Geoscience Canada

Igneous Rock Associations 11.
The Geology and Petrology of Seafloor Volcanic Rocks of the Northeastern Pacific Ocean, Offshore Canada

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Volume 37, Number 2, June 2010

URI: https://id.erudit.org/iderudit/geocan37_2ser01

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Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

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Cite this article

Cousens, B. (2010). Igneous Rock Associations 11. The Geology and Petrology of Seafloor Volcanic Rocks of the Northeastern Pacific Ocean, Offshore Canada. *Geoscience Canada*, *37*(2), 49–64.

Article abstract

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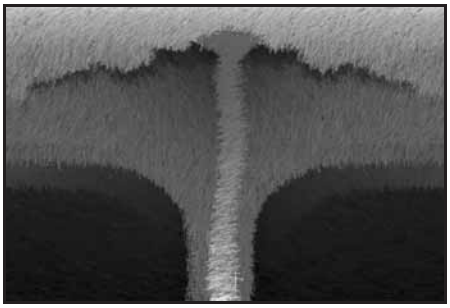

Igneous Rock Associations 11. The Geology and Petrology of Seafloor Volcanic Rocks of the Northeastern Pacific Ocean, Offshore Canada

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SUMMARY
The seafloor within Canada's Exclusive Economic Zone in the northeastern Pacific Ocean features examples of three kinds of volcanic activity: mid-ocean ridge, near-ridge seamount, and intraplate seamount volcanism. Volcanism on the northern Juan de Fuca and Explorer ridges, at inter-transform pull-apart rifts, and at near-ridge seamounts close to the Juan de Fuca and Explorer ridges, produces lavas with unusually variable geochemical compositions. Lavas incorporate variable contributions from both trace-element-depleted upper mantle and trace-element-enriched veins, blobs or streaks embedded in the depleted upper mantle. The latter may have originated as dispersed parts of ancient mantle plumes similar to a modern plume responsible for the formation of the intraplate Bowie Seamount.

SOMMAIRE
Les fonds océaniques de la Zone économique exclusive du Canada de la région nord-est du Pacifique montrent des exemples de trois types d'activité volcanique : volcanisme de dorsale médio-océanique, de monts sous-marins de dorsale, et de monts sous-marins d'intra-plaque. Le volcanisme de la dorsale Explorer et de la portion nord de la dorsale de Juan de Fuca, au droit des rifts d'extension de failles inter-transformantes, et non loin des monts sous-marins jouxtant la dorsale Explorer et celle de Juan de Fuca produisent des laves de composition géochimique anormalement variable. Les laves renferment des quantités variables de matériaux du manteau supérieur appauvris en éléments traces mais aussi de filons enrichis en éléments traces, en amas ou traînées ennoyés dans le manteau supérieur. Ces derniers peuvent provenir de reliquats d'anciens panaches mantelliques similaires aux panaches modernes à l'origine de la formation du mont sous-marin de Bowie.

INTRODUCTION
The seafloor of the northeastern Pacific Ocean is typical of most oceanic regions in that it features three different kinds of volcanic edifices that produce primarily basaltic volcanic rocks and their intrusive equivalents: mid-ocean ridges, where new oceanic crust is produced; near-ridge seamounts, which form adjacent to mid-ocean ridges but are not part of the mid-ocean ridge system itself; and intraplate seamounts that form well away from plate boundaries, such as the Hawaii–Emperor seamount chain (Fig. 1). The floor of the NE Pacific includes one of the best-studied mid-ocean ridge segments in the world, the Juan de Fuca Ridge. However, most other volcanic features in the NE Pacific are poorly understood petrologically.

The offshore regions of British Columbia, Washington, Oregon, and northern California have played an important role in the development of the theory of plate tectonics and our understanding of plate motion and evolution. Some examples will illustrate the diversity of research in the region. First, in 1955 the United States Coast and Geodetic Survey ship *Pioneer* performed one of the first large-scale marine magnetic surveys, encompassing the Juan de Fuca and Explorer ridges and demonstrating the existence of magnetic stripes on the seafloor (Raff and Mason 1961; Vine and Wilson 1965). The seafloor record was then used to reconstruct the tectonic history of western North America (Atwater 1970; Atwater and Stock 1998). Second, when non-transform offsets of mid-ocean ridge segments were first recognized along the Galapagos Spreading Centre and East Pacific Rise, application of the concepts learned there were key to reconstructing the history of the Juan de Fuca Plate (Riddihough 1977, 1984; Riddihough et al. 1983; Wilson 1988). Third, the discovery of massive sulphide deposits at the Middle Valley (e.g. Goodfellow and Blaise 1988; Davis and Villinger 1992; Bjerkgard et al. 2000) and Endeavour (e.g. Tivey and Delaney 1986; Delaney et al. 1992;

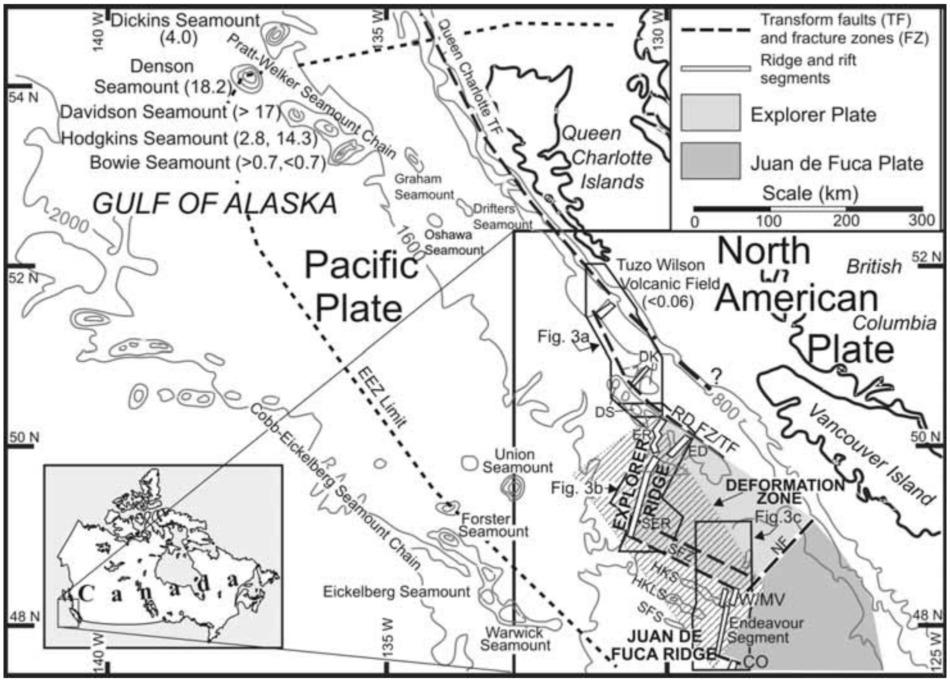

Figure 1. Geological features of the northeastern Pacific Ocean, modified from Dalrymple et al. (1987). Numbers in brackets are K-Ar ages of lavas in Ma. Grey contours are water depths in metres. The lined pattern indicates a zone of deformation and seismicity, proposed to be a new transform boundary (Dziak 2006). Near-ridge seamounts include the Heck (HKS), Heckle HKLS), Springfield (SFS), Dellwood (DS), Graham, Drifters, Oshawa and Union seamounts. Intraplate seamounts include Bowie, Dickins, Hodgkins, Davidson, and Denson (the latter three also include an older, near-ridge phase), as well as many edifices in the Cobb-Eickelberg seamount chain. The short dash line is the limit of Canada's Exclusive Economic Zone (EEZ). CO: Cobb Offset; DK: Dellwood Knolls; ED: Explorer Deep; ER: Explorer Rift; RD FZ/TF: Revere−Dellwood Fracture Zone/Transform Fault; SER: Southern Explorer Ridge; SFZ: Sovanco Fracture Zone; W/MV: West/Middle Valley; NF: Nootka Fault.

Kelley et al. 2001) segments of the northern Juan de Fuca Ridge (Fig. 1) led to vigorous research efforts, including basalt petrology, in both areas (e.g. Karsten et al. 1990; Stakes and Franklin 1994; Cousens et al. 2002; Teagle and Alt 2004; Woodcock et al. 2006). Fourth, the breakup of oceanic microplates and the evolution of plate boundaries are beautifully exemplified by the Dellwood Knolls and Tuzo Wilson Volcanic Field (Chase 1977; Riddihough et al. 1980; Carbotte et al. 1989; Allan et al. 1993). Fifth, the Pratt–Welker (or Bowie–Kodiak) seamount chain in the Gulf of Alaska is recognized to be partly of intraplate origin, and geochronological data from the chain were used to constrain the motion of the Pacific Plate in the hotspot reference frame (Turner et al. 1980; Wessel and Kroenke 1998).

In the following sections, the geology, petrology and geochemistry of volcanic features within Canadian northern Pacific waters (i.e. Canada's Exclusive Economic Zone (EEZ); Fig. 1) will be reviewed, including the northern segments of the northern Juan de Fuca Ridge and Explorer Ridge, the Dellwood Knolls and Tuzo Wilson Volcanic Field, the Heck/Heckle and Dellwood near-ridge seamount chains, and finally the southern Pratt–Welker seamount chain. Particular emphasis is placed on incompatible minor and trace elements as well as radiogenic isotope ratios (Sr, Nd, Pb), which serve to distinguish different mantle sources for basalts in the NE Pacific. The relative abundance of incompatible elements, particularly the rare earth elements (REE), is a function of source abundances at the time of melting and the degree of partial melting of the source (e.g. Sun and McDonough 1989). Although many subdivisions of mid-ocean ridge basalt (MORB) chemical types have been proposed, ratios of incompatible trace elements are commonly used to classify MORB as depleted or normal (N), transitional (T), and enriched (E) types. Typically, primitive mantle-normalized values for either La/Sm (La/Sm_{pmn}) or Nb/Zr (Nb/Zr_{pmn}) are <0.8, 0.8 to 1.2, and >1.2 in N-, T-, and E-MORB, respectively. Additionally, radiogenic isotope ratios tell us about the time-integrated parent-daughter ratio in mantle sources for oceanic volcanism, and can establish whether mantle enrichment events are recent or ancient (e.g. Hofmann 1997). The geochemistry of volcanic rocks from the NE Pacific demonstrates that enriched components (veins, blobs, mantle plumes) in the upper mantle are a major contributor to intraplate, near-ridge, and ocean ridge volcanism to a degree not commonly seen in other seafloor regions.

NORTHERN JUAN DE FUCA RIDGE AND EXPLORER RIDGE

Tectonic Evolution

The Juan de Fuca and Explorer plates are the remnants of the Farallon Plate, most of which has been consumed by subduction beneath the North American Plate over the past 150 Ma (Riddihough 1984). As the area of the plate has diminished and the Farallon–Pacific spreading centre has approached the North American margin, the Farallon Plate has broken up into the Gorda, Juan de Fuca, and Explorer plates (Riddihough 1984; Wilson et al. 1984). The Sovanco fracture zone, which links the northern segments of the Juan de Fuca Ridge to Explorer Ridge, formed at approximately 7.4 Ma and lengthened rapidly as Explorer Ridge shifted to the northwest (Botros and Johnson 1988; Fig. 2). However, the Explorer Plate has only been independent from the Juan de Fuca Plate since ca. 4 Ma, when resistance to subduction reached a critical value and the Nootka Fault was initiated (Riddihough 1984; Botros and Johnson 1988; Fig. 2). Subsequently, the orientation of Explorer Ridge rotated clockwise via several rift propagation events and an eastward ridge jump during the last 0.7 Ma. Thus, the modern Explorer Ridge con-

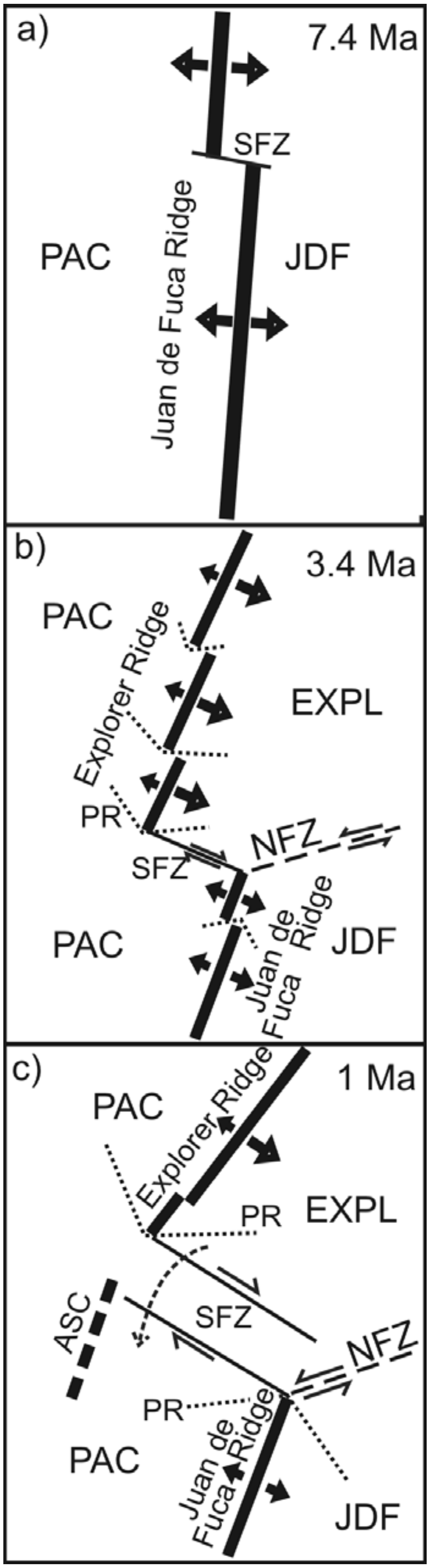

Figure 2. Tectonic evolution model for the northern Juan de Fuca and Explorer ridges (modified from Botros and Johnson 1988). Solid arrows indicate direction of spreading; size of arrow is proportional to spreading rate. a) The Sovanco fracture zone (SFZ) is initiated at ~7.4 Ma. b) Explorer Plate (EXPL) separates from Juan de Fuca Plate (JDF) at 3.4 Ma as resistance to subduction initiates the Nootka Fault Zone (NFZ); breakup and clockwise rotation of the Explorer Ridge occurs by ridge propagation (V-shaped dotted lines labeled 'PR', V points in direction of ridge propagation). c) By 1 Ma, rotation of Explorer Plate has widened the SFZ into a broad zone of deformation which now rotates counterclockwise (dashed arrow) and results in abandonment of a spreading centre (thick dashed line labelled ASC, now called Explorer Seamount). Over the last 1 Ma, northwesterly ridge jumps have occurred at the north end of both the Juan de Fuca and Explorer ridges (Fig. 1). PAC: Pacific Plate.

sists of three segments, the more robust Southern Explorer Ridge (SER), the Explorer Deep rift to the northeast, and a complex set of *en-echelon* rifts, termed the Explorer Rift, to the north (Botros and Johnson 1988: Fig. 1). The latter two rifts terminate along the Revere–Dellwood fracture zone (Figs. 1 and 3a).

Multibeam bathymetry and sidescan sonar surveys in the early 1980s demonstrated that SER is in a period of sustained high magma supply, having a minimum depth of only 1750 m near its north end, tapering to a depth of >2400 m at its south end (Kappel and Ryan 1986). The SER is split by a narrow central rift that disappears at the shallowest part of the ridge (Fig. 3b). In 2002, the National Oceanographic and Atmospheric Administration (NOAA) conducted an EM300 and deep-tow Autonomous Benthic Explorer survey of the northern SER as well as Explorer Rift and Explorer Deep (Embley 2002; NOAA 2002).

The Explorer–Pacific–North America triple junction has jumped northward over the last 700 000 years, manifested in pull-apart regions at the Dellwood Knolls and the Tuzo Wilson Volcanic Field (Riddihough et al. 1980; Carbotte et al. 1989; Davis and Currie 1993; Figs. 1 and 3a). Recent structural and seismicity studies suggest that Explorer Plate is unstable, and plate deformation is consistent with the initiation of a new, broad Pacific–Juan de Fuca transform boundary that cuts across the Explorer and Pacific plates from the southern end of the Queen Charlotte Islands to the northern Juan de Fuca Ridge (lined pattern, Fig. 1; Rohr and Furlong 1995; Dziak 2006). If so, then at some point in the future all spreading on Explorer Ridge will cease and most of the Explorer Plate will merge with the North American Plate.

Northern Juan de Fuca Ridge

The first regional studies of the northern Juan de Fuca Ridge began in the late 1960s at the University of British Columbia and the University of Washington (McManus et al. 1972; Barr 1974; Barr and Chase 1974). Based on widely spaced, single-beam echo-sounder, seismic reflection and magnetic data, Barr and Chase (1974) proposed that active spreading centres were located along the Endeavour Trough, West Valley, and Middle Ridge, but Middle Valley was not considered an active spreading centre because of the thick sediments filling the valley. Dredging from bathymetric highs recovered pillow lavas, pillow fragments, and holocrystalline rocks, all basaltic in composition.

A revolution in understanding the geology and segmentation of the northern Juan de Fuca Ridge began with the first multibeam bathymetric and sidescan sonar surveys in 1983 (Johnson et al. 1983; Karsten et al. 1986; Fig. 3). Discontinuities in magnetic anomaly stripes, first identified by Raff and Mason (1961), were recognized to result from migrating non-transform offsets (i.e. propagating rifts and overlapping spreading centres; Hey 1977; Macdonald and Fox 1983). Spreading segments were accurately located, and these were named, from south to north, the Endeavour, West Valley, and Middle Valley segments

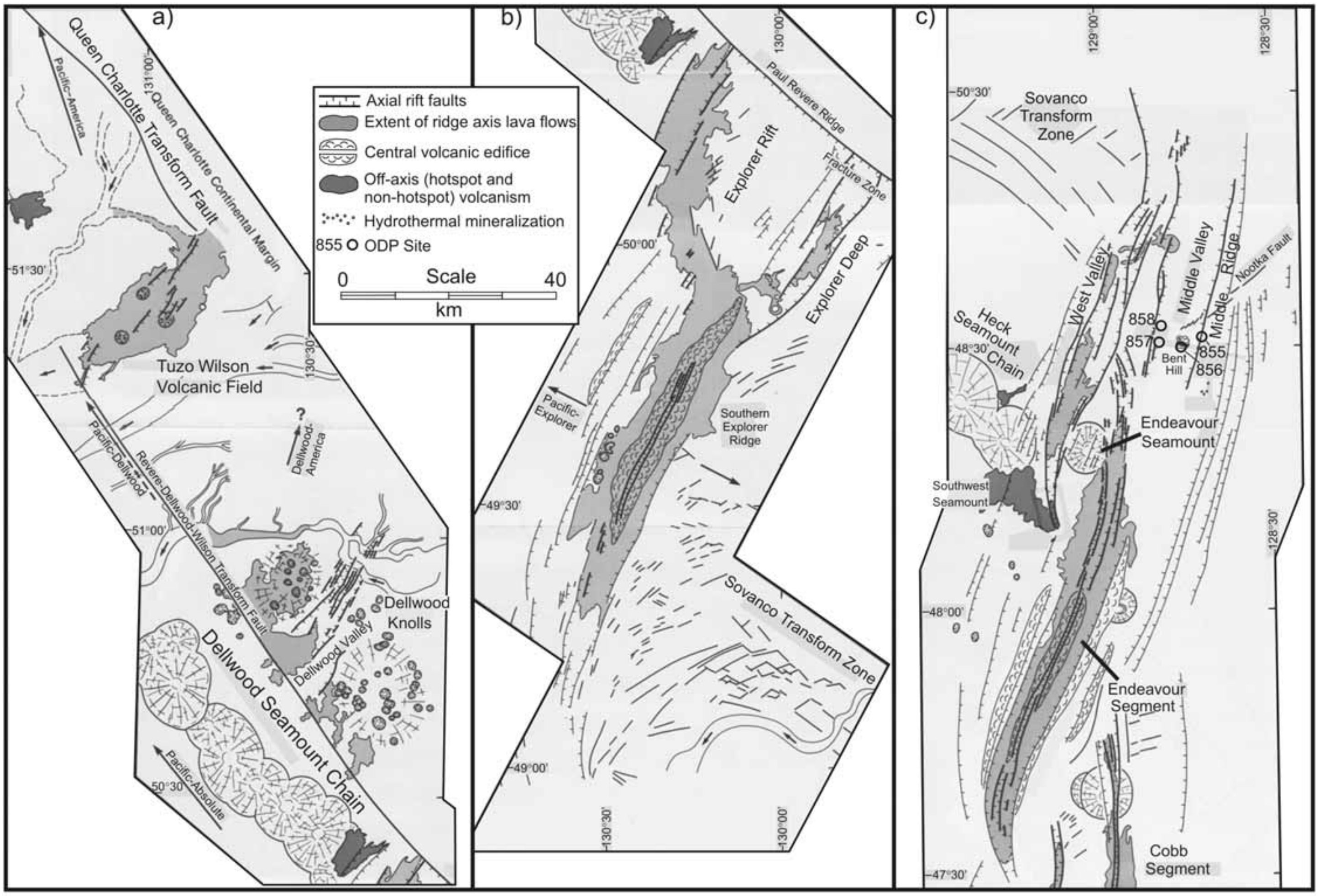

Figure 3. Geological interpretations of multibeam bathymetry and sidescan sonar imagery for, a) the Dellwood Knolls and Tuzo Wilson Volcanic Field; b) the Explorer Ridge; and c) the Endeavour segment of the northern Juan de Fuca Ridge. Modified from Davis and Currie (1993). See Figure 1 for locations.

(Figs. 1 and 3c). West Valley and Middle Valley are parallel to one another, and West Valley is considered to represent a 'ridge jump' from Middle Valley during the Brunhes Normal Epoch (e.g. Davis and Currie 1993). Shallow and deep-towed sidescan sonar systems clearly identified young, sediment-free crust at the spreading segments, outlined faults, and, when combined with sea-bottom photographs, formed the basis of a geological map of the ridge system (Fig. 3c). As a result, rock sampling could now be aimed at specific geological targets, as opposed to random dredging aimed primarily at talus slopes (e.g. Woodcock et al. 2006; Caress et al. 2008).

Endeavour Segment

Karsten et al. (1990) reported a major- and trace-element study of lavas from the ridge axis and adjacent abyssal hills of the Endeavour Segment (ES), based on 56 dredges and submersible dives performed between 1971 and 1984. Compared to lavas from the southern Juan de Fuca Ridge, lavas from the Endeavour Ridge axis are commonly higher in Na_2O and K_2O, but lower in FeO^t, and are enriched in incompatible trace elements. Endeavour Segment lavas are also generally enriched in H_2O (0.33 to 0.48 wt%) compared to southern Juan de Fuca Ridge basalts (0.15 to 0.36 wt%) (Dixon et al. 1988). In contrast, off-axis lavas are chemically similar to southern Juan de Fuca Ridge basalts. Both enriched and depleted lavas were commonly found in adjacent (or even the same) dredge hauls, indicating that the mantle source is heterogeneous even at a local scale (recently demonstrated by Woodcock et al. 2006). Figures 4a and 5a show up-to-date total alkalis vs. silica (TAS; Le Bas et al. 1986) and CaO/Al_2O_3 vs. $Mg/(Mg+Fe^{2+})$ comparisons of southern Juan de Fuca and ES lavas (GEOROC 2009). The range of ES compositions is as large as that of the southern Juan de Fuca, with the exception that some southern lavas extend to lower Mg#s ($Mg/[Mg+Fe^{2+}]$) and are therefore more highly fractionated. But figures 6a and 7a show the extraordinary range of K_2O/TiO_2 and Nb/Zr_{pmn} in ES lavas, including N-, T-, and E-MORB, compared to the southern Juan de Fuca Ridge (N-, T-MORB only). Like K_2O/TiO_2, there is a difference of nearly an order of magnitude in Nb/Zr_{pmn} among ES lavas, but a variation of only a factor of 3 along the southern Juan de Fuca Ridge. Small variations in the degree of mantle partial melting and subsequent crystallization processes in seafloor magma reservoirs are likely responsible for the range of southern Juan de Fuca Ridge compositions, whereas the order of magnitude difference in K_2O/TiO_2 at a near constant Mg# of 0.65 in ES lavas requires a different explanation. Based on limited isotopic analyses, there is little difference in Sr and Nd isotope ratios between ES and southern Juan de Fuca Ridge basalts (Eaby et al. 1984; Rhodes et al. 1990; Fig. 8a). Therefore, the generally higher Rb/Sr and lower Sm/Nd ratios in ES axial lavas do not appear to be the result of an ancient enrichment event (> a few hundred Ma) or else the isotopic signature of ES lavas would reflect this.

Karsten et al. (1990) concluded that extreme variability in trace-element ratios requires a heterogeneous source, feeding multiple parental melts to even the shortest ridge segments. Seismic reflection data indicate that a magma lens exists beneath the ES (Rohr et al. 1988), but this magma lens has not eliminated, by mixing, the heterogeneity of primary magmas. Karsten et al. (1990) also noted no correlation between chemistry and ridge axis morphology, concluding that magma supply to the ridge and the extent of partial melting were less important parameters than source heterogeneity. Although E-MORB commonly erupts where a ridge axis is near a hotspot (e.g. Schilling et al. 1982), there is no tectonic evidence for a hotspot in the region. The nearby Heck and Heckle seamount chains might be viewed as evidence of hotspot activity, but the chemistry of the lavas dredged from these seamount chains argue strongly against a hotspot origin (Barr 1974; see 'Near-Ridge Seamounts' section). These constraints led Karsten et al. (1990) to suggest that recent tectonic changes along the northern Juan de Fuca Ridge have played a role in magmatic evolution. As the ridge has re-oriented itself over the past 0.2 Ma by ridge propagation, a cooler adiabatic gradient beneath the ridge has resulted in smaller-volume partial melts that are chemically diverse and have short residence times in axial magma reservoirs. Melting of enriched domains embedded in the upper mantle may be enhanced under these conditions, and these enriched melts have made a greater contribution to axial lavas during the last 0.2 Ma. Prior to 0.2 Ma, thermal conditions were normal, and therefore off-axis lavas are N-MORB similar to, or even more depleted than, the southern Juan de Fuca Ridge.

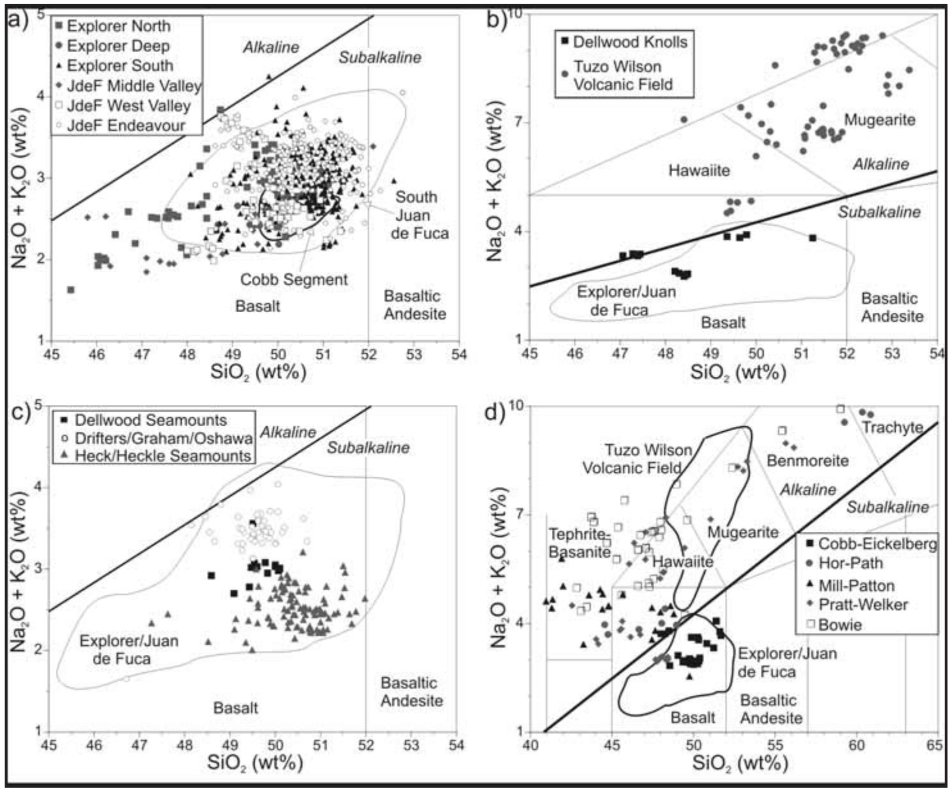

Figure 4. Total alkali vs. SiO_2 diagram for northeast Pacific volcanic rocks, with fields defined by Le Bas et al. (1986), and alkaline–tholeiitic boundary from Macdonald and Katsura (1964). a) Mid-ocean ridges; b) Dellwood Knolls and Tuzo Wilson Volcanic Field; c) near-ridge seamounts; and d) intraplate seamount lavas. Data from GEOROC (2009) and PetDB (2009), except for b), from B. Cousens (unpublished data, 2010).

Middle Valley

Middle Valley, north of the Endeavour Segment (Figs. 1 and 3c), is a sediment-filled rift graben where the youngest volcanism appears to be restricted to sill complexes within the sediments (Stakes and Franklin 1994). Prior to 10 000 years ago, Middle Valley and the Endeavour Segment were probably a single continuous spreading centre (Davis and Villinger 1992). Older basaltic lavas have been dredged and drilled (Ocean Drilling Program (ODP) Site 855) along the eastern margin (Middle Ridge) of the rift valley (Barr and Chase 1974; Stakes and Franklin 1994; Fig. 3c). The older lavas are moderately evolved tholeiitic basalts (MgO <8%, Ni <150 ppm in non-porphyritic rocks) with low abundances of incompatible elements (Ba <40 ppm, Nb <5 ppm, Rb <5 ppm). Middle Ridge basalts have low K_2O/TiO_2 (<0.15) and La/Sm_{pmn} (<0.7) (Van Wagoner and Leybourne 1991; Stakes and Franklin 1994); $^{87}Sr/^{86}Sr$ ranges from 0.70232 to 0.70239, $^{143}Nd/^{144}Nd$ from 0.51314 to 0.51321, and $^{206}Pb/^{204}Pb$ from 18.30 to 18.40, all falling in a very restricted range (Cousens, unpublished data, 2010). Like off-axis basalts from the Endeavour Segment, Middle Ridge basalts are N-MORB and are similar to basalts of the southern Juan de Fuca Ridge.

The ODP Leg 139 drilling (Site 856) beneath the Bent Hill topographic high in Middle Valley (Fig. 3c) intersected relatively fresh picritic sills at depths less than 200 m (Stakes and Franklin 1994), and further drilling during ODP Leg 169 sampled sills and basement lavas just south of Bent Hill at depths >430 m (Bjerkgard et al. 2000; Teagle and Alt 2004). The sills are among the most primitive (Mg# >0.74) basaltic rocks recovered from

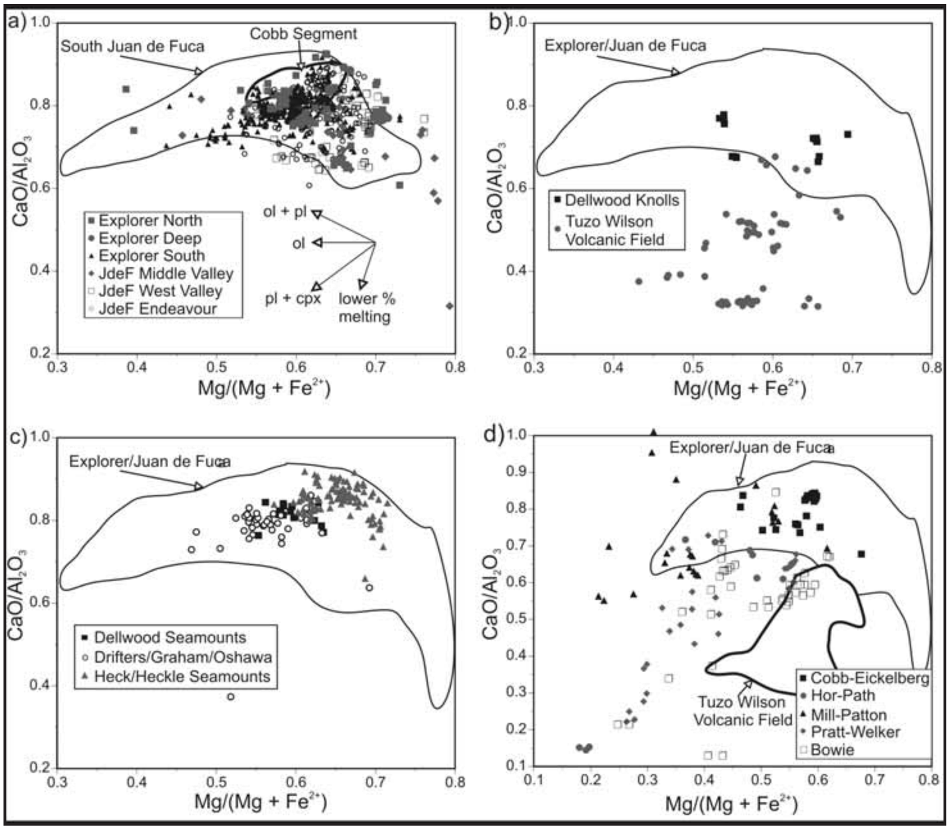

Figure 5. CaO/Al_2O_3 vs. atomic $Mg/(Mg+Fe^{2+})$ diagrams for northeast Pacific volcanic rocks, assuming $Fe^{2+} = 0.9*Fe^{total}$. a) Mid-ocean ridges. Arrows indicate schematic trends of residual liquids during crystallization of olivine (ol), olivine plus plagioclase (ol+pl), or plagioclase plus clinopyroxene (pl+cpx) at 1 kbar pressure, as well as the trend of liquids produced by decreasing degrees of partial melting of peridotite (from Niu et al. 2002); b) Dellwood Knolls and Tuzo Wilson Volcanic Field; c) near-ridge seamounts; and d) intraplate seamount lavas. Data sources as in Figure 4.

the Juan de Fuca Ridge; they have very low concentrations of incompatible elements, La/Sm_{pmn} <0.3, and $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ range from 0.70236 to 0.70258 and 0.51318 to 0.51329, respectively. The least altered basement lava is more evolved (<7% MgO) but remains light-REE-depleted (La/Sm_{pmn} ~0.7), much like the basalts dredged and drilled from Middle Ridge. Leg 169 sills and lavas have $^{143}Nd/^{144}Nd$ between 0.51318 and 0.51323 (Bjerkgard et al. 2000).

Sill complexes drilled at ODP Site 857 (Fig. 3c) in central Middle Valley are intensely hydrothermally altered, the original igneous geochemistry has been obscured, and only the most immobile elements are useful (such as the REE, Nb, Zr; Stakes and Franklin 1994). The sills contain small pseudomorphs of olivine, plus plagioclase and clinopyroxene phenocrysts. Based on Ni content <100 ppm, the magmas are moderately evolved. The sills can be split into two groups based on normalized REE patterns, one that is light-REE depleted (N-type) similar to lavas drilled at Site 855, and another that is slightly light-REE enriched (T-type). The two sill types alternate with depth. La/Sm_{pmn} does not correlate with $^{143}Nd/^{144}Nd$, the most reliable isotopic indicator in these sills, which ranges from 0.51312 to 0.51324 (Cousens, unpublished data, 2010). Drilling at nearby Site 858 penetrated basement flows that are less altered than the sills at Site 857. The lavas are remarkably homogeneous in composition, with normalized Ce/Yb >1.3 (T-type; Stakes and Franklin 1994) and $^{143}Nd/^{144}Nd$ between 0.51312 and 0.51320 (Cousens, unpublished data, 2010).

Lavas and sills from Middle Valley are commonly N-MORB from a depleted mantle source, similar to lavas from the southern Juan de Fuca Ridge. The picritic sills at Site 856 are the youngest magmas recovered from this segment of the ridge and display some of the most primitive compositions reported for the Juan de Fuca Ridge, suggesting that they postdate the existence of any robust magma chamber at Middle Valley (Stakes and Franklin 1994). Site 856 sills are similar chemically to lavas from the nearby Heck and Heckle near-ridge seamounts (Leybourne and Van Wagoner 1991). Sills at Site 857 have multiple magma sources with distinct REE patterns, including one having N-type patterns like Site 855 lavas and another more like T-type lavas from Site 858. It is possible that Site 858 lavas represent a shallow axial seamount that formed late in the magmatic history of Middle Valley, and that this seamount fed some of the sills at Site 857 (Stakes and Franklin 1994).

West Valley

West Valley is an incipient spreading centre, where rifting commenced after a ridge jump from Middle Valley during the Holocene (Davis and Currie 1993). Young volcanism is restricted to the southern half of the segment and comprises small volcanoes on the rift valley floor, 60–250 m in height, that are easily visible in sidescan sonar images (Davis et al. 1984; Karsten et al. 1986; Fig. 3c). Lava flows on the rift valley floor are extremely plagioclase-phyric, suggesting plagioclase concentration, and the complexly zoned feldspars indicate multiple magma mixing events (Van Wagoner and Leybourne 1991; Cousens et al. 1995). Flows with high backscatter (little to no sediment cover) are also present on the west flank of West Valley, and emanate from a small off-axis cone southwest of the rift valley. The latter vent, termed Southwest Seamount (Fig. 3c), spills lava flows into the southern end of West Valley.

The lavas from West Valley are diverse chemically, ranging from alkali-poor olivine-hypersthene tholeiites to near nepheline-normative tholeiite at Southwest Seamount (Fig. 4a). Chemically, these lavas span the range of compositions for the entire Juan de

Fuca system, ranging from highly light-REE-depleted N-MORB to the most enriched E-MORB. K_2O/TiO_2 ranges from 0.01 to 0.35, Nb/Zr_{pmn} from 0.01 to 2.3, and La/Sm_{pmn} from 0.5 to 2.2 (Figs. 6a, 7a and 9). The lavas also display a considerable range in Sr, Nd and especially Pb isotopic compositions ($^{206}Pb/^{204}Pb$ = 18.2-19.2; Fig. 8) that correlate positively with increases in incompatible element ratios such as Nb/Zr (Fig. 7a) and La/Sm (Fig. 9), indicating that they are mixtures of melts from depleted and enriched mantle sources.

Southwest Seamount, perched on the south end of the Heck seamounts (Fig. 3c), emits lavas dominated by the light-REE-enriched component with the most radiogenic Sr and Pb isotope ratios. These lavas have low CaO/Al_2O_3 (<0.7) given their intermediate Mg# (0.61–0.55, Fig. 5a), which could be explained by ~20% clinopyroxene fractionation from other West Valley magmas but at pressures much higher than would be expected for an incipient rift in thin crust (Cousens et al. 1995). Alternatively, 5–10% partial melting of mantle peridotite at pressures of 10–20 kbar can yield primary magmas with CaO/Al_2O_3 <0.7 (e.g. Falloon and Green 1988), which could then evolve by low-pressure fractionation of olivine to decrease the Mg# of the erupted magmas. Finally, low CaO/Al_2O_3 and Mg# may be consistent with a source rich in pyroxenite (e.g. Pertermann and Hirschmann 2003). Cousens et al. (1995) propose that the enriched mantle component also includes a hydrous phase, possibly amphibole. Consistent with the ridge morphology, the complex petrogenesis and small volume of erupted lavas indicate a relatively cool ridge environment (Cousens et al. 1995).

Explorer Ridge

Cousens et al. (1984) published the first petrological and geochemical data from Explorer Ridge, based on dredge hauls from the early 1970s, 1977 and 1979, all prior to multibeam bathymetric surveys (Davis et al. 1984, 1985). Most of the samples were from the northern half of the ridge system, including Paul Revere Ridge (Revere–Dellwood transform wall; Fig. 3b), Explorer Rift, Explorer Deep, and the northern half of the Southern Explorer (SER) segment. With rare exception, dredge hauls recovered young glassy pillow lavas with no ferromanganese crust or sediment cover (Cousens 1982). Some dredge hauls also sampled blocky lavas with no glass surface. Michael et al. (1989) followed with a more detailed study of SER using samples collected with multibeam bathymetric information. Lavas from SER contain variable abundances of plagioclase, clinopyroxene and olivine phenocrysts, commonly in glomeroporphyritic clusters. The ubiquitous occurrence of clinopyroxene is likely related to the high H_2O content of SER basalts (Michael and Chase 1987; Michael et al. 1989).

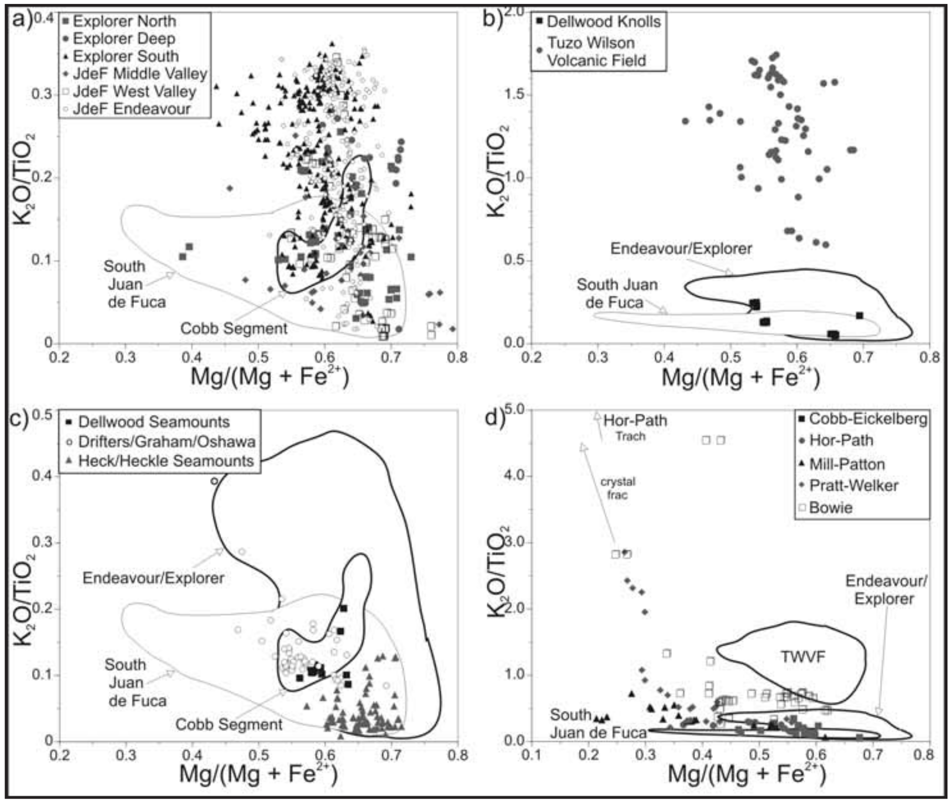

Figure 6. K_2O/TiO_2 vs. $Mg/(Mg+Fe^{2+})$ diagrams for northeast Pacific volcanic rocks. a) Mid-ocean ridges; b) Dellwood Knolls and Tuzo Wilson Volcanic Field, c) near-ridge seamounts, and d) intraplate seamount lavas. Arrows indicate trajectory for crystal fractionation and off-scale position of Horton and Pathfinder seamount trachytes. Data sources as in Figure 4.

All three segments of Explorer Ridge (Explorer Rift, Explorer Deep, and South Explorer Ridge) are chemically heterogeneous, and exhibit a wide range of SiO_2 and total alkali contents (Fig. 4a). Some lavas from both Explorer Rift and SER are transitional to alkaline basalt. Like the Endeavour and West Valley segments, Explorer Ridge basalts span a large range of K_2O/TiO_2 and Nb/Zr values and extend to much higher ratios than basalts from the southern Juan de Fuca Ridge (Figs. 6a and 7a). Remarkably, virtually the whole range of Nb/Zr is seen in lavas from the shallowest part of SER, within a small area centred at 49.75°N (Michael et al. 1989; Fig. 3b). The La/Sm_{pmn} ranges from 0.5 to 1.4 at Explorer Rift, 1.6 to 1.85 at Explorer Deep, and 0.7 to 2.3 along SER (Fig. 9). Few isotopic data are available for Explorer basalts, but the ranges of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are greater than those at West Valley (Fig. 8).

The $^3He/^4He$ ratios in Juan de Fuca Ridge basalts (not shown) range from 7.8 to 8.8 R_A (times the modern atmospheric ratio; Lupton et al. 1993). Helium isotopic ratios in Explorer N-MORB and E-MORB are 8.3 R_A and 7.6 R_A, respectively (Carbotte 1987). Lupton et al. (1993) noted a negative correlation between $^3He/^4He$ and

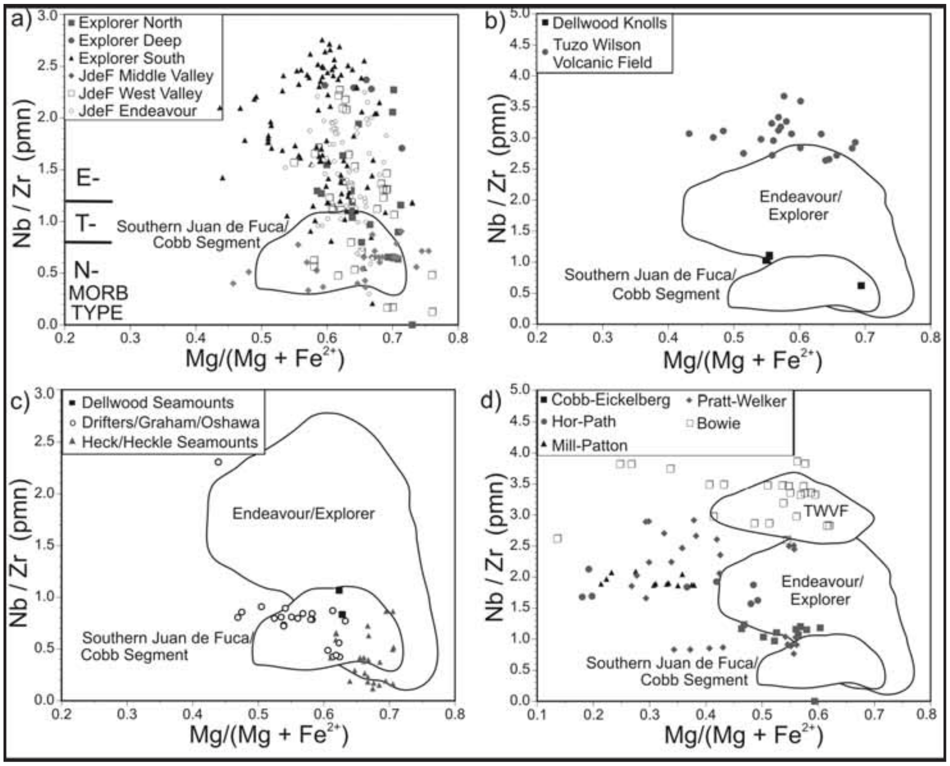

Figure 7. Nb/Zr_{pmn} vs. $Mg/(Mg+Fe^{2+})$ diagrams for northeast Pacific volcanic rocks. a) Mid-ocean ridges; note division into N-, T-, and E-type MORB on left side, b) Dellwood Knolls and Tuzo Wilson Volcanic Field (TWVF); c) near-ridge seamounts; and d) intraplate seamount lavas. Data sources as in Figure 4. Primitive mantle normalization values from Sun and McDonough (1989).

$^{87}Sr/^{86}Sr$ for Juan de Fuca Ridge basalts (Eaby et al. 1984). Given $^{87}Sr/^{86}Sr$ of 0.70233 and 0.70252 for the N- and E-MORB chosen for He analysis, the same relationship appears to hold for these two Explorer Ridge basalts. This negative correlation is unusual for MORB in general (Lupton 1983), and indicates that the high-$^{87}Sr/^{86}Sr$ component in Explorer and Juan de Fuca Ridge lavas does not originate in deep, un-degassed mantle.

Like the Endeavour and West Valley segments, small-scale chemical heterogeneity argues against the presence of a persistent magma reservoir beneath Explorer Ridge, even in the magmatically robust shallow region of SER. However, smaller magma reservoirs must exist at various points along the ridge to explain the abundance of evolved magmas. Lavas with enriched mantle sources are common along SER, and are also found in Explorer Rift and Explorer Deep. SeaMARC II sidescan sonar (Davis et al. 1984) and EM300 reflectance (Embley 2002) data show lava flows extending from the shallow culmination of SER into the rift valleys to the southeast, and perhaps as far as the dredge locations in Explorer Deep. If so, the fresh, E-type lavas dredged from Explorer Deep in 1979 did not have a source within the rift, and thus Explorer Deep may not be volcanically active as has been assumed. In any case, the enriched component in the sub-SER mantle may be present as streaks, veins or blobs in a depleted mantle matrix, or is contained within a mantle hotspot centred beneath the shallowest point of SER (i.e. the point of greatest magma supply; Michael et al. 1989). Major-element data were used by Michael et al. (1989) to constrain depth and percentage of melting for Explorer N- and E-MORB, and to determine that the percent melting of the enriched mantle component is higher than that of the depleted component. This is corroborated by the observation that middle to heavy REE abundances are higher in the N-MORB than in the E-MORB lavas. In addition, the enriched mantle component melts at a shallower average depth than the depleted component.

THE PACIFIC—EXPLORER—NORTH AMERICA TRIPLE JUNCTION: DELLWOOD KNOLLS AND TUZO WILSON VOLCANIC FIELD

Dellwood Knolls

The Dellwood Knolls are two volcanic edifices on the east side of the northwestern end of the Revere–Dellwood fracture zone and west of the Queen Charlotte Fault (Bertrand 1972; Riddihough et al. 1980; Davis 1982; Davis and Currie 1993; Rohr and Furlong 1995; Figs. 1 and 3a). The two seamounts are separated by the Dellwood Valley, a zone of microseismicity, faulting, and anomalously thin sediment cover that is interpreted to represent a spreading centre that has split an original single edifice in two (Rohr and Furlong 1995). This is a very young feature, however, and shallow reflectors in the valley are only offset by a few tens of metres (Rohr and Furlong 1995). SeaMARC II sidescan sonar images show that young lava flows cover much of the surface of the northwestern knoll and spill across the Revere–Dellwood fault where it intersects the southwestern side of the knoll (Davis et al. 1984; Davis and Currie 1993; Fig. 3). A hard reflector also fills part of a submarine channel north of the northwestern knoll. The southeastern knoll is mostly sediment-covered and only two hard reflectors are visible along the southwestern edge of the seamount, both of which cross the Revere–Dellwood fracture zone (Fig. 3a). Bulk densities for both seamounts, calculated from gravity data, are only 2.5 g/cm^3, suggesting that the edifices are composed of a mixture of basalt and lower density sediment (Riddihough et al. 1980).

Dredging, in 1970, recovered young (<1 Ma) vesicular pillow basalts from the northwestern knoll and highly altered, manganese-encrusted pillow basalt from the southeastern knoll (Bertrand 1972). A 1994 cruise (PGC-94-04) recovered glassy pillow lavas from a flow just south of the 1970 dredge on the northwestern knoll. Lavas from the northwestern knoll are fresh, slightly olivine-phyric lavas with abundant vesicles and rare, partially resorbed plagioclase xenocrysts. The

1970 sample from the northwestern knoll is transitional basalt, plotting on the Hawaiian tholeiite-alkalic basalt boundary, whereas the 1994 lava is tholeiitic basalt with a higher SiO_2 content (Fig. 4b). Both lavas have low K_2O/TiO_2, (Fig. 6b), Nb/Zr_{pmn}, (Fig. 7b), and La/Sm_{pmn} (0.66–1.15; Fig. 9), and overlap with N-type MORB of the Juan de Fuca Ridge. Northwestern knoll basalts have $^{87}Sr/^{86}Sr$ between 0.70240 and 0.70245, $^{143}Nd/^{144}Nd$ of 0.51315, and $^{206}Pb/^{204}Pb$ between 18.70 and 18.75 (Cousens, unpublished data, 2010; Cousens et al. 1984), all typical of N-MORB from the Juan de Fuca and Explorer ridges (Fig. 8). The altered basalt from the southeastern knoll has a higher K_2O content (alteration?), higher K_2O/TiO_2 and La/Sm_{pmn} (1.26) than lavas from the northwestern knoll. The measured $^{87}Sr/^{86}Sr$ of 0.70279 to 0.70290 (Cousens et al. 1984) is higher than most MORB from the Juan de Fuca and Explorer ridges, and may partly be due to seafloor alteration. In summary, extremely sparse sampling of the Dellwood Knolls has recovered both N-type and E-type MORB. The lavas fall within the compositional range of northern Juan de Fuca and Explorer Ridge basalts.

Tuzo Wilson Volcanic Field

Northwest of the Dellwood Knolls is another broad zone of high reflectivity in sidescan sonar data, originally called the J. Tuzo Wilson Knolls after the famous University of Toronto geophysicist (Chase 1977), later termed the Tuzo Wilson Seamounts (Cousens et al. 1985; Carbotte et al. 1989), and more recently the Tuzo Wilson Volcanic Field (TWVF; Allan et al. 1993; Rohr and Furlong 1995; Fig. 3a). Discovered in 1973, the field consists of two ridge-shaped edifices oriented northeast–southwest and having heights of 700 and 500 m above the seafloor. The two edifices are surrounded by numerous (~75) lava cones and volcanic ridges, usually <100 m in height, that cover an area of at least 20 by 30 km (Allan et al. 1993). The lavas have no sediment cover and a very high magnetization intensity; a single attempt to date a Tuzo Wilson lava by K-Ar, yielded an age indistinguishable from zero (Cousens et al. 1985).

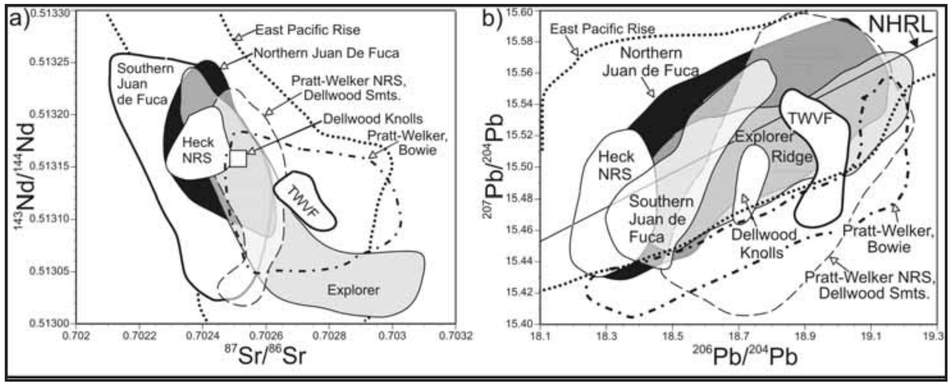

Figure 8. a) $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ and b) $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagrams for all northeastern Pacific oceanic lavas. NHRL: Northern Hemisphere Reference Line, from Hart (1984); Northern Juan de Fuca: Endeavour, Middle, and West Valley segments; NRS: near-ridge seamounts; TWVF: Tuzo Wilson Volcanic Field. Data sources as in Figure 4.

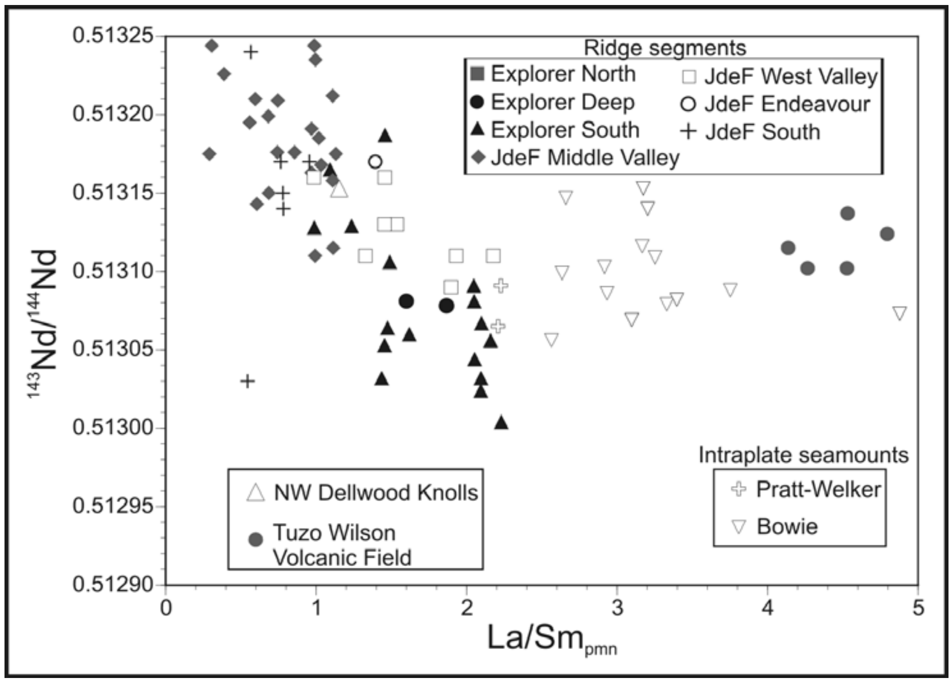

Figure 9. The La/Sm_{pmn} vs. $^{143}Nd/^{144}Nd$ diagram for all northeastern Pacific oceanic lavas. MORB from ridge segments shows good negative correlation between trace element enrichment (La/Sm) and $^{143}Nd/^{144}Nd$, whereas most alkalic lavas from the Tuzo Wilson Volcanic Field and intraplate seamounts have variable La/Sm over a small range of $^{143}Nd/^{144}Nd$. Data sources as in Figure 4.

Chase (1977), based on the major-element chemistry of the lavas recovered in 1973, considered the TWVF to be a hotspot. Carbotte et al. (1989) noted that the Revere–Dellwood fracture zone continues northwest of the Dellwood Knolls and appears to terminate at the south end of the TWVF (Fig. 3a). Both the Dellwood Knolls and TWVF are therefore located between the Revere–Dellwood and Queen Charlotte transform faults. Curiously, a dark reflector lies to the northwest of the TWVF, hinting that there is some recent volcanic activity even farther to the north (Davis and Currie 1993). Carbotte et al. (1989) proposed that spreading was occurring at both the Dellwood Knolls and TWVF, although the duration and total amount of spreading that has occurred at each of these features is difficult to constrain. They finally note that widely distributed microseismicity on Explorer Plate, the Dellwood Knolls and TWVF suggests that a rigid-plate assumption "may not be appropriate", and that the Pacific–North America–Explorer triple junction may not be a discrete point but rather a diffuse zone between the north end of Explorer Ridge and the TWVF. Cousens et al. (1985), Allan et al. (1993) and Rohr and Furlong (1995) propose that the TWVF and the Dellwood Knolls represent 'leaky transform' or pull-apart rift volcanism within the crustal block bounded by the Revere–Dellwood and Queen Charlotte transforms faults, and that they are not true spreading centres.

Petrographically, all samples recovered from the TWVF are fresh, highly vesicular, glassy pillow lavas. They commonly contain olivine and plagioclase phenocrysts, and basalts from the northeastern edifice are also clinopyroxene-bearing and glomeroporphyritic. The lavas consist of alkalic basalts, hawaiites, mugearites and benmoreites (Fig. 4b), and are enriched in the alkalis, P_2O_5, H_2O, the light REE and other incompatible elements (Cousens et al. 1985; Allan et al. 1993). The TWVF lavas also have high Fe^{3+}/Fe^{2+}, and calculated oxygen fugacities are higher than those of Pacific MORB. Measured H_2O contents are commonly >1%, and these are minimum estimates as the lavas have degassed upon eruption. Lavas from the southwestern edifice are more enriched in incompatible elements compared to lavas elsewhere in the field. Both glasses and whole-rock samples have lower FeO, CaO, and CaO/Al_2O_3 at a given Mg# compared to Juan de Fuca MORB (Fig. 5b). The lavas are evolved, with MgO contents <7% and Ni <100 ppm, but Mg#s are relatively high because of the low FeO content of the lavas. K_2O/TiO_2, Nb/Zr_{pmn}, and La/Sm_{pmn} are distinctly higher than MORB, and are higher than E-MORB from the northern Juan de Fuca and Explorer Ridges (Figs. 6b, 7b and 9). Isotopically, TWVF lavas fall at the 'enriched' end of the Juan de Fuca MORB spectrum: $^{87}Sr/^{86}Sr$ ranges from 0.70267 to 0.70279, $^{143}Nd/^{144}Nd$ from 0.51310 to 0.51314, and $^{206}Pb/^{204}Pb$ from 18.88 to 19.01 (Fig. 8). $^{3}He/^{4}He$ ranges from 5.3 to 8.9 R_A, but with high uncertainties (Zadnick 1981; Kyser and Rison 1982). The TWVF lavas also overlap isotopically with intraplate alkaline rocks of the Pratt–Welker seamount chain to the northwest; in particular, they share a low $^{207}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$ (below the Northern Hemisphere Reference Line of Hart 1984), which is uncharacteristic of Juan de Fuca MORB (Fig. 8).

Low Cr, Sc, FeO and CaO/Al_2O_3 are indicative of extensive clinopyroxene fractionation. Thermodynamic modelling shows that fractionation must have occurred at pressures >2 kbar, consistent with the evolution of TWVF magmas beneath oceanic crust >6 km in thickness (Allan et al. 1993). High H_2O, K_2O, P_2O_5 and light REE contents require that a K-bearing phase (e.g. amphibole or phlogopite) and apatite are present in the TWVF mantle source. However, the lack of heavy-REE depletion in the lavas indicates that garnet is not a residual mantle phase, and melting likely occurred in the spinel or plagioclase stability field. Assuming an amphibole peridotite source (e.g. Zabargad Island peridotite), TWVF primary melts were derived by 5–10% partial melting. The source of Explorer Ridge E-MORB is considered to be similar to that of the TWVF, but the percentage of melting of the Explorer source is higher (12–17%; Michael et al. 1989). However, the evidence from Pb, Sr, Nd and He isotopes indicates that incompatible element enrichment of the TWVF mantle source must be a recent event, because these isotopic ratios fall within the field for Pacific MORB (Fig. 8).

The lack of a large eruptive volume or a thermal swell argues against a mantle plume origin for the TWVF. Cousens et al. (1985) and Allan et al. (1993) conclude that the TWVF and Dellwood Knolls are the result of leaky transform volcanism between the Revere–Dellwood and Queen Charlotte faults, but the magma types erupted at the two localities are very different. Petrologically, this requires dramatically different mantle sources at a small scale (<100 km).

NEAR-RIDGE SEAMOUNT CHAINS

Along the northern Juan de Fuca system, two prominent seamount chains extend onto the Pacific Plate from spreading centres: the Heck/Heckle pair (Barr 1974; Leybourne and Van Wagoner 1991; Van Wagoner et al. 1995) and the Dellwood Seamounts (Cousens et al. 1984) (Figs. 1 and 3). These seamount chains formed immediately adjacent to the ridge, and seamounts within each chain are progressively older with increasing distance from the ridge. These seamounts generally lack evidence for a hotspot source, and differ in origin from volcanoes produced where hotspots meet spreading ridges, such as Axial Seamount on the southern Juan de Fuca Ridge (Desonie and Duncan 1990; Rhodes et al. 1990).

Heck and Heckle Seamount Chains

The Heck and Heckle seamount chains extend 70 and 80 km, respectively, northwest of the northernmost part of the Juan de Fuca Ridge (Barr 1974; Fig. 1). Magnetic anomalies of the oceanic crust continue undeflected across the chains, proving their near-ridge origin. Based on the thicknesses of manganese crusts, the northernmost Heckle seamount is ~3.5 Ma in age, which matches its age deduced from magnetic anomalies (Barr 1974). The southernmost seamount in the Heck chain, Endeavour Seamount, is trapped between the northernmost Endeavour and southernmost West Valley ridge/rift segments (Karsten et al. 1986; Fig. 3c).

The Heck and Heckle seamount chains have been dredged at nine localities (Barr 1974; Leybourne and Van Wagoner 1991). The rocks recovered include variably palagonitized glassy lavas (pillows, clinker, sheet flows) coated with manganese crusts, and hyaloclastites. The Endeavour Seamount lava is highly plagioclase-phyric, but all others are aphyric to sparsely phyric (plagioclase +/- olivine, rare clinopyroxene). The basalt glasses are remarkably primitive, having Mg#s >0.6 (and many with a Mg# near 0.7), and low total alkalis (Fig. 4c). CaO/Al_2O_3 ratios are high (Fig. 5c), as are Cr (>400 ppm) and Sc (>26 ppm), but Ni is <100 ppm, indicating significant olivine fractionation but no clinopyroxene crystallization. K_2O contents, and K_2O/TiO_2, are very low (Fig. 6c), as are Nb/Zr (Fig. 7c), and La/Sm_{pmn} (<0.5; not shown). Primitive mantle-normalized incompatible-element patterns show remarkable depletion in the light REE, much like picritic sills at ODP Site 856, and are well below levels seen elsewhere on the northern Juan de Fuca Ridge (Leybourne and Van Wagoner 1991). These rocks have among the lowest $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ and highest $^{143}Nd/^{144}Nd$ of seafloor lavas from the northeast Pacific (Hegner and Tatsumoto 1989; Cousens et al. 1995; Fig. 8).

The Heck and Heckle seamount lavas have a source that is highly depleted in incompatible elements, both at the time of magma generation (low La/Sm) and over geologic time (low $^{87}Sr/^{86}Sr$); they are therefore unlike adjacent West Valley lavas, both petrographically and chemically. The seamounts lack calderas that would be indicative of longer term magma chambers (Clague et al. 2000), and the primitive compositions of the lavas are consistent with rapid migration through the crust prior to eruption. Geochemical modelling suggests that the seamounts have tapped an off-axis source that has had any enriched components removed by an earlier partial melting event, probably beneath the adjacent ridge axis (Leybourne and Van Wagoner 1991; Cousens et al. 1995).

Dellwood Seamounts

The Dellwood seamount chain (Figs. 1 and 3a) extends northwesterly from the northern Explorer Ridge and includes three edifices, two of which are coalesced (Davis and Currie 1993). The seamounts rise nearly 1400 m above the seafloor. They lack calderas, and late-stage(?) vents pockmark the southeastern-most edifice, although none of the vents are young based on the evidence of sidescan sonar backscatter. The seamounts are more massive than the Heck and Heckle edifices. Where the southeastern edifice meets Explorer Rift there is an off-axis lava flow associated with two faults (Davis and Currie 1993; Fig. 3a).

Three dredge hauls have previously sampled the Dellwood seamounts: 71-15-77 crossed the young off-axis flow at the base of the southeastern edifice, while two others sampled the central and southern peaks (Cousens et al. 1984). Based on its reported location, a fourth dredge sample (70-25-7) allegedly from the Dellwood seamounts (sample D-1 in Church and Tatsumoto 1975; Hegner and Tatsumoto 1989), is probably fresh basalt from Explorer Rift.

Dellwood seamount lavas are very different from Heck and Heckle seamount basalts. The Dellwood seamount lavas are more evolved, with Mg# <0.62, Ni <80 ppm, but Cr >285 ppm and Sc >40 ppm. They have higher total alkalis (Fig. 4c), K_2O and intermediate K_2O/TiO_2 compared to most Explorer Ridge MORB (Fig. 6c). Nb/Zr_{pmn} (Fig. 7c) and La/Sm (not shown) are ~1 (Cousens et al. 1984), and both $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ are higher than values for Heck and Heckle (Hegner and Tatsumoto 1989; Fig. 8).

Although sampling is restricted, it appears that Dellwood Seamount basalts contain an enriched component that is not found in Heck and Heckle near-ridge seamounts. This variety in seamount chemistry mirrors the results of studies of similar chains adjacent to the East Pacific Rise (e.g. Graham et al. 1988). Near-ridge seamounts that are now located off the west coast of the Queen Charlotte Islands (Oshawa, Drifters, and Graham seamounts) but originating at Explorer Ridge between 11 and 14 Ma, are also composed of tholeiitic, N- to E-type MORB basalts (Cousens et al. 1999). The Oshawa−Drifters−Graham lavas are similar to MORB from the Explorer Ridge and lavas from the Dellwood Seamounts (Figs. 5c, 6c and 7a), and strongly resemble the older (ca. 14−18 Ma), tholeiitic phase of volcanism represented by the southern Pratt–Welker seamounts (Fig. 1; see next section). Thus, the enriched mantle component in northern Juan de Fuca, Explorer, and Dellwood seamount sources was present beneath the northern Juan de Fuca Ridge at least as long ago as 14 Ma.

INTRAPLATE MAGMATISM: BOWIE SEAMOUNT AND THE PRATT−WELKER CHAIN

Two intraplate seamount chains are found in the NE Pacific, the Cobb–Eickelberg and Pratt–Welker (Kodiak–Bowie) group (Fig. 1). The focus of modern volcanism of the Cobb–Eickelberg chain is Axial Seamount on the southern Juan de Fuca Ridge (Johnson and Embley 1990; Chadwick et al. 2005). The youngest edifice in the Pratt–Welker chain is Bowie Seamount, which was recently named as Canada's second Marine Protected Area (Fisheries and Oceans Canada 2008).

The 1460 km-long Pratt–Welker chain has been used as a test of the fixed hotspot reference frame (Silver et al. 1974; Turner et al. 1980; Dalrymple et al. 1987). Turner et al. (1980) calculated a revised Pacific Plate pole of rotation utilizing new K–Ar dates from the northernmost and southernmost seamounts in the chain. They also recovered both older, tholeiitic and younger, alkalic capping lavas from some of the southern seamounts. Dalrymple et al. (1987) determined an ^{40}Ar-^{39}Ar age for Welker Seamount in the central part of the chain that is too old to fit the pole of rotation of Turner et al. (1980), and concluded that the Pratt–Welker chain (and others in the Gulf of Alaska) was formed by multiple episodes of short-lived intraplate volcanism rather than being formed by a single melting anomaly (e.g. Hawaii–Emperor). A zone of low mantle seismic velocity that has been imaged ~150 km northeast of Bowie Seamount at a depth of ~700 km is interpreted as a mantle plume (Nataf and VanDecar 1993).

Little has been published on the petrology of the Pratt–Welker chain. Turner et al. (1980) briefly outline five magma types recovered from the chain, including 1) tholeiitic basalt (Macleod and Pratt 1973), 2) transitional basalt, 3 and 4) two types of alkalic basalt, and 5) trachyte (R.B. Forbes et al., unpublished data, 2010; Forbes and Hoskin 1969; Forbes et al. 1969). Incompatible element abundances and La/Sm_{pmn} all increase from Group 2 to 5 (R.B. Forbes, personal communication 1981). Lavas recovered from Welker Seamount include hawaiite, mugearite, and benmoreite, all with low MgO, Ni, Cr and Sc, and light-REE-enriched trace element patterns (Dalrymple et al. 1987). The Sr, Nd and Pb isotope ratios have been determined on the Turner et al. (1980) samples, and all fall within the range of Pacific E-MORB (Hegner and Tatsumoto 1989; Fig. 8).

Bowie Seamount

Bowie Seamount, located 180 km west of the Queen Charlotte Islands (Fig. 1), rises to a water depth of only 25 m. The seamount was exposed above sea level during Pleistocene glacial lowstands, forming a wave-eroded upper terrace at 65 to 100 m depth that lacks glacially rafted material and includes wave-abraded and sorted lapilli and shell fragments (Herzer 1971). Volcanic peaks and fresh tephra deposits are emplaced on this terrace, and likely postdate the last glacial maximum. The bulk of the seamount is reversely magnetized (older than 0.7 Ma) but the main peak is normally magnetized, consistent with the presence of young, fresh lavas at the summit (Michkofsky 1969).

Lavas recovered from Bowie seamount range from alkalic basalt and basanite through hawaiite, mugearite and benmoreite (Engel et al. 1965; Herzer 1971; Cousens et al. 1985; Cousens 1988; Channing 2001; Fig. 4d). Lavas from the upper part of the edifice and from two dredge hauls on the southeastern flank are fresh, vesicular, glassy extrusive basalts. The basaltic rocks contain plagioclase (usually labradorite), olivine (Fo_{80}) and clinopyroxene phenocysts in a fine-grained groundmass enclosing interstitial glass. Hornblende is found in some of the summit samples, as are small gabbroic, plagioclase-magnetite, and ultramafic xenoliths that may represent disaggregated cumulates (Herzer 1971). The evolved samples are non-vesicular to finely vesicular, composed of flow-oriented plagioclase laths (An_{30-50}), minor olivine, magnetite and clinopyroxene, rare hornblende and apatite phenocrysts, and interstitial glass. A dredge haul from 1300–1600 m depth on the northeastern ridge flank of the volcano recovered more altered, ferromanganese-encrusted alkalic basalt and mugearite (Channing 2001), likely derived from the older, reversely magnetized part of the seamount.

Bowie glass and whole-rock analyses span a wide range of compositions, from basanite to near-trachyte, and cover the entire compositional range for the Pratt–Welker and other Gulf of Alaska seamount chains (Fig. 4d). Like TWVF lavas, volcanic rocks from Bowie seamount are enriched in alkali elements, have high K_2O/TiO_2 compared to northern Juan de Fuca Ridge basalts (Fig. 6d), and high Nb/Zr and La/Sm_{pmm} (Figs. 7d and 9). Bowie lavas show decreasing CaO/Al_2O_3 with decreasing Mg# (Fig. 5d), indicative of pyroxene or hornblende fractionation. All lavas from Bowie, from both the normally magnetized peak and the reversely magnetized flanks, have steep REE patterns from La through Dy, where the slope of the pattern flattens out to Lu, exactly like lavas from the TWVF. The REE patterns for the evolved lavas are parallel to those of the basaltic lavas, suggesting that they are related by fractional crystallization.

Bowie seamount lavas exhibit a remarkable range in isotopic compositions, particularly Pb isotopes, with $^{206}Pb/^{204}Pb$ ranging from 18.26 to 19.18 (Cousens, unpublished data, 2010; Cousens 1988; Fig. 8). In a $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ plot (Fig. 8a), there is some overlap with Juan de Fuca and Explorer Ridge MORB, and the TWVF alkalic lava field sits in the centre of the Bowie data field. The Pratt–Welker alkalic lavas cover the same isotopic range as Bowie seamount. Note that all NE Pacific volcanic rocks exhibit a common range in $^{143}Nd/^{144}Nd$ but a different range in $^{87}Sr/^{86}Sr$, although some overlap exists between lava groups (Fig. 8a). The Pb story is more complicated. Bowie and other Pratt–Welker alkalic lavas form a data array parallel to, but below, the Northern Hemisphere Reference Line (Hart 1984; Fig. 8b). There is very little overlap between Bowie and Pratt–Welker alkalic rocks and Juan de Fuca or Explorer MORB, but there is some overlap with near-ridge seamounts within or southeast of the Pratt–Welker chain.

Cousens (1988) pointed out that Bowie lavas, like those of the TWVF, are highly enriched in incompatible elements but have near-MORB-like isotopic compositions (Fig. 8). The incompatible element enrichment could reflect a recent metasomatic event in a depleted mantle source, and the small difference in $^{87}Sr/^{86}Sr$ (~0.0005) and Rb/Sr (0.05) between Juan de Fuca MORB and Bowie seamount basaltic rocks indicates that this event occurred during the last 500 Ma. Alternatively, Bowie seamount lavas could represent mixtures of magmas derived from a depleted mantle (DM) and a HIMU-like (high 'μ', where μ is the U/Pb ratio) mantle source, in which the percent melting of the DM source is low compared to that of the HIMU source; this model applies to alkalic lavas from the Pratt–Welker chain.

DISCUSSION: MANTLE SOURCES IN THE NORTHEASTERN PACIFIC

Traditionally, alkalic lavas in oceanic settings are associated with Hawaiian-type mantle plumes that tap enriched mantle sources (e.g. Greenough et al. 2005a, b), whereas incompatible-element-depleted tholeiitic lavas are ascribed to melting of the depleted upper mantle (e.g. Sun et al. 1979; Presnall and Hoover 1984). The outstanding characteristic of seafloor rocks from the NE Pacific is the intimate coexistence of depleted and enriched components in the upper mantle (summarized in Cousens 1996). Although the sample density is sparse (with the exception of new work on the Endeavour Segment; Woodcock et al. 2006; Harris et al. 2008), the accumulated data demonstrate the high degree of geochemical heterogeneity, and the small scale of this heterogeneity, in mid-ocean ridges and seamounts off Canada's west coast. Correlations between isotopic ratios, trace-element enrichment, and major-element characteristics indicate that the spectrum of lava compositions is the result of mixing of melts from the enriched mantle component with melts of DM. Two questions immediately arise: what is the enriched component (more than one?), and how is the enriched component introduced into the upper mantle?

Characteristics of the enriched component in NE Pacific volcanic rocks include high total alkalis, H_2O, K_2O/TiO_2, and K_2O/Na_2O, but low FeO and CaO/Al_2O_3. The alkalic lavas are enriched in the light-REE, large-ion lithophile (LIL), and high-field-strength (HFS) elements, but display the same middle- to heavy-REE abundances as tholeiitic lavas. The enriched component has slightly higher $^{87}Sr/^{86}Sr$ and commonly higher $^{206}Pb/^{204}Pb$, but lower $^{207}Pb/^{204}Pb$ at a given $^{206}Pb/^{204}Pb$, compared to tholeiitic lavas. The $^3He/^4He$ ratios are similar to normal MORB, but there is a general tendency for He isotope ratios to be lower in lavas with a greater contribution from the enriched mantle source. The La/Sm_{pmn} correlates positively with $^{87}Sr/^{86}Sr$ and negatively with $^{143}Nd/^{144}Nd$ in NE Pacific mid-ocean ridge lavas, but little correlation exists among the alkalic lavas alone (Fig. 9). Garnet does not appear to be a residual phase in the enriched mantle source, as the slope from the middle- to heavy-REE is too low (Allan et al. 1993). Therefore some other minor phase must be responsible for the enrichment in light REE and LIL elements.

The high water content of NE Pacific alkalic magmas suggests that one trace phase in the enriched mantle source is a hydrous phase, possibly phlogopite or amphibole. An alternative, namely influx of a hydrous fluid alone into a depleted mantle source, would likely not result in the simultaneous introduction of the LIL, HFS, and light REE (e.g. Eggler 1987) as observed in TWVF alkalic lavas (Cousens 1996). Melting of phlogopite-bearing peridotite produces potassic rather than sodic magmas, but melting of amphibole- and clinopyroxene-bearing lherzolite yields magmas with low CaO/Al_2O_3, variable Mg#s, and K_2O/Na_2O <1, characteristic of enriched lavas of the NE Pacific. Conversely, modelling of amphibole-bearing peridotite melts that have mixed with depleted upper mantle lherzolite melts can reproduce the trace element–isotope mixing trends evident in NE Pacific basalts (Allan et al. 1993; Cousens 1996).

The ridge topography and highly heterogeneous nature of MORB along the Endeavour and West Valley segments do not support a hotspot-type source for the enriched lavas (Karsten et al. 1990; Van Wagoner and Leybourne 1991). The shallow depth of the northern end of the SER may be consistent with a mantle plume, as is a possible gradation from mixed E- and N-MORB mantle at the shallowest depths to primarily N-MORB mantle farther south (Michael et al. 1989). No evidence for a thermal anomaly exists in the TWVF region, but geophysical characteristics of the Pratt–Welker chain are consistent with a mantle plume origin (Lambeck et al. 1984; Chapman et al. 1987; Harris and Chapman 1989, 1991; Nataf and VanDecar 1993). The proximity of the TWVF to the southern terminus of the Pratt–Welker chain suggests that the mushroom-shaped top of the plume may have expanded southeastward beneath the oceanic lithosphere as far as the TWVF but not as far as the Dellwood Knolls. Near-ridge seamounts are either similar chemically to the adjacent ridge lavas or are more primitive and highly depleted in incompatible elements; a plume source therefore seems unlikely (but see Davis and Karsten 1986).

In summary, with the exception of the Pratt–Welker seamounts (alkalic lavas only) and the Axial–Cobb–Eickelberg seamount chain to the south (Desonie and Duncan 1990; Rhodes et al. 1990), there is little evidence that mantle plumes are present in the NE Pacific. It is more likely that enriched components are widely distributed in the NE Pacific upper mantle, and that conditions during melting (plate boundary reorganization, cool thermal environments, incipient rifting, localized zones of melting) enhance melting of the enriched component relative to DM and produce lavas that define a mixing array between the two end members. As noted by Karsten et al. (1990), the Cobb Offset, a non-transform offset that bounds the south end of the Endeavour Segment (Fig. 1), is a geochemical boundary that separates the primarily N-MORB Gorda and southern Juan de Fuca spreading segments from the highly heterogeneous N- to E-MORB northern Juan de Fuca, Explorer and TWVF oceanic rifts. The Cobb Offset is, therefore, the southern boundary of a distinct northern Pacific enriched-mantle province that imparts a distinctive geochemical flavour to seafloor volcanic rocks off the coast of western Canada.

ACKNOWLEDGEMENTS
This manuscript presents the work of many seafloor researchers in the NE Pacific, and thanks are extended to all of them for collaborations and discussions over the past 28 years. Many thanks to Jarda Dostal for convincing me to take on this manuscript, to Mike Perfit and Brendan Murphy for supportive reviews, and to Georgia Pe-Piper for nurturing this igneous petrology series.

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Received June 2009
Accepted as revised January 2010