Oceanic mafic magmatism in the Siletz terrane, NW North America: Fragments of an Eocene oceanic plateau?

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A B S T R A C T

The Siletz terrane, a predominantly mafic accreted oceanic terrane, is located in the Cascadia forearc region of Oregon, Washington and Vancouver Island. The terrane represents a late Palaeocene–Eocene large igneous province that consists of pillow lavas, massive flows and intrusive sheets. Previously it has been proposed that the Siletz terrane represents either an accreted oceanic plateau, hotspot island chain, backarc basin, island arc, or a sequence of slab window volcanics. A province-wide geochemical reassessment of the terrane, including new high precision Sr-Pb-Nd-Hf isotope data, has been used to assess the validity of the proposed tectonomagmatic models for the Siletz terrane. The trace element data show little evidence of crustal contamination, or an arc signature, and the samples have rare earth element (REE) patterns that are flat to light REE enriched. These features are similar to other oceanic plateaus such as the Ontong Java and the Caribbean. Initial isotope ratios range from \( ^{206}\text{Pb}/^{204}\text{Pb}: 18.751 \) to 19.668, \( ^{207}\text{Pb}/^{204}\text{Pb}: 15.307 \) to 15.661, \( ^{208}\text{Pb}/^{204}\text{Pb}: 38.294 \) to 39.2128, \( ^{176}\text{Hf}/^{177}\text{Hf}: 0.28300 \) to 0.28316 (\( \epsilon_{\text{Nd}}: 9.0 \) to 14.5). \( ^{143}\text{Nd}/^{144}\text{Nd}: 0.51282 \) to 0.51299 (\( \epsilon_{\text{Hf}}: 5.0 \) to 8.1) and \( ^{87}\text{Sr}/^{86}\text{Sr}: 0.70302 \) to 0.70380. These data are consistent with a mantle source of the Siletz terrane that appears to have been heterogeneous and slightly enriched. The enriched signature has characteristics of both EM2 and HIMU components and this, combined with a calculated mantle potential temperature well above ambient mantle, indicates derivation of the Siletz magmatism from a mantle plume, possibly the Yellowstone Hotspot. We therefore conclude that the Siletz terrane represents an accreted oceanic plateau.

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1. Introduction

Accreted oceanic mafic terranes are an ubiquitous feature not only of most destructive plate margins (e.g., the northern Andes, (Kerr et al., 2002a); the coastal ranges of western Canada and Alaska (Greene et al., 2009a, 2009b), and Japan (e.g.,Ichiyama et al., 2014)), but also of continental collision zones such as that represented by the closure of the Tethyan ocean (e.g., Turkey (Whattam and Stern, 2011); Tibet (Chen et al., 2001); and central Iran (Moghadam et al., 2010)). Such mafic accreted terranes are common throughout most of Earth’s history (e.g., Kerr, 2014) and so may have also contributed significantly to the growth of continental crust (Condie, 1998; Stern and Scholl, 2010). Many accreted oceanic mafic rocks represent areas of over-thickened (>6–7 km) oceanic crust (such as seamounts, ocean islands, aseismic ridges or oceanic plateaus) that was too buoyant to subduct (Cloos, 1993; Tetreault and Buiter, 2014). This uplifted and accreted oceanic crust affords an excellent opportunity to study the structure, composition and origin of a part of the ocean floor that would otherwise be relatively inaccessible.

This study focuses on the Siletz terrane, a mostly Eocene large igneous province (LIP) located in the present Cascadia forearc region of Oregon, Washington and Vancouver Island (Fig. 1), consisting of a series of accreted basaltic pillow lavas, massive flows and intrusive sheets (Snayev et al., 1968; Wells et al., 2014). The terrane is composed of both subaerial and submarine rocks, with an estimated magmatic volume of \( 2.6 \times 10^{6} \) km\(^{3}\) (Trehu et al., 1994). Eruption and intrusion of the Siletz terrane magmas are thought to have taken place from ~56 to 49 Ma (Duncan, 1982; Haessler et al., 2000; Hirsch and Babcock, 2009; Massey, 1986; Wells et al., 2014) during a time of major plate reorganisation in the Pacific (Atwater, 1989; Engebretson, 1985). The terrane was rotated during accretion, shortly after formation within 300 km of the North American Pacific continental margin (McCrorry and Wilson, 2013). The province has been variously known as: Siletzia (Irving, 1979), the Coast Range Volcanic Province (Babcock et al., 1992), the Siletz–Crescent terrane (McCrorry and Wilson, 2013) and the Siletz terrane (Fleming and Trehu, 1999; Snayev et al., 1968) used in this paper.

At present, there is little consensus on the tectonic setting in which the Siletz terrane magmas were generated. Previously proposed models include initial melting of the Yellowstone mantle plume head (Pyle et al., 2009; Wells et al., 2014), accretion of a hotspot island chain...
The ~650 km-long Siletz Terrane consists of three main volcanic formations: the Siletz River Volcanics in Oregon, the Crescent Formation in southwestern Washington and the Olympic Peninsula, and the Metchosin Igneous Complex on the southeastern coast of Vancouver Island (Fig. 1). Although exposure is generally poor across most of the Siletz terrane, it is clear that the lower part of the terrane sequence contains mostly submarine pillow basalts, pillow breccia, gabbros and occasional sheeted dyke units (Duncan, 1982; Haeussler et al., 2000; Massey, 1986; Snavely et al., 1968; Wells et al., 2000). These subaerial units are interbedded with brecciated lapilli tuffs, laminated tuffs and volcaniclastic sediments. The thickest part of the terrane occurs in central Oregon, where it reaches 27 ± 5 km (Trehu et al., 1994). Beneath northwestern Oregon and southwestern Washington, the terrane is approximately 20 km thick (Parsons et al., 1999), thinning to 10 km in northwestern Washington and southwestern Vancouver Island and down to 6 km offshore Vancouver Island (Hyndman et al., 1990).

The western boundary of the terrane is poorly exposed at the Hurricane Ridge fault (Fig. 1) on the Olympic Peninsula, Washington (Cady, 1975; Hirsch and Babcock, 2009). Using magnetic anomalies this boundary has been traced southwards (offshore Oregon) and northwards (off the coast of Vancouver Island) (Fig. 1) (Fleming and Trehu, 1999; Snavely et al., 1980). In the north, the Leech River Fault, a thrust contact on Vancouver Island, represents the eastern boundary of the terrane (Massey, 1986) while another thrust contact (Wildlife Safari fault) near Roseburg, Oregon, defines the eastern boundary in the south of the terrane (Wells et al., 2000) (Fig. 1). The southern margin of the Yakutat terrane in Alaska (Davis and Pfafker, 1986) and the Wheatfield Fork Terrane of the Franciscan Complex in Northern California (McLaughlin, 2009) have also been proposed to be remnants of the Siletz terrane.

The age of the Siletz terrane has generally been constrained using 40Ar–39Ar whole rock dating techniques, placing the maximum age range of the terrane between 56 and 49 Ma, with the majority of the terrane having erupted between 54 and 50 Ma (Brandan, 2014; Duncan, 1982; Pyle et al., 2009). Nanoplankton ages from interbedded sediments have also been correlated by Wells et al. (2014) with other ages from across the terrane. In addition to this, limited U–Pb ages have also been determined. Haeussler et al. (2000) reported a U–Pb zircon age of 50.5 Ma for the Bremerton Igneous Complex in the Crescent Formation and U–Pb zircon ages of 52 and 54 Ma have been determined for the volcanics of the Metchosin Igneous Complex by Yorath et al. (1999). Several areas of the terrane have not been dated, resulting in some uncertainties in the relative timing of magmatism across the terrane. In addition, correlating the stratigraphy of different units across the terrane has proven difficult due to the lack of exposure.

Accretion is thought to have occurred rapidly after, and probably even during, the eruption of the terrane, first in the south between 51 and 49 Ma (Wells et al., 2014) and subsequently in the north from 48 Ma to 45 Ma (McCroy and Wilson, 2013; Wells et al., 2014). Accretion of the Siletz terrane may have triggered the break-up of the subducting Farallon slab and back-stepping of the subduction zone to the west of the accreted Siletz terrane (Gao et al., 2011).

It has been proposed that at the time of formation (Early Eocene) there were 4 (or 5) plates in the region: the Farallon, Kula, Pacific, North American (and Resurrection) plates (Fig. 2) (Haeussler et al., 2003; Seton et al., 2012). During this time a major change in the plate configuration took place, which resulted in an adjustment in spreading direction between the Pacific and Farallon plates from WSW–ENE to E–W (Atwater, 1989). The Pacific-Kula ridge also underwent a change in spreading direction from N–S to NW–SE (Seton et al., 2012) before an eventual cessation of spreading (Engelbreton, 1985). Most early Eocene plate reconstruction models agree that the Farallon–Kula ridge was striking NE–SW at the time of formation of the Siletz terrane, intersecting the North American plate to the east, forming a triple junction with the Pacific plate in the west and a slab window at the adjacent margin of the North American continent (Atwater, 1989; Breitsprecher et al., 2003; Engelbreton, 1985; Madsen et al., 2006; Seton et al., 2012).

The existence of an additional Resurrection plate between the Kula plate and the North American plate, to the north of the Farallon plate, has been proposed to account for the migration of magmatism along the southern margin of Alaska during the late Paleocene to early Eocene (Haeussler et al., 2003). The Kula-Resurrection ridge has been modelled to have been subducted by 50 Ma (Breitsprecher et al., 2003; Seton et al., 2012).
3. Petrography and sample locations

The terrane comprises vesicular basalts, dolerites, and gabbros, with occasional rhyolites and leucogabbros (a representative selection of photomicrographs can be found in Supplementary Material 1). The mafic rocks consist mostly of plagioclase, clinopyroxene and Fe–Ti oxide. Sub-ophitic textures in the plagioclase and clinopyroxene are common across the samples and zeolite-filled amygdales are abundant. Several samples collected from the Siletz River Volcanics also contain olivine in addition to the minerals noted above. The basalts and dolerites vary from phryic to aphyric, with the phryic samples containing up to ~20% plagioclase and clinopyroxene phenocrysts. Glomerocrysts of clinopyroxene and plagioclase are also common in the Crescent Formation and sections of the Siletz River Volcanics. Opaque phases predominantly consist of skeletal ulvospinel and ilmenite. Opaque minerals comprise between 10% and 20% of most samples and are particularly abundant in the Siletz River Volcanics (Roseburg).

The Metochinos Igneous Complex and some Crescent Formation samples display greenshist-facies alteration with chlorite, albite and epidote. Other Crescent Formation samples, and the Siletz River Volcanics to the south, have undergone zeolite to prehnite–pumpellyite facies alteration and contain zeolite, calcite, pumpellyite and prehnite. Palagonite is also a common alteration phase throughout the Siletz terrane samples and is interpreted to represent altered volcanic glass. Broad locations of the samples analysed for isotopic ratios are shown in Fig. 1 with precise locations given in Supplementary Material 2.

4. Analytical methods

4.1. Major and trace elements

Following removal of weathered surfaces by saw the samples were crushed in a steel jaw crusher and powdered using an agate Tema® mill at Cardiff University, Wales. Samples were then digested by fusion in platinum crucibles on a Claisse Fluxy automated fusion system using 0.1 ± 0.0005 g of sample with 0.4 ± 0.0005 g of lithium tetraborate flux (full methods described by McDonald and Viljoen (2006)). Major element abundances were analysed using a JY Horiba Ultima 2 inductively coupled plasma optical emission spectrometer (ICP-OES) and trace element abundances using a Thermo X7 series inductively coupled plasma mass spectrometer (ICP-MS) at Cardiff University. Accuracy and precision of the data were assessed using the international reference material JB-1A, which was run with each sample batch (Supplementary Material 3). The vast majority of elements are within 2σ of certified values and those that are not in this range are not included.

4.2. Sr-Nd-Hf-Pb radiogenic isotopes

Twenty samples were selected for radiogenic isotope analyses based on lack of alteration, geographical spread and geochemical variability for a range of coverage. Chemical separations and mass spectrometric analyses were conducted in Class 100 laminar flow hoods in the Class 1000 clean laboratories at the Pacific Centre for Isotope and Geochemical Research at the University of British Columbia. Leaching was carried out prior to digestion as most samples show prehnite–pumpellyite to greenschist grade alteration and have LOI values between 0.5 and 2.0%. The leaching procedures are described in Nobre Silva et al. (2009). For each sample around 250 mg of rock powder was digested in sub-boiled HF and HNO3 in 15 ml savillex beakers on a hotplate for around 48 h at 130 °C. The samples were subsequently dried down, 6 N HCl added and fluxed for 24 h, as outlined in Weis et al. (2006). Pb, Sr, Hf and Nd were separated from single powder dissolutions by sequential ion exchange column chemistry, having passed through the Pb columns twice to ensure purity (Weis et al., 2006, 2007). Pb, Hf, and Nd isotopic ratios

Fig. 2. Suggested plate configuration map at 53 Ma, Adapted from Haeussler et al. (2003), Seton et al. (2012) and Wells et al. (2014), where the stars represent the proposed positions of the Yellowstone hotspot; 1 (O’Neill et al., 2005); 2 (Doubrovine et al., 2012) and 3 (Müller et al., 1993).
were measured on a Nu Plasma MC-ICP-MS 1700 or Nu Plasma II MC-ICP-MS instrument and Sr isotopic ratios were measured on a Triton TIMS instrument following procedures described by Weis et al. (2006). Full procedural blanks gave Sr, Nd, Hf and Pb concentrations of: Pb: 23.4 pg; Hf: 4–5 pg; Sr: 0.2–0.6 pg and Nd: 53–495 pg, which are negligible relative to sample concentrations.

5. Geochemical results

5.1. Major and trace elements

A representative dataset of the samples analysed for isotopes can be found in Table 1 and the full dataset in the Supplementary Material 4. The silica content of the analysed samples varies between 39.7 and 74.6 wt.% with the majority of samples having ~50 wt.% SiO₂, while the Mg# varies between 18.5 and 70.8. The Cr abundance varies between 3.4 and 576 ppm and the Ni ranges between 3.1 and 1244 ppm. The Mg# varies between 18.5 and 70.8. The Cr abundance varies between 3.4 and 576 ppm and the Ni ranges between 3.1 and 1244 ppm. The LOIs of the samples are mostly between 0.5 and 2% but extend up to ~6%, which, along with the petrography, indicates that varying degrees of alteration have affected the rocks of the Siletz terrane. Under such conditions many elements, in particular the large-ion lithophile elements (i.e., K₂O, Ba, Rb), may become mobile (e.g., Hastie et al., 2007; Pearce, 1996).

Accordingly, these elements may not be representative of the original magmatic abundances in the rocks. The samples have therefore been classified using the Zr/Ti vs. Nb/Y diagram (Pearce, 1996), which utilizes some of the relatively immobile high field strength elements (Fig. 2). On this classification diagram it can be seen that the majority of samples in this study are tholeiitic basalts while a small number of samples, largely from the Siletz River Volcanics, trend towards alkaline compositions (Fig. 3). This classification is generally in broad agreement with the major element data, with the majority of samples falling in a range of 44–52 SiO₂ wt.%, although there is more variability in the alkali oxides (K₂O + NaO) (alkali-silica diagram shown in Supplementary Material 5), than reflected in Fig. 3.

In Fig. 4 representative trace elements and ratios are plotted against Zr as it is relatively immobile and incompatible over the range of observed compositions (Cann, 1970). Many of the more immobile elements such as Nb, Th and La generally show a positive correlation with Zr (Fig. 3), and so are a more robust representation of the original magmatic variations among the rocks. The scatter observed on the diagrams in Fig. 4 is therefore unlikely to be related to alteration but due to variation in magmatic composition such

<table>
<thead>
<tr>
<th>Sample #</th>
<th>225CM</th>
<th>423CM</th>
<th>B019</th>
<th>450CS</th>
<th>374CS</th>
<th>205MET</th>
<th>202MET</th>
<th>073RB</th>
<th>116SRV</th>
<th>144SRV</th>
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<tr>
<td>SiO₂</td>
<td>51.31</td>
<td>49.06</td>
<td>49.14</td>
<td>48.37</td>
<td>47.71</td>
<td>47.61</td>
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<td>TiO₂</td>
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<td>1.59</td>
<td>1.37</td>
<td>2.39</td>
<td>2.86</td>
<td>0.96</td>
<td>1.32</td>
<td>1.92</td>
<td>2.23</td>
<td>1.91</td>
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<tr>
<td>FeO*</td>
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<td>11.88</td>
<td>10.92</td>
<td>13.40</td>
<td>15.05</td>
<td>11.58</td>
<td>13.32</td>
<td>13.15</td>
<td>13.12</td>
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<td>0.25</td>
<td>0.25</td>
<td>0.21</td>
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<td>0.22</td>
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<td>7.55</td>
<td>6.22</td>
<td>4.65</td>
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<td>14.23</td>
<td>11.91</td>
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<td>12.79</td>
<td>11.81</td>
<td>9.88</td>
<td>11.64</td>
<td>12.37</td>
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<td>2.18</td>
<td>2.11</td>
<td>2.43</td>
<td>2.51</td>
<td>1.46</td>
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<td>2.43</td>
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<td>K₂O</td>
<td>0.25</td>
<td>0.42</td>
<td>0.10</td>
<td>0.28</td>
<td>0.32</td>
<td>0.04</td>
<td>0.05</td>
<td>0.09</td>
<td>0.26</td>
<td>0.18</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.10</td>
<td>0.16</td>
<td>0.16</td>
<td>0.26</td>
<td>0.27</td>
<td>0.09</td>
<td>0.11</td>
<td>0.34</td>
<td>0.19</td>
<td>0.25</td>
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<tr>
<td>LOI</td>
<td>1.29</td>
<td>1.11</td>
<td>1.90</td>
<td>1.01</td>
<td>1.54</td>
<td>1.11</td>
<td>1.68</td>
<td>0.95</td>
<td>1.39</td>
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<tr>
<td>Total (ppm)</td>
<td>99.83</td>
<td>100.67</td>
<td>99.80</td>
<td>99.53</td>
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<td>98.60</td>
<td>100.25</td>
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<td>97.31</td>
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* Denotes total Iron. ** Total recalculated to an anhydrous basis.
as an enriched source or degree of partial melting. Other, more mobile, trace elements such as Sr display a positive correlation in most of the samples but much more scatter is evident. The Sm/Yb ratio varies from 0.35 to 5 for the main cluster of data, but extends up to 6.12 (Fig. 4). A similar pattern is apparent for the La/Yb ratio of the rocks, with a main cluster between 1 and 2 and extending up to ~33.

In addition to this, a group of samples, mostly from the Metchosin Igneous Complex and the Crescent Formation, have lower (<1) Sm/Yb ratios.

On a primitive mantle normalised diagram (Fig. 5), samples from the Siletz River Volcanics and Crescent South and some samples from Roseburg show enrichment in the most incompatible elements relative to the less incompatible elements, while the remainder of samples show generally flat patterns. All samples show a large variation in Ba/Rb ratio, which is usually constant in unaltered oceanic basalts (Hofmann and White, 1983); this is consistent with Rb depletion during post-magmatic alteration. Chondrite-normalised REE patterns (Fig. 5) display flat to slightly depleted HREE and middle REE patterns (Dy/Yb ratio ranges between 1.5 and 3.4) (Fig. 6). The LREE in the Siletz samples show flat-to-enriched patterns, with several samples from the Siletz River Volcanics displaying the most enriched LREE patterns (La/Sm up to 9.8). There is little variation from east to west in the Dy/Yb ratio of the rocks of the Siletz terrane. The highest Dy/Yb values are found in the central part of the terrane (Fig. 6) and the lowest values are seen in the Metchosin Igneous Complex, the northernmost samples of the Crescent Terrane and from the Roseburg area in the southernmost part of the terrane. Some of these low Dy/Yb samples (from the Metchosin Igneous Complex) are also LREE depleted (Fig. 6).
5.2. Sr-Nd-Hf-Pb radiogenic isotopes

The measured isotope ratios for the samples used in this study have been age corrected for in-situ decay between 54.5 and 50.5 Ma using the trace element abundances in Table 1 and Supplementary Material 4 and both the measured and initial values are reported in Table 2. The initial isotope ratios for the analysed samples range from $^{206}\text{Pb}/^{204}\text{Pb}$: 18.751 to 19.668, $^{207}\text{Pb}/^{204}\text{Pb}$: 15.507 to 15.661, $^{207}\text{Pb}/^{204}\text{Pb}$: 38.294 to 39.2128, $^{176}\text{Hf}/^{177}\text{Hf}$: 0.28300 to 0.28316 ($\varepsilon_{\text{Hf}}$: 9.0 to 14.5), $^{143}\text{Nd}/^{144}\text{Nd}$: 0.51282 to 0.51299 ($\varepsilon_{\text{Nd}}$: 5.0 to 8.1) and $^{87}\text{Sr}/^{86}\text{Sr}$: 0.70302 to 0.70380 (Table 2, Fig. 7) (ages used to correct the measured isotopic ratios are detailed in Supplementary Material 6). The Metchosin Igneous Complex samples display the most depleted and restricted isotope ratios of the entire Siletz terrane, and this is particularly evident in Hf–Nd isotopic space (Fig. 7d). The Crescent Formation samples show more variation in isotope ratios and this variation increases southward. The more-depleted Crescent Formation samples have elevated $^{87}\text{Sr}/^{86}\text{Sr}$ values compared to the other samples, which may be related to seawater alteration as all other isotope values for these samples are not anomalous. In particular Nd and Hf isotope systems are relatively resistant to alteration and so are likely to represent the primary composition of the rocks (White and Patchett, 1984; Nobre Silva et al., 2010).

The samples from northern Oregon and southern Washington (the Crescent South group of the Crescent formation, and the Siletz River Volcanics) show a similar amount of isotopic variation to one another, with the majority of samples from this area falling in the main cluster of data. The samples from the Roseburg area, in the south of the terrane, show the most isotopic variation. For example, Sample 073RB, which has the highest $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of 19.668 and so plots closest to the HIMU mantle component in $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams (Fig. 7), also has the highest La/Sm ratio of 9.8. Sample 095RB, also from the Roseburg area of the terrane, plots closest to EM2 and the Immaha mantle component (IM) fields in all isotopic spaces (Fig. 7). The Immaha component is thought to be the mantle plume source of the Columbia River Flood Basalts (CRFB) and the Snake–Yellowstone volcanics (Wolff et al., 2008).

There is little correlation between major and trace elements and isotope abundances with the exception of the more trace element-depleted samples (in comparison to the other more-enriched samples) (Fig. 5) also having the most depleted isotopic ratios of the terrane (Figs. 6 and 7). Samples with lower Pb and Sr isotopic ratios and higher $\varepsilon_{\text{Hf}}$ and $\varepsilon_{\text{Nd}}$ values also have the lowest La/Sm ratios (0.9–1.3) and the
most-depleted incompatible element abundances. There is also a negative correlation between Dy/Yb and Hf isotopic ratios (Fig. 6). As this trend is distinguishable in both trace elements and radiogenic isotopes it indicates that the differences observed are a reflection of the composition of the source regions rather than varying degrees of partial melting alone. The overall variation in isotopes generally increases southward across the terrane (Fig. 6).

All samples analysed have higher Pb isotopic ratios and $^{87}\text{Sr}/^{86}\text{Sr}$ values and lower $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ than the Pacific MORB Mantle (PMM) (Fig. 7). The Cobb Seamount chain (CS), a series of seamounts located near the East Pacific Rise (Chadwick et al., 2014), have consistently higher $^{143}\text{Nd}/^{144}\text{Nd}$ and lower $^{87}\text{Sr}/^{86}\text{Sr}$, $^{176}\text{Hf}/^{177}\text{Hf}$ and Pb isotopic ratios than the Siletz terrane samples. The Siletz terrane samples also generally overlap the Karmutsen Flood Basalt (KFB) field, which are a series of predominantly tholeiitic basalts located on Vancouver Island and form part of the accreted Jurassic aged Wrangellia oceanic plateau (Greene et al., 2009b) (Fig. 7). In Pb-Pb isotopic space the Siletz terrane shares similar isotopic characteristics to the Caribbean Plateau (Fig. 7).

6. Discussion

6.1. Mantle source composition

Although the samples analysed in this study span a range of compositions from basalts to more evolved rocks there is no correlation between the degree of fractionation undergone by each sample and the radiogenic isotope ratios. This indicates that the samples are unlikely to have been contaminated with lherzolitic material during fractionation and are therefore likely to record the isotopic signature of the mantle source. Although no evidence for crustal contamination has been observed, some LREE enrichments are noted, which are most likely related to enriched components in the source or subsequent differentiation. In isotope plots (Fig. 7), the Siletz terrane data show similarity with the trends observed in the Karmutsen flood basalts, an oceanic plateau nearby and in a comparable setting (Greene et al., 2009b). Binary mixing curves between MORB-source mantle and the Imnaha mantle component, EM2, and HIMU mantle components are shown in Fig. 7, with 10% increments. Trace element abundances used for the mantle components are discussed in Supplementary Material 7. A 53 Ma age corrected depleted Gorda MORB mantle (DGM) composition (Davis et al., 2008; Salters et al., 2011) was used as the end-member to represent a possible depleted mantle component.

The positive $\varepsilon_{\text{Hf}}$ and $\varepsilon_{\text{Nd}}$ values of all the Siletz samples reflect long-term incompatible element depletion of the source. In Pb-Pb, Pb-Nd and Pb-Hf isotopic space the Siletz data lie mostly between the DGM–HIMU and DGM–EM2 mixing curves (Fig. 7), while a dominance of EM2 is required in the other diagrams, especially in three samples, B019, 424CM and 095RB (and to a lesser extent 202MET). The Imnaha component also lies adjacent to the DGM–EM2 mixing curve, which indicates that the 3 samples with the significant EM2 component share similar isotopic signatures to the Columbia River Flood Basalts and the Snake River–Yellowstone hotspot trace (Wolff et al., 2008). Carlson (1984) also recognised that this component was present in the source of the CRFB, but proposed that it represented subducted sediment rather than a mantle plume component. However, the trace element data rule out the possibility of subducted sediment in the analysed samples as there is no ‘arc signature’ present in the mantle-normalised diagrams (i.e., no marked negative Nb-Ta anomaly or Th spike) (Fig. 5). Therefore, except for the 3 samples discussed above, the Siletz isotope data are...
quite different from that of the Immaha component and require a difference source than the Columbia River Flood Basalts and Snake River–Yellowstone hotspot track.

There is a significant EM2 signature present in the majority of the data, indicating the presence of a deep mantle derived component (Weaver, 1991; Workman et al., 2004); this EM2 component is not as significant as in other Pacific OIBs, such as the Samoan Islands (Fig. 7).

The most enriched samples display higher Dy/Yb values, indicating that these samples have undergone smaller amounts of melting of a lower melt fractions are preferentially sampling isotopically distinct enriched pods or plums (Cousens, 1996) or streaks within a mantle plume (Kerr et al., 1995).

As noted above the data also extend partially towards the HIMU component in Pb-Pb, Pb-Nd and Pb-Hf isotopic space (Fig. 7), indicating that this component may be present in the source of the Siletz basalts (especially in sample 073RB and to a lesser extent sample TK009). The involvement of a HIMU like signature is consistent with observations in other NE Pacific locations, such as the Cobb Seamounts (Chadwick et al., 2014), Explorer MORB (Cousens et al., in review), the Karmutsen flood basalt province (Greene et al., 2009a, 2009b) and the Garibaldi belt (Mullen and Weis, 2013). The samples which plot closest to HIMU have a more alkaline signature (highlighted in Fig. 7c) which suggests a relationship between the HIMU component and less extensive (deeper) melting, as is also observed at the Cobb Seamounts (Chadwick et al., 2014).

The PREMA component (Fig. 7) represents a common deep mantle component [or FOZO or C (Hanan and Graham, 1996; Stracke, 2012)]. It is also the Kea component in Hawaii and was interpreted to represent the average deep Pacific mantle (Nobre Silva et al., 2013). Some of the samples analysed from the Crescent Formation and Metchosin Igneous Complex lie adjacent to, or at the PREMA component composition in the Pb-Pb, Pb-Hf and Pb-Sr isotopic diagrams (Fig. 7c, d, e, f). However, while Siletz samples do appear to trend towards PREMA in some isotopic diagrams (Pb-Pb), the majority of the Siletz terrane data, in most isotopic spaces, do not overlap with this component (Fig. 7). In addition, although it has been debated whether this signature actually exists as a discrete physical component, PREMA does appear to be a relatively common source composition for other well-characterised Pacific oceanic lavas, including the Hawaiian basalts (Fig. 7) (e.g., Nobre Silva et al., 2013), as well as those related to the Iceland and Yellowstone plumes (Hanan and Graham, 1996). Although the Siletz terrane isotopic data demonstrates some similarity to the trends observed in, for example, the Hawaiian Islands, most notably in Hf–Nd isotopic space, the Siletz terrane samples are distinctly more radiogenic in the Pb isotopic ratios together with lower 87Sr/86Sr (Fig. 7). Multiple components are therefore most likely required to explain the trends observed in the isotopic data (Fig. 7) i.e., a depleted component isotopically similar to DGM, along with an enriched signature that straddles between EM2 and HIMU. The enriched signature, although prevalent throughout the terrane, is less apparent in the samples from the north-east, i.e., the Metchosin Igneous Complex and some Crescent Formation samples (Fig. 7).

### Table 2
Radiogenic isotope results.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>225CM</th>
<th>230CM</th>
<th>423CM</th>
<th>424CM</th>
<th>B019</th>
<th>450CS</th>
<th>374CS</th>
<th>362CS</th>
<th>392CS</th>
<th>205MET</th>
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<tr>
<td>206Pb/204Pb</td>
<td>38.7887</td>
<td>38.7246</td>
<td>38.6958</td>
<td>38.4750</td>
<td>38.7590</td>
<td>38.7620</td>
<td>38.1266</td>
<td>38.9244</td>
<td>38.7082</td>
<td></td>
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<tr>
<td>206Pb/204Pb</td>
<td>15.5393</td>
<td>15.5493</td>
<td>15.5495</td>
<td>15.5224</td>
<td>15.5498</td>
<td>15.5541</td>
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<td>15.5362</td>
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<tr>
<td>206Pb/204Pb</td>
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<td>38.691</td>
<td>38.332</td>
<td>38.431</td>
<td>38.724</td>
<td>38.737</td>
<td>39.085</td>
<td>38.821</td>
<td>38.626</td>
<td></td>
</tr>
<tr>
<td>206Pb/204Pb</td>
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<td>15.545</td>
<td>15.533</td>
<td>15.521</td>
<td>15.548</td>
<td>15.553</td>
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<tr>
<td>176Hf/177Hf</td>
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<td>0.28175</td>
<td>0.28326</td>
<td>0.283079</td>
<td>0.283097</td>
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<td>0.28308</td>
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<td>0.28306</td>
<td>0.283097</td>
<td>0.283196</td>
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<tr>
<td>176Hf/177Hf</td>
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<td>13.4</td>
<td>11.9</td>
<td>10.8</td>
<td>11.5</td>
<td>10.9</td>
<td>11.3</td>
<td>10.3</td>
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<tr>
<td>143Nd/144Nd</td>
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<td>0.512985</td>
<td>0.512962</td>
<td>0.512990</td>
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<tr>
<td>87Sr/86Sr</td>
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<td>0.703813</td>
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<td>0.703232</td>
<td>0.70316</td>
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6.2. Mantle source T and P conditions

We have also attempted to determine the pressure and temperature of the mantle source region of the basalt of the Siletz terrane (Supplementary Material 8). Due to the relatively low magnesium contents and abundant clinopyroxene fractionation, few of the samples are suitable for the calculations. The methods outlined in Lee et al. (2009), which are based on Si and Mg contents of the magma resulted in only 7 samples producing mantle temperature and pressures, while the PRIMELTS modelling software of Herzberg and Asimow (2015) produced results for 30 samples, 7 of which are in agreement with the temperature and pressure values obtained using the modelling of Lee et al. (2009). The results for these 7 samples were relatively consistent across the two techniques, producing a range of initial mantle potential temperatures (Tp) between ~1400 and 1500 °C and pressures between 1.5 GPa and 2.4 GPa (i.e., melting at less than 100 km). Mid-ocean ridge basalts display Tp ranges between ~1280 and 1400 °C, while intra-plate magmas are produced at Tp above ~1400 °C (Herzberg et al., 2007; Lee et al., 2009). The Tp conditions estimated for the Siletz terrane data therefore support a mantle plume related origin for the Siletz terrane. The PRIMELTS 3 modelling results also require an olivine addition of on average 3% which indicates that subsequent to melting of the source, the magma is likely to have undergone significant fractionation in a crustal magma chamber to generate the observed compositions.

The results of this modelling, in combination with the isotopic data discussed in the previous section, indicate that the melts forming the Siletz terrane were derived from a heterogeneous and partially enriched
mantle source, with an elevated temperature. The volume of melt produced (~2.6 × 10^6 km^3; Trehu et al., (1994)) is consistent with extensive mantle source, with an elevated temperature. The volume of melt produced between 25 and 33%), which are comparable to the expected melting calculated for the Ontong Java Plateau and the Caribbean Plateau (~30% melting) (Fitton and Godard, 2004; Herzberg and Gazel, 2009). PRIMELTS3 is also indicative of a hotter-than-ambient mantle source and depleted mantle (Fig. 7). The amount of melting modelled in PRIMELTS3 is also indicative of a hotter-than-ambient mantle source with melting percentages of ~27% (with the majority of samples producing results between 25 and 33%), which are comparable to the extent of melting calculated for the Ontong Java Plateau and the Caribbean Plateau (~30% melting) (Fitton and Godard, 2004; Herzberg and Gazel, 2009).

6.3 Tectonic implications

There have been many tectonic models proposed to explain the origin of the Siletz terrane and its resulting geochemical and physical characteristics. One model which may explain the characteristics of the Siletz terrane is its formation in a marginal basin setting (Brandon, 2014; Wells et al., 1984), yet this does not accurately explain the proposed geometry of the plates at the time of eruption (Wells et al., 2012; Müller et al., 1993; O’Neill et al., 2005). In addition to this, several plate reconstructions propose that the Yellowstone hotspot was present in this area at the time of the formation of the Siletz terrane (Doubrovine et al., 2012; Müller et al., 1993; O’Neill et al., 2005).

Volcanic ash layers/tuffs are typically unusual in oceanic plateaus (Kerr, 2014), while there are abundant volcanoclastic horizons throughout the terrane, especially in the upper subaerial flows. Progressive shallowing throughout the sequence from deep to shallow water subaerial environments indicates continual dynamic uplift by the plume (as well as accumulation of the lava pile) while also explaining the abundance of ash and volcanoclastic material. This has also been observed at other well-characterised mantle plume-related oceanic plateaus, such as in the Western Cordillera of Colombia, in the Caribbean Plateau (Kerr, 2014) and also in limited occurrences in the Ontong Java Plateau where tuff layers and sedimentary reworking occur (Mahoney et al., 2001).

The Siletz basalts are most depleted in the north and northeast, being more enriched than typical N-MORB. The depth of melting also appears to increase towards the centre of the terrane. Sample 073RB is the most western sample and additionally has the largest HIMU component.
Overall, the mantle characteristics of the Siletz terrane best represent mixing of depleted mantle with an additional enriched input from a mantle plume. The temperature of the primary magmas has been calculated at 1400–1500 °C, which is hotter than ambient mid-ocean-ridge related mantle. The enriched component and mantle plume source has been proposed to represent the Yellowstone hotspot (Fig. 8) (cf. Duncan, 1982; McCrory and Wilson, 2013; Wells et al., 2014). The depleted mantle source component recorded in the relatively depleted samples from the NE (the Metchosin Igneous Complex and Crescent Formation) is comparable to mid-ocean ridge source mantle (more extensive melting), most likely the Farallon–Kula/Resurrection ridge, and the off axis interaction of an additional hotter enriched mantle source region (Fig. 8). Alternatively, the depleted component may be sampling a depleted relatively refractory portion of the mantle plume (Kempton et al., 2000; Kerr et al., 1995).

6.4. Youngest oceanic plateau?

Oceanic plateaus represent vast areas of over-thickened predominantly basaltic oceanic crust (>5 × 10⁶ km²) the majority of which erupted over a few million years (Kerr, 2014). Elevated topography and greater crustal thickness in comparison with ‘normal’ oceanic crust lead to an increase in buoyancy in oceanic plateaus. Therefore, notably for plateaus that collide with subduction zones shortly after formation (~5 Ma), the probability of partial accretion to the adjacent upper continental plate margin and so preservation within the geologic record is greatly increased (Cloos, 1993). Accreted oceanic plateaus

Fig. 7. Initial isotope ratios of the Siletz terrane samples. Also plotted are age-corrected (53 Ma) isotope ratios for mantle components (Supplementary Material 7), PMM - Pacific MORB mantle (Chauvel and Blichert-Toft, 2001), DGM - Depleted Gorda MORB mantle (Davis et al., 2008; Salters et al., 2011), IM - Innaha mantle component (source of the primary Columbia River Flood basalts and thought to represent the Yellowstone hotspot; Wolff et al., 2008), CS - Cobb seamount chain (a series of seamounts located near the East Pacific Rise; Chadwick et al., 2014), and KFB - Karmutsen flood basalts of the Wrangellia terrane, Vancouver Island (Greene et al., 2009b). Also shown are compositional fields of the Ontong Java Plateau (OJP) (Mahoney et al., 1993a, 1993b; Tejada et al., 2002, 2004), Caribbean Plateau (CP) (Hastie et al., 2008; Hauff et al., 2000; Kerr et al., 1997, 2002b; Thompson et al., 2004), Kerguelen Plateau (KP) (Weis and Frey, 2002; Weis et al., 2002), the Hawaiian Islands (HI) (Garcia et al., 2010; Tanaka et al., 2002; Weis et al., 2011) and the Samoan Islands (SI) (Salters et al., 2011; Workman et al., 2004). Error bars for the Siletz terrane data are smaller than the symbols. Binary mixing curves between DGM and the Innaha mantle component, EM2 and HIMU mantle components are also shown, where each increment represents 10% addition of the mixing component to the DGM.
have had a significant role in the growth of the continental crust; however, secondary processes such as deformation and burial lead to difficulties in the recognition of their characteristics once accreted (Kerr et al., 2000). Despite this, many examples of crustal growth through oceanic plateau accretion have been recognised in the geological record, including sections of the Wrangellia terrane (Greene et al., 2009a, 2009b), which along with the Siletz terrane highlights the role of oceanic plateaus in the growth and evolution of the western margin of North America.

Several well-characterised oceanic plateaus have similar heterogeneous trace element compositions to the Siletz terrane, e.g., the Cretaceous Caribbean plateau (Kerr and Mahoney, 2007) and the Late Triassic (ca. 225–231 Ma) Karmusten flood basalts of Vancouver Island and Alaska (Greene et al., 2009a, 2009b). In contrast, the largest oceanic plateau, the Cretaceous Ontong Java Plateau, is more depleted and anomalously homogeneous in composition (Fitton and Godard, 2004) (Figs. 4 and 6). While geochemistry alone cannot be used to distinguish oceanic plateaus in the geological record, their Nb/La ratio is often ~1 (Kerr, 2014), and this is generally reflected in the Siletz terrane data, which clusters between ratios of 1 and 1.5. Samples also show similar flat-to-LREE-enriched patterns with no significant Nb-Ta depletions or Th enrichments (Fig. 5).

Features of the terrane which support an oceanic plateau origin include: moderately enriched isotopic compositions, flat to slightly enriched REE patterns and the vast size and magmatic volume of the terrane (estimated to be 2.6 × 10⁶ km³; Trehu et al., 1994), the bulk of enriched REE patterns and the vast size and magmatic volume of the terrane. The enriched components may therefore represent melting from a heterogeneous and partially enriched mantle source with an above ambient temperature. This source composition is comprised of a relatively depleted signature and EM2- and HIMU-like enrichments. The enriched components may therefore represent melting of a heterogeneous mantle plume, possibly the Yellowstone Hotspot, which likely interacted with a mid-oceanic ridge, the Kula–Farallon (or Farallon–Resurrection) ridge.

5. Although individually, the geochemical signatures and physical characteristics of the Siletz terrane can be interpreted differently, when taken together, the evidence for the Siletz terrane representing an accreted oceanic plateau linked to a mantle plume is compelling.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.lithos.2017.01.005.

References
