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GEOCHEMISTRY OF OPHIOLITIC BASALTS FROM THE METCHOSIN IGNEOUS COMPLEX ON SOUTHERN VANCOUVER ISLAND, AND THEIR INFERRED PALEOTECTONIC SETTING

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ABSTRACT

Major and trace elements geochemistry of Early Eocene rocks from the Metchosin Igneous Complex, a partial ophiolite located on Vancouver Island provide insight on its paleotectonic origin. Major and trace elements composition of volcanic rocks from the Metchosin Igneous complex indicate that they have compositions akin to MORB. These volcanic rocks extend from N-MORB to E-MORB compositions in various trace elements tectonic discriminant diagrams, and therefore support the hypothesis that the Southern Vancouver Ophiolite formed in a transitional tectonic setting, likely a divergent plate margin located near a continent. Mantle normalized trace element patterns of basalts from the Metchosin Igneous Complex are similar to those of the Gulf of California. A plausible modern analogue is therefore the Gulf of California of the Red Sea where a mid-ocean ridge developed into a continental rift.

INTRODUCTION

Ophiolites have now been recognized throughout the world to have mostly formed in supra-subduction environments (Beccaluva et al., 1979, 1983; Pearce et al., 1984). The purpose of this study is to report the trace element contents of basalts from the Metchosin Igneous Complex in order to constraint the paleotectonic environment of origin of this ophiolite. In addition to major elements, Zr, Y, REE (rare earth elements) determinations, the highly incompatible elements (bulk distribution coefficient D<0.01) Ta, Th, Hf contents were also measured. These trace elements have the advantage of being relatively immobile in aqueous fluids and therefore less sensitive to hydrothermal alteration. Elements such as Ta, Th and Hf and their relative ratios are very useful to detect subduction zone geochemical signature (Wood et al., 1979; Pearce, 1982; 1996). Basalts trace element compositions from the Metchosin Igneous Complex have MORB rather than subduction zone signature.

GEOLOGICAL SETTING

The Metchosin Igneous Complex located on southern Vancouver Island of British Columbia, represents the northerly continuation of the Coast Range Basalt Province, a Palaeocene to Early Eocene basaltic sequence that extends from Oregon to beneath the continental shelf off the west coast of Vancouver Island (Yorath et al., 1999). The Metchosin Igneous Complex is a partial ophiolite, which comprises the volcanic rocks of the Metchosin formation, several gabbroic intrusions called the Sooke gabbro, and sheeted dikes located between the extrusive and the intrusive rocks (Fig. 1). This complex is bounded to the South by the Strait of Juan de Fuca, to the north by the Leech River Fault and underlies an area of approximately 725 km^2. Massey (1986) mapped the area and described the stratigraphy, field relationships and made lithological descriptions. The text that follows comes from the work of Massey (1986) and Yorath and co-workers (1999). The Metchosin formation has been subdivided into a ~1.5 km-thick lower,

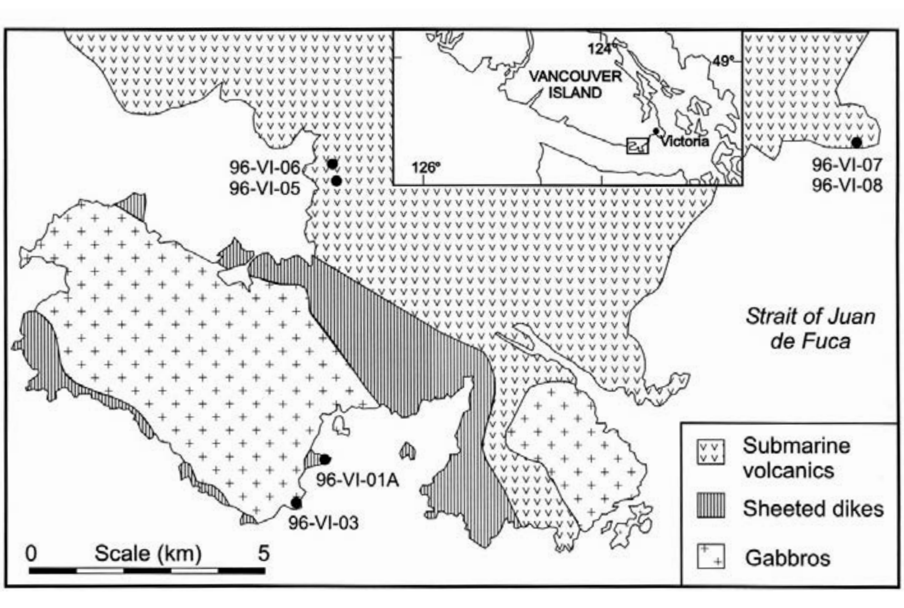

Fig. 1 - Geological map of the Metchosin Igneous Complex, Vancouver Island Ophiolite (adapted from Muller, 1980; Massey, 1986). Samples from this study are located.

submarine unit and a ~1 km-thick upper subaerial unit both having similar tholeiitic major and minor elements geochemistry (Muller, 1980). The lower unit consists of pillows and massive basalts with interbedded tuffs, breccia, and volcaniclastic sediments. The upper unit is made of amygdaloidal sheet flows. Geological field mapping done by Massey (1986) allowed to estimate that the volcanic and sheeted-dike portions of the ophiolitic stratigraphy of the Metchosin complex has a thickness of ~3 km. The complex dips about 30° to the northeast and its base although not exposed is interpreted from LITHOPROBE seismic reflection profiles to lay at a depth of 6-8 km. Field relationships and geochronologic data indicate that all units within the complex are contemporaneous with the Early Cenozoic era. For example Duncan (1982) determined on a basalt from the Metchosin volcanics an age of 57.8 ± 0.8 Ma by Ar-Ar total fusion method and additionally a hornblende diorite from the gabbroic section was dated at 52 ± 2 Ma by U-Pb on zircon (R. Zartman in Massey, 1986).

The upward shoaling and emergent sequence of the Metchosin formation lead Massey (1986) to suggest that it developed as an island. Lava geochemistry of the Metchosin Complex shows characteristics transitional between oceanic crust and island arc whereas other volcanic sequences of the Coast Range Basalt Province have slightly enriched ocean-floor basalts overlain by oceanic island basalts (Yorath et al., 1999). The sheeted dikes indicates the development of the Metchosin Complex in an extensional regime, all units are contemporaneous, and lava geochemistry rules out a within-plate setting (Massey, 1986). Instead, Massey (1986) and Yorath et al. (1999) favored the tectonic environment of a partially emergent oceanic island formed in a marginal basin.

I have made a reconnaissance rock sampling of the area in order to determine their compositions and infer on their origin by using tectono-magmatic discriminant diagrams.

WHOLE-ROCK GEOCHEMISTRY

Whole-rock chemical compositions for 6 samples are presented in Tables 1 and 2, and their petrographic descriptions are included in the appendix. Homogeneous core portions of specimens free of weathering (clay alteration halos) or hydrothermal veins were selected for crushing and pulverizing in an alumina ceramic swing mill. For pillow lavas, the core of samples were selected whenever possible. Samples were analyzed by ICP-AES for major and trace elements Sc, V, Ni, Cu, Zn, Sr, Y, Ba at ActLabs (Ontario, Canada). Additionally, trace elements Rb, Sr, Y, Zr, Nb were determined by the author using X-ray fluorescence (XRF) and Sc, Cr, Co, REE, Hf, Ta, Th, U, Au were measured by instrumental neutron activation analysis (INAA), both methods under the guidance of Mike Gorton at the University of Toronto. Analytical techniques for INAA are described in Stix and Gorton (1992). Results for the trace element contents of the international standard of icelandic

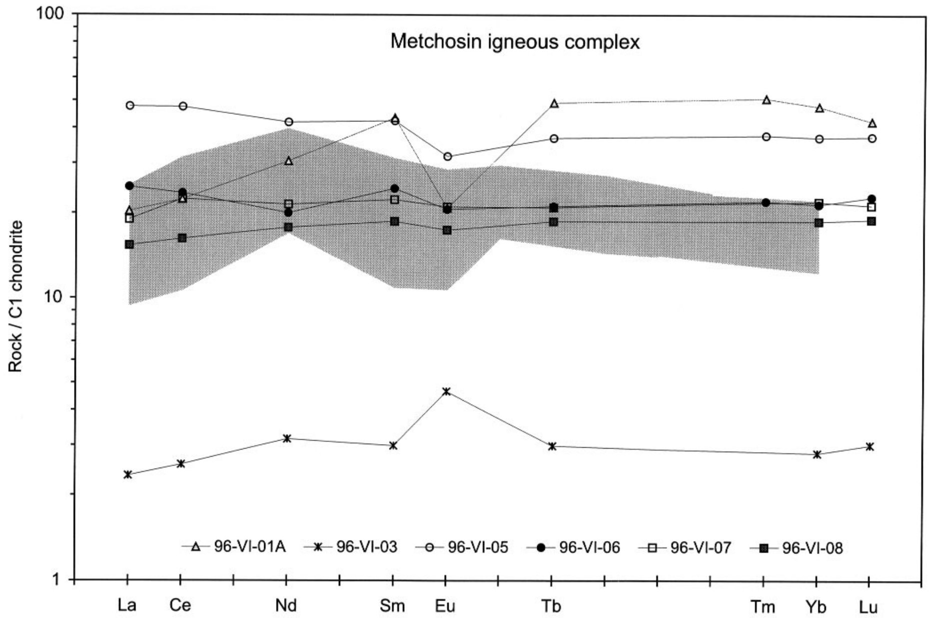

Fig. 2 - Rare earth element (REE) pattern for basalts, diabase dike and gabbro from the Metchosin Igneous Complex. Field of flows and dykes from the Metchosin Igneous Complex is from Yorath et al. (1999). Chondrite normalizing values are from Anders and Grevesse (1989).

Table 1 - Major element analyses (in weight %) of rocks from the Metchosin Igneous Complex

Sample	Rock	SiO_2	TiO_2	Al_2O_3	Fe_2O_3t	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5
96-VI-01A	Diabase	50,24	1,06	14,43	10,21	0,13	6,16	12,86	3,63	0,08	0,08
96-VI-03	Ol gabbro	45,10	0,17	20,00	6,76	0,11	11,19	13,69	1,19	0,05	0,01
96-VI-05	Flow breccia	47,31	1,84	13,14	15,62	0,24	6,53	8,99	3,4	0,15	0,27
96-VI-06	Pillow lava	45,78	1,47	11,36	16,04	0,30	7,09	12,27	2,02	0,13	0,14
96-VI-07	Massive flow	47,70	1,35	13,53	13,77	0,20	6,60	11,47	2,31	0,13	0,12
96-VI-08	Pillow lava	50,64	1,22	12,16	11,72	0,23	7,93	9,61	3,33	0,07	0,12

Whole rock analyses determined by ICP-ES (see text for details).
Fe_2O_{3t} is the total amount of iron expressed as Fe_2O_3; LOI = loss on ignition, Mg# = 100 * Mg/[(Mg+(0.9*Fe2+)].

Table 2 - Trace element analyses (in ppm) of rocks from the Metchosin Igneous Complex

Sample	96-VI-01A	96-VI-03	96-VI-05	96-VI-06	96-VI-07	96-VI-08	BIR-1	BIR-1
Rock	Diabase	Ol gabbro	Breccia	Pillow lava	Massive flow	Pillow lava	measured[1]	recommended[2]
Sc (inaa)	52,2	25,8	53,7	45,3	52,6	54,8	45,0	44
Sc (icp)	50	25	52	45	52	55	-	-
V	306	73	398	424	367	305	-	-
Cr	189	1012	88	76	60	165	427	382
Co	30,3	52,7	55,1	51,1	51,9	59,9	52,6	51,4
Ni	48	223	60	51	56	91	-	-
Cu	8	51	90	143	181	135	-	-
Zn	26	48	127	117	103	89	-	-
Rb	2	2	2	2	1	1	b.d.l.	0,25
Sr (xrf)	135	118	119	104	110	25	103	108
Sr (icp)	131	114	112	100	107	25	-	-
Y (xrf)	69	5	51	33	29	28	14	16
Y (icp)	72	4	53	33	31	27	-	-
Zr	66	12	167	96	88	71	16	15,5
Nb	4,9	0,9	12,7	5,9	5,8	3,4	1,2	0,6
Ba	19	8	32	35	24	10	-	-
La	4,78	0,55	11,18	5,82	4,47	3,61	0,57	0,62
Ce	13,5	1,5	28,6	14,2	13,5	9,8	2,1	1,95
Nd	13,8	1,4	18,9	9,1	9,7	8,1	1,8	2,5
Sm	6,38	0,44	6,23	3,59	3,28	2,75	1,1	1,1
Eu	1,17	0,26	1,78	1,16	1,18	0,98	0,52	0,54
Tb	1,78	0,11	1,34	0,77	0,76	0,68	0,32	0,36
Tm	1,23	b.d.l.	0,91	0,53	b.d.l.	b.d.l.	b.d.l.	0,26
Yb	7,74	0,46	6,01	3,49	3,57	3,04	1,77	1,65
Lu	1,03	0,07	0,91	0,55	0,52	0,46	0,26	0,26
Hf	1,71	0,31	4,50	2,32	2,36	1,95	0,62	0,6
Ta	0,32	0,03	0,76	0,40	0,28	0,22	0,032	(0.04)
Th	0,80	0,07	1,39	0,47	0,34	0,19	0,1	(0.03)
U	0,07	b.d.l.	0,28	0,10	0,07	0,13	b.d.l.	(0.01)
Au (ppb)	b.d.l.	7,7	4,3	8,0	4,6	b.d.l.	5,2	(1.6)

1. INAA done on BIR-1 also gave Fe_2O_{3t}-11.34%, Na2O-1.77%, Sb-0.52ppm, Ni-184ppm. B.d.l.-below detection limits.
2. Recommended values of Govindaraju (1994): Fe_2O_{3t}-11.26%, Na2O-1.75%,Sb-(0.58)ppm, Ni-166ppm. Proposed values are in parentheses. Also Jochum et al. (1994) determined Ta, Th and U values of respectively 0.03, 0.031, 0.0097 ppm.

basalt BIR-1 are provided in Table 2 and show that measured concentrations generally agree within analytical uncertainty with recommended values of Govindaraju (1994). Additional results obtained from various laboratories and methods on two internal basalt standards are provided in Constantin (1995; 1999).

Previous major elements geochemistry for the Metchosin Igneous Complex was reported by Muller (1980) and Yorath et al. (1999) as well as some trace element geochemistry (Ba, Cr, Sr, V, Zr, Y, Nb and rare earth elements) but no Ta, Th or Hf data was reported. Five of our samples have major elements composition of a tholeiite whereas the olivine gabbro has clearly the texture and composition of a cumulate. Normalized trace elements data from the Metchosin Igneous Complex are shown in Figures 2 to 5. Normalization to chondrite reveals that submarine volcanic rocks have subparallel flat normalized REE patterns and extends the existing range of flows and dykes (n = 11) to higher REE compositions, and (Fig. 2). In details, samples 96-VI-05 and 96-VI-06, respectively a breccia and a pillow lava taken 300m apart, are characterized by high Fe_2O_3 content (up to 16%) although with relatively high MgO (6.5-7%), low TiO_2 content (1.5-1.8%) and are the most differentiated in the suite (Table 1). This breccia has distinctly higher REE abundances than the pillow (~25-35x chondrite for the former and ~15-20x chondrite for the latter) whereas both show a slight LREE enrichment $(La/Yb)_n$~1.2 (both have flat shapes of normalized REE patterns, similar Hf/Ta = 5.8 and La/Ta = 14.6 ratios), a weak negative Eu anomaly, comparable Mg# ratios (~ 45). Volcanic rock samples 96-VI-07 and -08 are distant of 10 m from each other and have similar flat shapes of normalized REE pattern with $(La/Yb)_n$ ~0.8 with no Eu anomaly, and comparable Hf/Ta = 8.4-8.9 and La/Ta = 16.0-16.5 ratios. Chondrite normalized REE pattern shows that the diabase from the Sheeted dike complex has a LREE-depleted pattern with $(La/Yb)_n$ = 0.43, (LREE abundances are at 15-20x chondrite, HREE abundances are at 30-40x chondrite) and a strong negative Eu anomaly. The olivine gabbro has strong positive Eu anomaly, slightly LREE-depleted pattern with low REE contents characteristic of a cumulate.

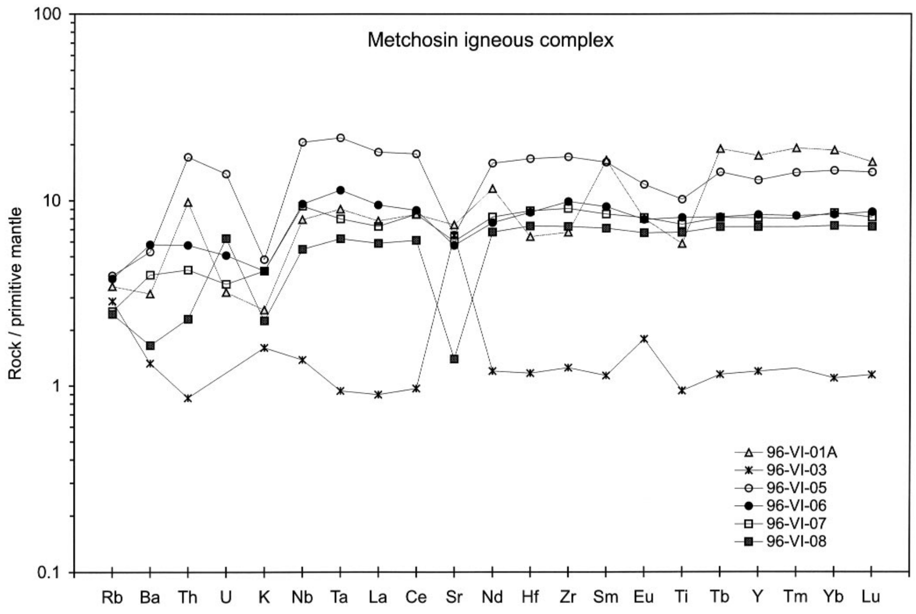

Fig. 3 - Trace elements patterns normalized to primitive mantle values of Hofmann (1988) for basalts, diabase dikes and gabbro from the Metchosin Igneous Complex.

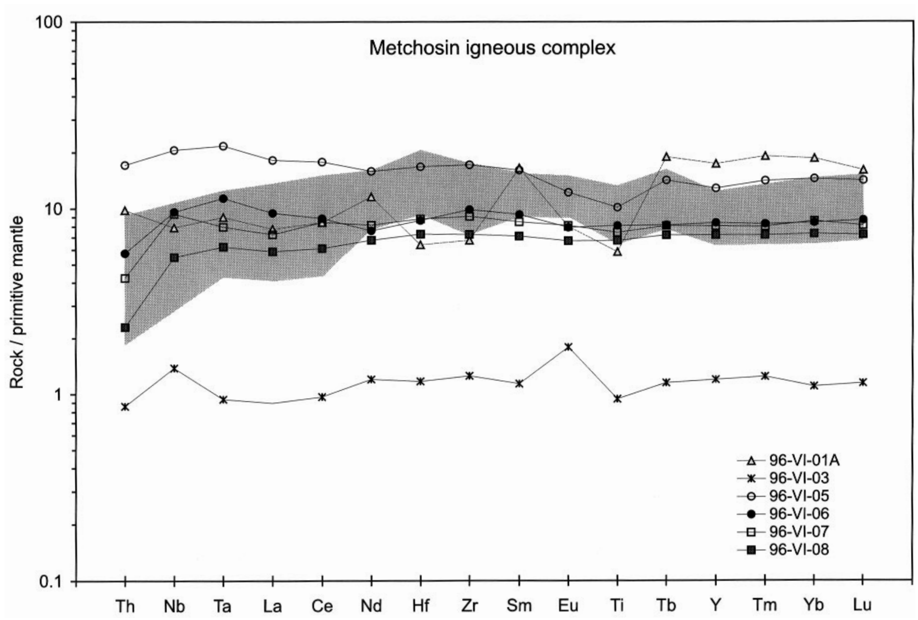

Fig. 4 - Trace elements patterns normalized to primitive mantle. Same plot as Fig 3 except that elements Rb, Ba, U, K, Sr were removed. Grey field represents the range of basalts from the Gulf of California (data taken in Saunders et al., 1982).

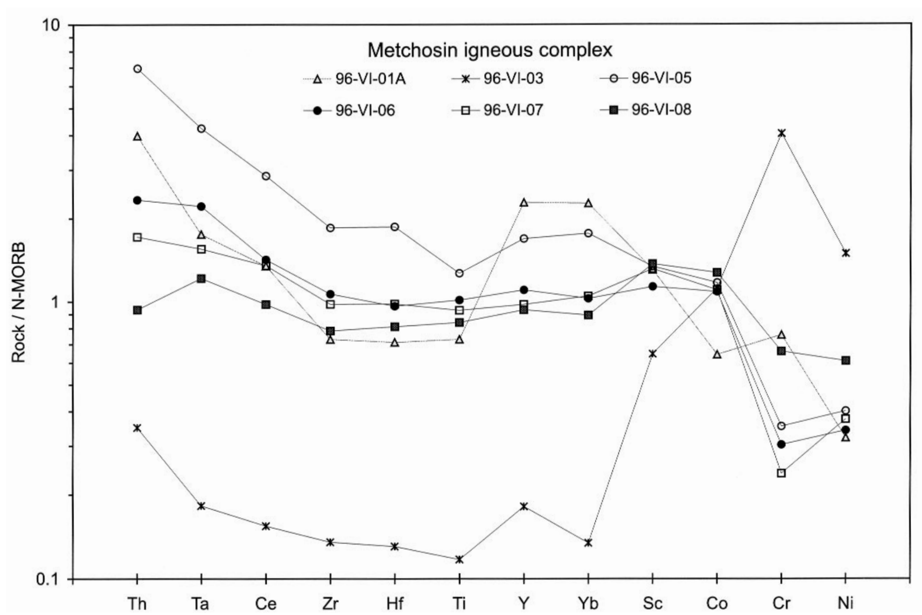

Fig. 5 - Trace elements patterns normalized to N-MORB values of Pearce (1982) for basalts, diabase dike and gabbro from the Metchosin Igneous Complex.

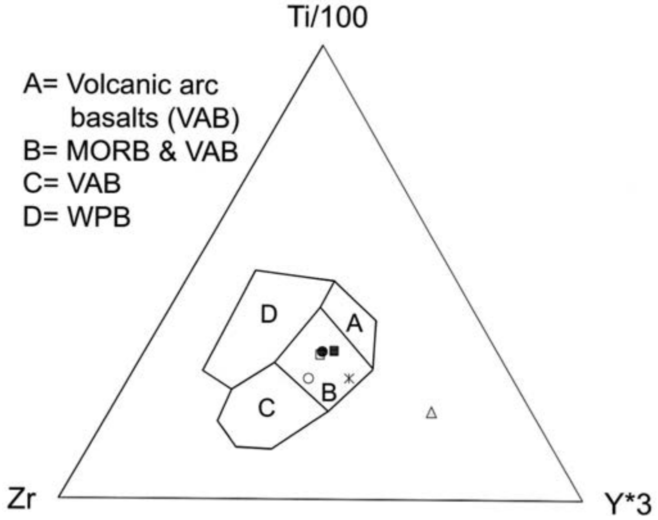

Fig. 6 - Ti - Zr - Y tectonic discriminant diagram of Pearce and Cann (1973) applied to rocks from the Metchosin Igneous Complex. Same symbols as in Fig. 5.

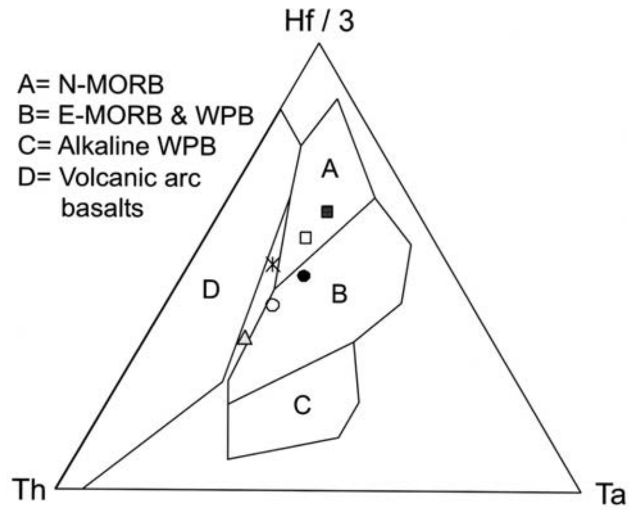

Fig. 7 - Th - Ta - Hf tectonic discriminant diagram of Wood et al. (1979) for rocks from the Metchosin Igneous Complex. Same symbols as in Fig. 5.

Diagrams of trace element data normalized to primitive mantle values are shown in Fig. 3 and display marked variations in Sr, K, U, Rb, Ba. These elements are known to be mobile under hydrothermal alteration (Pearce and Cann, 1973). Normalized trace elements patterns with these mobile elements removed are displayed in Fig. 4 and show that most samples have flat pattern except for the diabase which show pronounced negative anomalies in Zr, Hf, Ti, and Eu. Pillow lavas and massive flow have absolute concentrations at 8-10x mantle values. The flow breccia displays trace elements patterns normalized to N-MORB. For most samples absolute values for incompatible elements Th to Yb are near MORB values (0.8-2x) whereas compatible elements Cr and Ni are noticeably lower (0.3-0.7x). Sample 05 has a profile normalized trace elements with a steep slope with high values from Th to Ce, which is flat for elements Zr to Co.

In order to infer on the paleotectonic environment of the Metchosin Igneous Complex, three tectonic discriminant diagrams were used: 1- Ti-Z-Y diagram of Pearce and Cann (1973) which is a good indicator of within plate affinity (Fig. 6), 2- Th-Ta-Hf diagram of Wood et al. (1979) which is a good indicator of subduction zone affinity (Fig. 7), and 3- Th/Yb versus Ta/Yb diagram which also allows to discriminate between arc and non-arc environments (Fig. 8). Rocks from the Metchosin Igneous Complex plot in the combined field of mid-ocean ridge basalt (MORB) and volcanic arc basalts (VAB), which clearly show that they don't have a characteristic within plate affinity (Fig. 6). One exception is the diabase that has negative Ti, Zr, Hf anomalies in figure 4 and consequently plots toward the yttrium apex in Fig. 6, well outside any of the four fields defined by Pearce and Cann (1973). Also note that the olivine gabbro is plotted only for informative purposes since these discrimination diagrams are not calibrated for cumulates.

In the Th-Ta-Hf and on the Th/Yb versus Ta/Yb discriminant diagrams (Figs. 7, 8), pillow lavas and massive flow from this study range from the N-MORB field to the E-MORB field revealing that they don't have the typical geochemical signature of volcanic arc basalts. On the other hand, the diabase plot in between the VAB and the MORB fields in Fig. 7, and within the VAB field in Fig. 8. The application of these diagrams suggests that the Metchosin Igneous Complex does not have a clear subduction zone signature either.

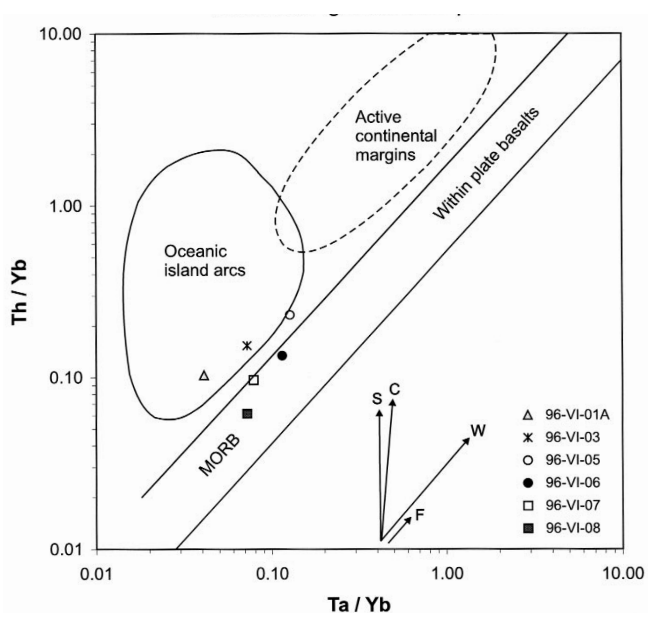

Fig. 8 - Th/Yb versus Ta/Yb tectonic discriminant diagram of Pearce (1983) for rocks from the Metchosin Igneous Complex. Arrows indicate the following petrogenetic vectors according to Pearce (1983): S- subduction zone enrichment, C- crustal contamination, W- within plate enrichment, F- fractional crystallisation.

DISCUSSION

Evidences for wedge depletion in basalts come from ratios of conservative elements of different compatibilities during melting, such as Ta/Yb (Pearce, 1982; 1983), Zr/Nb and Ti/Zr ratios (McCulloch and Gamble, 1991; Pearce and Peate, 1995). Wood et al. (1979) and Wood (1980) indicated that N-type MORB have Hf/Ta>7 (average ratio of 15.5 from Hofmann, 1988; Sun and McDonough, 1989) and La/Ta ~15, E-MORB have 2.5<Hf/Ta<7 (average ratio of

4.3 from Sun and McDonough, 1989) and La/Ta ~10, within-plate basalts (ocean-island and continental basalts) have Hf/Ta<2.5 and Zr/Y>4.5 (Pearce and Norry, 1979), whereas magmas linked to subduction zones such as the Vanuatu arc have La/Ta = 120-240, Th/Ta = 10-22 (Briqueu et al., 1984).

Previous results of petrotectonic interpretations diagrams of the Metchosin volcanic units (Yorath et al., 1999) indicate transitional arc - ocean floor basalts on the basis of mainly major elements discriminant plots and trace elements V, Cr, Zr, Y, Sr, REE. According to these authors the transitional geochemical character of this volcanic sequence and of the entire Coast Range Basalt Province argues against an open ocean setting but rather point to a marginal basin either as a back-arc basin (e.g. Mariana, Lau Basin) or in a transform marginal basin (e.g. Andaman Sea, Gulf of California), both of which are known to contain rocks of diverse geochemical characters. Massey (1986) and Yorath et al. (1999) favoured the tectonic environment of a transform marginal basin analogous to the modern Andaman Sea, although to my knowledge no geochemical data is available for basalts from this region.

It is generally accepted that back-arc and marginal basins are the extensional features produced by seafloor spreading type processes broadly similar to those occurring at mid-ocean ridges (Wilson, 1989). Back-arc basins occur near active subduction zones and volcanic arcs, themselves developed on continental or oceanic crust. Modern examples of back-arc basins are characterized by volcanic products with general geochemical signature ranging from arc to MORB-type magma source that often occur together (e.g. Lau Basin, Ewart et al., 1994; Okinawa Trough, Shijo et al., 1999). Back-arc basalts that have major elements and REE, Zr, Y compositions similar to MORB (e.g. Lau Basin) generally plot in the fields of volcanic arc in Hf-Ta-Th or Th/Yb vs Ta/Yb discriminant diagrams. Since basalts from the Metchosin Igneous Complex have no Ta or Nb negative anomalies in normalized trace element plots, there is no geochemical evidence for a subduction zone component, except perhaps for the diabase dike that plots near the field of the destructive plate-margin basalts (Figs. 7, 8). This diabase has Th/Yb, Ta/Yb, Th/Ta ratios similar to average arc basalt composition from the New Britain arc estimated by McCulloch and Gamble (1991) assuming Nb/Ta and Zr/Hf ratios of respectively 15.5 and 36 (Jochum et al., 1986; 1990; 1997; which are near the values of 16 and 39 proposed by Wood et al., 1979).

Unlike many back-arc basin in the western Pacific, marginal basin are not linked to an active subduction zone or volcanic arc. This is the case for the Gulf of California where the adjacent arc (Baja California) is essentially inactive (Saunders et al., 1982). Basalts from the Gulf of California have trace elements characteristics similar to N-MORB from elsewhere along the East Pacific Rise (Saunders et al., 1982). Furthermore, volcanic rocks dredged from the Red Sea axial rift show typical N-MORB trace element and isotopic compositions with no continental contamination despite the fact that they were produced during recent continental break-up and ocean opening (Eissen et al., 1989). In turn, the Metchosin volcanics have trace element composition similar to basalts erupted in the Gulf of California as shown by their mantle normalized trace element patterns (Fig. 4). In addition, neodymium and strontium isotopic determinations done on 3 samples from the Metchosin Igneous Complex showed them to be derived from a depleted mantle source comparable to mid-ocean ridge or modern ocean islands basalts (Andrew et al., 1991).

Contrary to many ophiolites, no evidence was found for rocks with boninitic affinities (c.a. IUGS classification 52 < SiO_2 < 63 wt %, MgO > 8 wt %, TiO_2 < 0.5%; Le Bas and Streckeisen, 1991). Consequently the ophiolite from Southern Vancouver Island is different for example from the Troodos ophiolite complex which has basaltic rocks with clear negative Ta anomalies and geological features interpreted to represent oceanic crust formed in the earliest stages of island arc developments rather than formation in a back-arc basin. One of the reasons put forward by Rautenschlein et al. (1985) was the absence of N-MORB type basalts in Troodos, which are usually found in modern back-arc basin.

CONCLUSIONS

Major and trace element compositions of volcanic rocks from the Metchosin Igneous complex indicate that they have compositions akin to MORB. Volcanic rocks from the Metchosin Igneous Complex extend from N-MORB to E-MORB compositions in various trace elements tectonic discriminant diagrams, and therefore support the hypothesis that the Southern Vancouver Ophiolite formed in a transitional tectonic setting, likely a divergent plate margin located near a continent. A plausible modern analogue is the Gulf of California or the Red Sea where a mid-ocean ridge developed into a continental rift. This interpretation is largely based on similarities between mantle normalized trace element patterns of basalts from Metchosin Igneous Complex and those of the Gulf of California. However, additional sampling and geochemical analyses are necessary, particularly for the sheeted dikes, in order to better constraint the entire paleotectonic environment of origin of this ophiolite.

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APPENDIX

Summary of sample descriptions obtained from petrographic observations

96-VI-01A: Aphyric diabase dike from the sheeted dike complex. Located at Sooke near Aylard farm - Creyke point along the shore of Becher Bay. Specimen was taken from the interior of a large vertical dike approximately 5m in width.

Thin section observations: Intersertal to intergranular texture with 45% euhedral plagioclase lath (average 0.4 mm; up to 2 mm long), 40% subhedral clinopyroxene microcrystals (average 0.2 mm), 5% anhedral Fe-Ti oxide, 8% alteration minerals (saussurite), ~ 2% altered interstitial mesostasis.

96-VI-03: Olivine gabbro. Located at Sooke near Aylard farm - Alldridge point along the shore of Becher Bay. Massive fine- to medium-grained sample taken from the gabbroic section.

Thin section observations: Subhedral granular texture with 55% subhedral plagioclase (average 0.5 mm; up to 3 mm), 20% subhedral olivine (average 0.3 mm; up to 1.5 mm), 17% anhedral clinopyroxene (average 0.3 mm; up to 0.5 mm), 5% anhedral orthopyroxene (average 0.3 mm; up to 0.5 mm), 3% alteration, traces of Fe-Ti oxides and sulphides.

96-VI-05: Lava - diabase breccia. Specimen taken along 10m high road cut located on Gillespsie road 3.2 km north of intersection with East Sooke road. Outcrop is on the east side of the road, and shows mainly rusty colored massive volcanic and/or intrusive rocks. Specimen selected is a strongly brecciated and metamorphosed bright green colored basalt - diabase. *Thin section observations:* Grain size varies from fine to medium grained and no vesicles were observed. Locally shows primary igneous intergranular to ophitic texture with 20% euhedral to subhedral plagioclase laths (average ~1 mm long; up to 2 mm), 20% interstitial subhedral to ophitic clinopyroxene (up to 1.5 mm) and noticeably high content (10%) of anhedral Fe-Ti oxide minerals (up to 2 mm). About 20% of Pl+Cpx+Opaque are mechanically reduced to subangular fragments. Chlorite and brown clays alteration matrix represent 30% of the sample.

96-VI-06: Aphyric pillow lava located in vertical contact with massive basalts. Located 300m north of sample 96-VI-05. Pillows vary from 20cm up to 2m in diameter. Sample consists of 1/4 of a green colored pillow (20 cm in diameter).

Thin section observations: Metamorphosed quenched margins. Primary texture made of 50% mesostasis and spherulites is well preserved with 10% plagioclase euhedral microlites (up to 0.4mm) mostly fresh. All ferromagnesian minerals are completely altered into chlorite. Overall alteration is 40% with mostly chloritized matrix and numerous epidote+chlorite+albite±carbonate veins.

96-VI-07: Aphyric massive lava flow. Outcrop is located at Tower point along the water of the Juan de Fuca straight. Outcrop contains a majority of pillow basalts (0.5-1.5m in diameter), and minor basalt breccias and massive flows 2-3m thick. Specimen was taken along the immediate margin of a massive lava flow.

Thin section observations: microcrystalline basalt with an intergranular texture. Primary mineralogy is very fresh: 42% plagioclase lath (average 0.1 mm), 40% clinopyroxene microcrystals (average 0.1 mm), 8% euhedral Fe-Ti oxide minerals, 5% mesostasis completely replaced by clays, 5% round segregation vesicles (average 0.5 mm in diameter) partly filled by dark fine grained mesostasis and mostly with later hydrothermal minerals (green clays).

96-VI-08: Aphyric pillow basalt. Specimen located 10 meters East of sample 96-VI-07. Small altered piece, margin of a small bright green pillow (diameter ≤50 cm and/or interstitial material) representative of the majority of the outcrop.

Thin section observations: Intersertal to vesicular texture with 6% plagioclase microlite (average ≤0.2 mm), 6% clinopyroxene microcrystals (average ≤0.2 mm), 3% olivine microcrystals, 40% mesostasis, 15% round segregation vesicles (~2 mm in diameter) filled mesostasis and subsequent with yellow and green hydrothermal minerals (pumpellyite + chlorite + clays followed by prehnite + carbonate + quartz), 30% alteration after primary minerals and mesostasis.