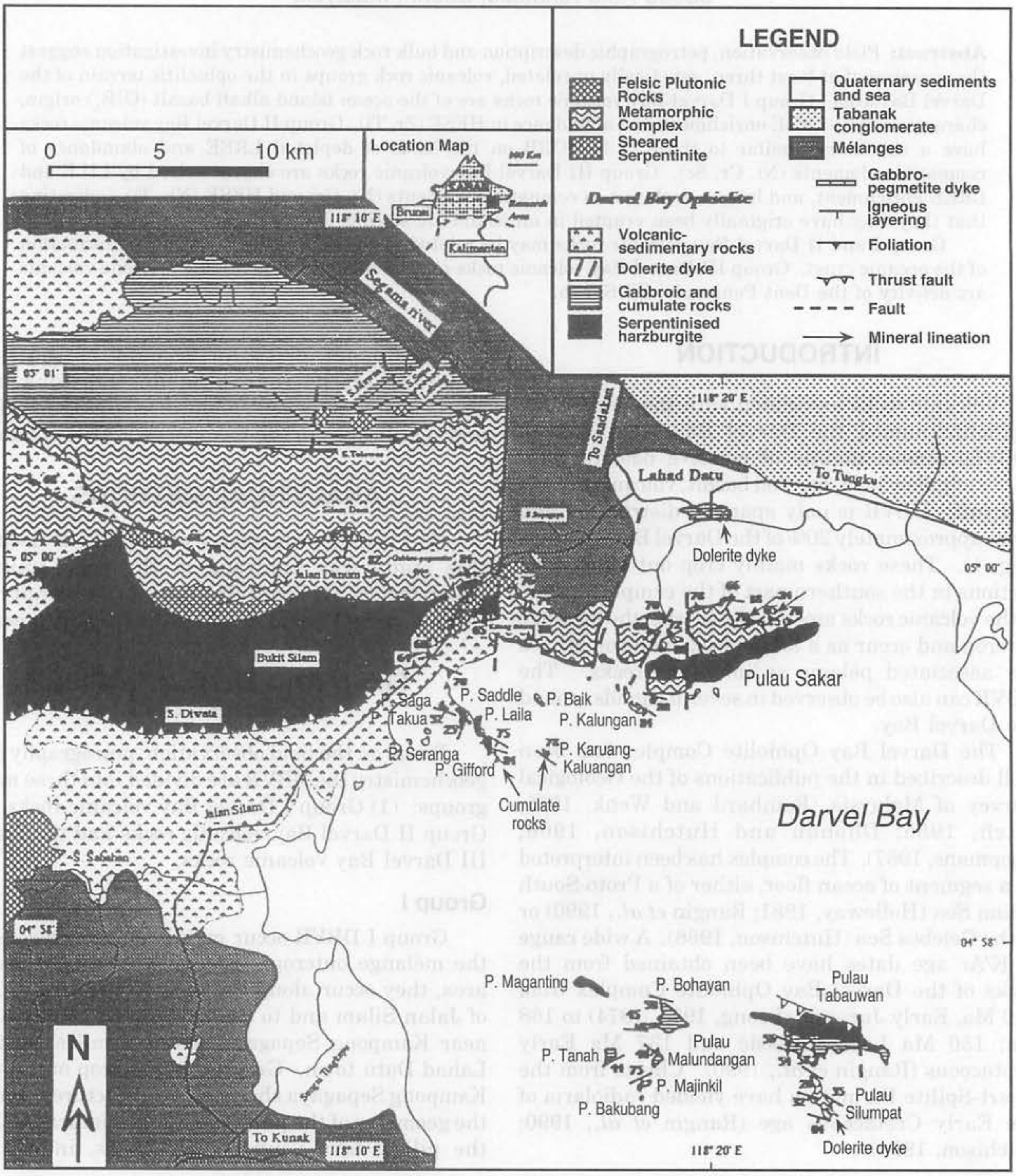

Figure 1. Simplified geological map of the Darvel Bay Complex, Sabah, Malaysia (from Omang, 1993).

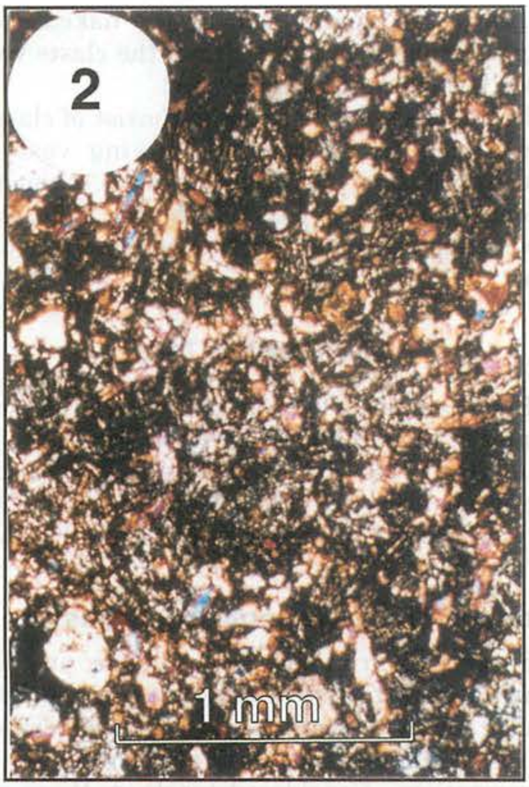

Figure 2. Photomicrograph of Group I DBVR illustrating microporphyritic texture and containing mainly microphenocrysts/ microcrystalline olivine, plagioclase laths, clinopyroxene and Fe-Ti oxides. Cross polarised. x4 magnification.

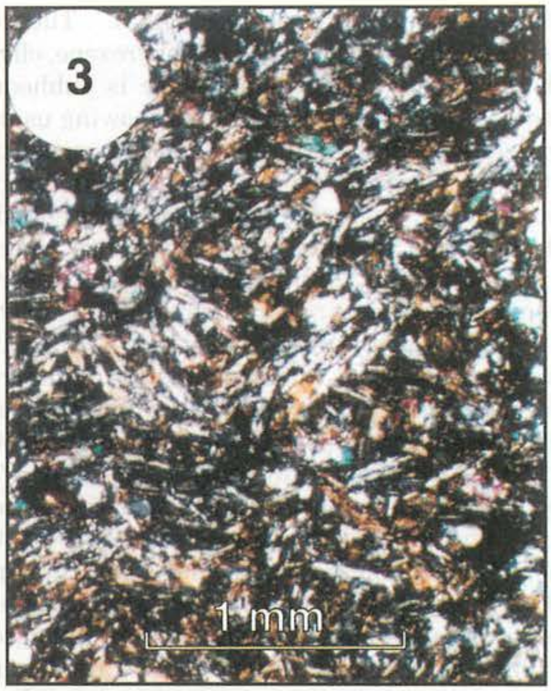

Figure 3. Photomicrograph of Group II DBVR illustrating interstitial texture and containing mainly plagioclase laths, clinopyroxene and Fe-Ti oxides. Cross polarised. x4 magnification.

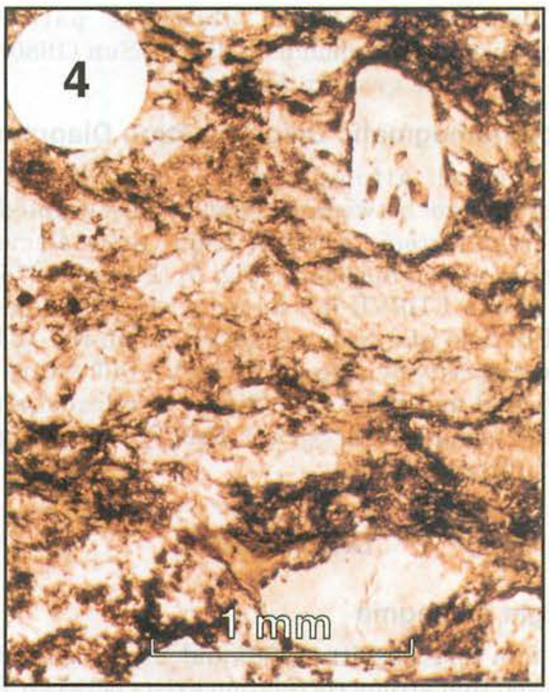

Figure 4. Photomicrograph of Group III DBVR (layered basaltic-andesite) illustrating intersertal/ glassy textures and containing mainly plagioclase laths, clinopyroxene, green amphibole and Fe-Ti oxides. Plane polarised. x4 magnification.

completely replaced by green hornblende and/or chlorite. The olivine is hexagonal in shape and may constitute less than 5% of the rock.

Group II

Group II DBVR is mainly exposed along Jalan Silam (JS8, JS118.5, JS121, JS123). The other localities are in the Sungai Sabahan (SgB2), south of the study area, in a disused quarry along the Jalan Sandakan (JSN3), in the north of the study area. The main feature of this group is its characteristic massive structure. This basaltic rock is greenish and brownish in colour. No layering and flow structures were found. Poorly developed pillow structures are sometimes preserved in this group. The actual thickness of this group is very difficult to measure in the field but on the basis of the group exposed on several outcrops scale, it can be estimated that thickness may be up to 200 metres or more. This group is rarely associated with the pelagic sedimentary rocks. There are only a few localities where the rocks can be seen associated with the reddish brown radiolarian cherts (Locality JS123). Some of them have been epidotized causing the rocks to appear yellowish in colour. Some of the rocks have been brecciated, probably due to tectonism.

In thin section, the massive basalt is fine to medium grained and commonly shows interstitial textures but sometimes amygdaloidal/vesicular textures are also preserved (Fig. 3). The rock consists mainly of plagioclase, clinopyroxene, olivine and Fe-Ti oxides. The plagioclase is subhedral, elongated and prismatic in shape, showing usually Carlsbad and albite twinning, and may constitute up to 30%. Some of the plagioclase is altered into sericite and carbonate. Clinopyroxenes are euhedral and subhedral in shape with grain size ranging from 0.2 mm to 0.7 mm. But a large phenocryst clinopyroxene is preserved in sample JS121. Olivine occur as euhedral and/or subhedral microphenocrysts, as colourful crystals under cross polarised light between plagioclase and clinopyroxene crystals. Olivine make up to 10% of the rock. Fe-Ti oxides may constitute less than 7%. Green amphibole, subhedral and prismatic in shape, may develop due to the breakdown of the clinopyroxene. These crystals may constitute up to 10% of the rock (e.g. sample JS121) and some of them have been replaced marginally by pale green acicular actinolite (e.g. sample SgB2). Epidote is a common mineral occurring in these rocks and may be developed due to the breakdown of plagioclase. Chlorite grains occur as aggregate minerals and may be formed by the breakdown of amphibole, pyroxene and actinolite.

Group III

Group III of the DBVR consist of layered basaltic-andesite (Fig. 4) and volcanic breccia. Layered basaltic-andesite is mainly exposed on several islands south of Lahad Datu town, including Pulau Sakar (southern part only) (sample PS9) and its surrounding (Pulau Kalung Kalungan) (sample PK2C, PKx). Volcanic breccia is exposed in one locality along the Jalan Silam at km 113 (JS113).

Layered basaltic-andesite

On the southern coast of Pulau Sakar (Locality PS9) the layered basaltic-andesite rocks of a few centimetres thick are found, where the layering indicates that the rocks are dipping south. This feature also suggests younging towards the south. The rocks are always greenish in colour, but sometimes brownish on the weathered surface.

In thin section, the rocks consist of plagioclase, amphibole, epidote, chlorite and Fe-Ti oxides, commonly shows intersertal texture but amygdaloidal/vesicular texture (less than 2%) can also observed. The alignment of grains which show a weakly preferred orientation can be seen in the sample.

Volcanic breccia

Volcanic breccia is found only on the mainland, along the Jalan Silam at km 113 and km 129. Most of the clasts in the volcanic breccia are of basalt fragments. The clasts are angular in shape and amygdales are clearly seen by the naked eye or using the hand lens. The size of the clasts varies from a few cm up to 5 cm across.

In thin section, these rocks consist of clasts of mainly basaltic fragments showing vesicular texture. Most of the vesicles are occupied by carbonate, quartz, zeolite and chlorite. The clasts are subangular to angular and range in size up to 2 cm.

GEOCHEMISTRY

Five samples of the Group I DBVR, seven samples of the Group II DBVR, six samples of the Group III DBVR and three samples of Neogene volcanic arc rocks from Dent Peninsula, Sabah were analysed. Result of the analyses are given in Tables 1, 2 and 3.

Major and Trace Element Geochemistry

Several covariation plots of major and trace elements were tested to determine if the DBVR could be subdivided into geochemical compositional groups that might facilitate their genetic interpretation. Considered together, these plots (Figs. 5, 6 and 7) clearly establish the DBVR can be divided into three groups, which do not appear to be related to a single fractionation trend and are therefore not co-genetic.

Spider Diagram

Incompatible trace elements patterns, normalised to the chondrite data of Sun (1980) for the DBVR are given in Figure 8.

Tectonomagmatic Discrimination Diagrams

Several attempts have been made to discriminate between magma series erupted in different tectonic settings using trace elements discrimination diagrams (Fig. 9) (Pearce, 1975).

Group I DBVR fall in the within-plate basalt (WPB) field and Group II DBVR fall in the MORB field respectively. Group III DBVR fall within the IAT field and those from Neogene volcanic arc of Sabah (samples TB, SgPgD, SgPgP) suggesting an arc affinity.

DISCUSSION

Origin of Magma

Sun and Nesbitt (1978) and Sun *et al.* (1979) showed that strong correlation exists between TiO_2 contents (inversely proportional to the amount of melting) and Al_2O_3/TiO_2 and CaO/TiO_2 ratios in MORB samples to close primary liquid compositions. According to their interpretations, primary MORB

Table 1. Geochemical analyses of Group I volcanic rocks of the Darvel Bay Ophiolite. Oxides in weight percentage (wt%) and trace elements in part per million (ppm). Total iron as Fe_2O_3 ($Fe_2O_3^* = Fe_2O_3 + FeO \times 1.111$), *Mg* (magnesian number) = $Mg/(Mg + Fe^{2+})$, where $Mg = MgO/40$, $Fe^{2+} = Fe_2O_3 \times 0.9/72$. Data presented on a volatile-free basis. LOI = loss on ignition at 1,100°C.

Oxides/Elements	SAMPLE NO.				
	JS101b	KSP1	KSP2	KSp	KgSp
SiO_2	48.86	49.00	47.91	51.42	50.36
TiO_2	2.996	2.924	2.959	2.645	2.952
Al_2O_3	17.06	11.14	11.15	10.32	11.07
$Fe_2O_3^*$	10.40	12.10	12.41	11.98	11.13
MgO	8.13	7.56	9.47	5.14	5.01
MnO	0.341	0.097	0.111	0.088	0.101
CaO	5.11	11.51	10.84	12.31	12.95
Na_2O	5.04	4.71	4.40	5.64	5.52
K_2O	0.936	0.004	0.002	0.000	0.045
P_2O_5	0.824	0.457	0.479	0.404	0.502
Total	99.69	99.50	99.73	99.95	99.63
LOI	4.97	4.27	4.11	4.20	4.19
Al_2O_3 + CaO	22.17	22.65	21.99	22.63	24.02
CaO/Al_2O_3	0.29	1.03	0.97	1.19	1.17
Mg	61.1	55.5	60.4	46.2	47.4
Na_2O/CaO	0.97	0.41	0.41	0.42	0.43
Ni	142	373	430	444	230
Cr	153	593	610	616	443
V	211	242	231	219	235
Sc	23	23	20	22	23
Pb	5.9	1.6	1.8	0.0	1.4
Sr	208.5	140.4	63.6	121.3	244.9
Rb	26.1	0.4	0.3	0.7	1.2
Ba	131	79	37	257	98
Th	5.1	4.3	4.6	3.1	4.0
Zr	295.2	255.7	263.4	233.0	254.1
Nb	60.9	44.4	45.4	39.6	44.2
Y	34.2	27.1	27.9	25.2	27.0
La	34	38	38	36	37
Ce	73	75	85	76	77
Nd	39	38	41	38	40
Cu	29	108	57	119	81
Zn	99	134	141	115	111
Cl	45	9	29	–4	–2
Ga	18	17	19	16	16

Table 2. Geochemical analyses of Group II volcanic rocks of the Darvel Bay Ophiolite. Oxides in weight percentage (wt%) and trace elements in part per million (ppm). Total iron as Fe_2O_3 (Fe_2O_3* = Fe_2O_3 + FeO x 1.111), *Mg* (magnesian number) = Mg/(Mg + Fe^{2+}), where Mg = MgO/40, Fe^{2+} = Fe_2O_3 x 0.9/72. Data presented on a volatile-free basis. LOI = loss on ignition at 1,100°C.

Oxides/Elements	SAMPLE NO.						
	JS8	JS118.5	JS121	JS121.5	JS123	JSN3	SgB2
SiO_2	50.13	48.97	50.09	50.32	50.81	50.64	50.51
TiO_2	0.996	1.134	1.072	0.981	1.254	1.407	1.306
Al_2O_3	16.11	17.21	16.46	16.35	14.68	15.12	15.37
Fe_2O_3*	9.65	9.28	9.32	9.10	11.18	9.17	11.64
MgO	8.83	5.36	8.62	8.19	7.44	8.45	7.98
MnO	0.162	0.168	0.164	0.153	0.196	0.179	0.204
CaO	10.69	13.15	10.68	10.50	9.25	10.46	8.87
Na_2O	3.52	3.68	3.52	3.82	3.54	3.69	3.71
K_2O	0.229	0.844	0.316	0.281	1.055	0.467	0.049
P_2O_5	0.097	0.112	0.115	0.104	0.110	0.228	0.058
Total	100.41	99.91	100.36	99.80	99.51	99.81	99.69
LOI	3.18	5.09	2.73	3.01	2.43	2.26	3.52
Al_2O_3 + CaO	26.80	30.36	27.14	26.85	23.93	25.58	24.24
CaO/Al_2O_3	0.67	0.76	0.65	0.64	0.63	0.69	0.58
Mg	64.7	53.6	64.9	64.3	58.0	64.8	57.8
Na_2O/CaO	0.33	0.28	0.33	0.36	0.38	0.35	0.42
Ni	129	111	113	116	59	153	39
Cr	432	365	380	377	175	325	67
V	258	239	257	248	318	280	406
Sc	43	36	41	39	43	37	42
Pb	0.3	1.0	0.1	0.6	0.1	2.7	–0.4
Sr	134.7	111.2	134.0	121.5	88.2	414.8	164.9
Rb	3.4	12.7	4.2	3.9	9.7	3.4	0.4
Ba	22	33	22	23	44	46	30
Th	0.6	0.3	0.0	0.7	–0.1	0.1	0.1
Zr	61.7	61.5	69.8	61.0	72.6	114.3	58.0
Nb	1.0	1.0	0.8	0.8	0.8	3.0	1.0
Y	24.9	28.8	26.4	24.6	34.9	28.8	20.9
La	2	1	2	2	0.1	4	1
Ce	3	4	8	2	5	14	3
Nd	6	7	8	6	7	13	5
Cu	66	55	47	55	59	23	19
Zn	78	83	78	74	95	84	52
Cl	–68	–30	–70	–38	–32	–35	26
Ga	14	14	14	13	14	15	15

Table 3. Geochemical analyses of Group III volcanic rocks from the Darvel Bay Ophiolite. Samples SgPgD, SgPgP and TB are from Neogene volcanic arc (Dent Peninsula, SE Sabah) for comparison. Oxides in weight percentage (wt%) and trace elements in part per million (ppm). Total iron as Fe_2O_3 ($Fe_2O_3{}^* = Fe_2O_3 + FeO \times 1.111$), *Mg* (magnesian number) $= Mg/(Mg + Fe^{2+})$, where $Mg = MgO/40$, $Fe^{2+} = Fe_2O_3 \times 0.9/72$. Data presented on a volatile-free basis. LOI = loss on ignition at 1,100°C.

Oxides/ Elements	SAMPLE NO.									
	PK2C	PKx	PS9	LB4a	JS129	JS134	SQ3	SgPgD	SgPgP	TB
SiO_2	54.25	55.34	58.81	58.26	67.95	57.57	54.08	60.16	56.89	62.79
TiO_2	0.902	0.934	0.767	0.946	0.626	0.555	0.626	0.691	0.705	0.533
Al_2O_3	16.91	16.79	16.04	16.40	11.76	15.29	15.60	17.50	17.95	16.64
$Fe_2O_3{}^*$	9.43	9.76	10.01	11.39	5.84	5.65	7.73	6.36	7.66	5.82
MgO	6.67	6.19	4.70	4.76	2.52	5.81	4.89	2.31	3.68	3.07
MnO	0.207	0.209	0.146	0.192	0.139	0.102	0.122	0.224	0.178	0.114
CaO	5.69	5.26	6.49	3.10	8.17	9.56	13.37	7.10	7.87	5.62
Na_2O	5.89	5.33	2.86	4.58	2.42	4.43	2.68	3.35	3.09	2.77
K_2O	0.060	0.055	0.030	0.239	0.034	0.737	0.545	2.127	1.808	2.370
P_2O_5	0.098	0.097	0.089	0.137	0.164	0.103	0.082	0.242	0.246	0.139
Total	100.11	99.98	99.95	100.00	99.62	99.80	99.73	100.06	100.07	99.86
LOI	3.60	2.77	3.87	3.67	3.91	9.11	8.02	0.77	0.46	1.74
Al_2O_3 + CaO	22.60	22.05	22.53	19.50	19.93	24.85	28.97	24.60	25.82	22.26
CaO/Al_2O_3	0.34	0.31	0.41	0.19	0.86	0.63	0.86	0.41	0.44	0.34
Mg	58.6	55.9	48.4	45.5	46.3	67.3	55.9	42.1	49.0	51.3
Na_2O/CaO										
Ni	28	25	22	15	15	143	49	13	15	11
Cr	18	20	34	22	17	245	163	27	17	13
V	291	273	312	266	179	177	224	184	199	135
Sc	39	37	34.60	36	17	23	34	24.1	20	18.3
Pb	–0.1	1.4	4.2	3.7	8.1	7.2	1.1	15.4	17.8	13.6
Sr	119.2	163.1	256.0	179.8	605.7	125.0	155.3	384.6	434.0	301.3
Rb	0.4	0.7	0.3	4.6	0.9	11.4	8.8	69.3	64.6	90.6
Ba	17	21	9	41	12	48	27	377	414	316
Th	–0.4	0.6	–0.3	0.0	2.0	0.0	–0.3	5.2	6.2	8.0
Zr	63.1	70.4	64.6	60.8	81.5	88.5	41.7	88.5	80.5	100.8
Nb	1.2	1.3	0.6	1.4	2.2	0.8	0.6	2.2	2.7	3.4
Y	24.5	26.3	21.6	28.3	20	15.2	12.8	22.9	21.3	16.3
La	1	2	2	4	5	6	2	11	13	14
Ce	7	7	7	8	14	15	4	22	27	26
Nd	6	8	7	8	10	13	4	16	18	16
Cu	173	89	90	67	15	17	66	19	51	30
Zn	133	99	81	138	64	64	53	83	84	50
Cl	–14	70	22	901	–43	–54	–60	41	275	53
Ga	14	16	16	16	14	17	15	16	18	16

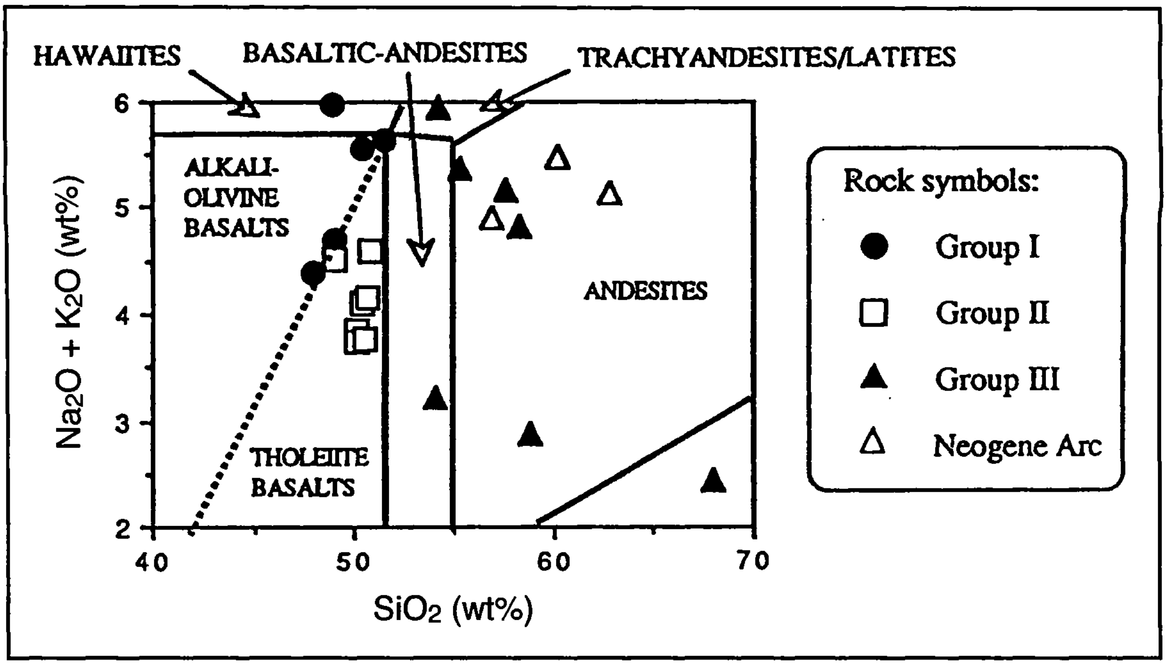

Figure 5. SiO_2 versus alkalis diagram for DBVR. Data from Neogene volcanic arc is for comparison. Fields from MacKenzie *et al.* (1982).

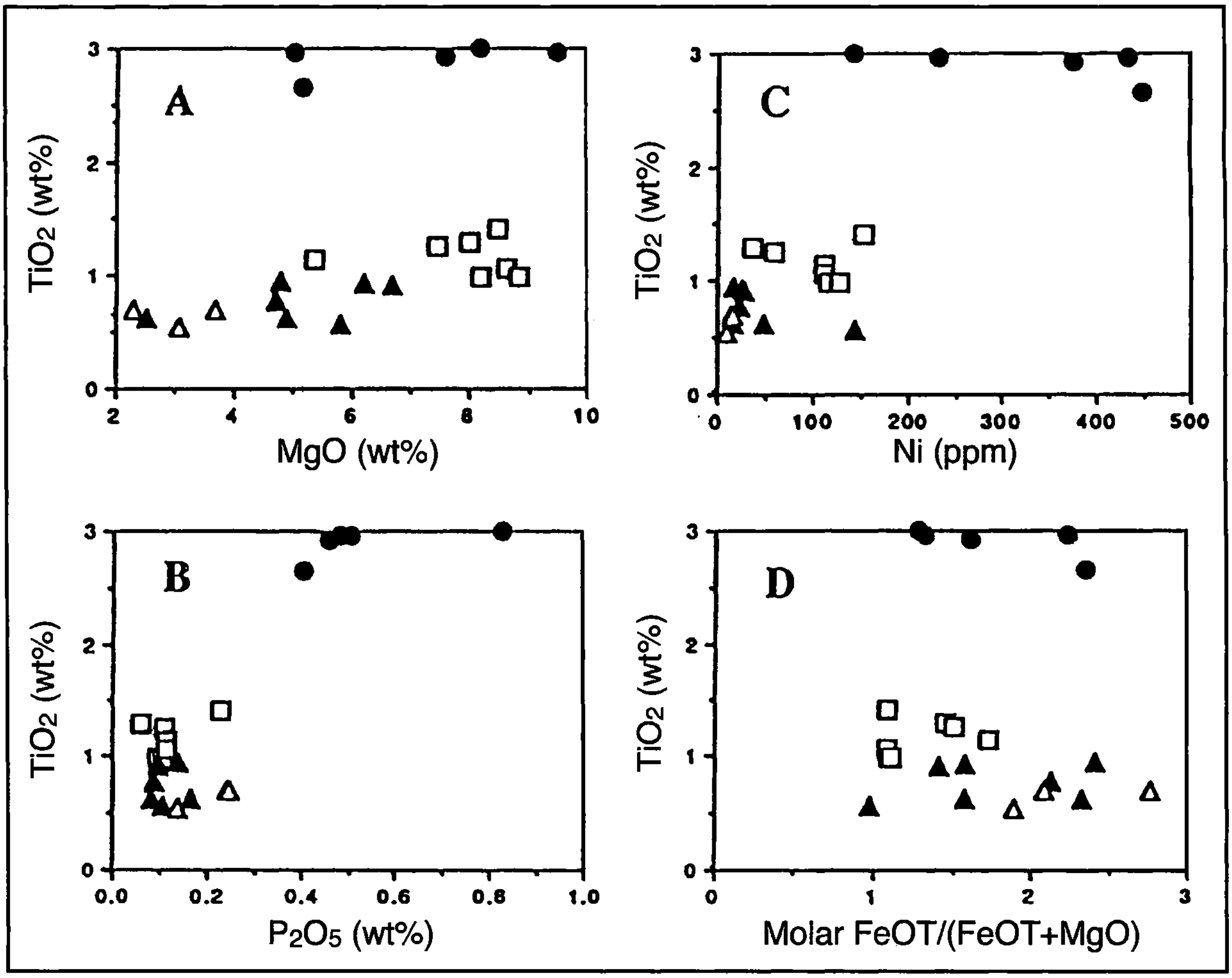

Figure 6. Plots of TiO_2 versus (A) MgO, (B) P_2O_5, (C) Ni, and (D) Molar FeOT/(FeOT + MgO), show three compositional groups of DBVR. Rock symbols are the same as Figure 5.

with the lowest TiO_2 (~ 0.8 wt%) and corresponding high Al_2O_3/TiO_2 (~ 20) and CaO/TiO_2 (~ 17) is generated by a large degree of melting (~ 25%) of pyrolite source, where as primary MORB with high TiO_2 (~ 1.5 wt%) and corresponding low Al_2O_3/TiO_2 (~ 10) and CaO/TiO_2 (~ 7) is generated by smaller degrees of melting (< 15%) of similar pyrolite source (0.2 wt% TiO_2). In Figure 10, Group I DBVR samples plot along the higher TiO_2 extension of the MORB trend. This raises the possibility that parental magma for the group may have been produced by a very small amount of melting of a pyrolitic source. But their Y/Nb versus Zr/Nb ratios (Fig. 10a) suggest a OIB_A/E-MORB (Zr/Nb < 10 and Y/Nb < 1; Wilson, 1989) related to the mantel source with a large plume component.

Almost all Group II DBVR samples plot within the MORB field delineated by Sun and Nesbitt (1978) on the basis Al_2O_3-CaO-TiO_2 relationships of the primary MORB compositions (Fig. 10b and c). However, as discussed above, the Y/Nb versus Zr/Nb ratios suggest that this suite probably represents N-MORB formed from heterogeneous mantle source rather than by different degrees of partial melting of a homogeneous mantle source.

The high Al_2O_3/TiO_2 and CaO/TiO_2 ratios characterize low-Ti basalts of ophiolites and island arcs (Fig. 10b and c) are unlikely to be derived by high degrees of partial melting of a pyrolite source (Sun and Nesbitt, 1978). Thus, the parental magma of Group III DBVR cannot be attributed to extensive partial melting of an undepleted mantle source.

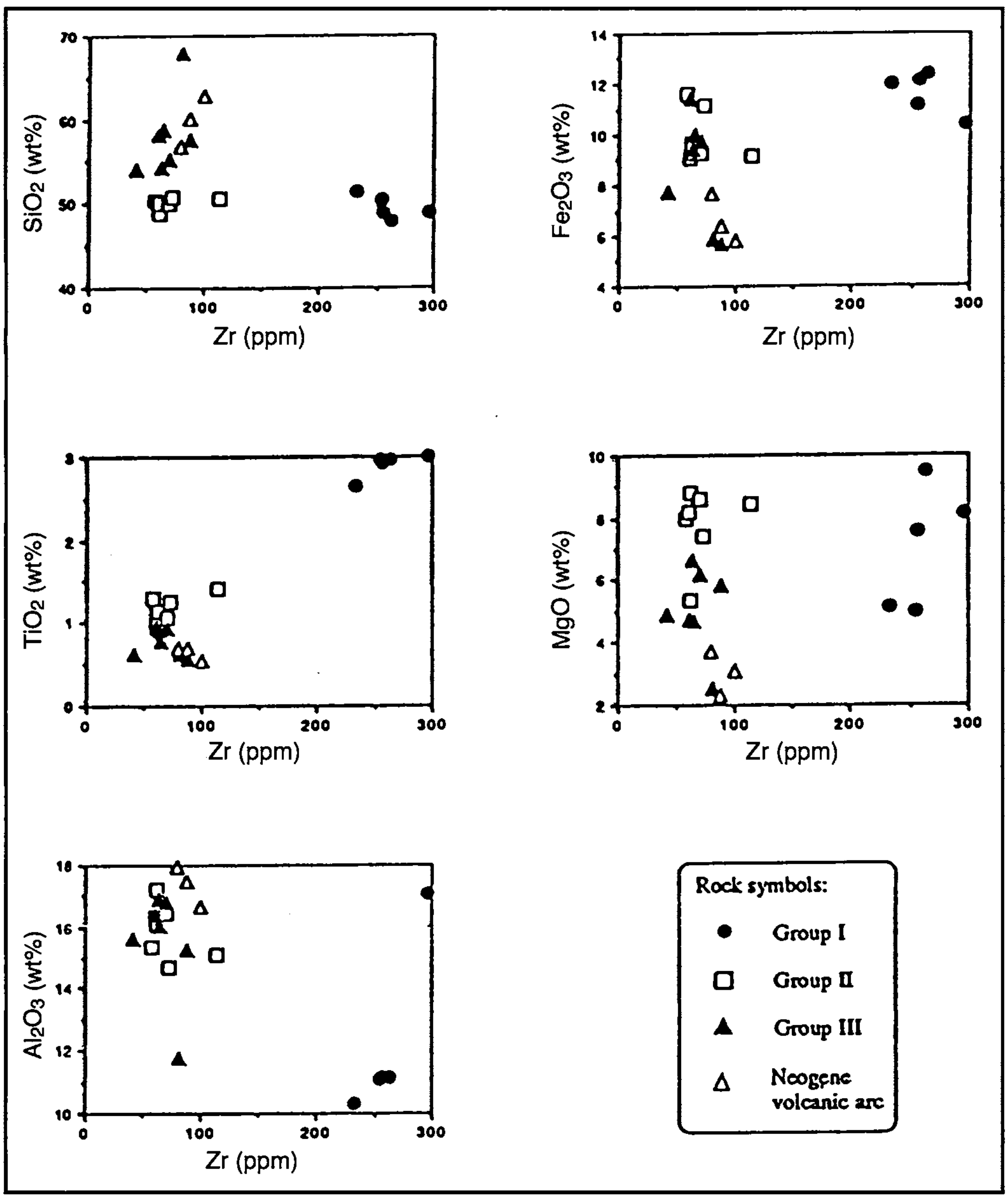

Figure 7a. Plots of Zr versus major element for DBVR.

The relatively low MgO, Ni and Cr contents of Group III DBVR and their high Al_2O_3/TiO_2 and CaO/TiO_2 ratios are consistent with remelting of a mantle source already depleted in incompatible elements by previous episodes of melting, as has been proposed for low-Ti ophiolites basalts (Sun and Nesbitt, 1978; Pearce and Norry, 1979; Duncan and Green, 1980). However, Cameron *et al.* (1983) suggested a petrogenetic model involving mixing of two chemically and isotopically distinct components; (1) an incompatible element-depleted MORB-type source and (2) a hydrous, incompatible element-enriched fluid phase derived from either subducted continental or oceanic material in an island arc, or from ocean island-type mantle sources.

Tectonic Significance

The bulk rock geochemistry data suggests the existence of tectonic environments from major ocean basin to island-arc settings. Group I and II Darvel Bay volcanic rocks may be related to the volcanic activity during formation of the oceanic crust. Group II Darvel Bay volcanic rocks (N-MORB affinity) may represent the spreading ridge-axis volcanism whereas the Group I Darvel Bay volcanic rocks (OIB_A/E-MORB affinity) represent the off-axis volcanism. Group III Darvel Bay volcanic rocks (IAT affinity) may be related to the Middle Miocene volcanic arc activity of the Dent Peninsula, SE Sabah. This magmatic arc formed either due to southeastward subduction of the proto South China

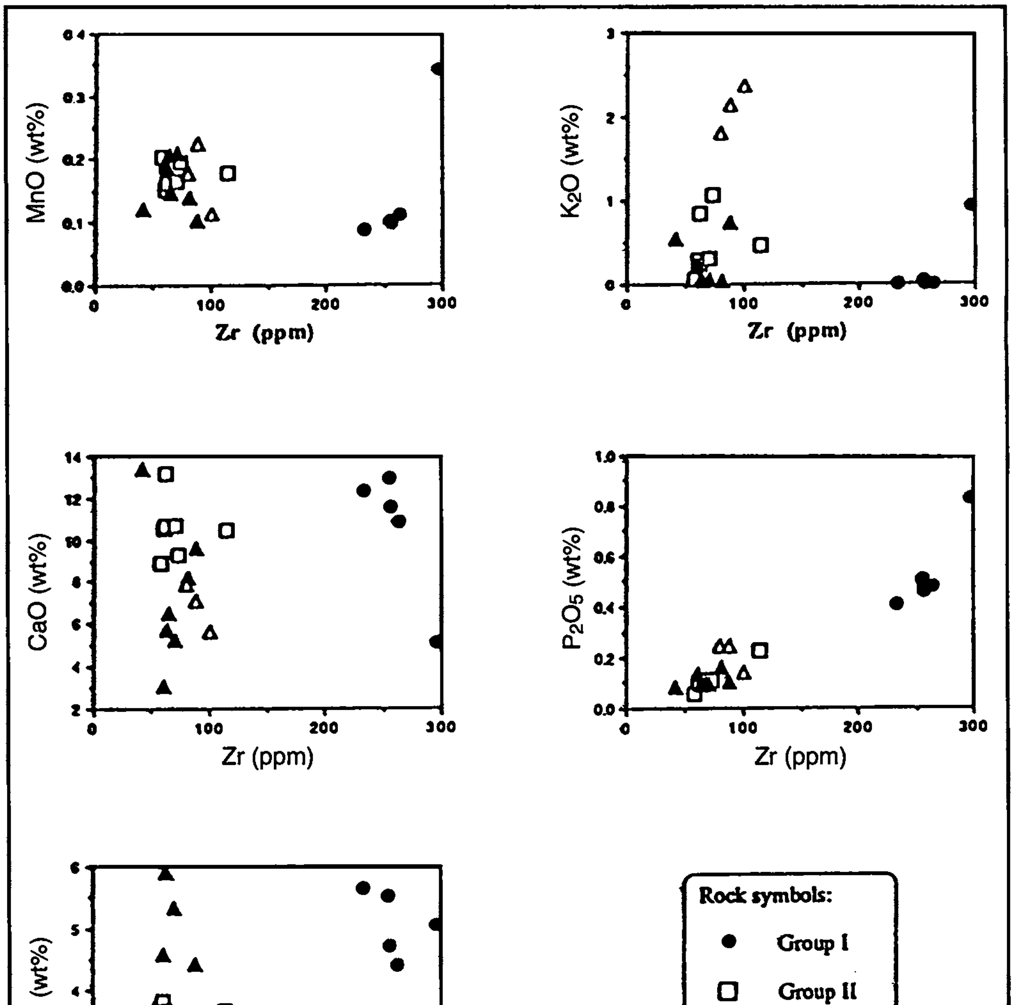

Figure 7b. Plots of Zr versus major element for DBVR.

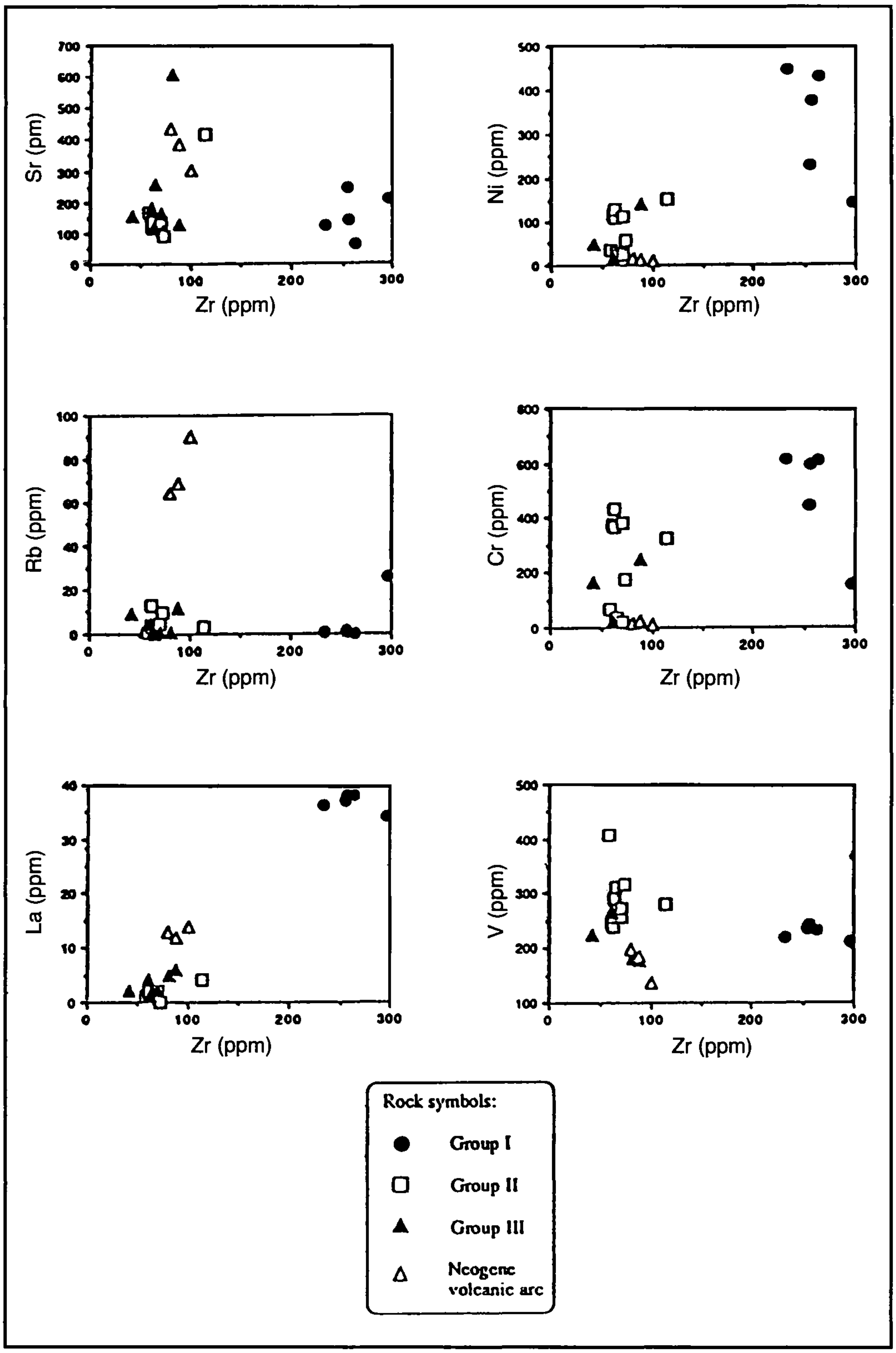

Figure 7c. Plots of Zr versus selective trace element for DBVR.

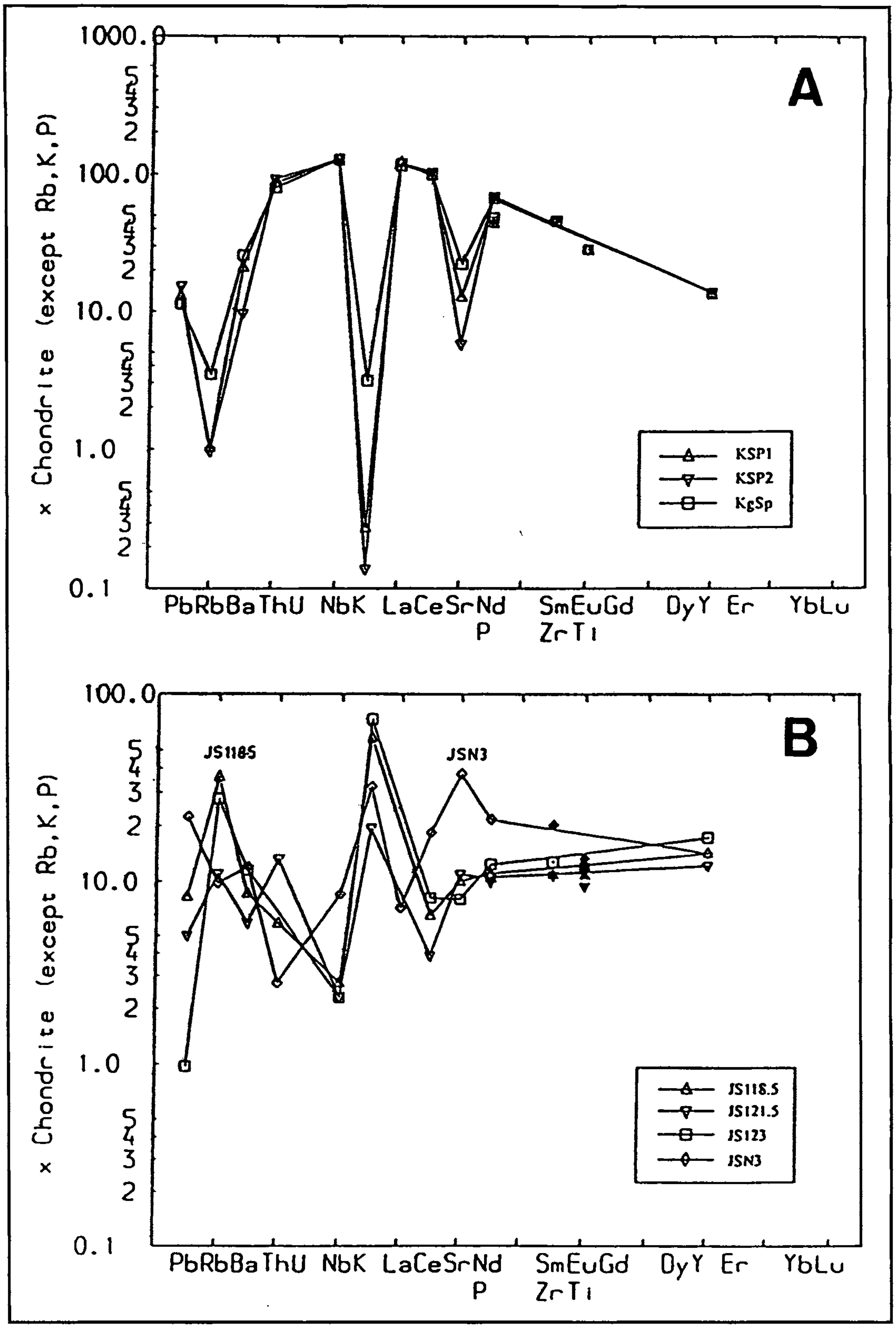

Figure 8A and B. (A) Spider diagram of Group I DBVR and (B) Spider diagram of Group II DBVR. Sample/chondrite (except Rb, K, P) normalization and element arrangement are according to Sun (1980). Close symbols are for P, Zr and Ti.

Sea oceanic crust beneath Sabah (Taylor and Hayes, 1983) or due to northward subduction of the Celebes Sea (Rangin *et al.*, 1990; Hutchison, 1992).

CONCLUSIONS

- Field observation, petrographic description and bulk rock geochemistry investigation suggest the presence of at least three, genetically unrelated, volcanic rock groups in the Darvel Bay area.
- Group I Darvel Bay volcanic rocks are of the ocean island alkali basalt (OIB_A) origin, characterised by LREE enrichment and abundance in HFSE (Zr, Ti).
- Group II Darvel Bay volcanic rocks have a chemistry similar to those of N-MORB on the basis of depleted LREE and abundance of compatible elements (Ni, Cr, Sc).
- Group III Darvel Bay volcanic rocks are characterised by LILE and LREE enrichment, and have a depletion in compatible elements (Ni, Cr) and HFSE (Nb, Ti), indicating that they may have originally been erupted in an island-arc setting.
- Group I and II Darvel Bay volcanic rocks may be

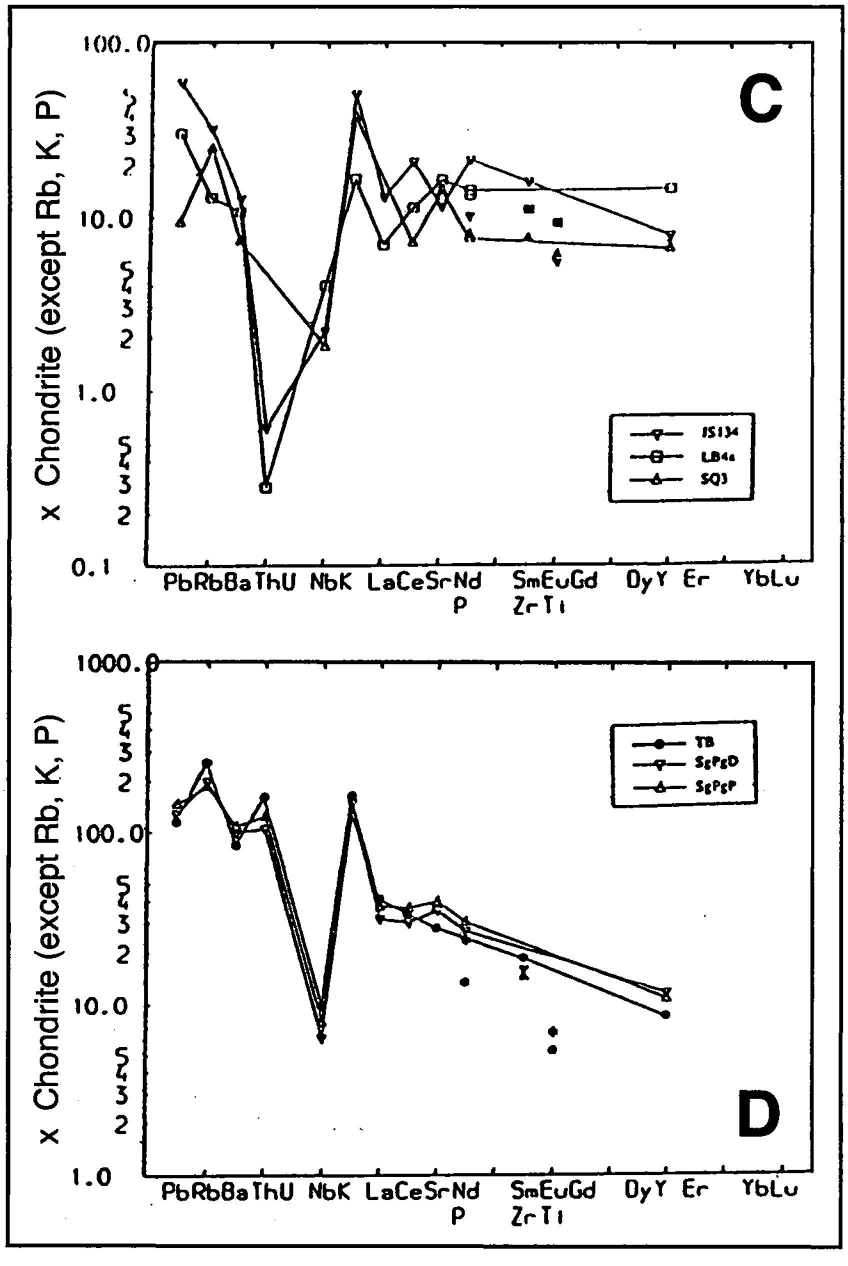

Figure 8C and D. (C) Spider diagram of Group III DBVR and (D) Spider diagram for the Neogene volcanic arc of Dent Peninsula, Sabah. Sample/chondrite (except Rb, K, P) normalization and element arrangement are according to Sun (1980). Close symbols are for P, Zr and Ti.

related to the activity of volcanic during formation of the Mesozoic oceanic crust. Group III Darvel Bay volcanic rocks may be related to the Middle Miocene volcanic arc activity of the Dent Peninsula, SE Sabah.

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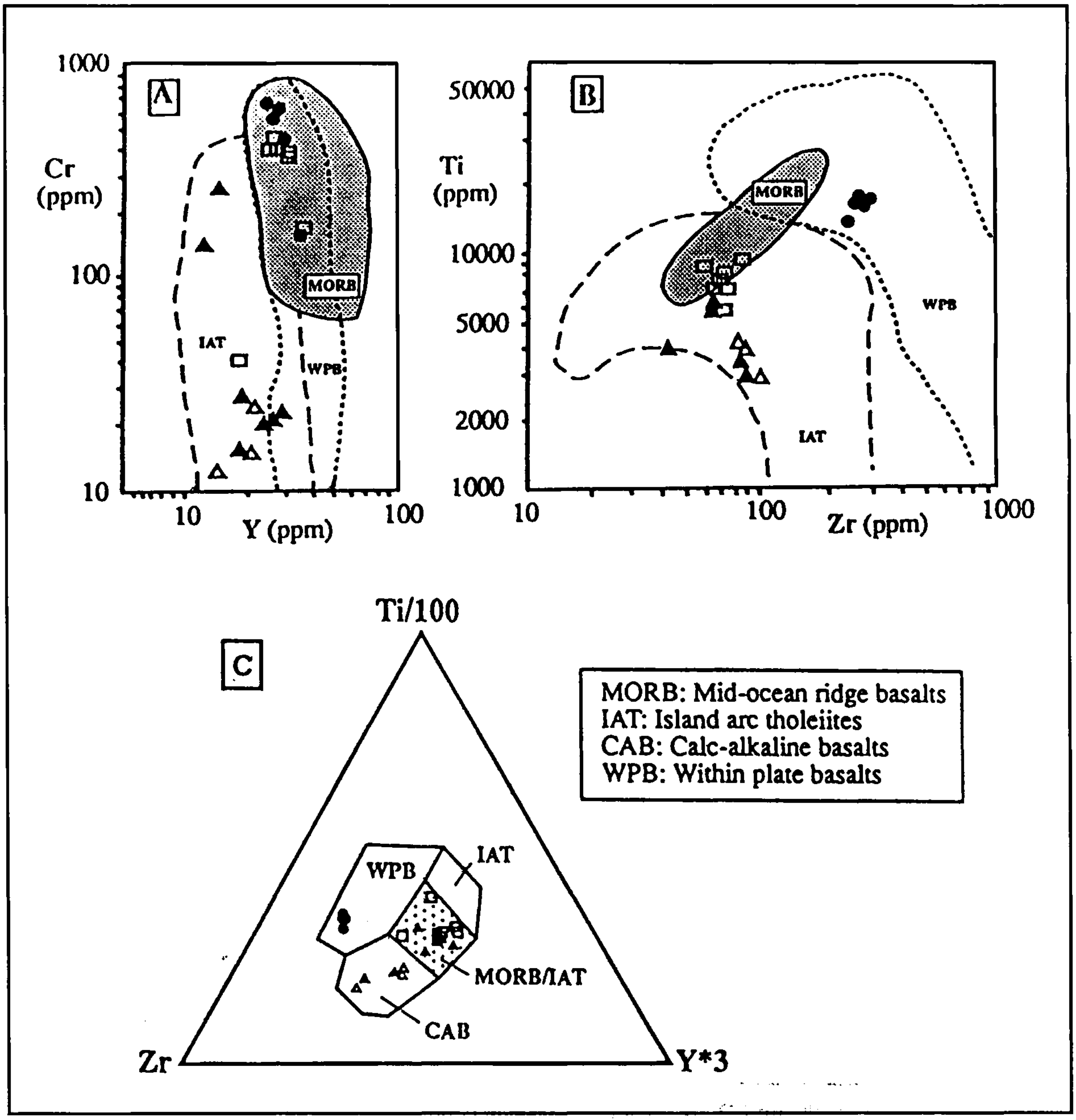

Figure 9. Tectonic discriminant diagrams of the DBVR. (A) Y-Cr diagram of Pearce *et al.* (1984), (B) Zr-Ti diagram of Pearce (1980), (C) Zr-Ti/100-Y*3 diagram of Pearce and Cann (1973). Rock symbols are the same as Figure 1.

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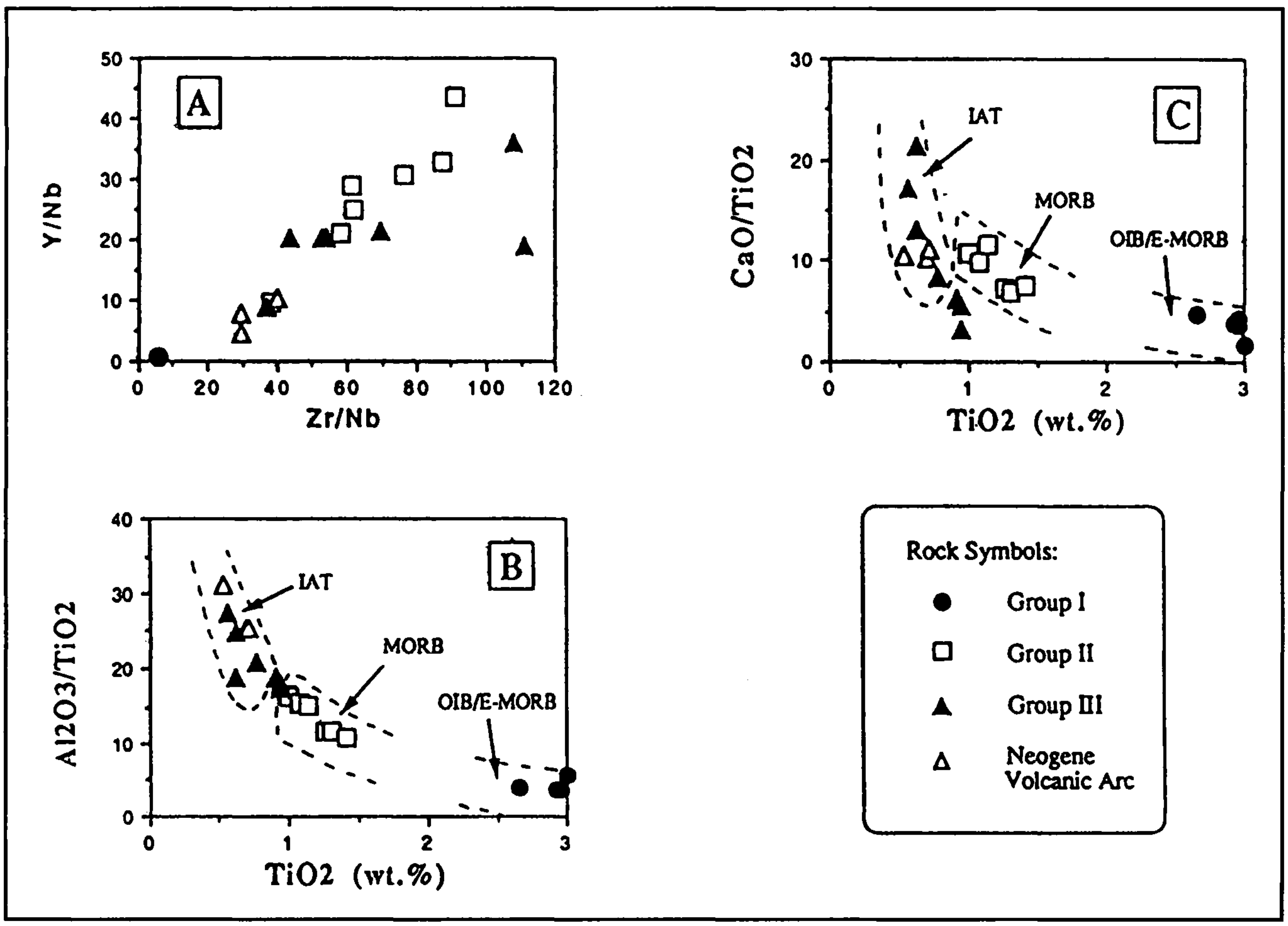

Figure 10. Plots of (A) Zr/Nb versus Y/Nb, (B) TiO_2 versus Al_2O_3/TiO_2, and (C) TiO_2 versus CaO/TiO_2 for DBVR. Data from Neogene volcanic arc are for comparison.

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