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Volcanic-hypabyssal rock geochemistry of a subduction-related marginal basin ophiolite: Southeast Bohol Ophiolite-Cansiwang Mélange Complex, Central Philippines

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ABSTRACT: The Early Cretaceous Southeast Bohol Ophiolite-Cansiwang Mélange Complex and the Alicia Schist form the basement of southeastern Bohol Island in central Philippines. New geochemical data show that four discrete groups constitute the volcanic and associated hypabyssal rocks of the ophiolite-mélange complex: boninitic rocks (BON), enriched and normal mid-ocean ridge basalt-like rocks (E-MORB; N-MORB) and high-magnesian andesites (HMA). Of these four groups, the BON are the most depleted in REEs and with the most pronounced negative Nb anomalies. Both MORB-like types exhibit subduction-zone influence as reflected in their slight negative Nb anomalies. Characteristically with flat and LREE-depleted patterns, the HMA samples appear to mimic N-MORB patterns but with lower REE concentrations. This geochemical diversity is best explained by a suprasubduction zone environment of formation as is also evident from field geological information. Formation of the Cansiwang Mélange is believed to have been concurrent with the ophiolite's emplacement by subduction-accretion along a forearc margin. This tectonic boundary was later jammed into inactivity with the entry of the Alicia Schist that most likely was an oceanic bathymetric high. The intercalation of both tuffaceous materials and pelagic chert with the pillow basalts are consistent with a marginal basin tectonic setting.

Key words: ophiolite, geochemistry, forearc, suprasubduction, Philippines

1. INTRODUCTION

Generation of oceanic crust that constitute ophiolites occur in a variety of settings (e.g., Coleman, 1977; Shervais, 1990; Abelson et al., 2001; Tamayo et al., 2004). Miyashiro (1973) had initially recognized that some ophiolitic basalts and volcanogenic sediments are chemically and stratigraphically similar to those found in island arcs. Later studies showed subduction-related marginal basins as possible source regions (e.g., Brouxel and Lapierre, 1988), which best explains both the arc-related geochemistry of igneous rocks and the presence of volcanogenic sediments that could only come from nearby volcanic islands. These ophiolites are now known as supra-subduction zone (SSZ) ophiolites (Pearce et al., 1984), that sensu lato include both crust-mantle sequences associated with forearc extension (Troodos, Oman, and the Coast Range ophiolite of California) and those formed in backarc basins (e.g., the Josephine ophiolite). Petrochemical diversity is usually associated with backarc environments (e.g., Dadd, 1998; Xu et al., 2003) that are, for most parts, dominated by rocks geochemically indistinguishable from mid-oceanic ridge basalts (MORB). However, forearc ophiolites constitute most of the major ophiolite occurrences in the world because of the higher possibility for on-land preservation of ophiolites along forearc margins during collision or subduction (e.g., Bedard et al., 1998; Wallin and Metcalf, 1998; Wakabayashi and Dilek, 2000; Kato and Saka, 2006).

The Southeast Bohol Ophiolite Complex (SEBOC)–Cansiwang Mélange Complex is part of the Cretaceous basement complex of Bohol Island. Studies on this ophiolite-mélange complex (e.g., Yumul et al., 1995; de Jesus et al., 2000; Yumul, 2003; Faustino et al., 2003) have recognized the likelihood that it was generated in a marginal basin and emplaced along a subduction margin. This paper presents a more thorough geochemical study of the volcanic-hypabyssal rocks of the ophiolite-mélange complex and compares the results with other such complexes of known tectonic origins and with present-day marginal basins. This is done to constrain the setting in which it was generated and to contribute to what is known on how this part of the Philippine island arc system had evolved through time.

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2. GEOLOGIC OUTLINE

The roughly oval-shaped Bohol Island covers 4,117 km^2 and is at the southeastern corner of Visayas, the central Philippine region which includes the islands of Panay, Negros, Cebu, Samar and Leyte (Fig. 1). This part of the Philippine archipelago is flanked by two active trench systems: the Early to Middle Miocene Negros Trench to the west where the Southeast Sulu Sea basin is subducting eastwards and the Philippine Trench to the east, site of the oblique westward subduction of the Philippine Sea Plate since 5 Ma (Rangin et al., 1999). Crossing the eastern half of the Visayan region is the Pliocene sinistral Philippine Fault that accommodates a component of the oblique convergence between the Philippine Sea Plate and the archipelago (e.g., Aurelio, 2000).

The tectono-stratigraphy beneath the Tertiary volcano-sedimentary cover of southeastern Bohol is subdivided, in ascending order, into the Alicia Schist, the Cansiwang Mélange and the SEBOC (Faustino et al., 2003). These basement units are juxtaposed by thrust faults verging eastwards. The Alicia Schist is composed of chlorite schist, amphibolite schist and quartz sericite schist believed to have been formed by regional metamorphism unrelated to the emplacement of the ophiolite (Diegor et al., 1995; de Jesus et al., 2000; Faustino et al., 2003). A SW-NE schematic section through the Alicia area (Fig. 2a, b) illustrates that the Alicia Schist is not directly in contact with the ophiolite. This same section shows that the metamorphic gradient is truncated, if retrograde metamorphism is to be expected relative to the nearest harzburgite body, with the higher grade amphibolite schist sandwiched between lower grade chlorite schist and quartz-sericite schist, below and above it, respectively. Regional mapping (Acosta et al., 1997) has shown that the schistose fabric is more likely part of a strongly developed regional foliation that is distinct from and predates ophiolite-emplacement deformation. These field relationships thus prove that the Alicia Schist is not the metamorphic sole of the SEBOC (Yumul et al., 2001; Faustino et al., 2003).

The Cansiwang Mélange is a tectonic serpentinite mélange believed to have formed by accretion along a sediment-starved trench (Barretto et al., 2000; de Jesus et al., 2000). It is made up of fault-bounded packets of deformed lithologies varying in size from a few centimeters to several hundreds of meters wide set in serpentinized matrix. Thrust faults that cut through the mélange are orientated in a grossly similar manner as those found in the intact ophiolite massifs (de Jesus et al., 2000). Ophiolite-derived harzburgite, microgabbro, basalt, chert and tuffaceous volcanic materials make up most of the clasts. Notably absent are Alicia Schist-derived materials which is taken to indicate that the metamorphic body was only introduced into the subduction system at the very last stages of trench activity (de Jesus et al., 2000).

Thrust atop the mélange is the ~2 km-thick SEBOC, a complete ophiolite suite distributed in a northerly trend as three blocks separated by post-ophiolite sedimentary cover. The northernmost block is at Alicia where the sequence of thrusted ophiolite, mélange and Alicia Schist is well-exposed. Only the mantle section of the ophiolite, composed almost entirely of harzburgite, is found in this locality. South of it is the Guindulman block which is composed of massive harzburgite with rare occurrence of lherzolite and dunite pods and is underlain by the Cansiwang Mélange. The only complete ophiolite exposure is the Duero block at the southernmost part of the study area, from Sitio Mayana to the town of Duero (Fig. 1). Harzburgite with lenses of dunite and wehrlite make up the residual rocks, and interlayered dunite, clinopyroxenite and wehrlite constitute the layered ultramafic cumulate sequence. Anorthosite and diabase dikes cut some sections of the massive harzburgite. Up-section, xenoliths of diabase in massive gabbro suggest this plutonic section's proximity to the roof of the magma chamber. The sheeted dike complex is composed of parallel, chloritized or epidotized microgabbro, basalt and diabase that are 10 to 20 cm wide and devoid of any screens of country rock. The dikes trend northeast and steeply dip northwest. Sheet flows and pillowed volcanic rocks are exposed both as intact outcrops at Mayana, Alejawan River and as blocks within the Cansiwang Mélange along the Cansiwang Road. Volcanic rocks at Mayana are conformably overlain by manganiferous sediments and chert. Thin-bedded chert and cherty mudstones are best exposed along the Alejawan River, where the volcanic rocks are also freshest. Radiolarian and silicified foraminifer dates yield an Early Cretaceous, most likely Late Albian age (Faustino et al., 2003). As previously mentioned, volcanic rocks in the melange occur as megaclasts exhibiting pillow structures in roughly upright positions. These volcanic rocks are mostly epidotized and chloritized, and are intercalated with either chert or poorly indurated, tuffaceous volcaniclastic rocks. Megaclasts within the Cansiwang Mélange were most likely derived from the same crustal section of the marginal basin that produced the SEBOC (Faustino et al. 1998; de Jesus et al. 2000). Results from mapping (de Jesus et al. 2000; Faustino et al. 2003), geophysical survey (Barretto et al., 2000) and preliminary geochemical characterization (Yumul et al., 1995) all indicate that the Cansiwang Melange formed by accretion of materials scraped off from both the overlying and underlying plates to build a forearc accretionary prism. Because of its close genetic and compositional affinity with the overlying ophiolite, and for ease of discussion, they are, from hereon collectively referred to as an ophiolite-melange complex. Details on the stratigraphy and paleontology of overlying sedimentary formations and how they document the shallowing history of Bohol is in Faustino et al. (2003).

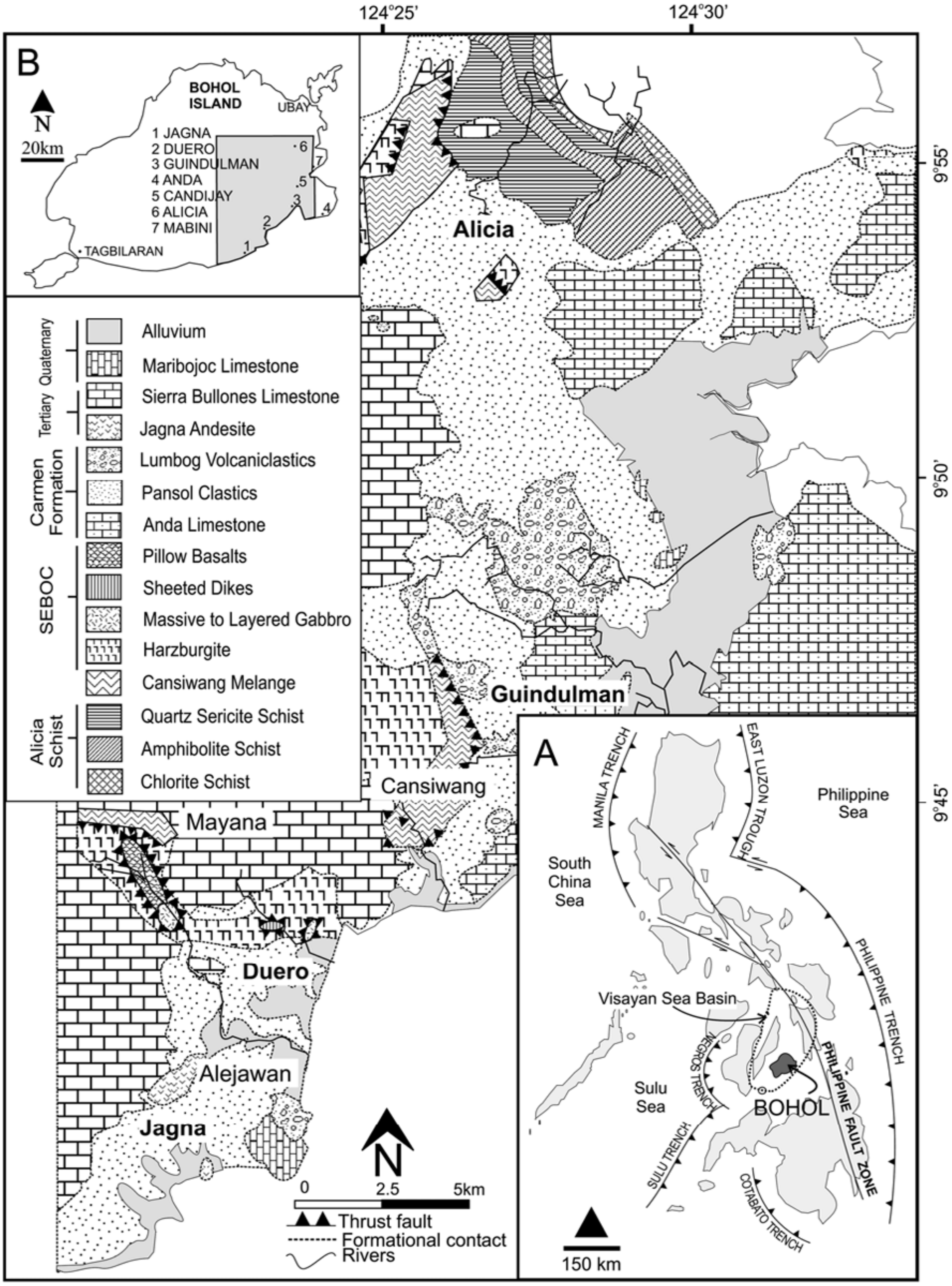

Fig. 1. (Inset A) Schematic map of the Central Philippines showing the major tectonic features that influence the region. Bohol is at the southeastern boundary of the Visayan Sea Basin. (Inset B) The highlighted portion of Bohol island is the mapped area which covers 7 municipalities in Southeast Bohol. Geologic map of Southeast Bohol. The Early Cretaceous basement complex is subdivided into three distinct bodies as distinguished in the legend box. The metamorphic mass, Alicia Schist, is composed of amphibolite schists, quartz sericite schists and chlorite schists. The Southeast Bohol Ophiolite Complex is composed of harzburgites, isotropic and layered gabbros, sheeted dikes, pillow basalts with associated deep-marine and tuffaceous sedimentary rocks. The Cansiwang Mélange is composed of ophiolite-derived clasts set in serpentinite matrix.

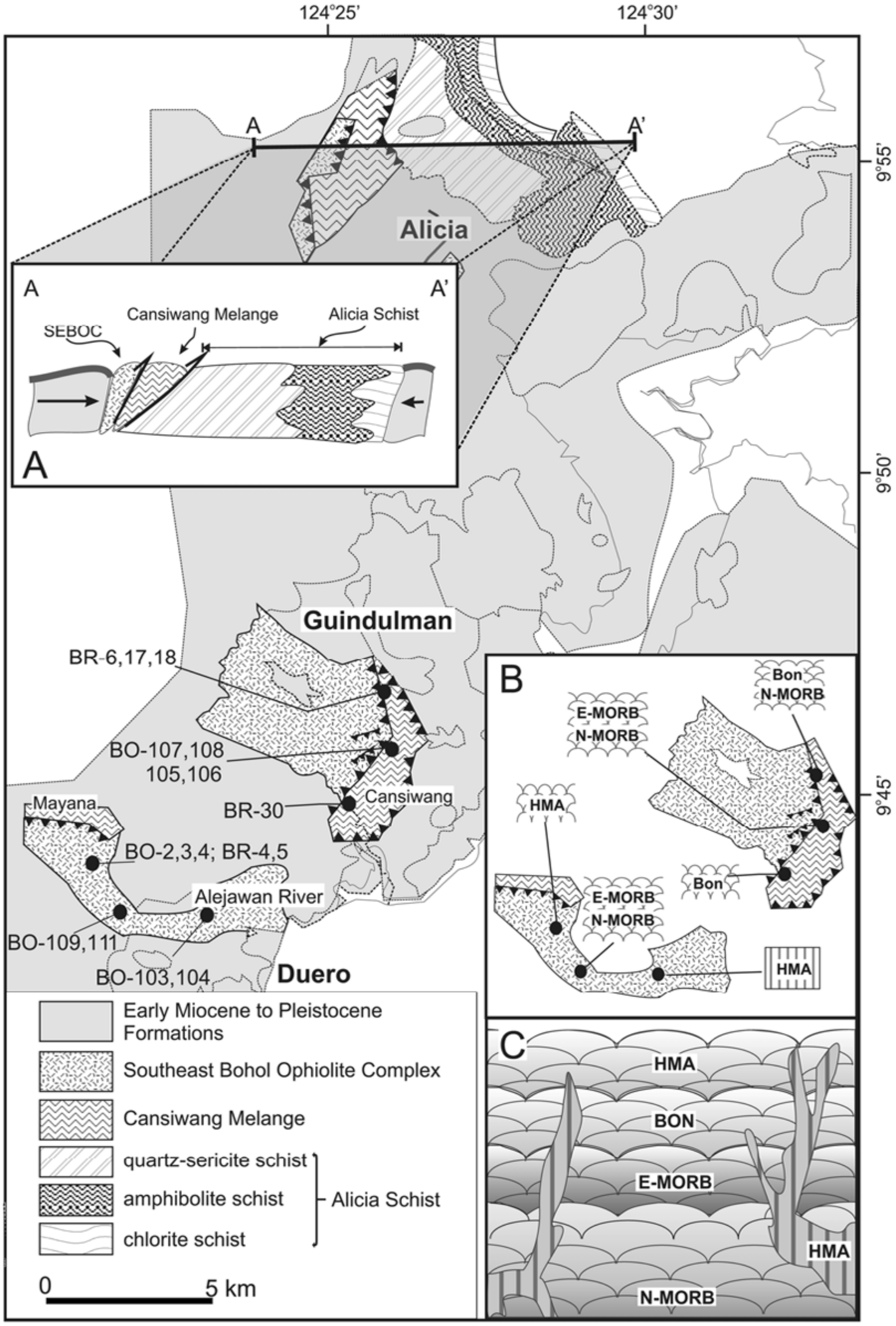

Fig. 2. Geologic map of the study area. For easier recognition of the ophiolite distribution, younger sedimentary and volcanic formations were lumped together as Early Miocene to Pleistocene formations. Locations where samples were taken are also shown. Samples were gathered from the Guindulman and Duero blocks of the ophiolite. Inset A shows a schematic cross-section showing the stratigraphic relationship between the three members of the basement complex of Bohol. The units, in ascending order are Alicia Schist, Cansiwang Mélange and the SEBOC, all of which are juxtaposed by thrust faults verging eastwards. Inset B is an illustration of the geographic and stratigraphic distribution of the different geochemical populations of SEBOC's volcanic rocks. Inset C shows that the MORB-like group floors most of the other geochemical assemblages indicating its formation ahead of all the other volcanic rock groups.

3. METHODOLOGY

As is common in tropical areas, sampling of the different units is often limited by poor outcrop exposure due to thick soil and forest cover. Good exposures are usually limited to fresh road cuts and stream beds. However, even at such locales, the degree of weathering is often too severe to allow for any sensible sampling for geochemical purposes. Despite these conditions, we managed to collect representative samples from different sections of the ophiolite-mélange complex. Seven pillow basalts and two sheeted dike samples from the Duero block, and eight volcanic rocks from the Cansiwang Mélange east of Guindulman (Fig. 3) were analyzed for whole rock major and trace elements by a Philips PW 1480 X-ray fluorescence (XRF) at the Tokyo University. Details regarding XRF procedures, precision and accuracy are in Yoshida and Takahashi (1997). Selected whole rock trace elements and rare-earth elements (REE) were analyzed with a VG Elemental PlasmaQuad 3 inductively coupled plasma mass spectrometer (ICP-MS) at the Department of Earth Sciences, University of Hong Kong (Table 1; Fig. 4a to d). Sample preparation, ICP-MS operating conditions, calibration strategies and data reduction procedures are essentially similar to those of Jenner et al. (1990).

4. PETROCHEMISTRY

Most samples are not very much different at outcrop and hand-sample scales, with megascopic compositions ranging from basalt to andesite. Samples BR-6, 17, 18, 30, BO-107, 108, 105 and 106 are all basalts from pillowed flows, closely associated with both tuffaceous and cherty sedimentary materials, that occur as megaclasts within the mélange in Guindulman. The pillow structures, although not exactly horizontal, are in the upright position. From the Duero Massif, samples BO-109 and 111 are basalts and samples BO-2, 3, 4, BR-4 and 5 are from andesitic lava flows. Samples BO-103 and 104 are both from the sheeted dike section of SEBOC that were megascopically identified as diabase. All the samples have undergone ocean floor metamorphism with plagioclase, pyroxenes and glasses altered to chlorite. Some plagioclases are also altered to clay whereas pyroxenes are metamorphosed to fibrous amphibole. The high loss-on-ignition (LOI) values of the rocks are consistent with these petrographic characteristics. In order to avoid misreading metamorphic for magmatic signatures, weight is accorded to the less mobile high field strength elements (HFSE) and REE in the discussion.

Petrographically, the samples can be segregated into basalts and andesites with very little textural difference to distinguish rocks from either massif with the exception of two pillow basalts from Guindulman. Samples BR-18 and BO-30 are notably different with spinifex texture that indicates quenching. The rest of the sampled rocks exhibit typical aphanitic, diabasic or porphyritic textures with occasional glomeroporphyritic and intergranular textures. Despite these very minimal differences in mineralogy and texture, geochemical compositions of the sampled outcrops display very pronounced variations. Whole-rock major, trace and REE data are presented in Table 1 showing geochemical segregations as explained in succeeding sections. Variation diagrams of major elements recalculated as anhydrous with respect to the FeO*/MgO ratio as fractionation index is presented in Figure 4. All samples have Al_2O_3 concentrations typical of tholeiites (between 13–16%). As the alkalis may have been remobilized through seafloor metamorphism, they are not taken into account for magmatic characterization. Succeeding discussions also treat other major element signatures with caution for the same reason. Thus, with also little differences in petrographic characteristics, the less mobile REEs and trace elements were chiefly used to further differentiate these samples. As a result, four geochemical groups of volcanic rocks from the ophiolite-mélange complex are recognized: boninitic rocks (BON), enriched and normal mid-ocean ridge basalt-like rocks (E-MORB and N-MORB) and high-magnesian andesites (HMA).

4.1. Boninitic Rocks

The BON rocks occur as megaclasts in the Cansiwang Mélange at Guindulman. One particular sample was gathered upsection of N-MORB samples (Fig. 2a, c). Textures vary from variolitic to spinifex suggesting rapid crystallization with phenocrysts of clinopyroxene and plagioclase set in a groundmass of glass and microlites of clinopyroxene and plagioclase. Porphyritic or intergranular textures with the pyroxenes making up most of the glomeroporphyritic clasts are also observed. Some altered pyroxenes have been converted to metamorphic hornblende, plagioclase to clay and the volcanic glass to chlorite. These samples plot in the calc-alkali field (SiO_2 versus FeO*/MgO diagram) but exhibit positive TiO_2 and negative MgO and CaO trends relative to increasing FeO*/MgO, akin to tholeiites. Typical of high-Ca boninites, BON samples have $SiO_2 <52\%$, $Ca/Al_2O_3 > 0.75$ and high MgO (between 10 wt.% to 16.6 wt.%). Significantly lower incompatible trace element concentrations than MORB or typical arc basalts also characterize this group. However, the presence of plagioclase phenocrysts, the lack of olivine in the mineralogy and a pronounced negative Zr anomaly preclude these rocks to be true boninites. These rocks have notably low contents of HFSE (TiO_2 and P_2O_5) and heavy REE (HREE). Their Zr/Y values are less than unity and Nb is depleted relative to Th and La (Fig. 4a). Except for the low SiO_2, which can be attributed to the chloritization of the glassy matrix, these geochemical signatures are the same as those of the Betts Cove Ophiolite boninites (Bedard et al., 1998) and from the modern Mar-

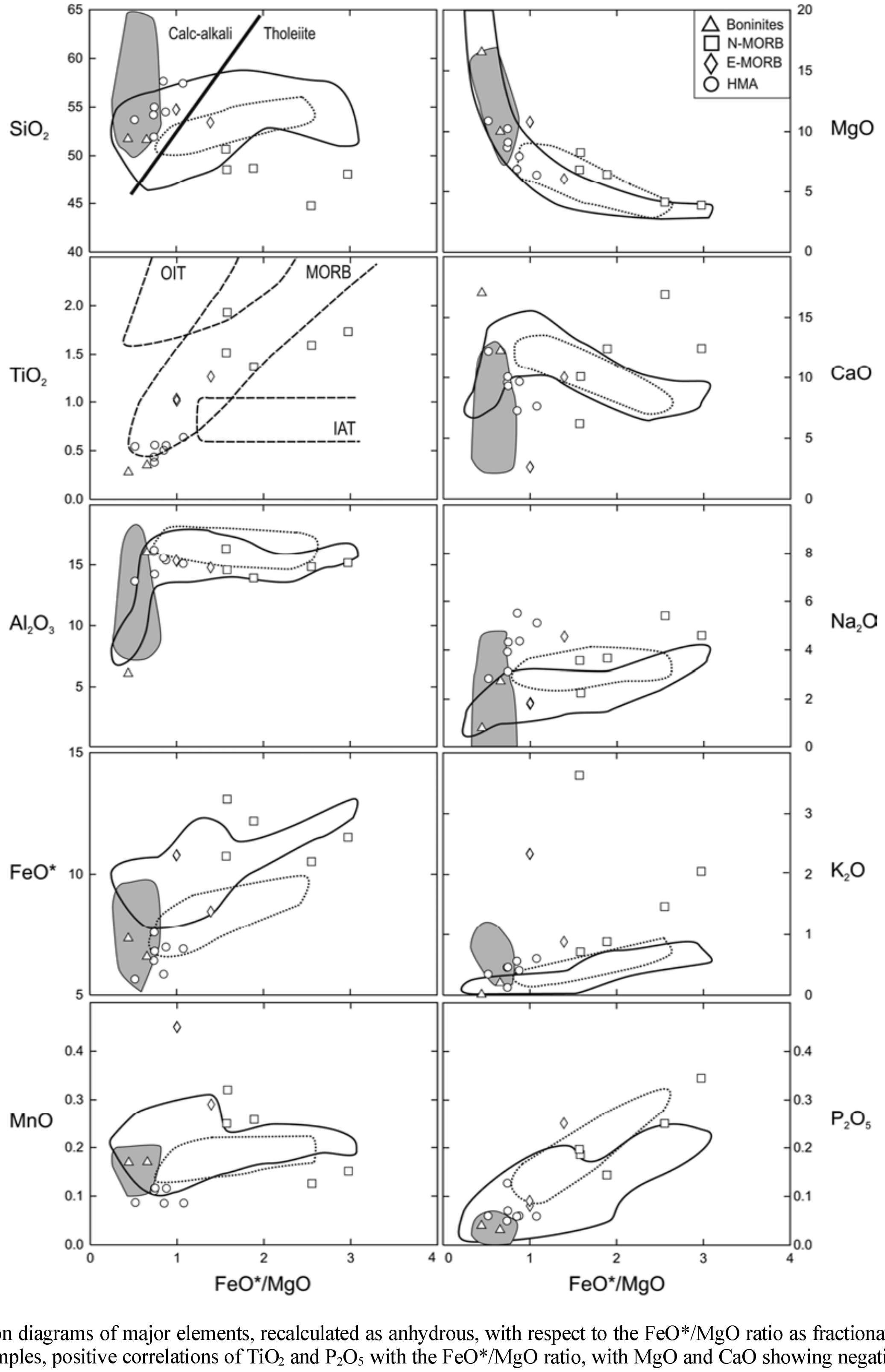

Fig. 3. Variation diagrams of major elements, recalculated as anhydrous, with respect to the FeO*/MgO ratio as fractionation index. For most of the samples, positive correlations of TiO_2 and P_2O_5 with the FeO*/MgO ratio, with MgO and CaO showing negative correlation, correspond to the tholeiitic fractionation trend. However, SiO_2 contents with increased FeO*/MgO indicate calc-alkalic compositions for most of the samples and concentrations of TiO_2 show a group of samples that better approximates MORB values than do the rest. Fields for mid-oceanic ridge basalts (MORB), island arc tholeiite (IAT) and oceanic island tholeiite (OIT) are after the Basaltic Volcanism Study Project (1981). Other defined field are as follows: solid line – Lau backarc basin basalts (Hawkins, 1977; Falloon et al., 1987); dotted line – Mariana Trough basalts (Hawkins et al., 1990); gray filled area – boninites (Beccaluva and Serri, 1988).

Table 1. Major, trace and rare earth element compositions of selected Bohol ophiolite – mélange volcanic rocks. Major elements are presented recalculated as anhydrous.

geochem group	BON		E-MORB			N-MORB					HMA						
sample locality	Guindulman		Guindulman		Duero	Guindulman				Duero	Duero						
sample number	BR-18	BR-30	BO-107	BO-108	BO-111	BR-6	BR-17	BO-105	BO-106	BO-109	BO-2	BO-3	BO-4	BR-4	BR-5	BO-103	BO-104
rock type	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s volc	p/s vdc	sd	sd
SiO_2	48.00	51.99	54.34	54.27	51.29	47.01	47.13	39.61	44.29	45.57	55.98	52.35	51.60	53.55	48.98	56.43	52.50
TiO_2	0.33	0.28	1.00	1.02	1.21	1.87	1.41	1.41	1.60	1.28	0.62	0.53	0.52	0.43	0.36	0.49	0.53
Al_2O_3	14.93	6.11	15.20	15.22	14.19	14.12	15.23	13.14	13.98	13.02	14.72	14.79	13.12	15.92	15.34	15.27	13.59
Fe_2O_3	6.11	7.37	10.71	10.68	8.13	12.67	10.00	9.31	10.61	11.41	6.73	6.70	5.43	6.34	7.16	5.73	6.50
MnO	0.16	0.17	0.45	0.45	0.28	0.31	0.23	0.11	0.14	0.24	0.08	0.11	0.08	0.11	0.11	0.08	0.11
MgO	9.29	16.61	10.70	10.70	5.83	8.01	6.37	3.65	3.57	6.04	6.25	7.65	10.46	8.60	9.66	6.74	8.71
CaO	11.39	17.11	2.61	2.60	9.63	9.76	5.77	14.96	11.46	11.63	7.44	9.28	11.75	9.46	9.50	7.11	8.89
Na2O	2.54	0.82	1.83	1.79	4.37	2.18	3.33	4.79	4.23	3.44	4.98	4.20	2.73	3.88	2.95	5.40	4.13
K2O	0.19	0.01	2.32	2.32	0.84	0.69	3.38	1.30	1.89	0.82	0.59	0.39	0.33	0.45	0.12	0.55	0.44
P2O5	0.03	0.04	0.08	0.09	0.24	0.18	0.08	0.22	0.32	0.13	0.06	0.06	0.06	0.05	0.12	0.06	0.07
LOI	6.95	1.18	10.15	9.06	4.66	2.38	6.05	13.90	10.55	5.79	1.42	2.68	5.69	2.94	4.86	2.57	3.08
FeO*/MgO	0.66	0.44	1.00	1.00	1.39	1.58	1.57	2.55	2.97	1.89	1.08	0.88	0.52	0.74	0.74	0.85	0.75
Ba	12	4	85	121	73	177	287	93	155	38	30	23	33	32	nd	49	76
Cr	402	1025	365	485	222	269	431	283	316	217	126	469	748	284	nd	167	677
Ni	99	157	bdl	bdl	72	80	72	61	67	45	49	106	175	112	nd	63	160
Pb	bdl	1	bdl	bdl	bdl	1	1	1	1	1	bdl	1	bdl	2	nd	bdl	1
Sr	157	98	127	35	335	103	88	70	209	266	99	76	199	144	nd	136	195
V	159	240	163	120	145	186	170	249	255	296	112	126	217	160	nd	259	211
Y	8.46	5.98	34.51	32.69	16.70	19.91	28.15	27.99	33.79	29.19	7.61	8.31	12.71	9.94	nd	14.17	13.97
Zr	6.02	3.84	96.06	98.40	104.68	62.18	80.01	88.57	99.86	78.76	13.51	14.11	19.14	16.08	nd	23.38	26.72
Nb	0.01	0.04	6.22	7.21	10.98	1.61	1.71	1.70	1.88	1.44	0.29	0.34	0.53	0.40	nd	0.59	0.55
La	0.38	0.16	13.62	29.18	14.47	2.23	3.95	3.20	3.81	2.72	0.50	0.56	0.88	0.68	nd	0.93	1.01
Ce	1.24	0.47	29.25	60.02	36.46	6.76	9.72	10.81	11.69	8.89	1.36	1.59	2.97	2.10	nd	2.52	2.75
Pr	0.22	0.09	4.10	8.83	5.29	1.18	1.88	1.78	1.99	1.55	0.23	0.26	0.53	0.36	nd	0.42	0.48
Nd	1.42	0.59	17.90	34.18	23.64	6.14	9.76	9.36	10.97	8.39	1.35	1.41	2.98	2.05	nd	2.33	2.67
Sm	0.60	0.31	3.99	7.04	4.99	2.01	3.05	2.93	3.48	2.77	0.47	0.58	1.05	0.74	nd	0.94	1.02
Eu	0.38	0.14	1.10	1.67	1.54	0.72	1.19	1.05	1.20	1.03	0.19	0.22	0.38	0.28	nd	0.41	0.38
Ti	2096	1670	6068	6195	7564	11578	9078	9540	10387	8202	3817	3320	3257	2609	2288	3017	3340
Gd	0.86	0.62	4.24	6.45	4.23	2.51	3.76	3.45	3.97	3.27	0.68	0.78	1.29	0.96	nd	1.33	1.40
Dy	1.20	0.85	4.18	5.60	3.04	3.01	4.45	4.40	5.10	4.32	0.94	1.12	1.73	1.30	nd	1.92	1.98
Yb	0.82	0.59	2.59	3.18	1.22	1.98	2.58	2.83	3.28	2.83	0.74	0.83	1.17	0.96	nd	1.47	1.48
Lu	0.13	0.09	0.46	0.50	0.18	0.31	0.41	0.45	0.49	0.44	0.11	0.13	0.18	0.14	nd	0.24	0.24
Ta	0.00	0.00	0.31	0.41	0.51	0.09	0.11	0.11	0.11	0.08	0.02	0.03	0.03	0.02	nd	0.04	0.04
Th	0.00	0.03	3.47	7.09	1.17	0.10	0.11	0.12	0.10	0.08	0.07	0.11	0.04	0.05	nd	0.14	0.12
U	0.00	0.00	0.52	0.92	0.39	0.03	0.26	0.16	0.16	0.29	0.02	0.03	0.02	0.02	nd	0.04	0.05

Major oxide concentrations are hydrous percentages. Fe_2O_3 is total Fe.

p/s volc	pillow/sheet volcanic rock
sd	sheeted dike sample
bdl	below detection limit
nd	no data

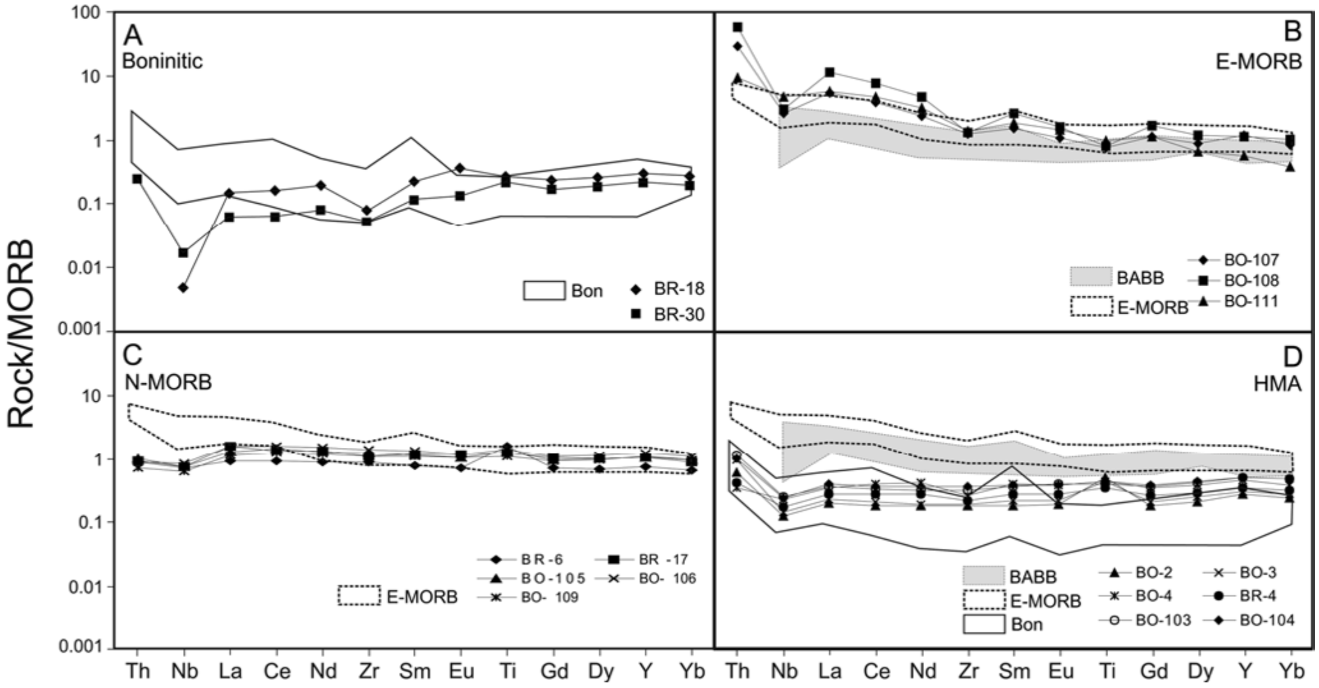

Fig. 4. Multi-element graphs for the different geochemical populations of the ophiolite-mélange complex. The elements have been normalized to N-MORB composition using the values of Sun and McDonough (1989). For comparison, Bon (Beccaluva and Serri, 1988; Hawkins, 2003), E-MORB (Earthref.org, access date: June 2005) and BABB (Saunders and Tarney, 1979) were also plotted.

iana forearc boninitic rocks (Bloomer, 1987). The Y versus Nb/Th diagram (Jenner et al., 1990) shows BR-30 manifesting typical arc-signature (Fig. 5a).

4.2. E-MORB

Volcanic rocks that belong to the E-MORB group were sampled atop the N-MORB in both the intact ophiolite section and the mélange (Fig. 2a, c). The basalts show subophitic to intergranular texture with plagioclase and clinopyroxene phenocrysts. Sparse olivine phenocrysts are replaced by chlorite and serpentine. Groundmass consists of devitrified glass, plagioclase laths and clinopyroxene. Samples have 53.4 to 54.8 wt.% SiO_2, intermediate to high MgO (6.1 to 10.8 wt.%) and low to intermediate Al_2O_3 (14.8 to 15.3 wt.%). Predictably, samples classified as E-MORB and N-MORB have higher TiO_2 concentrations than do other rock groups. With FeO*/MgO as fractionation index, positive slopes of TiO_2 and P_2O_5 combined with negative MgO trends illustrate tholeiitic fractionation signature. This tholeiitic affinity is also evident in the SiO_2 versus FeO*/MgO graph. The Zr/Y is below 5 and the relatively high values of Ti and Zr, are similar to typical N- and E-MORB. The multi-element comparison with N-MORB (Fig. 4b) shows this group to approximate E-MORB trends but with arc-related characteristics of negative Nb, Zr and Ti anomalies. During partial melting, Th/Yb and Ta/Yb remain relatively constant, thus, values derived from volcanic rocks would reflect source region composition and characteristics (Pearce, 1982). The E-MORB of SEBOC shows more affinity to an enriched mantle source with contributions from arc components to account for the high Th/Yb (Fig. 5b).

4.3. N-MORB

Rocks of this group are overlain by either the BON or E-MORB rocks in the mélange and by E-MORB flows in the ophiolite massif (Fig. 2a, c). Petrographically similar to the E-MORB, the N-MORB group shows the highest Nb/Th compared to all the other groups and, except for a slight negative Nb anomaly, mimics REE trends of N-MORB sampled from present-day ocean basins (Fig. 4c and 5a).

4.4. High Magnesian Andesites

Sampled sheeted dikes and some pillow and sheet flows of the main ophiolite mass in Duero are of high-magnesian composition. Very fine-grained pyroxene augite and plagioclase set in groundmass of volcanic glass and microlaths of feldspars characterize these rocks. These samples plot in the calc-alkali field (SiO_2 versus FeO*/MgO diagram) but exhibit positive TiO_2 and negative MgO and CaO trends relative to increasing FeO*/MgO, akin to tholeiites. Their silica con-

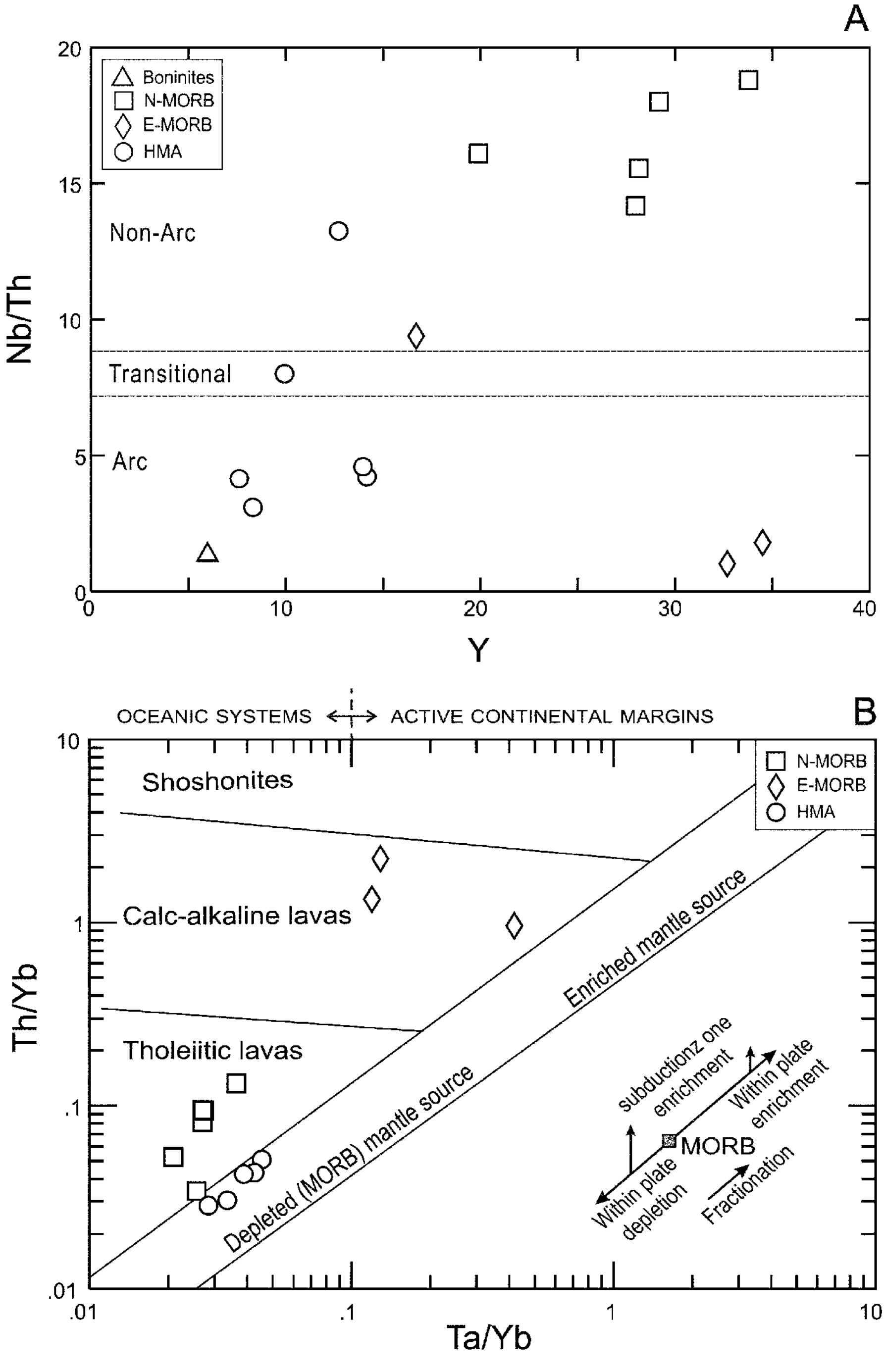

Fig. 5. (**A**) Y versus Nb/Th plot showing the varied affinity of the HMA group and the non-arc signature of the N-MORB samples. (**B**) The Th/Yb versus Ta/Yb diagram (after Pearce et al., 1981) shows the subduction imprints on the rocks collected from the SEBOC and Cansiwang Mélange. See text for discussion.

tents range from 52.0 wt.% to 57.4 wt.%. Concentrations of TiO_2 (0.4 to 0.6 wt.%) in the samples are similar to those of typical island arc tholeiites (IAT) but are lower than for most backarc basin basalts (BABB) based on the criteria of Wilson (1989). These volcanic-hypabyssal rocks have Zr/Y values below 5, generally low Nb/Th and high Th/Yb (Fig. 5a, b). Multi-element abundances of the HMA are similar to high-magnesian basaltic andesites from backarc basins (Hawkins, 1995; Pearce et al., 1995) with HREE enrichment relative to the LREE, relatively flat REE patterns but with negative Nb anomalies and elemental abundances distinctly lower compared to N-MORB (Fig. 4d).

5. DISCUSSION

Based on present geographic and tectonic positions of the different units, it appears that the N-MORB rocks serve as platform on which most of the other volcanic rocks were either formed or thrust atop (Fig. 2a, c). The BON and E-MORB lie on top of the N-MORB. It is difficult to determine, based on field relationships, the association between the BON and E-MORB. The sheeted dike complex and the upper sections of the pillow and sheet lavas of the main ophiolite massif in Duero have HMA geochemistry. The N- and E-MORB rocks are the only groups found in both the intact ophiolite and the mélange complex, whereas the HMA are exclusively from the Duero block and the BON were only sampled from the Cansiwang Mélange. The inset Figure 2c suggests the possible relationship between the different rocks as discussed in the next sections.

5.1. Petrochemical Constraints on SEBOC Genesis

The petrochemistry of volcanic-hypabyssal rocks from the ophiolite-mélange complex provides a window into the geodynamics of the ophiolite's history, with each of the four geochemical groups possibly indicating different formation conditions. One of the primary concerns when examining the geochemistry of a rock suite is cogenesis. The multi-element diagrams show that the four geochemical rock groups cannot be related by simple crystal fractionation or by several stages of partial melting of a homogenous source because their trends cut across each other (Fig. 4a to d). Even within a group, the sample patterns intersect, suggesting slightly different sources, or varying processes of formation. However, despite having evolved from a range of source region compositions as illustrated by Figure 5b, all the samples exhibit varied degrees of subduction influences. The high-Ca type BON suggests an episode of crustal rock formation from a mantle source more refractory than residua from MORB generation. This requires higher melting temperatures than for the previous melting event or the addition of water to lower the solidus, conditions present during the earliest stages of arc formation or arc-splitting (e.g., Crawford et al., 1981, 1989; Hickey and Frey, 1982). The presence of N-MORB and E-MORB rocks with slight subduction signatures and HMA is consistent with formation in a subduction-related marginal basin. Depletion in Zr, Ti and LREE relative to N-MORB show that all the volcanic-hypabyssal rocks from the ophiolite-mélange complex were formed with influence from arc-related processes, albeit in variable measures (Fig. 4a to d). More convincingly, the Th/Yb vs. Ta/Yb plot (Fig. 5b) and the pronounced negative Nb anomalies indicate influence from a subduction zone (Jenner and Fryer, 1980). Only the N-MORB samples have slope equal to unity typical of MORB and uncontaminated intraplate basalts with the rest plotting above the MORB array with marked Th enrichment. Although the N-MORB samples approximate trace element concentrations of a true MORB, depletion in Nb reflects formation from a subduction-modified mantle. These geochemical signatures clearly show that the SEBOC is a SSZ ophiolite strengthening earlier claims, based largely on geological field information (e.g., Faustino et al., 1998; Yumul et al., 1995, 2001, 2003), with definitive rock-chemistry data.

5.2. A Marginal-Basin Ocean Floor

One key to understanding the true nature of an ophiolite is to compare modern-day settings with similar petrochemically diverse volcanic rocks, intercalated sediments, and associated mélange. The diverse tectonic affinities of the volcanic rocks from this ophiolite-mélange complex have also been observed in a number of ophiolites and marginal basins which include the Mariana Trough and Lau Basin in the Western Pacific (e.g., Bloomer, 1983; Tamayo et al., 2001; Hawkins, 2003; Suerte et al., 2005; Ishiwatari et al., 2006). In backarc basins, such as the Lau Basin, MORB rocks dominate the heterogeneous assemblages. However, both arc-like and OIB-like rocks are also present. Even island-arc tholeiites have occasionally been erupted along the BAB ridges (Hawkins et al., 1984, 1990). The few arc-tholeiitic and calc-alkaline rocks analyzed from Lau Basin are believed to be eruptive products of a paleo-frontal arc and the forearc rifting of a then active Lau arc. Because of a later stage trench-ward arc jump, these forearc rocks were trapped in their present backarc location (Hawkins, 1995). Conversely, MORB-like rocks are also found in forearc settings. In the Mariana forearc, MORB have been accreted along the subduction zone margin after its translation from a true MOR setting (Johnson and Fryer, 1990). Work on the Coast Range Ophiolite (Giaramita et al., 1998) has classified it as a forearc crust-mantle sequence based on the petrochemical diversity and preponderance of IAT over MORB lavas.

In the ophiolite-mélange complex of Bohol, petrochemical diversity among the volcanic-hypabyssal suites range from boninitic through HMA to N- and E-MORB compositions with the MORB-like rocks occurring at more sites than do the others. The consistency of subduction imprint in all geochemical populations negates the likelihood that these MORB-like rocks came from a true MOR. The elevated Th and negative Nb anomaly of the HMA are also clearly subduction imprints. Although MORBs can form at forearc regions with the subduction of a spreading ridge, such a scenario is not supported by available field data. The observed N- and E-MORB in this ophiolite-mélange complex can be more appropriately explained by generation during marginal-basin rifting, most likely in a backarc setting. Consistent with the marginal basin origin model for this oceanic crust are the types of sedimentary rocks intercalated with the volcanic rocks. Along Alejawan River, chert is found intercalated with volcanic rocks and towards the top of the section, layered chert cap lava flow materials. In the Cansiwang area, both chert and tuffaceous sediments are found intercalated with volcanic rocks. These two contrasting types of sediments indicate that the basin in which they were deposited was nearby an arc that supplied the tuffaceous materials but was deep and wide enough to allow for the deposition of pelagic siliceous rocks. Backarc basins more closely fit this situation as they provide the breadth lacking in forearc basins. In addition, such sedimentary relationships have been reported for other supra-subduction zone backarc basin ophiolites (e.g., Shervais and Kimbrough, 1985; Ueda and Miyashita, 2005). Using the Lau Basin for analogy, with its preponderance of MORB-like rocks and the occurrence of both tuffaceous and cherty sediments, the volcanic rocks of the Bohol ophiolite-mélange complex are petrochemically comparable to their putative equivalents in that present-day backarc basin. However, the presence of the BON population needs accounting for if most of the other rock groups formed in a backarc setting.

Boninites are hypothesized to form during incipient subduction events and are related to forearc extension processes (Cameron et al., 1979). These rocks can also form in mature backarc basins floored by boninitic basement previously produced by forearc extension (e.g., Falloon et al., 1992; Hawkins, 1995). Boninite formation is also attributed to cessation of arc volcanism followed by arc-splitting (Crawford et al., 1981). No data supports the last two models as being applicable to the generation of the BON rocks of Bohol. Thus, with the data at hand, this particular rock group appears to have been erupted during incipient subduction along a forearc, probably coincident with the accretion of the Cansiwang Mélange.

This then brings into question how the highly diverse assemblage came together. In the absence of geochronological constraints, field association and regional tectonic studies by other workers have become the basis for the following suggestions. Although most plate reconstruction studies of Southeast Asia only go as far back as 50 Ma or less (e.g., Hall, 2002; Pubellier et al., 2003, 2004), most of these position the central and northern Philippines in suitable locations for the region to have possibly developed from arc-backarc volcanism. Thus, it is proposed that initially, a backarc system existed which developed a MORB-like ocean floor. Products of this stage correspond to the N- and E-MORB populations. There has to have been changes in regional tectonic configurations later on that resulted in the translation of that oceanic crust towards a destructive/subduction system. Incipient subduction of the oceanic floor resulted into the generation of boninitic rocks and high magnesian andesites on the overlying crust. Resulting from this event is the eruption of the BON and HMA rocks and the accretion of the Cansiwang Mélange. The existence of the boninitic rocks together with the field relationship between the ophiolite and the mélange support a forearc setting during the emplacement of the main ophiolite massifs (Faustino et al., 2003). This is consistent with previous studies in this part of the Central Philippines which have called for the existence of an ancient subduction zone southeast of Bohol Island (e.g., Mitchell et al., 1986; Yumul et al., 2000). Geophysical studies, such as bathymetric and gravity surveys, suggest that the ocean floor southeast of Bohol has characteristics similar to present-day trenches. Seismic tomography revealed northwest verging anomalies near Bohol that may correspond to an ancient subduction system (Besana et al., 1997). The Cretaceous age of this ophiolite-mélange complex implies the possibility that it was part of the Cretaceous proto-Philippine Sea Plate, fragments of which are now exposed along segments in the Philippines as ophiolites and ophiolitic complexes (e.g., Yumul et al., 2001; Dimalanta et al., 2006).

6. CONCLUSIONS

There are four distinct geochemical populations found in the volcanic-hypabyssal rocks of the SEBOC and its associated Cansiwang Mélange: boninitic rocks, high magnesian andesites, normal- and enriched-MORB. All these rock groups have whole rock trace and rare earth element geochemistries that can only be explained by generation in a suprasubduction marginal basin. The presence of chert and tuffaceous sedimentary rocks intercalated or capping the volcanic rocks is consistent with a backarc marginal setting. The generation of the boninitic rocks in tandem with the field relationships between the ophiolite and the Cansiwang Mélange, support a forearc emplacement of SEBOC. Corollary to this, the existence of a paleo-subduction zone southeast of Bohol Island is also suggested, an idea that has been previously recognized.

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