Lithosphere-asthenosphere mixing in a transform-dominated late Paleozoic backarc basin: Implications for northern Cordilleran crustal growth and assembly

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ABSTRACT

The Slide Mountain terrane is part of a North American Cordilleran-long backarc basinal assemblage that developed between the ensialic arc terranes (Yukon-Tanana and affiliated pericratonic terranes) and the North American craton in the middle to late Paleozoic. The Slide Mountain basin started to open in the Late Devonian, and spreading continued through the late Paleozoic in an oblique (transform-dominated) manner. Such that the pericratonic terranes were translated into southerly latitudes. The basin closed, also in an oblique manner, by the Early Triassic, resulting in the reaccretion of the Yukon-Tanana terrane to the northwestern Laurentian margin. Both the opening and closing likely involved hundreds to possibly thousands of kilometers of intra-oceanic and/or intra-arc strike-slip displacement, sinistral during the ocean’s Late Devonian to mid-Permian opening and dextral during its late Permian closing.

In southeastern Yukon, Canada, the Early Permian Slide Mountain terrane is dominated by maﬁc and ultramaﬁc volcanic and plutonic rocks of the Campbell Range Formation. These rocks are narrowly distributed, for over 300 km, on either side of the Jules Creek–Vangorda fault, a fault that separates Slide Mountain terrane from Yukon-Tanana terrane. The Campbell Range basaltic volcanic and high-level intrusive rocks have geochemical and isotopic signatures that vary systematically across the Jules Creek–Vangorda fault: ocean-island basalt (OIB) and enriched mid-ocean ridge basalt (E-MORB) suites with lower εNd, occur exclusively south of the fault, whereas north of the fault they have normal mid-ocean ridge basalt (N-MORB) and backarc basin basalt (BABB) signatures with higher εNd values. The εNd values are inversely correlated with Nb/Thpm and Nb/La pm, suggesting that the lower εNd values present in the E-MORB and OIB are mantle source features of these basalts and not due to continental crustal contamination. Isotopic and multi-element mixing calculations illustrate that the OIB-like basalts were derived primarily from enriched continental lithospheric mantle, whereas the N-MORB and BABB suites were sourced primarily from the upwelling backarc asthenospheric mantle; E-MORBs represent mixtures of depleted asthenospheric and enriched lithospheric mantle.

The geochemical and isotopic variations in the Campbell Range Formation across the Jules Creek–Vangorda fault is attributed to formation in different parts of an extending continental-backarc basin and then their subsequent juxtaposition by continued displacement along the fault.

Despite the juvenile isotopic signatures present in the Slide Mountain terrane, they occur as thin klippe atop rocks of recycled continental crustal afﬁnity, suggesting that they were likely only minor contributors to Cordilleran crustal growth.

INTRODUCTION

The North American Cordillera has been held up as a model for the importance of accretionary processes in continental crustal growth and evolution (e.g., Monger and Nokleberg, 1996; Monger, 1997). During its evolution, the dominant mechanism of addition of juvenile crust to the orogen is thought to have been through the accretion of juvenile terranes to its external parts (Samson et al., 1989; Samson and Patchett, 1991). In contrast, the extensive subduction-generated magmatic arcs that developed at different times and places along the Cordilleran continental margin are largely considered to be localities where continental crustal recycling is the predominant process during crustal evolution (e.g., Hildreth and Mooibath, 1988). Geological, geochemical, and isotopic data from both the craton and the terranes with a peri-Laurentian geological history (e.g., Yukon-Tanana terrane) illustrates that abundant rocks formed within magmatic arcs that involved signiﬁcant continental crustal recycling with little net addition of juvenile material to the continent (Creaser et al., 1997; Patchett and Gehrels, 1998; Piercey et al., 2003; Piercey et al., 2006).

During the late Paleozoic, the Cordilleran margin was characterized by a Sea of Japan-like backarc ocean (e.g., Slide Mountain terrane in Canada, Seventymile terrane in Alaska, and Golconda allochthon in western United States) separating a rifted continental arc fragment (Yukon-Tanana and aﬃliated pericratonic terranes) from the cratonic margin (Nelson, 1993; Creaser et al., 1999; Nelson et al., 2006). Continental margin backarc basins (e.g., Okinawa Trough and Sea of Japan) are settings where juvenile material is potentially added to continental margins by rifted margin magmatic processes (e.g., Poulet et al., 1995; Shinjo, 1999), and if suﬃciently long lived, and, importantly, preserved through subsequent tectonism, the remnants of backarc basins may represent a signiﬁcant addition of juvenile material to...
continental margins (e.g., Patchett and Gehrels, 1998; Creaser et al., 1999; Piercey et al., 2006; van Staal, 2007).

The Slide Mountain and equivalent oceanic terranes extend for much of the length of the North American Cordillera, occurring in thrust sheets and klippe between the pericratonic late Paleozoic continental arc terranes and the North American continental margin (Figs. 1 and 2). The Slide Mountain ocean initially opened in the Late Devonian (~365 Ma) (Nelson, 1993), coeval with the onset of arc magmatism in the pericratonic terranes, and closed in the Late Permian by its westward subduction beneath the pericratonic terranes (Mortensen, 1992b; Creaser et al., 1999; Nelson et al., 2006; Piercey et al., 2006). Although much of the terrane was subducted in the Late Permian, some of the inboard portion of the terrane is preserved in British Columbia in the southern Canadian Cordillera and lies atop rocks of the North American craton (Keen Creek assemblage of Klepacki, 1985). Some of the outboard portions of the terrane are in stratigraphic and structural contact with rocks of the pericratonic Yukon-Tanana terrane in the northern Canadian Cordillera (Murphy et al., 2006), whereas some of the more juvenile portions of the terrane that formed in intra-oceanic settings are locally preserved throughout British Columbia and Yukon (Nelson, 1993; Ferri, 1997; Lapierre et al., 2003).

Mafic magmatism occurred intermittently in the Slide Mountain terrane. The oldest mafic rocks in the terrane are Late Devonian to Early Mississippian in age (Klepacki, 1985; Struik and Orchard, 1985; Nelson, 1993). Little record of Carboniferous magmatism is preserved (e.g., Nelson, 1993); rocks of this age may have been largely subducted in the Late Permian. In the Late Pennsylvanian to Early Permian, however, the terrane exhibits a significant flare-up of magmatic activity from the southern Canadian Cordillera to Alaska (e.g., Klepacki, 1985; Struik and Orchard, 1985; Nelson, 1993; Roback et al., 1994; Ferri, 1997; Lapierre et al., 2003). Lower Permian basalt is the defining constituent of the Campbell Range Formation in southeastern Yukon (Mortensen, 1992a, 1992b; Plint and Gordon, 1997; Murphy and Piercey, 1999; Murphy et al., 2006). The geological, geochemical, and isotopic characteristics of the Campbell Range Formation are the subject of this paper.

Geochemical data for basalt of Slide Mountain terrane have been reported by Roback et al. (1994), Smith and Lambert (1995), Plint and Gordon (1997), Patchett and Gehrels (1998), Creaser et al. (1999), Dusel-Bacon and colleagues (Seventymile terrane, Dusel-Bacon and Cooper, 1999; Dusel-Bacon et al., 2006), Lapierre et al. (2003), Pigage (2004), and Piercey et al. (2006). As might be expected, most samples are normal mid-ocean ridge basalts (N-MORBs) with juvenile isotopic signatures (Piercey et al., 2006). However, enriched mid-ocean ridge basalts (E-MORBs) and rocks with geochemical signatures indistinguishable from those of modern plume-related environments have been documented in widely spaced localities (ocean-island basalts [OIBs]) (Lapierre et al., 2003; Piercey et al., 2006). These enriched
signatures have led Lapierre et al. (2003) to infer widespread influence of mantle plumes in the generation of Slide Mountain terrane basalts.

One little discussed aspect of the evolution of the paired arc (Yukon-Tanana and other pericratonic terranes)–backarc ocean (Slide Mountain terrane) system is the requirement for substantial latitudinal displacement to be embedded within the system, as strike-slip faults within the arc and/or as oceanic transform faults. Numerous lines of evidence suggest that Yukon-Tanana terrane, the largest pericratonic arc terrane, was a part of northwestern Laurentia before the onset of Late Devonian backarc rifting (Colpron et al., 2006, 2007; Nelson et al., 2006; Piercey and Colpron, 2009); however, by the mid-Permian, it and companion terranes were at sufficiently southerly latitudes for limestone
containing the McCloud fusulinid fauna to have been deposited on them (Miller, 1988; Stevens, 1995; Belasky et al., 2002; Nelson et al., 2006). Because species of the McCloud fauna occur on the craton only as far north as the latitude of Texas (Ross, 1969), there is an implication that the Slide Mountain ocean had significant strike-slip displacement, before final re-attachment to northwestern Laurentia by the Triassic (Bermanek et al., 2010). At present, however, the details of this displacement history are not completely understood.

In this paper, we document the geological characteristics and setting of the Campbell Range Formation of Slide Mountain terrane in southeastern Yukon and present new geochemical and isotopic data from the terrane. We use these data to support an interpretation that the range of geochemical signatures that we and others have documented has more to do with the compositional diversity of the source regions for the basalt rather than the influence of an active mantle plume. We argue that the plume-like attributes of the basalts were likely inherited from a lithospheric mantle. Furthermore, we attribute the formation and juxtaposition of the different geochemical domains to an origin along a “leaky” transform fault, the Jules Creek–Vangorda fault. The Jules Creek–Vangorda fault is inferred to be one of a system of sinistral strike-slip faults along which the plate containing the ensialic arc terrane was transported to more southerly latitudes in which the McCloud fauna existed.

Our study points out that although the record of the continental margin and pericratonic ensialic arcs such as represented by Yukon-Tanana terrane is predominantly one of continental arc magmatism and attendant recycling of ancient crustal material (Mortensen, 1992b; Piercey et al., 2006; Piercey and Colpron, 2009), there are juvenile backarc basin rocks within the Slide Mountain terrane. We will evaluate what role this juvenile magmatism has played in Cordilleran crustal growth during the late Paleozoic and whether or not it has been an important contributor to net crustal growth of this orogen.

**SLIDE MOUNTAIN TERRANE IN SOUTHEASTERN YUKON**

In southeastern Yukon, the Slide Mountain terrane occurs primarily in a narrow, elongate and arcuate belt extending for over 300 km between Faro and the British Columbia–Yukon border south of Watson Lake (Figs. 2–4). It consists of a Carboniferous sediment-dominated assemblage (Fortin Creek group of Murphy et al., 2006; Mount Aho and Rose Mountain formations of Pigage, 2004) and a Lower Permian sequence of basalt, chert, and argillite, the Campbell Range Formation. Mafic and ultramafic intrusions, probably comagmatic with the basalt, are also significant components of the terrane.

The Fortin Creek group is composed primarily of Carboniferous to Lower Permian carbonaceous phylite, chert, chert-pebble conglomerate, lesser quartzofeldspathic wacke and limestone, and rare felsic and mafic metavolcanic rocks. Metavolcanic rocks have alkalic (felsic) and N-MORB (mafic) affinities suggesting a rift setting (Murphy et al., 2006). The Fortin Creek group is increasingly more deformed to the north, where it is stratigraphically overlain by a conglomerate containing clasts of the highly strained Fortin Creek group. The precise age of this conglomerate at this locality is not known, but it is Middle Triassic or younger (Bermanek, 2009). The zone of intense deformation in the Fortin Creek group therefore must be Late Permain to Early Triassic in age, and is inferred to be part of the subduction complex at which the remainder of the Slide Mountain ocean was consumed.

The Campbell Range Formation consists of weakly deformed and relatively well preserved basalt and chert. Basalt comprises black to dark-grey massive and pillowed lava flows, interflow and interpillow hyaloclastite, and brecciated (fragmental varieties (Murphy and Piercey, 1999; Murphy et al., 2002). Epidote-quartz-hematite alteration is common. Primary igneous mineralogy is generally well preserved with phenocrysts and microphenocrysts of olivine, clinopyroxene, and plagioclase still present, even in proximity to hydrothermal mineralization (e.g., Ice Deposit, Mann and Mortensen, 2006). Locally, primary igneous minerals are pseudomorphed by very low grade secondary minerals.

Chert, argillite, and lesser limestone are locally important in the Campbell Range Formation. Maroon, pink, and green chert commonly form ribbons 10–30 cm in thickness and are typically interlayered with argillite (Murphy et al., 2002). These sedimentary members are often foliated and folded to a greater extent than the surrounding basaltic rocks (Murphy et al., 2002).

Mafic and ultramafic plutonic rocks are spatially associated with the Campbell Range Formation. These comprise gabbro, leucogabbro, pyroxenite, and variably serpentinitized peridotite, forming bodies ranging in size from a few hundred square meters to over 2 km$^2$ (Figs. 2 and 3; Murphy et al., 2002, 2006). The spatial association of the mafic and ultramafic plutonic rocks with the Campbell Range basalt implies a genetic relationship, and they are likely the coeval subvolcanic roots to the basalt (Figs. 2 and 3; Murphy et al., 2002, 2006).

The Campbell Range Formation is constrained by both fossil and radiometric ages to be Early Permian. In the Finlayson Lake district, chert in the lower Campbell Range Formation has yielded early Pennsylvanian to Early Permian radiolarians (Harms in Plint and Gordon, 1997), yet basalt locally overlies the Money Creek Formation, a unit that unconformably overlies limestone with Late Pennsylvanian to Early Permian fauna (Figs. 2–4). On strike to the west near Faro (Fig. 2), chert of the Campbell Range Formation contains Early Permian (Asselian–Sakmarian) radiolarians (Pigage, 2004). Two U-Pb zircon ages of ~274 Ma (Early Permian) have been obtained from leucogabbro that crosscuts the Campbell Range basalt (Mortensen, 1992a; Murphy et al., 2006).

The Slide Mountain terrane in southeastern Yukon lies primarily between the North American continental margin sequence and the Yukon-Tanana terrane, an ensialic late Paleozoic arc terrane with a pre–Late Devonian basement of inferred northwestern North American affinity (Figs. 2–4; Colpron et al., 2006; Nelson et al., 2006; Piercey et al., 2006; Piercey and Colpron, 2009). Along their north and eastern contacts, the Slide Mountain and Yukon-Tanana terrane lies in fault contact with North American continental margin rocks along the Jura-Cretaceous Inconnu thrust fault (Figs. 2 and 3; Murphy et al., 2006). To the south and west, the relationship between rocks of Slide Mountain and Yukon-Tanana terranes is more complex. The Jules Creek–Vangorda fault separates the Devonian-Carboniferous rocks of Slide Mountain terrane (Fortin Creek group and equivalent rocks) from coeval rocks of the Yukon-Tanana terrane (Money Creek Formation and Wolverine Lake group); however, the basalt- and chert-dominated lower Permian part of Slide Mountain terrane, the Campbell Range Formation, lies in depositional contact on older rocks on both sides of the fault (Figs. 2 and 3; Murphy et al., 2006). The unfaulted nature of the contact between the Campbell Range Formation of Slide Mountain terrane and rocks of Yukon-Tanana terrane is prima facie evidence that the two terranes evolved together in the same geodynamic setting in the Early Permian. The Early Permian rocks of the Campbell Range Formation are coeval with arc volcanic rocks of the Klinkit Group located south of the Tintina fault near the British Columbia–Yukon border (Fig. 1; Simard et al., 2003).

The Jules Creek–Vangorda fault is an important structure that contains significant Campbell Range basalt and, importantly, affiliated plutonic rocks, within only a few kilometers of the
Figure 3 (legend on following page). Geological map of the Campbell Range Formation and associated rocks of the Finlayson Lake region, Yukon. Map modified from Murphy et al. (2006).
fault for a strike length of over 300 km. Furthermore, the Campbell Range Formation occurs at about the same elevation on both sides of the fault, implying a strike-slip origin with sinistral motion but with a likely dextral reactivation in the late Paleozoic (see discussion).

**GEOCHEMISTRY AND RADIOGENIC ISOTOPES**

**Sampling and Analytical Methods**

Samples of basalt from the Campbell Range Formation and coeval subvolcanic intrusions were collected during regional mapping in the 1998 and 2001 field seasons. Samples from the 1998 field season were analyzed at the Geological Survey of Canada, Ottawa, Canada (Table 1). Samples were analyzed using fused bead X-ray fluorescence (XRF) for most of the major elements. Water ($H_2O_T$) and $CO_2T$ were analyzed by infrared spectroscopy, and FeO was analyzed by modified Wilson titration. Trace elements were analyzed by combined inductively coupled plasma–emission spectrometry (ICP-ES: Ba, La, Pb, Sc, Sr, V, Y, and Yb) and mass spectrometry (ICP-MS: remaining rare-earth elements [REE], Cs, Rb, Th, U, Ga, Hf, and Ta). Analytical precision calculated from repeat analyses of internal basaltic reference materials (Piercey et al., 2004) is given as percent relative standard deviation (%RSD = 100*standard deviation/mean), and yielded values of: 0.43%–6.52% for major elements, 0.72%–8.80% for the transition elements (V, Ni, Cr, Co), 2.21%–5.92% for the high field strength elements (HFSEs) (Nb, Zr, Hf, Y, Sc, and Ga), 2.35%–6.96% for the low field strength elements (LFSEs) (Cs, Rb, Th, and U), but slightly higher for Ba and Sr (1.49%–15.75%), and 2.15%–6.47% for the REEs.

Samples from the 2001 field season were analyzed by XRF for their major elements (on fused discs), selected trace elements (on pressed pellets: Ni, Co, Cr, V, Cu, Pb, Zn, As, Ga, Sr, Rb, and Ba), and loss on ignition (LOI) at the University of Western Ontario (UWO), London, Ontario, Canada, following the methods outlined in Wu (1984), Mata et al. (1998), and Young (2002). The remaining trace elements and REEs were analyzed by ICP-ES (S, Sc, Mo, W, Cd, Be, and Li) and ICP-MS (Nb, Ta, Zr, Hf, Y, Cs, Th, U, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu) at the Ontario Geoscience Laboratories, Sudbury, Ontario, Canada, using a closed-beaker multi-acid digestion prior to analysis (Burnham et al., 2002; Burnham and Schwayer, 2004). Precision for XRF analysis, based on replicate analyses of reference materials, is less than ±2% for major elements (±5% for PO$_4$ and Na$_2$O) and ±5%–10% for trace elements (Wu, 1984; Mata et al., 1998; Young, 2002). Accuracy for XRF analyses based on analyses of U.S. Geological Survey

**LEGEND**

**SLIDE MOUNTAIN TERRANE**

**LAYERED ROCKS**

- **Lower to Middle Permian**
  - Gatehouse Formation
  - limestone and quartzite

- **Lower Permian**
  - Campbell Range Formation
  - basalt and varicoloured chert

**INTRUSIVE ROCKS**

- **Early Permian**
  - ultramafic and mafic intrusions

**YUKON-TANANA TERRANE**

**LAYERED ROCKS**

- **Lower Permian**
  - Money Creek Formation
  - dark phylite and sandstone, chert, chert-pebble conglomerate, diamicrite

- **Mid-Pennsylvanian to Lower Permian**
  - Finlayson Creek limestone
  - massive bioclastic limestone

- **Upper Mississippian to mid-Pennsylvanian**
  - undifferentiated White Lake and King Arctic formations
  - green and pink chert, limestone, sandstone, conglomerate, mafic metavolcanic rocks

- **Upper Mississippian**
  - Whitefish limestone
  - massive bioclastic limestone

- **Lower Mississippian**
  - Tuchita River Formation
  - intermediate, felsic and mafic volcanic rocks, sandstone, chert, limestone

- **WOLVERINE LAKE GROUP**
  - undifferentiated mafic and felsic volcanic rocks and dark clastic rocks

- **Upper Devonian to Lower Mississippian**
  - Cleaver Lake Formation
  - calc-alkaline basalt, rhyolite, chert and volcanic-derived sandstone

- **GRASS LAKES GROUP**
  - felsic to intermediate metavolcanic rocks and carbonaceous phylite

- **GRASS LAKES PLUTONIC SUITE**
  - granite, quartz monzonite, granodiorite

- **Lower to Middle Permian**
  - Finlayson Creek limestone
  - massive bioclastic limestone

- **Upper Mississippian**
  - Tuchita River Formation
  - intermediate, felsic and mafic volcanic rocks, sandstone, chert, limestone

- **GRASS LAKES PLUTONIC SUITE**
  - granite, quartz monzonite, augen granite

- **Upper Devonian to Lower Mississippian**
  - Cleaver Lake Formation
  - calc-alkaline basalt, rhyolite, chert and volcanic-derived sandstone

- **GRASS LAKES GROUP**
  - felsic to intermediate metavolcanic rocks and carbonaceous phylite

- **Upper Devonian to Lower Mississippian**
  - Cleaver Lake Formation
  - calc-alkaline basalt, rhyolite, chert and volcanic-derived sandstone

- **Pre-Upper Devonian**
  - North River Formation
  - quartzose metaglastic rocks, marble and non-carbonaceous pelitic schist

- **Late Devonian to Early Mississippian**
  - Simpsons Range Plutonic Suite
  - granite, quartz monzonite, granodiorite

**INTRUSIVE ROCKS**

- **GRASS LAKES PLUTONIC SUITE**
  - granite, quartz monzonite, augen granite

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- **Pre-Upper Devonian**
  - North River Formation
  - quartzose metaglastic rocks, marble and non-carbonaceous pelitic schist

**POST - YTT / SMT AMALGAMATION**

**NORTH AMERICAN CONTINENTAL MARGIN**

- **Triassic**
  - dark shale, siltstone and limestone

- **Paleozoic**
  - undifferentiated formations of Selwyn Basin, McEvoy Platform, Earn Group and Mt. Christie Formation

- **YUKON-TANANA TERRANE**
  - undifferentiated mafic and felsic volcanic rocks, limestone

- **SLIDE MOUNTAIN TERRANE**
  - ultramafic and mafic intrusions

**Figure 3 (legend).**
Figure 4. Stratigraphic sections for the Finlayson Lake region Yukon with relationship of the Campbell Range Formation to other rocks of the Yukon-Tanana terrane. From Murphy et al. (2006).
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Lithosphere-asthenosphere mixing, northern Cordilleran crustal growth and assembly

Standard basalt BHVO-1 as an unknown is typically less than ±10%, with many elements ±5% of recommended values (Mata et al., 1998). Precision and accuracy for trace element analyses by ICP-ES and ICP-MS at the Ontario Geo- science Laboratories is <7% RSD for precision, and below 8% RSD for accuracy (except Nb = 9.8% RSD and Pr = 12.3% RSD; Lightfoot and Farrow, 2002; Burnham and Schweyer, 2004). The geochemical data are presented in Table 1; key major and trace element ratios are presented in Table 2.

Thirteen samples were analyzed for Sm-Nd isotopic compositions at the University of Alberta Radiogenic Isotope Facility. Samples were analyzed by thermal ionization mass spectrometry (TIMS) and multicollector–inductively coupled plasma–mass spectrometry (MC–ICP-MS), following the methods of Creaser et al. (1997) and Unterschutz et al. (2002). Values for the Geological Survey of Japan (GSJ) Shin Etsu Nd isotope standard were calculated using an age of 274 Ma, the approximate age of the rocks from the Campbell Range Formation (Mortensen, 1992a; Murphy et al., 2006). Values used for the chondrite uniform reservoir (CHUR) to obtain initial 143Nd/144Nd and εNd values are calculated from the model 147Sm/144Nd and 146Nd/144Nd values.
ever, in some cases samples do exhibit replace-
veins and visible hydrothermal alteration; how-
made to sample the freshest samples without

Element Mobility

TABLE 1. WHOLE-ROCK GEOCHEMICAL DATA FOR BASALTIC ROCKS FROM THE CAMPBELL RANGE FORMATION (continued)

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Note: All samples are from Universal Transverse Mercator (UTM) Zone 9, North American Datum 1983. Abbreviations: DB—diabase; MB—massive basalt; MG—massive greenstone; N-MORB—normal mid-ocean ridge basalt; OIB—ocean-island basalt; PB—pillow basalt; N—north of Jules Creek-Vangorda Fault; S—south of Jules Creek-Vangorda Fault.

of 0.2137 and 0.513163, respectively (Goldstein et al., 1984). Results for the Nd isotopic analy-

Alteration-Metamorphism and Element Mobility

During the course of this study, samples were selected to provide the best possible representa-
tion of samples for the regional distribution of the Campbell Range Formation. Attempts were made to sample the freshest samples without veins and visible hydrothermal alteration; how-
ever, in some cases samples do exhibit replace-
morphism of primary minerals by secondary hydro-
thermal and/or metamorphic assemblages (descriptions of the Campbell Range basaltas above). The presence of secondary chlorite-
epidote-sericite ± minor carbonate alteration and metamorphic minerals implies that some of the Campbell Range belt basaltas have experienced grenschist-grade metamorphism.

These conditions imply that most of the major elements, except Al2O3, TiO2, and P2O5 (e.g.,
Lesher et al., 1986; MacLean, 1990; Jenner,
1996). To semiquantitatively test whether the lat-	er elements have remained immobile, we have plotted a selection of elements and key element ratios against the Al2O3/Na2O alteration index (Fig. 5; Spitz and Darling, 1978). From Figure 5, no systematic relationship between these element ratios and the degree of alteration and meta-
morphism is apparent, suggesting that they have remained immobile during these processes.
Analytical Results

The basaltic rocks from the Campbell Range Formation can be separated into four suites based on their immobile incompatible-element systematics, and patterns on primitive mantle- and chondrite-normalized trace element plots (Figs. 6–10). The following subsections outline the geochemical and Nd-isotopic attributes of each suite.

OIB Suite

Rocks of the OIB suite have alkalic basaltic affinities with basaltic Zr/TiO2 values and Nb/Y >0.7 (Fig. 6A), broadly coincident with their SiO2 contents (Table 1). The suite has relatively elevated TiO2 contents (1.51%–2.19%; Table 1; Fig. 6), and low Al2O3/TiO2 ratios (7–9), similar to modern E-MORB and OIB (Al2O3/TiO2 ~5–9.5; Fig. 6; Sun and McDonough, 1989). The OIB suite contains higher HFSE and REE.

### TABLE 2. KEY MAJOR AND TRACE ELEMENT RATIOS FOR BASALTIC ROCKS FROM THE CAMPBELL RANGE FORMATION

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<th>Ti/Zr</th>
<th>Nb/La</th>
<th>Nb/Th</th>
<th>Nb/Y</th>
<th>Nb/Yb</th>
<th>Zr/Y</th>
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<th>Hf/Sm</th>
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Note: ΔNb = log (Nb/Y) + 1.74 – 1.92 log (Zr/Y) (Fitton et al., 1997). Abbreviations: BABB—backarc basin basalt; DB—diabase; E-MORB—enriched mid-ocean ridge basalt; MB—massive basalt; MG—massive greenstone; N-MORB—normal mid-ocean ridge basalt; OIB—ocean-island basalt; PB—pillow basalt; PM—normalized to primitive mantle values of Sun and McDonough (1989); N—north of Jules Creek-Vangorda Fault; S—south of Jules Creek-Vangorda Fault.

### TABLE 3. SAMARIUM-NEODYMIUM ISOTOPE GEOCHEMICAL DATA FOR SELECT BASALTIC ROCKS FROM THE CAMPBELL RANGE FORMATION

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Note: Abbreviations: BABB—backarc basin basalt; E-MORB—enriched mid-ocean ridge basalt; MB—massive basalt; MG—massive greenstone; N-MORB—normal mid-ocean ridge basalt; OIB—ocean-island basalt; PB—pillow basalt; PM—normalized to primitive mantle values of Sun and McDonough (1989); N—north of Jules Creek-Vangorda Fault; S—south of Jules Creek-Vangorda Fault.
Figure 5. Key trace elements and element ratios against the Spitz-Darling (Spitz and Darling, 1978) Al$_2$O$_3$/Na$_2$O alteration index. The lack of correlation between the various elements and ratios with the alteration index suggests that the variance in these elements is independent of alteration and thus that they were immobile during alteration and metamorphism.
contents than other suites in the Campbell Range Formation (Table 1). The elevated HFSE and REE contents of the basalts are illustrated by their steep primitive mantle–normalized trace element profiles (Fig. 7A), which are characterized by strong light rare-earth element (LREE) enrichment (La/Sm = 3.9–5.2), heavy rare-earth element (HREE) depletion (Sm/Yb = 1.1–1.7), and distinctive positive Nb anomalies relative to Th (Nb/Th = 1.6–1.7) and La (Nb/La = 1.8–2.0). The OIB suite has distinctive incompatible-element ratios that point to derivation from enriched, OIB-like, mantle sources. Furthermore, they have lower εNd values compared to other suites in the Campbell Range Formation (Fig. 8; Table 3). In comparison to the other suites in the Campbell Range Formation, they have the lowest Zr/Nb and Hf/Sm ratios and highest Zr/Y, Nb/Y, Zr/Yb, Nb/Yb, Ti/Yb, La/Sm, Sm/Yb, Nb/La and Nb/Th values (Figs. 8–10; Table 2); furthermore, they have ΔNb > 0, pointing to derivation from an enriched source (Fig. 8; Table 2; Fitton et al., 1997; Baksi, 2001; Condie, 2003). The Ti/Y ratios of the OIB-suite rocks are also consistent with the OIB-like attributes of these rocks, and they lie within the field for nonarc, alkalic rocks on the Ti-Y plot of Shervais (1982) (Fig. 9).

Isotopically, the OIB suite has the lowest εNd values in the Campbell Range Formation with two samples yielding εNd = +2.2 and +3.6 (Table 3). These values are much lower than the depleted mantle (DM) reservoir at 275 Ma, which has εNd = +9.5 (Fig. 10), and suggest that the OIB suite has been derived from a source, or has had influence from a reservoir, with a history of LREE enrichment (i.e., Sm/Nd < CHUR; Goldstein et al., 1984; DePaolo, 1988). Furthermore, the OIB suite has sufficiently low Sm/Nd ratios (Sm/Nd < 0.3), such that the rocks may have meaningful depleted mantle model ages (TDM), and yields TDM ages of 0.79 Ga and 0.91 Ga (Table 3).

**N-MORB Suite**

Rocks having N-MORB affinities have basaltic Zr/TiO2 values and subalkalic Nb/Y values (Nb/Y < 0.7; Fig. 6). They have the lowest HFSE and REE concentrations (Table 1) and the lowest TiO2 contents (TiO2 = 0.94%–3.23%, avg. = 1.51%) of all the Campbell Range Formation samples, with Al2O3/TiO2 values (Al2O3/TiO2 = 4–15, avg. = 11) akin to modern N-MORB (Al2O3/TiO2 ~11; Fig. 6; Sun and McDonough, 1989). The low HFSE and REE concentrations are illustrated by the smooth but LREE-depleted (La/Sm = 0.7–1.2) primitive mantle–normalized trace element profiles (Figs. 7C and 7D). Furthermore, the N-MORB suite is undepleted in HREE (Sm/Yb = 0.7–1.2) and yields TDM ages of 0.79 Ga and 0.91 Ga (Table 3).

**Figure 6.** Niobium/Y-Zr/TiO2 discrimination diagram (A) of Winchester and Floyd (1977) as modified by Pearce (1996); and Al2O3/TiO2-TiO2 plot (B). Mid-ocean ridge basalt (MORB), enriched mid-ocean ridge basalt (E-MORB), and ocean-island basalt (OIB) data from Sun and McDonough (1989). BABB—backarc basin basalt; N-MORB—normal mid-ocean ridge basalt.
Figure 7. Primitive-mantle–normalized plots of (A) ocean-island basalt (OIB); (B) enriched mid-ocean ridge basalt (E-MORB); (C) normal mid-ocean ridge basalt (N-MORB) south of the Jules Creek fault; (D) N-MORB north of the Jules Creek fault; and (E) backarc basin basalt (BABB) suite rocks with modern analogues on each plot for comparison. Primitive-mantle normalization values from Sun and McDonough (1989). Modern N-MORB, E-MORB, and OIB from Sun and McDonough (1989) and backarc basin basalt (BABB) from Ewart et al. (1994).
Figure 8. Incompatible trace element plots illustrating that the different suites of the Campbell Range Formation lie on a mixing line with varying contributions from an enriched, ocean-island basalt (OIB)–like end member and a depleted, normal–mid-ocean ridge basalt (N-MORB)–like end member. Diagrams include: (A) Ti/Yb\textsubscript{pm}-Nb/Yb\textsubscript{pm} (pm—primitive-mantle normalized) and Zr/Yb\textsubscript{pm}-Nb/Yb\textsubscript{pm} (B) (after Pearce and Peate, 1995); (C) Zr/Nb-La/Sm; (D) Zr/Nb-Sm/Yb; (E) Hf/Sm-ΔNb; and (F) Zr/Y-Nb/Y plot. Plot of ΔNb in (F) from Fitton et al. (1997) and Baksi (2001), where ΔNb = 1.74 + 0.92 log(Y/Zr) + log(Nb/Zr). BABB—backarc basin basalt; E-MORB—enriched mid-ocean ridge basalt.
Figure 9. Discrimination diagram of Ti/V from Shervais (1982) illustrating the backarc basin nature of the rocks from the Campbell Range belt. BABB—backarc basin basalt; E-MORB—enriched mid-ocean ridge basalt; N-MORB—normal mid-ocean ridge basalt; OIB—ocean-island basalt.

Zr/Y, Nb/Yb, Nb/La, Nb/Th, and Nb/La and Nb/Th variations (Fig. 8; Table 2). Furthermore, they have δNb < 0, pointing to derivation from a depleted source (Fig. 8; Table 2; Fitton et al., 1997; Baksi, 2001; Condie, 2003). The low Ti/V ratios of the N-MORB suite are consistent with formation within a nonarc (or backarc) geodynamic environment (Fig. 9; Table 2).

The δNd values of all basalt samples in the Campbell Range Formation with samples ranging from +6.1 to +8.9, with the exception of P98-78, which has δNd = -4.0 (Table 3; Fig. 10). There are differences, albeit slight, between the samples north and south of the Jules Creek fault, with samples north of the fault having δNd = +7.5 to +8.9, whereas those south of the fault range from δNd = -4.0 to +7.1 (Table 3). With the exception of sample P98-78, this range is similar to slightly less than the DM reservoir at this time (δNd = +9.5; Goldstein et al., 1984; DePaolo, 1988) and suggests derivation from a reservoir with a history of LREE depletion (i.e., Sm/Nd > CHUR; Goldstein et al., 1984; DePaolo, 1988).

E-MORB Suite

Samples of the E-MORB suite have basaltic affinities with low Zr/TiO₂ and subalkalic Nb/Y values (Nb/Y < 0.7; Fig. 6). The E-MORB suite has TiO₂ contents (1.12%–2.00%, avg. = 1.57%) intermediate between the N-MORB and OIB suite, with Al₂O₃/TiO₂ (7–14, avg. 9.5) ratios similar to E-MORB (Al₂O₃/TiO₂ = 9.5; Fig. 6) (Sun and McDonough, 1989). The E-MORB suite has primitive mantle-normalized patterns that are intermediate between the N-MORB and OIB suites, with relatively flat to enriched LREE (La/Sm = 1.4–3.0; Table 2), weakly positive Nb anomalies relative to Th (Nb/Th = 1.6–1.9; Table 2) and La (Nb/La = 1.2–1.5; Table 2), and relatively flat HREE (Sm/Yb = 0.6–1.0; Table 2; Figs. 7 and 8). The δNd values of the E-MORB suite lie in an intermediate position in the Campbell Range Formation array between the OIB and N-MORB end members (Fig. 8). The intermediate position of the E-MORB suite is reflected by incompatible-element ratios (Zr/Nb, Hf/Sr, Zr/Y, Nb/Y, Zr/Yb, Nb/Yb, Ti/Yb, La/Sr, Sm/Yb, Nb/La, and Nb/Th) that are intermediate between N-MORB and OIB (Fig. 8; Table 2). Notable, however, is the E-MORB suite still has δNd values > 0, suggesting a significant contribution from enriched mantle sources (Fig. 7; Table 2; Fitton et al., 1997; Baksi, 2001; Condie, 2003). Like the N-MORB and OIB suites, the Ti/V ratios of the E-MORB suite imply formation within a nonarc (or backarc) geodynamic environment (Fig. 9; Table 2).

Samples of the E-MORB suite have intermediate δNd values with δNd = +3.3 to +6.0, which is slightly lower than the DM reservoir at this time (δNd = +9.5; Goldstein et al., 1984; DePaolo, 1988), and intermediate between the N-MORB and OIB suites (Table 3; Fig. 10).

BABB Suite

The BABB suite is identical to the N-MORB suite, but with weakly developed negative Nb and Ti anomalies. It exhibits low TiO₂ content (0.6–1.2 wt%) with Al₂O₃/TiO₂ values slightly higher than the N-MORB suite (13–27; Fig. 6; Tables 1 and 2), a feature common to BABB suite rocks (e.g., Woodhead et al., 1993; Stolper and Newman, 1994; Hawkins, 1995; Newman et al., 2000; Taylor and Martinez, 2003). The primitive mantle–normalized trace element patterns of the BABB suite differ from the N-MORB suite by having a distinctive negative Nb anomaly relative to Th and La (Nb/Th = 0.3–0.5; Nb/La = -0.3; Table 2; Fig. 7). This anomaly is the “subduction signature” present in most modern BABB suites (e.g., Fryer et al., 1990; Hawkins, 1995; Taylor and Martinez, 2003). Akin to the MORB suite, the BABB suite lies toward the depleted end of the Campbell Range Formation array with high Zr/Nb and Hf/Sr ratios, low Zr/Y, Nb/Yb, Nb/Y, Nb/La, La/Sr, and Sm/Yb ratios, and Nb/La and Nb/Th values, and δNb < 0, all pointing to derivation from a depleted mantle source region (Fig. 7; Table 2; Fitton et al., 1997; Baksi, 2001; Condie, 2003). The Ti-V systematics of the BABB suite are similar to that of the N-MORB suite, but the BABB suite straddles the arc-nonarc boundary on the Ti-V plot (Fig. 9), similar to their transitional Th-Nb-La systematics (Fig. 7) and consistent with derivation in a backarc basin geodynamic setting.

The δNd isotopic signature of the BABB suite is virtually identical to that of the N-MORB suite with δNd = +6.4 and +8.6 (Fig. 10; Table 3), implying derivation from a similar depleted mantle source, but with a weak subduction component added to that depleted source (i.e., lower Nb/Th relative to N-MORB; e.g., Fryer et al., 1990; Hawkins, 1995; Taylor and Martinez, 2003).

GEOGRAPHIC DISTRIBUTION OF GEOCHEMICAL SUITES

The different geochemical suites in the Campbell Range Formation show a systematic pattern with respect to the Jules Creek–Vangorda fault, marking the fault as an important lithospheric break and supporting its interpretation as a significant transcurrent fault. North of the fault, where the formation is stratigraphically underlain by basinal clastic rocks and chert of the Fortin Creek group, the rocks are N-MORB.
to BABB in affinity, with no samples having incompatible-element–enriched signatures (i.e., no E-MORB or OIB; Fig. 11). South of the fault, the Campbell Range Formation is stratigraphically underlain by rocks of the ensialic Yukon-Tanana terrane, and E-MORB signatures predominate, with lesser OIB and N-MORB signatures (Fig. 11). Neodymium isotopic signatures also vary systematically across the fault. South of the fault, the rocks have $\varepsilon_{Nd} = +2.2$ to +3.6 for the OIB suite and $\varepsilon_{Nd} = +3.3$ to +6.0 for the E-MORB suite, whereas N-MORBs have values ranging from $\varepsilon_{Nd} = -4.0$ to +7.1 (Table 3; Fig. 11). The N-MORB and BABB suites north of the fault have $\varepsilon_{Nd} = +7.5$ to +8.9 and $\varepsilon_{Nd} = +6.4$ to +8.6, respectively, values that overlap those south of the fault but fall toward higher $\varepsilon_{Nd}$ (Fig. 11).

The stratigraphic relationships between the various suites cannot be determined owing to limitations of outcrop exposure and lack of stratigraphic markers. South of the Jules Creek–Vangorda fault, samples of E-MORB, OIB, and N-MORB occur in relatively close proximity, suggesting that these samples are stratigraphically interlayered (Fig. 11). A similar case can be made for the samples north of the fault, as samples of both N-MORB and BABB character are spatially associated with one another, and the BABB could be equivalent to the N-MORB suite but with a greater subduction component (Fig. 11) (Hawkins, 1995; Gribble et al., 1996; Taylor and Martinez, 2003).

One explanation for the contrast in isotopic and geochemical character of the Campbell Range Formation basalts across the Jules Creek–Vangorda fault is that the rocks on opposite sides of the fault formed along the fault in different parts of the backarc basin and were subsequently juxtaposed along it (e.g., Fig. 12). In the next section, we present evidence that the geochemical and isotopic diversity of the Campbell Range Formation is a consequence of mixing of magmas from different source regions and that basalt north of the fault is
sourced primarily from depleted mantle melts, while basalt south of the fault is sourced from magma derived from melting of depleted and enriched mantle sources.

MAGMA SOURCE CHARACTERISTICS OF THE CAMPBELL RANGE BASALTS

The geochemical and isotopic data for Campbell Range Formation basaltic rocks consistently lie on arrays between N-MORB and OIB end members (Figs. 7, 8, and 10), implying that the various suites formed as variable mixtures of incompatible-element–enriched and –depleted mantle. The BABB suite also formed from N-MORB-like mantle (Fig. 7; e.g., Hawkins, 1995; Gribble et al., 1996), but the suite has higher La/Sm, and lower Nb/La and Th addition associated with the introduction of a subducted slab component into this N-MORB mantle (e.g., You et al., 1996; Fig. 7; Tables 1 and 2). The derivation of Campbell Range basalts from mixtures of enriched and depleted mantle is also supported by Nd isotopic data in which there is a progressive shift toward lower εNd values, with exceptions being the most incompatible-element–enriched basalts (i.e., E-MORB and OIB, Fig. 10; Table 3). It is also notable that the BABB suite has identical isotopic signatures to the N-MORB suites (εNd = +6.8 to +8.4), implying derivation from an isotopically similar source. An important implication of the isotopic differences between the enriched and depleted suites is that isotopically distinct end members are required, ruling out the possibility that their geochemical differences are due to variable degrees of partial melting of a common source region (Fig. 10). Crustal contamination is also improbable because Nb/La, Nb/Th, and La/Sm (with the exception of the BABB suite) progressively decrease with increasing εNd (Fig. 10), the opposite to what would be expected if crustal contamination was the main cause for the variation in εNd, (i.e., Nb/La and Nb/Th should decrease, and La/Sm should increase with decreasing εNd). Given the unlikelihood of crustal contamination, mixing of melts from a heterogeneous source area best explains the variation in isotopic and incompatible-element geochemistry for the Campbell Range basaltic rocks.

In order to quantify the degree of mixing between different end members, the isotopic mixing equation of Faure (1986) is employed:

$$R_m = \frac{R_1 C_1 + R_2 C_2 (1-X)}{C_1 + C_2 (1-X)},$$

where $R_m$ is the isotopic ratio of the mixture (e.g., εNd or 143Nd/144Nd); $R_1$ and $R_2$ are the isotopic compositions of the end members; $C_1$ and $C_2$ are the Nd concentrations of the end members; and $X$ is a proportionality factor that ranges from 0 to 1. In the case where $X = 0$, then the mixture consists entirely of component $C_1$; whereas, in the case where $X = 1$, it consists entirely of $C_2$; values that are mixtures lie between these two end members. In the isotopic mixing equations, the most depleted and enriched end members have been chosen according to those with the highest and lowest εNd values, respectively, from the N-MORB and OIB groups, respectively (Table 3). The results of these calculations are presented in Table 4 and illustrate that the N-MORB and BABB suites have contributions...
from enriched sources between 0% and 17%, with an average contribution of 8% (excluding sample P98-78). The OIB end member is dominated by the enriched component (54%–100%); whereas the E-MORB suite is consistent with mixing between the depleted and enriched end members with between 19% and 62%, with an average enriched component value of 33% (Table 4).

To further quantify the amount of mixing between the end members, and to provide a multi-element supplement to the Nd-isotopic data, binary elemental mixing equations for the most highly incompatible elements (Nb, Zr, Hf, Th, La, Ce, Pr, Nd, and Sm) are used. The binary mixing equation is given by the following (Faure, 1986):

$$C_n = C_1X + C_2(1-X),$$

where $C_n$ = concentration of element i in the mixture (i.e., the sample), $C_1$ and $C_2$ are the concentrations of element i in end members 1 and 2, and $X$ is a proportionality factor as described above. As with the incompatible-element plots described previously (e.g., Fig. 8), we have chosen this group of highly incompatible elements because they provide the best insight into the nature of the sources for the basalts (e.g., Pearce and Peate, 1995), and they will provide the best estimates of the degrees of mixing. Furthermore, the middle REE (MREE) to HREE, being more compatible and less sensitive to variations between enriched and depleted end members, were not used in the mixing models. Since mixing between two end members provides a single solution (i.e., a single proportion of the different end members), by having a number of different elements, there are more variables than unknowns, and to solve this type of system, a least-squares solution for the elements outlined above has been obtained (see Appendix A for details of the model and Table 5 for results). Notably, in this model, the choice of end members is slightly different than in the isotopic mixing calculations because there is slight decoupling between the most depleted and enriched samples isotopically and elementally. In selecting the end members, the samples that are most depleted and enriched in HFSE and REE, respectively (P98-77, enriched end member; 01MC-007, depleted end member), have been chosen. The results from the multi-component model are very similar to those of the model reliant solely on isotopic data (Tables 4 and 5). In particular, the OIB suite contains primarily enriched material ranging from 69% to 100% (average = 87%); the N-MORB
and BABB are derived from predominantly depleted sources with 0%–21% enriched component (average 6%); whereas the E-MORB suite represents a mixture between the two end members with 10%–30% enriched component (average = 18%) (Table 5). The beauty of the multicomponent mixing model, however, is that it does not rely solely on one isotopic value, providing a solution based on a greater number of variables, and can be calculated on samples that have not had any radiogenic isotopic analysis.

### DISCUSSION

#### Magma Mixing and the Settings of Campbell Range Magmatism

Although our modeling of the geochemical and isotopic data for the Campbell Range Formation indicates that mixing of melts from different mantle sources occurred, the nature of this mixing is not well constrained by physical and chemical attributes. For example, is this mixing between deep mantle plumes or enriched mantle and depleted upper mantle along a spreading ridge or backarc spreading center (e.g., Iceland or New Zealand; Fitton et al., 1997; Huang et al., 2000; Kempton et al., 2000)? Is it due to melting of a “plum pudding” mantle with blobs of enriched eclogitic or garnet-pyroxenitic material within a depleted matrix (e.g., Allègre et al., 1984; Zindler and Turcotte, 1986; Zindler and Hart, 1986; Langmuir et al., 1992; Hirschmann and Stolper, 1996; Niu and Batiza, 1997; Niu et al., 1999). A plum-pudding mantle with eclogitic or garnet-pyroxenite veins could account for the geochemical diversity in the Campbell Range Formation. The more enriched garnet-bearing domains could account for the OIB-like

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*end-member compositions.

Note: Abbreviations: BABB—backarc basin basalt; E-MORB—enriched mid-ocean ridge basalt; N-MORB—normal mid-ocean ridge basalt; OIB—ocean-island basalt; N—north of Jules Creek-Vangorda Fault; S—south of Jules Creek-Vangorda Fault.

A deep mantle plume as the source of enriched material in Slide Mountain rocks has been advocated by Lapierre et al. (2003), and is consistent with the geochemical attributes of these rocks (e.g., Fig. 7; Tables 1 and 2). In nearly all cases, plume magmatism is typically associated with: (1) a high volume of OIB-like magmas and (2) domal uplift and upward shaling of sedimentary facies (Rainbird, 1993; Rainbird and Ernst, 2001), neither of which is observed in the Campbell Range Formation. Most geological evidence points to thinning of the crust and extensional activity (e.g., synvolcanic faults), rather than crustal thickening; no evidence exists for shaling of sedimentary facies (Murphy and Piercey, 2000; Murphy et al., 2002). Furthermore, the OIB-like magmas are restricted to the area near the Jules Creek–Vangorda fault and are of minor volume (Fig. 11, Murphy et al., 2006).

Although the Campbell Range Formation may not have formed from a mantle plume, the low HREE and high LREE/HREE ratios in some samples clearly require “garnet” influence during their genesis. Many workers have discussed the “garnet signature” in MORB, suggesting that it may reflect a heterogeneous “plum pudding” mantle made up of enriched garnet-bearing domains, be they eclogite or pyroxenite, within a depleted spinel peridotite matrix (Allègre et al., 1984; Zindler et al., 1984; Allègre and Turcotte, 1986; Zindler and Hart, 1986; Langmuir et al., 1992; Hirschmann and Stolper, 1996; Niu and Batiza, 1997; Niu et al., 1999). A plum-pudding mantle with eclogitic or garnet-pyroxenite veins could account for the geochemical diversity in the Campbell Range Formation. The more enriched garnet-bearing domains could account for the OIB-like

<table>
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*mixing model end members.

Note: Abbreviations: BABB—backarc basin basalt; E-MORB—enriched mid-ocean ridge basalt; N-MORB—normal mid-ocean ridge basalt; N—north of Jules Creek-Vangorda Fault; S—south of Jules Creek-Vangorda Fault.
signatures, the depleted matrix could account for the N-MORB and BABB signatures, and mixtures of the two could account for the E-MORB signatures (Fig. 8). Similar results have been observed in the East Pacific Rise, where workers have suggested that the enriched plumes reside as physically distinct domains in a depleted matrix, and when melted result in melt-induced mixing between the depleted and enriched end members (Niu et al., 1996; Niu and Batiza, 1997; Niu et al., 1999). This type of mantle-melting mechanism could also occur within a mature backarc basin in which oceanic crust is forming.

We favor a variant of the plum-pudding model where the enriched garnet-pyroxenite or eclogitic lithologies reside in the subcontinental lithospheric mantle (e.g., Hawkesworth et al., 1990; McDonough, 1990; Menzies, 1990; Pouclet et al., 1995; DePaolo and Daley, 2000) and interact with upwelling depleted asthenosphere during rifting in the Campbell Range backarc basin. This model involves backarc spreading and transform faulting behind an extending continental arc system (Fig. 12, e.g., Piercey et al., 2006). In this model, the dominant enriched component resides in the subcontinental lithospheric mantle along a continent-bordering transform fault—magmatism would be in large part derived from the OIB-like lithospheric sources. With continued spreading and upwelling, coupled with the juxtaposition of oceanic and continental lithosphere along transform faults, depleted N-MORB asthenosphere interacts and mixes with lithospheric mantle leading to the formation of the E-MORB suite. With full-fledged seafloor spreading and extension, asthenospheric mantle dominates in the melting regime. In this model, the BABB suite is derived from an N-MORB-type asthenospheric source with minor influence from subducted slab metamorphism (e.g., Fryer et al., 1990; Hawkins, 1995; Pouclet et al., 1995). A similar model of asthenosphere-lithosphere evolution has been proposed to account for the observed shift from more alkalic to MORB-like basalts with time during the Miocene to Holocene evolution of the Sea of Japan (Fig. 12) (Pouclet et al., 1995).

**Implications for the Geodynamic Evolution of Slide Mountain Terrane**

Geological and paleontological data suggest that the Slide Mountain backarc basin was transform-dominated both during its opening and closing. Such a basin would have numerous settings where the two different geochemical and isotopic domains of the Campbell Range could form and be juxtaposed (Figs. 11 and 12). The domain sourced in depleted mantle lithosphere north of the fault (Fig. 11) could form along any one of the numerous intra-oceanic rift segments. In contrast, the domain with both depleted and enriched melt sources would lie only along the transforms bordering the ensialic Yukon-Tanana lithosphere (Fig. 12). Because these structures link directly to spreading centers, the juxtaposition of these two settings would naturally occur with increasing amounts of displacement. Hence, our model of the formation and juxtaposition of the two different domains along transform faults is entirely consistent with the transform-dominated nature of the Slide Mountain ocean (Fig. 12).

The Jules Creek–Vangorda fault system is the manifestation of the transform nature of this backarc basin and likely represents a leaky sinistral transform fault that separated the Yukon-Tanana ensialic arc terrane from its coeval obliquely opening backarc basin recorded by the Campbell Range Formation. The occurrence of Campbell Range Formation basalt and, importantly, affl uent plutonic rocks that occur on both sides of the Jules Creek–Vangorda fault for over a 300 km strike length, but only within a few kilometers of it, suggests that the fault is the first-order control on the emplacement of intrusions and volcanism. Because the Campbell Range Formation occurs at about the same elevation on both sides of the fault, normal- or thrust-sense displacement can be ruled out, leaving strike-slip as the only alternative. The presence of Middle Permian McCloud fauna in Yukon-Tanana terrane (Ross, 1969; Miller, 1987; Stevens, 1995) also suggests that in the Early Permian the terrane must have been traveling to more southerly latitudes relative to Laurentia. This motion must have been accommodated by sinistral transcurrent structures in or behind the coeval Devonian-Carboniferous arc represented by the ~281 Ma Klinik Group and correlative rocks of the Yukon-Tanana terrane (Simard et al., 2003; Roots et al., 2006). We infer that the Jules Creek–Vangorda fault is one of these structures.

Both regional and local considerations suggest that the Jules Creek–Vangorda fault may have been reactivated as a dextral fault in the Late Permian and again in the Mesozoic. Between the Middle Permian, when characteristic Yukon-Tanana terrane was at the latitude of Texas, and the Middle Triassic, when Yukon-Tanana terrane detrital zircons first appear in rocks of the northwestern North American continental margin sequence (Berenak, 2009; Beranek et al., 2010), the Slide Mountain ocean must have closed and Yukon-Tanana terrane translated dextrally by at least the same amount as it was translated sinistrally during the opening of the Slide Mountain ocean. Some of this displacement may have been partitioned onto the Jules Creek–Vangorda fault. Mesozoic reactivation is indicated by the observation that near Faro, the Campbell Range Formation is juxtaposed along the fault against Upper Triassic to Lower Jurassic (Beranek, 2009) conglomerate and Permian eclogite (Erdmer et al., 1998; Pigage, 2004).

**Implications for Crustal Growth at the Western North American Continental Margin**

The growth of continental crust reflect the balance between the addition of juvenile material from the mantle versus the recycling of previously formed evolved crust (Patchett and Arndt, 1986; Samson et al., 1989; Condie, 1990, 1998, 2000; Samson and Patchett, 1991; Patchett, 1992; McCulloch and Bennett, 1994; Hawkesworth and Kemp, 2006; Hawkesworth et al., 2010; Condie et al., 2011). During Earth’s history, many of the major crustal growth periods (e.g., Neoarchean, Paleoproterozoic, and Neoproterozoic) have been associated with major mantle plume events and/or accretionary tectonic activity, whereby significant masses of juvenile crust have been added either via magmatism or accretion to the crust (e.g., Patchett and Arndt, 1986; McCulloch and Samson et al., 1989; Condie, 1990; Samson and Patchett, 1991; Patchett, 1992; Bennett, 1994; Condie, 1998, 2000; Hawkesworth and Kemp, 2006; Hawkesworth et al., 2010). The evolution of convergent continental margin environments is marked by significant crustal recycling via weathering (e.g., Creaser et al., 1997; Piercy and Colpron, 2009) and the incorporation of crust into felsic magmatic rocks via assimilation (e.g., Hildreth and Moorbath, 1988). Juvenile crustal growth along these continental margins has largely been attributed to trapping of juvenile crust during accretion rather than through magmatism (Condie et al., 2011).

Numerous studies that have pointed out the importance of recycling of crust along the mid to late Paleozoic convergent western margin of Laurentia (Mortensen, 1992b; Creaser et al., 1997; Garzione et al., 1997; Gehrels and Ross, 1998; Patchett and Gehrels, 1998; Mortensen et al., 2006; Piercy et al., 2006; Piercy and Colpron, 2009); however, the importance of juvenile crustal additions to the orogen has not been fully evaluated (Creaser et al., 1997; Patchett and Gehrels, 1998; Creaser et al., 1999; Simard et al., 2003; Piercy et al., 2004). It is notable that during the Pennsylvanian to Early Permian there was extensive juvenile magmatism, both in Yukon-Tanana and in the coeval Slide Mountain backarc ocean, with juvenile isotopic signatures (i.e., eNd ≅ 0) recorded in both the Yukon-Tanana terrane (Simard et al., 2003)
and in the Slide Mountain terrane (Klepacki, 1985; Struik and Orchard, 1985; Nelson, 1993; Roback et al., 1994; Ferri, 1997; Lapière et al., 2003; this study). Despite episodic rifting over a 100-million-year history within the Slide Mountain ocean starting in the Late Devonian, igneous rocks of Pennsylvanian to Early Permian age are disproportionately preserved, and those that are preserved have predominantly juvenile isotopic signatures.

The Devonian to Permian backarc opening and closing of the Slide Mountain ocean along the western margin of the North American continent resulted in the accretion of the Slide Mountain terrane onto the cratonic margin (e.g., Nelson et al., 2006), suggesting that the Slide Mountain terrane potentially added significant juvenile crust to the continents and represents net juvenile crustal growth. However, despite their juvenile signatures, the Slide Mountain terrane represents relatively thin structural slivers atop a predominantly continental substrate (e.g., Nelson, 1993); therefore, they likely only represent minor contributors to Cordilleran juvenile crustal growth.

SUMMARY AND CONCLUSIONS

The Lower Permian Campbell Range Formation in the Finlayson Lake region of Yukon is part of the Slide Mountain terrane, a North American Cordilleran–long backarc basinal assemblage that developed between an ensialic arc system and the North American craton in the middle to late Paleozoic. It contains abundant basaltic and high-level intrusive rocks with trace element geochemical signatures similar to modern backarc basin assemblages, including ocean-island basalt (OIB), enriched mid-ocean ridge basalt (E-MORB), normal mid-ocean ridge basalt (N-NORB), and backarc basin basalts (BABB). The range of signatures is mirrored by their Nd isotopic characteristics, which range from $\epsilon_{Nd} = +2.2$ to +8.9. The geochemical and isotopic diversity is attributed to derivation from mantle sources that range from incompatible-element–enriched (e.g., OIB) through incompatible-element–depleted mantle (e.g., MORB and BABB). The $\epsilon_{Nd}$ values show an inverse relationship with Nb/Th$_{sm}$ and Nb/La$_{nu}$, suggesting that the lower $\epsilon_{Nd}$ values are a feature of the source of the basalts and not due to continental crustal contamination. We interpret the geochemical and isotopic characteristics of the Campbell Range Formation in the context of a model of an extending continental-backarc basin in which there are varying contributions from the lithospheric and asthenospheric mantle; their formation and juxtaposition is attributed to magmatism along a leaky transform fault within the basin. Isotopic and multielement mixing calculations illustrate that the OIB-like suite was derived primarily from enriched continental lithospheric mantle, whereas the N-MORB and BABB suites were sourced primarily from the upwelling backarc asthenospheric mantle; E-MORB represent mixtures of depleted asthenospheric and enriched lithospheric mantle.

The presence of OIB and E-MORB suites in the Campbell Range Formation and elsewhere in Slide Mountain terrane has been previously attributed to mantle plume magmatism within this backarc basin. The geological features of the OIB and E-MORB suites are inconsistent with a plume origin; however, we infer that they represent OIB-type material derived from the melting of lithospheric mantle during backarc basin formation. The occurrence of juvenile magmatism in the Campbell Range Formation illustrates that backarc basins, like the Slide Mountain ocean, may have contributed to Cordilleran juvenile crustal growth. However, the Slide Mountain terrane, including the Campbell Range Formation, form very thin crustal slivers atop a predominantly continental crustal substrate. Therefore, their net contribution to Cordilleran juvenile crustal growth was minimal.

ACKNOWLEDGMENTS

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APPENDIX A: DETAILS OF MULTI-ELEMENT MIXING MODELS

The mixing equation:

$$C_m = C_X + C_Y (1 - X)$$  \(1\)

employed in the elemental mixing calculations can be rearranged as follows:

$$C_X = (C_Y - C_m) / (1 - X),$$  \(2\)

which results in a series of linear equations for the different elements with a common proportionality factor ($X$). In the mixing model, we have used elements that are sensitive to source variations, namely the moderate to highly incompatible elements: Nb, Zr, Hf, Th, La, Ce, Pr, Nd, and Sm. Using the above elements results in a series of linear equations of the form:

$$(Nb - Nb_m)X = (Nb_m - Nb),$$  \(3\)

$$(Zr - Zr_m)X = (Zr_m - Zr),$$  \(4\)

$$(Hf - Hf_m)X = (Hf_m - Hf),$$  \(5\)

$$(Sm - Sm_m)X = (Sm_m - Sm).$$  \(6\)

This system of equations can be written in matrix form as follows, and is a matrix of the form $AX = B$:

$$\begin{bmatrix}
(Nb - Nb_m) & (Nb_m - Nb) \\
(Zr - Zr_m) & (Zr_m - Zr) \\
(Hf - Hf_m) & (Hf_m - Hf) \\
(Sm - Sm_m) & (Sm_m - Sm)
\end{bmatrix} \begin{bmatrix}
X
\end{bmatrix} = \begin{bmatrix}
0
0
0
0
\end{bmatrix}.$$  \(7\)

Because this is an over-determined system of equations, it requires solving in the least-squares sense and obtaining the optimum estimate for $X$:

$$X = \left( \begin{bmatrix}
(Nb - Nb_m) \\
(Zr - Zr_m) \\
(Hf - Hf_m) \\
(Sm - Sm_m)
\end{bmatrix} \right)^{-1} \begin{bmatrix}
(Nb_m - Nb) \\
(Zr_m - Zr) \\
(Hf_m - Hf) \\
(Sm_m - Sm)
\end{bmatrix}.$$  \(8\)

This mixing model provides the best estimate of mixing, taking into account all input elements, and returns the optimum solution for the model (e.g., Albarade, 1996; Davis, 2002).

REFERENCES CITED


Lithosphere-asthenosphere mixing, northern Cordilleran crustal growth and assembly


