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METCHOSIN VOLCANICS: A LOW-TITANIUM EMERGENT SEAMOUNT AT THE BASE OF THE CRESCENT TERRANE*
(92B)

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INTRODUCTION

At the southern tip of Vancouver Island, the Metchosin volcanics are the northernmost occurrence of the Early Tertiary Crescent Terrane of Washington and Oregon. The allochtonous base of the Crescent Terrane consists of ocean-floor tholeiites, within-plate tholeiitic and alkalic seamounts and sediments (Snavely *et al.*, 1968; Glassley, 1974; Cady, 1975; Muller, 1980) spanning the 62 to 49 Ma, or Paleocene to Early Eocene interval (Duncan, 1982). This base is a fragment of the Kula and Farallon plates sutured to the North American continent around 50 Ma (Magill *et al.*, 1981; Heller and Ryberg, 1983). The various tectonic models proposed generally emphasize the proximity and/or conjunction of an active ridge (Kula-Farallon) and hotspot (Yellowstone) close to the North American shore (Snavely *et al.*, 1968; Glassley, 1974; Cady, 1975; Muller, 1980; Globerman, 1980; Duncan, 1982; Wells *et al.*, 1984). Duncan's model takes into account the apparent symmetrical aging of the volcanic sequences to the north and south, while some of Wells' models also attempt to integrate the different degrees of tectonic rotation measured in these sequences. Generation at a leaky transform fault, in a "pull-apart" basin of the Gulf of California type (Wells *et al.*, 1984) or in a basin at the back of an Eocene arc (Clowes *et al.*, 1987) have been suggested as alternative models which incorporate the northward motion of the Chugach and Prince William terranes towards Alaska at that time.

All models except that of Clowes *et al.* (1987) include subduction of the Kula and Farallon plates east of the Crescent Terrane boundary with concomitant generation of the Eocene continental arc which stretches from the Yukon to the Absaroka Mountains in Montana (Challis arc in the United States). In this context of lively debate, it is interesting to re-examine in more detail the composition of the Metchosin basalts and other basalts of the Crescent Terrane to determine their nature, their correlations, and the relationship between composition, time of docking and the evolution of the contemporaneous Eocene arc. The Metchosin volcanics are particularly unusual in that they are not only an emergent sequence with ocean-floor affinity (Muller, 1980), but as we will demonstrate, they are also an example of low-titanium normal mid-oceanic ridge basalts (low-Ti MORB-N).

In spite of some alteration and the sparsity of trace element data, it is possible to define the magmatic trends and tectonic settings of older volcanic sequences by using a particular screening method (de Rosen-Spence, 1976; Spence, 1985; de Rosen-Spence and Sinclair, 1987; and in preparation). This screening method is based on the plotting and subsetting of major element data on twelve discriminant diagrams, and the comparison of the treated data with well known suites. The twelve discriminant diagrams are MgO versus CaO, MgO versus SiO_2, CaO versus SiO_2, Na_2O versus SiO_2, K_2O versus SiO_2, Alkali versus SiO_2, MgO versus FeO_t, MgO versus $10xTiO_2/FeO_t$, TiO_2 versus FeO_t, P_2O_5 versus TiO_2, MgO versus Al_2O_3 and K_2O/Na_2O versus SiO_2 . This method, which can be used directly for small sets of data, has also been adapted for computers in the LITHCHEM system which is a database system for storage, retrieval and graphic representation of whole-rock geochemical data (Harrop and Sinclair, 1986; Radlowski and Sinclair, 1989).

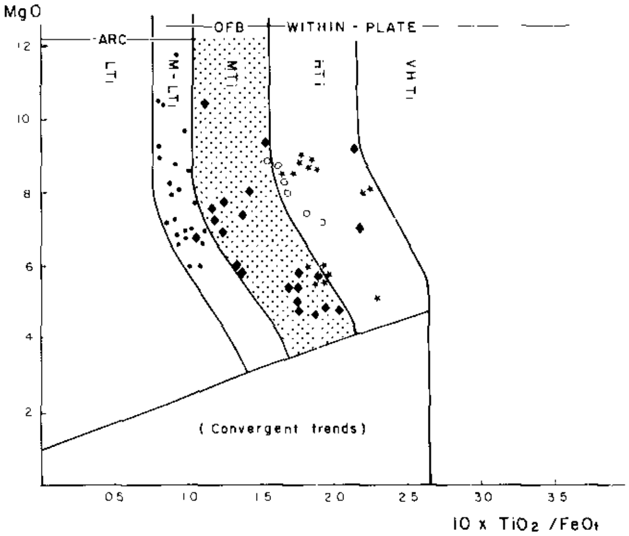

Figure 1-3-1. Different varieties of mid-oceanic ridge basalts (MORB) on MgO versus $10xTiO_2/FeO_t$: Thulean MORB-N of Kolbeinsey Ridge (filled circles), Thulean MORB-P of the Icelandic Rift Zone (filled diamonds), common MORB-N (shaded pattern), common MORB-P of Azores on mid-Atlantic Ridge (stars) and fragmented MORB-N of Tamayo rift (open circles). Data from Schilling *et al.* (1983), Sigvaldason (1969) and Bender *et al.* (1984). Note the increase in titanium of MORB-P relative to MORB-N of the same variety.

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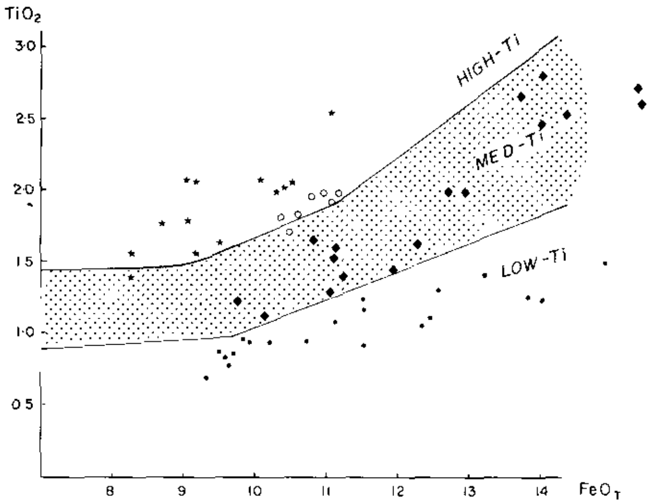

Figure 1-3-2. Different varieties of mid-oceanic ridge basalts (MORB) on TiO_2 versus FeO_t. Symbols as in Figure 1-3-1. Oceanic island (plume) tholeiites would be in the high-titanium (high-Ti) domain like common MORB-P, but with higher iron content (>10% FeO_t).

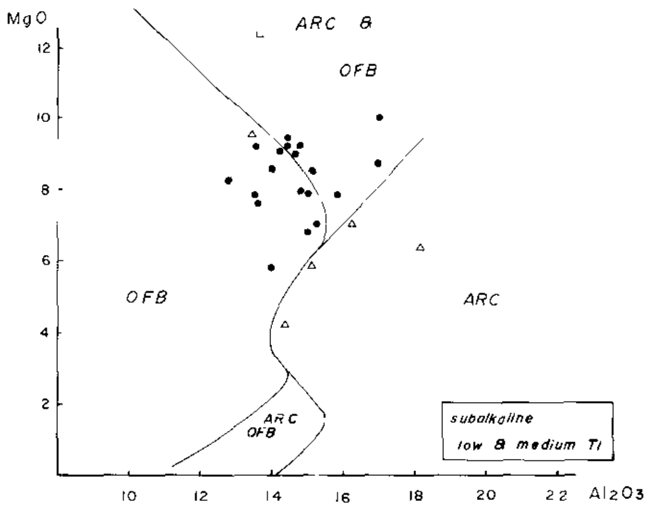

Figure 1-3-3. Metchosin volcanics on MgO versus Al_2O_3 showing the low aluminum content of Thulean MORB-N and slightly more aluminous composition of Thulean MORB-P. Symbols as in Figure 1-3-5.

DEFINITIONS

Much of our interpretation of the Metchosin and other Crescent Terrane basalts is based on the tectonic significance of their TiO_2/FeO_t ratio and phosphorus content. On the MgO versus TiO_2/FeO_t and TiO_2 versus FeO_t diagrams (Figures 1-3-1 and 1-3-2), we distinguish three varieties of normal mid-oceanic ridge basalts (MORB-N) herein named "fragmented", "common" and "Thulean" MORB-N varieties (Note: fragmented because of numerous transform faults, Thulean from the Thulean Magmatic Province of Tyrrell, 1937). The decreasing TiO_2/FeO_t ratios from fragmented to Thulean MORB correspond to increasing degrees of partial melting of the upper mantle, that is from 5 per cent for fragmented (Bender *et al.*, 1984) to 20 per cent for Thulean MORB (Sun and Sharaskin, 1979). Any of these three varieties of MORB-N may be variably contaminated by a nearby enriched plume of lower mantle origin and enriched in light rare-earth elements (LREE), zirconium, titanium, and commonly alkali, phosphorus and water (Schilling *et al.*, 1983; Michael and Chase, 1987). Mid-oceanic ridge basalt markedly enriched in titanium and/or phosphorus is defined here as MORB-P. A substantial contamination in titanium results in the shift of Thulean and common MORB to higher titanium domains (Figures 1-3-1 and 1-3-2). On P_2O_5 versus TiO_2 (Figure 1-3-3), contamination involving phosphorus and water besides titanium results in a shift from the main oceanic domain [ocean-floor (OFB), oceanic-island tholeiites (OIT) and alkaline (OIA)] to the arc domain. This shift is an artifact created by the decrease in titanium (and iron) in the presence of water and is diagnostic of such MORB-P. The TiO_2/FeO_t ratio remains unmodified and MORB-P therefore cannot be confused with arc basalts.

METCHOSIN VOLCANICS

PREVIOUS WORK

The Metchosin volcanics were mapped by Clapp and Cook (1917) and Muller (1977, 1980), and analyzed by Muller (1980). Recent drilling offshore of Vancouver Island revealed the northward extension of basalts with similar composition (Brandon, in Clowes *et al.*, 1987). The Metchosin volcanics, as described by Muller (1980): "consist of an estimated 3000 metres of pillow lavas, breccias and minor tuffs, succeeded by about 1000 metres of layered amygdaloidal flows . . . the transition of pillows to flows is marked by . . . a coquina of *Turitella* indicating Early Eocene age . . . the volcanics represent an emergent basaltic sequence". Recent dating gives an age of 55 Ma or earliest Eocene (Armstrong, in preparation).

Muller (1980) came to the conclusion that the Metchosin volcanics were of oceanic ridge (MORB) origin and not an oceanic island in spite of their emergent character. To explain their emergence, he proposed that they formed in a ridge-island setting similar to Iceland.

COMPOSITION RE-EXAMINED

The Metchosin basalts are only slightly altered and enough "unaltered" samples survived the altered-unaltered classification process (on a MgO versus CaO diagram, not shown) to characterize their original magmatic composition. Spilitization and small additions of magnesium and manganese in some samples were identified in flows and pillows. In tuffs, alteration is more varied and also includes leaching of sodium and calcium, and local addition of calcium.

The least altered or "unaltered" Metchosin samples, plotted on various discriminant diagrams (not reproduced), have been determined to be low-potassium, calcic tholeiites. Except for a few samples near the top of the pile, they are similar to common MORB-N in their aluminum, phos-

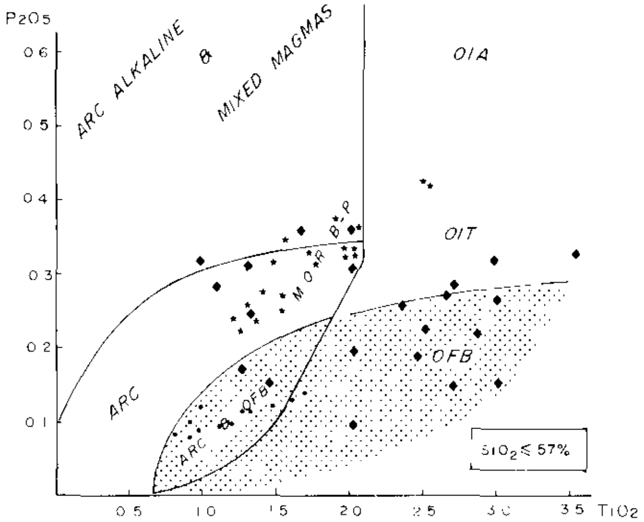

Figure 1-3-4. Different varieties of mid-oceanic ridge basalts (MORB) on P_2O_5 versus TiO_2. Symbols as in Figure 1-3-1. The various domains overlap with each other, in particular MORB and oceanic-island tholeiite (OIT) domains. Thulean MORB-P of the Icelandic Rift Zone is widely scattered and only seven samples can be diagnosed as MORB-P without trace elements, these have the lowest iron content, the others could be confused with common MORB-N (*see* previous plots). This example is important to show the limitations faced in the absence of trace element data.

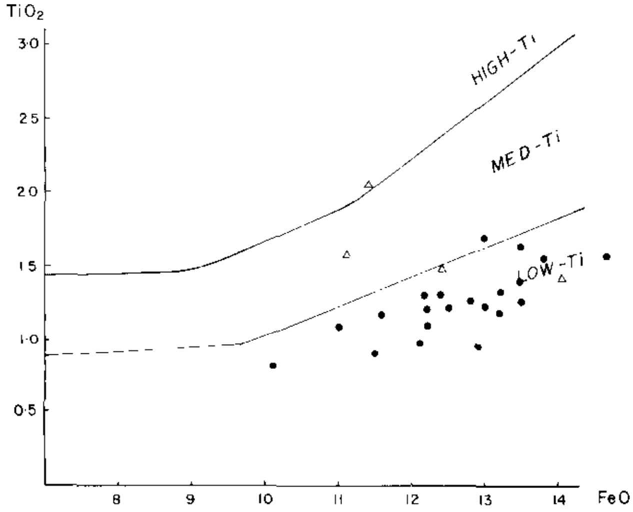

Figure 1-3-5. Metchosin volcanics on TiO_2 versus FeO_t illustrating their low titanium content. Thulean MORB-N, all samples (filled circles) and Thulean MORB-P (open triangles).

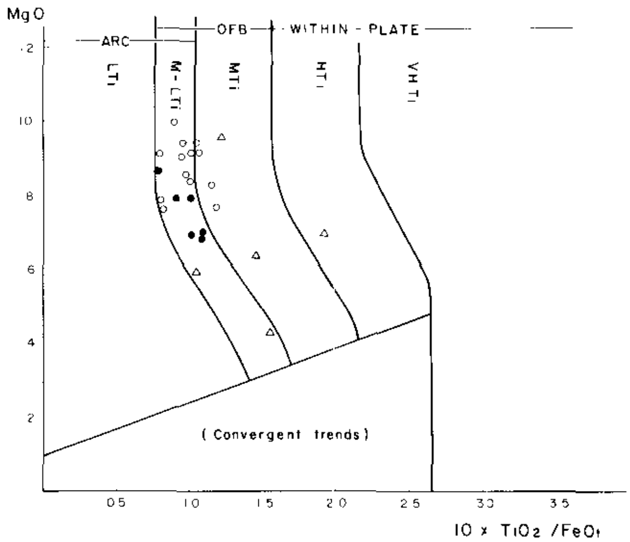

Figure 1-3-6. Metchosin volcanics on MgO versus $10xTiO_2/FeO_t$ illustrating their low titanium content. Thulean MORB-N: unaltered samples (filled circles) and altered samples (open circles), Thulean-MORB-P (open triangles). Thulean MORB-N and -P determined by their phosphorus content on Figure 1-3-7. Data from Muller (1980).

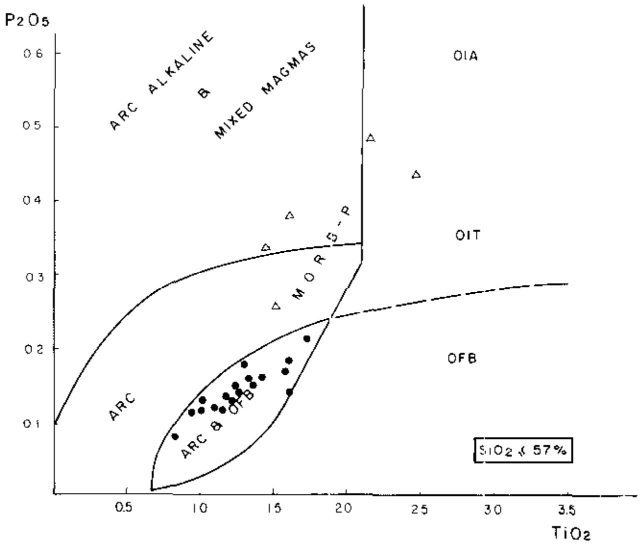

Figure 1-3-7. Metchosin volcanics on P_2O_5 versus TiO_2 showing the difference in phosphorus content leading to the separation of Thulean MORB-N and -P. Symbols as in Figure 1-3-5.

phorus and zirconium content but distinctly lower in titanium. As shown on MgO versus TiO_2/MgO (Figure 1-3-4) and TiO_2 versus FeO_t (Figure 1-3-5), they plot in the medium-low and lower titanium domain respectively, and so overlap with arc basalts. Their phosphorus content (Figure 1-3-6) is also compatible with both an arc or a MORB origin. Their MORB-like character, however, is evident on MgO versus Al_2O_3 (Figure 1-3-7) where their differentiation trend enters the low-alumina domain characteristic of ocean-floor basalts; it is also confirmed by their moderate zirconium content (Table 1-3-1, columns A to C). Thus, the Metchosin basalts show all the essential chemical characteristics of Thulean MORB-N-type basalts as defined earlier.

TABLE 1-3-1
SELECTED ANALYSES OF METCHOSIN VOLCANICS
(analyses from Muller (1980), recalculated 100% dry)

	Thulean MORB-N			Thulean MORB-P		
	A	B	C	D	E	F
SiO_2	50.09	50.02	50.77	48.27	49.40	51.52
TiO_2	0.83	1.21	1.73	1.61	2.15	2.45
Al_2O_3	17.08	15.27	14.09	18.15	16.26	14.27
Fe_2O_3	1.66	2.53	5.37	4.13	4.76	7.49
FeO	8.59	9.87	8.21	7.43	7.15	9.24
MnO	0.19	0.21	0.22	0.19	0.19	0.27
MgO	8.69	7.43	5.78	6.40	7.04	4.21
CaO	11.70	11.66	8.72	9.70	9.01	7.29
Na_2O	1.03	1.57	4.76	3.09	3.31	2.57
K_2O	0.06	0.08	0.14	0.66	0.24	0.27
P_2O_5	0.08	0.14	0.21	0.38	0.49	0.44
Zr ppm	86	103	170	160	220	310
Cr ppm	260	161	54	140	130	40

Thulean MORB-N: A– most primitive unaltered sample (42 /76-21I); B= average of six intermediate unaltered samples (17 /76-6M, 27 /76-20B1, 9 /76-4A, 40 /76-21G, 41 /76-21H, 43 /76-21J); C– most differentiated sample, spilitized, note the higher TiO_2, P_2O_5 and Zr accompanying the high iron enrichment (20 /76-16E2). Thulean MORB-P: D= unaltered sample (12 /76-4I); E= slightly altered sample (10 /76-4G). F– Thulean MORB-P with exceptionally strong iron enrichment (11 /76-4H). Note the higher TiO_2, Al_2O_3, P_2O_5 and Zr content of Thulean MORB-P in Column E compared to average Thulean MORB-N in Column B, for about the same MgO and total iron content.

The few samples near the top of the pile are richer in titanium, phosphorus (Figures 1-3-4 to 6) and zirconium (Table 1-3-1, columns D to F), and are identified as Thulean MORB-P, reflecting contamination from a local enriched plume. In Table 1-3-1, a few selected analyses illustrate the variations in composition resulting from differentiation of the Thulean MORB-N Metchosin magma and the enrichment in titanium, phosphorus and zirconium of the Thulean MORB-P samples.

Origin of Metchosin Basalts

The low-titanium (Thulean MORB) composition of the Metchosin basalts reflects a higher degree of partial melting of the upper mantle than found on most ridges and in marginal basins. It confirms their oceanic setting and precludes formation in a local pull-apart basin (3rd model of Wells *et al.*, 1984) or back-arc basin (Clowes *et al.*, 1987). Could this partial melting be sufficient to explain their emergence? Not necessarily so. The large degree of melting leads to voluminous outpourings of magma through fissures, but seemingly not to emergence in the largest occurrences of Thulean MORB-N: the North Atlantic ocean-floor including Kolbeinsey Ridge (Schilling, 1983), the Cretaceous mid-Pacific oceanic flood basalts (Tokuyama and Batiza, 1981; Saunders, 1986), and the tholeiites associated with Archean komatiites (de Rosen-Spence and Sinclair, in preparation). The build up of a seamount or an island seems to require a more localized source in the form of a plume. For the Metchosin volcanics, Muller (1980) proposed a situation similar to Iceland, but Iceland is a complex seamount built by an enriched lower mantle plume superimposed on a Thulean ridge, and the resulting tholeiites are typical Thulean MORB-P with higher titanium as shown on Figures 1-3-1 to 1-3-3. The Metchosin volcanics, by contrast, are uncontaminated Thulean MORB-N-type products and thus their emergence cannot be explained by the superimposition of a similar enriched plume, this in spite of the vicinity of the Yellowstone hotspot. Since Muller's work, however, there have been a number of studies of seamounts with MORB-like composition attributed to upper mantle thermal plumes. These thermal plumes can be independant of the enriched lower mantle plumes (Batiza and Vanko, 1984; Desonic and Duncan, 1990; Rhodes *et al.*, 1990) or can be generated in the upper mantle by a thermal entrainment process (Griffiths, 1986) and dynamic upwelling of the enriched mantle plumes. The latter situation would be similar to that of Kolbeinsey Island and the Manihiki Plateau, both of Thulean MORB composition: Kolbeinsey Island, on Kolbeinsey Ridge, is uncontaminated by the nearby Iceland plume (Schilling *et al.*, 1983), and the Manihiki Plateau (northeast of New Zealand), emergent at the time of eruption, is on the site of a Cretaceous triple junction (Clague, 1976) and was close to a hotspot.

By analogy with these examples, we propose that the Metchosin basalts could reflect the presence of a local upper mantle thermal plume imposed either on the Kula-Farallon Ridge, or on the site of the Pacific-Farallon-Kula triple-junction which is thought to have been in the vicinity (Wells *et al.*, 1984). The few samples of Thulean MORB-P are a reminder of the proximity of the Yellowstone hotspot of enriched lower mantle composition (as shown below), and of its possible thermal and dynamic influence on the nearby independant ridge system.

CRESCENT TERRANE

We examined some of the data available for the Eocene Crescent Formation of the Olympic Peninsula (data from Glassley, 1974; Cady, 1975; Lyttle and Clarke, 1975) and Black Hills (data from Globerman, 1980) in Washington, and for the correlative Siletz River volcanics in Oregon (data from Snavely *et al.*, 1968).

Crescent Formation

In the eastern Olympic Peninsula, the Crescent Formation is composed of two very distinct volcanic members separated by a tectonic contact (Glassley, 1974). These are an altered, ocean-floor lower member and a fresh plume-influenced upper member deposited in a shallow water to subaerial environment.

Our plots of the data for the lower member (Figures 1-3-8 to 10), are based mainly on Lyttle and Clarke's (*ibid.*) data because samples are separated into extrusive and possibly intrusive origin. They clearly indicate that this lower member is composed of Thulean MORB-N and Thulean MORB-P, and that all samples of possibly intrusive origin are of common MORB-N composition, suggesting that they are actually sills. One occurrence of flows is extremely poor in titanium (low-Ti plot on Figure 1-3-4) and phosphorus and may represent a case of extreme partial melting or of local depletion. Thulean MORB-N is also present in the basalts

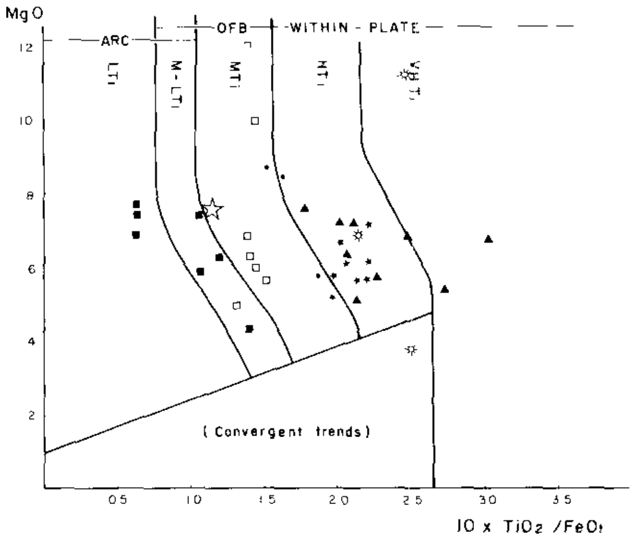

Figure 1-3-8. Crescent Terrane on MgO versus $10xTiO_2/FeO_t$ illustrating its chemical complexity. Crescent Formation lower member is Thulean MORB-N (filled squares) and MORB-P (open squares); the upper member is common MORB-P (filled triangles). Siletz River volcanics are composed of common MORB (filled circles), oceanic-island tholeiites (filled stars), oceanic-island alkaline (open suns) and one isolated altered Thulean MORB-N (large open star). MORB-P character determined on Figures 1-3-9 and 1-3-10. Note the three samples in the low titanium domain (increased partial melting or initial depletion). Data from Glassley (1974), Lyttle and Clarke (1975) and Snavely *et al.* (1968).

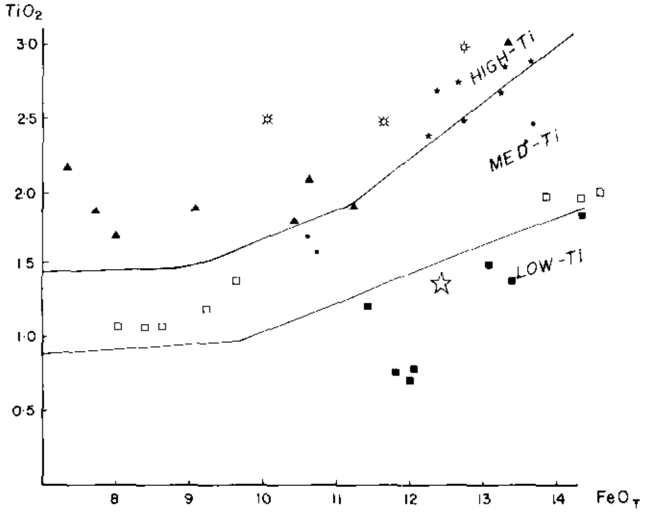

Figure 1-3-9. Crescent Terrane on TiO_2 versus FeO_t. Note the low titanium content of Thulean MORB-N of the lower Crescent Formation (filled squares) and southeast Siletz River (open star), the generally low iron content of Thulean MORB-P (open squares) and common MORB-P (filled triangles) of the lower and upper Crescent Formation, the high titanium and high iron content of the Siletz River Seamount (stars and suns).

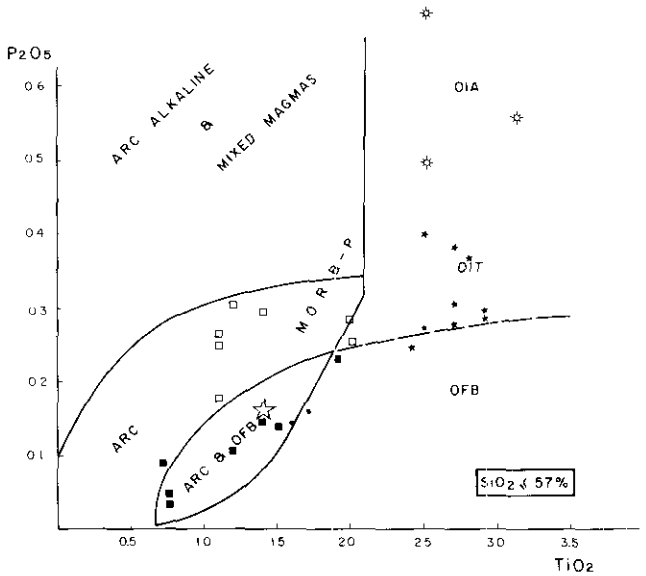

Figure 1-3-10. Crescent Terrane on P_2O_5 versus TiO_2 showing plume influence on the Thulean MORB of the lower Crescent Formation and the high titanium and phosphorus content of the Siletz River seamount. Symbols are as in Figure 1-3-8, but upper Crescent Formation was omitted owing to poor phosphorus analyses.

interbedded in the sediments of the "core rocks" of the central Olympic Peninsula, to the west (data from Cady, 1975).

The upper member, in the eastern Olympic Peninsula (data from Glassley, 1974) is interpreted to be composed of common MORB-P. It has the high TiO_2/FeO_t ratio of within-plate tholeiites but the lower iron content commonly associated with MORB-P (Figures 1-3-8 and 9). Analyses of phosphorus are too inaccurate to be useful in identifying MORB-P, but the moderate content of light rare-earth elements is also characteristic of MORB-P.

In the Black Hills to the southeast, Globerman (1980) has shown that the basalts, mainly subaerial, belong to the upper member of the Crescent Formation and are a mix of mid-oceanic-ridge basalts and enriched-plume tholeiites. They are richer in iron than the upper member in the Olympic Peninsula and probably were generated closer to the Yellowstone hotspot.

SILETZ RIVER VOLCANICS

The Siletz River volcanics were shown by Snavely *et al.* (1968) to be an emergent seamount composed essentially of oceanic tholeiites capped by alkaline rocks similar to Hawaiian lavas and resting on ocean-floor basalts. Our plots (Figures 1-3-8, 9 and 10) confirm this, although we can add that the isolated southeasternmost occurence of Siletz volcanics contains Thulean MORB-N. The Siletz River volcanics are therefore products of the Yellowstone enriched plume and, with their ocean-floor base, represent the southern extension of the upper member of the Crescent Formation. The southeastern exposure, on the other hand, represents an extension of the Thulean lower member. It should be remembered that such chemostratigraphy may be time transgressive.

SUCCESSION AND CORRELATION OF EVENTS

Two eruptive episodes are clearly evident from the above determinations. During the first episode (Paleocene and earliest Eocene), Thulean MORB-N was generated close to the North American continent, and locally an island or a plateau emerged (Metchosin), while towards the top and to the south, the enriching influence of the Yellowstone plume was felt (presence of Thulean MORB-P in the upper Metchosin succession and in the lower member of the Crescent Formation). The remnants of this Thulean-type crust are identified as far south as the Siletz River but we suspect that it exists at the southernmost tip of the Crescent Terrane, in the Paleocene Roseburg Formation (Baldwin, 1974; Duncan, 1982) for which we have no data.

During the second episode (Early Eocene to early Middle Eocene) and corresponding to the upper member of the Crescent Formation, common MORB-N was generated (intrusives in the lower member of the Crescent Formation, base of the Siletz River volcanics), but was promptly modified by the Yellowstone hotspot into common MORB-P in the eastern Olympic Peninsula and Black Hills. To the south, the unmodified products of this hotspot formed a classic oceanic island (Siletz River).

Metamorphism and shearing, which are limited to rocks of the first episode, confirm the validity of this division.

Docking and suturing to the craton by 50 Ma (Magill *et al.*, 1981; Heller and Ryberg, 1983) and attendant steepening of the subduction zone profoundly modified the composition of the Eocene arc (de Rosen-Spence and Sinclair, in preparation): shoshonites of the Kamloops and Penticton groups (Spence, 1985) started erupting at 51 Ma during a major period of extension (Ewing, 1981; Parrish *et al.*, 1988). Similar events occurred to the south, in the Challis arc down to the Absaroka Mountains (Armstrong, 1978; Iddings, 1895). Shoshonites are characteristic of collision episodes and it is symptomatic that they occur only in the southern segment of the arc opposite the Crescent Terrane, and not in its northern segment (central British Columbia to Yukon). If we take into account that there is a time lag of possibly 2 Ma between tectonic change and volcanism (Barsdell *et al.*, 1982), we can surmise that the actual docking must have occurred sometime about 53 Ma rather than 50 Ma ago.

Oblique collision at 53 Ma of an unsubductible thickened crust could have generated numerous transform faults across the ridge, to absorb the first impact of the collision, and so would have locally slowed down the partial melting processes. Such a slow-down would account for the change from Thulean MORB in the lower member of the Crescent Formation to common MORB in the upper member. The colliding mass would have been composed of the Metchosin plateau or island to the north, the Roseburg Formation of unknown composition (Thulean MORB ?) to the south, and some young, buoyant ridge fragment (lower Olympic Formation) thickened by addition of plume material (Thulean MORB-P) in between. The growth of seamounts (Black Hills, Siletz River) near the suture, and the buoyant activity of the Yellowstone hotspot prevented any further possibility of subduction. Finally, the plates attempted to reorganize around 48 Ma and, as a result, the subduction zone jumped west of the Crescent Terrane initiating the earliest Cascades volcanism (Wells *et al.* 1984), while activity waned in the Challis arc, starved by the demise of its own subduction zone.

This model of two distinct episodes, separated by collision and initiation of transform faults at 53 Ma, could reconcile some of the contradictory observations made by previous authors. It may explain some of the differences in rotation observed between the various sequences, while generation of transform faults in the second episode could be incorporated in the model of large-scale movements of detached terranes to Alaska, proposed by Wells *et al.* (*ibid*).

METCHOSIN AS A SYMPTOM OF AN ACTIVE MANTLE

The generation of Thulean MORB can be a powerful and long-lived event (60 Ma in the North Atlantic and mid-Pacific) and so one should expect to find other similar occurrences in the Paleocene and Eocene oceanic crust of the Pacific Ocean. Unfortunately, only one sample of the Eocene of the northern Pacific plate has been analyzed, Hole 178 of Leg 18 near the Aleutian arc (MacLeod and Pratt, 1973). This single sample, approximately 50 Ma old, has the characteristics of a Thulean MORB-P. Another occurrence, though far from the Crescent Terrane, was found on Gorgona Island (Colombia) where an emergent fragment of the Eocene Farallon plate is composed of komatiites and basaltic komatiites interbedded with tholeiites (Aitken and Etcheverria, 1984): these tholeiites also plot as Thulean MORB. Seen in this larger context, the composition of the Metchosin volcanics should not be considered as a local quirk, but as one of the symptoms of an episode of more intense partial melting along the Pacific ridges, either widespread as in the North Atlantic or restricted to certain areas of the ridges, possibly close to large, new lower-mantle plumes. This surge of partial melting would be analogous to that which was responsible for the oceanic flood basalts across the mid-Pacific (Nauru basin and others) and the Ontong-Java and Manihiki plateaux during the Cretaceous.

It may be significant, on a global scale, that at about the same time (latest Cretaceous to earliest Tertiary) the Yellowstone hotspot became active and Metchosin Thulean basalts erupted, so did the Galapagos hotspot and the Gorgona Island Thulean tholeiites, the Iceland plume and the first Thulean basalts of the Faroes and Rockall Plateau (data from Noe-Nygaard and Rasmussen, 1968; Harrison *et al.*, 1984), the Reunion hotspot (Courtillot, 1990) and Thulean basalts of the nearby old (68 to 46 Ma) Indian Ocean floor (data from Melson *et al.*, 1976). Note that, at present, only the North Atlantic ridge system has remained undisturbed and is still erupting Thulean MORB on Kolbeinsey and Reykjanes ridges.

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