The High Arctic LIP in Canada: Trace element and Sm–Nd isotopic evidence for the role of mantle heterogeneity and crustal assimilation

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The Cretaceous geological evolution of the Canadian Arctic was marked by voluminous magmatism comprising Canada's portion of the High Arctic large igneous province (HALIP) that is thought to have resulted from a mantle plume head. This magmatism is largely recorded as extensive Early Cretaceous lavas of the Isachsen Formation, Late Cretaceous continental flood basalts of the Strand Fiord Formation, and an extensive network of dykes and sills forming their plumbing systems. Axel Heiberg Island near South Fiord contains a small, structurally complex portion of the overall network of HALIP tabular intrusions, from which samples from the South Fiord intrusions and Isachsen Formation basaltic lavas were analysed to better understand their petrogenesis. Specifically, we apply trace-element ratios together with Sm–Nd isotope systematics in order to identify processes that shaped the chemical evolution of the South Fiord intrusions and Isachsen Formation lavas, to identify (1) mantle source chemistries and (2) the role of crustal assimilation. On the basis of Sm–Nd isotopic results, South Fiord intrusion magmas were derived from a homogeneous mantle source whereas a more heterogeneous source is invoked for the Isachsen Formation lavas. Furthermore, modelling with Th/La, Nb/U, Ba/Th and Ba/Nb suggests that South Fiord intrusive magmatism was contaminated by sedimentary rocks from the Sverdrup Basin. Conversely, a trend towards high Ba/Th in Isachsen Formation lavas suggests a subducted sediment component derived from extinct subduction zones. We surmise that (1) South Fiord intrusive rocks are geochemically distinct from the Isachsen Formation lavas and (2) the HALIP mantle plume head intersected and incorporated sediments from ancestral subduction zones to the present-day Aleutian and Alaska subduction zones to produce the Isachsen Formation flows, whereas the South Fiord intrusions (and correlated Strand Fiord magmatism) were generated from plume material that interacted with upper crustal sedimentary rocks.

Keywords: Large Igneous Provinces, geochemistry, Sverdrup Basin, Strand Fiord Formation, Isachsen Formation

Electronic Supplement 1: Major and trace element data

Electronic Supplement 2: Sm–Nd isotopes

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Introduction

The Mesozoic geodynamic evolution and the timing of tectonic events leading to the present-day configuration of the Arctic Ocean and its margins represent one of the last major ocean basin-scale puzzles to be understood in elucidating post-Pangaea rifting events. The Circum-Arctic landmasses of Canada, Norway and western

Siberia (Russia) along with offshore regions (for example, the Alpha–Mendeleev Ridge) are endowed with extensive mafic dyke swarms, sill provinces and lavas of Cretaceous age that have historically been amalgamated into, and been understood as fragments of, a once-contiguous 'High Arctic large igneous province' (HALIP) (Fig. 1; Maher, 2001; Drachev & Saunders, 2006).

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Figure 1. Pan-Arctic map showing distribution of dykes (red lines) as well as lavas and sills (orange-red shading) ascribed to the High Arctic LIP (Jowitt et al., 2014) exposed on land. Red star denotes probable location of mantle plume from Buchan & Ernst (2006). Black shading denotes the unrelated and younger North Atlantic Igneous Province. Dyke swarm distribution from Buchan & Ernst (2006). The orange circular anomaly along with stippled red lines in the Arctic Ocean, denoting aeromagnetic anomalies, are from Døssing et al. (2013). Black irregular thin stippled line on the Canadian side outlines the Sverdrup Basin. 'W' on northern Ellesmere Island represents location of the Wootton igneous complex, a part of the HALIP and is discussed in the text. Abbreviation: Q.E.I – Queen Elizabeth Islands.

Giant mafic dyke swarms are a major constituent of HALIP, largely in Canada but significant tabular intrusions also exist on Svalbard (Nejbert et al., 2011; Senger et al., 2014) and Franz Josef Land (Bailey & Brooks, 1988 and references therein; Amundsen et al., 1998). In the Canadian Arctic islands, the Queen Elizabeth Islands dyke swarm is a radiating swarm of ~500 km in maximum length that strikes in a radiating pattern towards a focus situated just off the northern coast of Ellesmere Island (Fig. 1). These dyke swarms, along with evidence of Cretaceous domal uplift centred north of Svalbard (Maher, 2001), suggest that HALIP was fed by a mantle plume head centred north of Ellesmere

Island near the Alpha Ridge (e.g., Ernst & Buchan, 2003; Maher, 2001).

The Canadian component of HALIP is associated with the Cretaceous tectonic rejuvenation of the Sverdrup basin, a long-lived epicontinental sedimentary basin that developed between the Carboniferous and the end of the Cretaceous (Fig. 2; Embry & Osadetz, 1988; Embry, 2011). Whereas much of the Sverdrup Basin evolution was by way of passive subsidence coupled with periods of uplift, this state of development was punctuated by two major active episodes: an initial active rifting which marks initial basin formation in the Carboniferous, and

Figure 2. Outline map of the Sverdrup Basin showing study sites of South Fiord (intrusives + 1 lava flow, this study) Geodetic Hills and Camp Five Creek for the Isachsen Formation lavas. Outline colours of the triangles keyed to symbol colour used in geochemical plots. Black dots represent wells drilled (Embry & Beauchamp, 2008). 'TH' denotes Tanquary High and the large open arrows pointing north-northwest south of the basin denote sediment provenance (map modified from Embry & Beauchamp, 2008).

a second rejuvenated period of subsidence during the interval between the Early Cretaceous and Cenomanian (Embry & Beauchamp, 2008). Mounting evidence from elsewhere on the globe strongly suggests that in many cases, but not all, LIPs herald major breakup events, such as the 201 Ma Central Atlantic Magmatic Province, the 135 Ma Parana–Etendeka LIP and the 60 Ma North Atlantic Igneous Province for the staged rifting of the central, southern and northern Atlantic Ocean, respectively (White & McKenzie, 1989; Milner et al., 1995; Peate, 1997; Courtillot et al., 1999; Marzoli, 1999; Smallwood & White, 2002; Ernst, 2014).

On the basis of previous stratigraphic work (Embry & Osadetz, 1988), four Cretaceous HALIP volcanic cycles occurred within Canada (Fig. 3): (1) Paterson Island Member of the Isachsen Formation (Valanginian–Early Barremian); (2) Walker Island member of the Isachsen Formation (Late Barremian–Aptian); (3) Strand Fiord Formation (Late Aptian–Early Cenomanian); and finally (4) Hansen Point volcanics (Late Cenomanian–Maastrichtian; Embry & Osadetz, 1988). Cycles 1, 2, 3 and 4 correspond with approximate numerical ages of 130 Ma, 120 Ma, 100 Ma and 85 Ma (Embry & Osadetz,

1988; Cohen et al., 2013). The HALIP historically has been divided into two chemical suites: a tholeiitic suite from 130 to 80 Ma and younger alkaline suite from 85 to 60 Ma (Tegner et al., 2011). In the Canadian component of HALIP, the tholeiitic suite corresponds with events 1–3 (Isachsen Formation and the Strand Fiord Formation) whereas the alkaline suite is represented by event 4 (Hansen Point Volcanics; Embry & Osadetz, 1988; Williamson, 1988; Jowitt et al., 2014).

Earlier age studies using the K–Ar and Ar–Ar methods suggested that a pulse of magmatism occurred in the Canadian Arctic from 112 Ma to 152 Ma along with a later pulse associated with the Strand Fiord Formation lavas from 95 Ma to 100 Ma (Villeneuve & Williamson, 2006 and references therein). In Svalbard, K–Ar ages from sills suggest magmatism occurred between 80 and 125 Ma with a peak at 117 Ma, and an Ar–Ar age of 120 Ma was recently determined from a sill in Svalbard (Nejbert et al., 2011; Polteau et al., 2016).

A small and growing number of U–Pb ages on tabular doleritic intrusions along with the gabbroic Wootton Igneous Complex (northern Ellesmere Island) are

clarifying and constraining ages from earlier K–Ar and Ar–Ar studies and yield evidence of magmatic activity between 121–126 Ma and ~92 Ma (Trettin & Parrish, 1987; Corfu et al., 2013; Estrada & Henjes-Kunst, 2013; Evenchick et al., 2014, 2015) map compilation, geochemistry, geochronology, and potential field data to document six intervals of Cretaceous magmatism in the central Sverdrup Basin. These are: 1. On the Eurasian side of the Arctic (Svalbard, Norway and Franz Josef Land, Russia) U–Pb ages from four diabasic sills (two each from Svalbard and Franz Josef Land) along with a bentonite ash layer yield a tight age range from 122 to 126 Ma (Corfu et al., 2013). In Canada, three U–Pb ages from two diabasic sills and a single pyroclastic unit are 105 Ma (pyroclastic unit), 120 and 126 Ma (two sills) on Ellef Ringnes Island (Evenchick et al., 2014, 2015) map compilation, geochemistry, geochronology, and potential field data to document six intervals of Cretaceous magmatism in the central Sverdrup Basin. These are: 1 which suggests that magmatism was longer lived when compared with the age range on the Eurasian side. In addition to the 120–125 Ma pulse of magmatism scattered about the Arctic Margins, a younger episode of mafic magmatism ensued approximately 30 myr later, largely affecting the Canadian side of the Arctic Ocean. Two separate studies on the gabbroic and microgranitic Wootton Igneous Complex, located along the extreme northern Ellesmere

Island coast, yielded U–Pb ages of 92.0 ± 1.0 Ma (Trettin & Parrish, 1987) and 92.1 ± 0.1 Ma (Estrada & Henjes-Kunst, 2013) on the gabbroic component, as well as 92.7 ± 0.3 Ma on three microgranite samples (Estrada & Henjes-Kunst, 2013).

On the basis of trace element and precious metal analysis, the Canadian component of HALIP was divided into ‘tholeiitic’ and ‘mildly alkaline’ groups (Jowitt et al., 2014). Initial Sm–Nd isotopic analyses on the younger volcanic suite (Strand Fiord Formation lavas) and the older volcanic suite (Isachsen Formation lavas) suggest that they were both derived from an upper mantle source (Estrada & Henjes-Kunst, 2004). The tholeiitic rocks may have Ni–Cu–PGE potential owing to trace element evidence of crustal assimilation along with variable precious metal ratios (Jowitt et al., 2014).

One powerful tool that may be used in assessing whether these igneous rocks from Canada and Russia are petrogenetically related HALIP fragments is Sm–Nd isotope geochemistry. In Canada, Nd isotopic data are available in the literature for four flows from the Early Cretaceous Isachsen Formation Basalts and four lavas from the earliest Late Cretaceous Strand Fiord Formation basalts (Estrada & Henjes-Kunst, 2004). In Franz Josef Land, Russia, two independent studies have reported on com-

Figure 3. Stratigraphic sequence of the Cretaceous component of the Sverdrup Basin highlighting the younger Strand Fiord Formation lavas (in orange) and the older Isachsen Formation lavas (in blue). Original diagram from Embry & Osadetz (1988). Orange and blue colours of the Strand Fiord Formation and Isachsen Formation lavas, respectively, are used for the geochemical plot symbols in the results and discussion sections.

Figure 4. (A) Map showing Axel Heiberg Island (orange) and the location of the 2013 South Fiord field area. (B) False-colour Landsat-7 satellite imagery of the South Fiord area showing locations of field sites (this study) and previously-mapped representative dykes of HALIP swarms (Buchan & Ernst, 2013).

bined 31 Sm–Nd analyses of mafic rocks (Amundsen et al., 1998; Levskii et al., 2006). Herein, we present trace-element data along with 20 new Sm–Nd isotopic analyses derived from samples collected from western Axel Heiberg Island in the vicinity of South Fiord during a field expedition in 2013 (Figs. 2 & 4) and from previously-collected samples of Isachsen Formation flows at Geodetic Hills, central Axel Heiberg Island and Camp Five Creek, northwestern Axel Heiberg Island (Fig. 2) during a previous field season (Williamson, 1988). These data allow characterisation of the geochemistry of mantle sources for HALIP, as well as post-melting processes which may have affected the initial chemistry of these melts. Did primary magmas interact with specific lithospheric mantle or crustal material, and if crustal interaction did occur was it with basement rocks of continental crust (i.e., cratonic), or with the sedimentary packages that overlie the cratonic basement? Finally, since volcanism associated with the younger Strand Fiord Formation or older Isachsen Formation lavas was fed through a network of dominantly tabular intrusions, we aim to determine whether the tabular intrusions in the vicinity of South Fiord (described below) were feeders of the Strand Fiord Formation and/or the Isachsen Formation lavas.

Methods

Field and sampling methods

Approximately 40 samples were collected from sills and dykes in the South Fiord area with thicknesses typically less than 10 m, as well as one lava flow of the Isachsen

Formation (Kingsbury et al., 2014). However, owing to such factors as deformation due to intruding evaporitic diapirs (e.g., South Fiord Dome; Fig. 4), as well as Paleocene–Eocene Eurekan orogenic deformation (Embry & Beauchamp, 2008), coupled with cyclic freeze-thaw processes, much of the topography consists of ridges mantled with talus. Thus, it was typically challenging to determine whether intrusions were conformable with or cross-cut sedimentary bedding. Samples were collected from both chilled margins and centres of the intrusions with a field appearance varying from aphanitic to phaneritic (crystals <1 cm in long dimension). One sample, collected from the exposed upper part of a ~50 m sill, stood out in being phaneritic with crystals as large as 1 cm in the long dimension. In addition to these samples from the South Fiord area, 19 supplemental samples of Isachsen Formation lavas from Geodetic Hills and Camp Five Creek were included in the sample set (locations shown in Fig. 2; Williamson, 1988; Williamson, unpublished data).

Major and trace elements

Rock samples were cut with a continuous-rim diamond-impregnated saw ensuring that all weathered surfaces were removed. A small section of a slab from each rock was made into a thin-section puck whereas another small section was allocated to precontaminate the crusher prior to each run, thereby reducing the risk of cross-contamination. Each slabbed rock was crushed in a Bico® WD Chipmunk crusher and sieved through a 10 mesh sieve (maximum chip size 2 mm). After each sample is crushed, the crusher was cleaned thoroughly using water and ethyl alcohol and dried to further ensure that cross-contamination was minimised. Crushed sample

was then pulverised using a Rocklabs® shatterbox fitted with an agate mill head. Three runs of two minutes each per sample at 750 revolutions per minute were done and include one precontaminate run and two aliquots each of ~10 grams for each sample. In order to prevent cross-contamination at this step, the agate mill was vigorously cleaned with water and dried with paper towels, then air-dried, and wiped with ethyl alcohol after each sample was processed. In addition, prior to the first sample run and after every fifth sample, to ensure cleanliness of the agate mill, a run with 95%-pure silica sand was processed. Three batches of samples, each with an internal standard (10–LT–05, a basaltic andesite from Lake Tahoe, California) were sent to ALS Geochemistry laboratories in North Vancouver, BC (<http://www.alsglobal.com>) for major element analysis via Inductively Coupled Plasma Atomic Emissions Spectrometry (ICP–AES) as well as trace and rare-earth element (REE) analysis via Inductively Coupled Plasma Mass Spectrometry (ICP–MS). Trace-element analytical uncertainties (1σ) for ALS Geochemistry laboratories based on repeat analysis of the Lake Tahoe internal standard are less than 1 ppm with the exception of Ba (15.8 ppm), Ce (2.0 ppm), Cr (12 ppm), Sr (16.0 ppm), V (8 ppm), Zr (5 ppm), Co (1.6 ppm), Cu (2.71 ppm), Ni (4.8 ppm), Pb (1.6 ppm) and Zn (3 ppm). MgO analytical uncertainty (1σ) is 0.09 wt. %.

Nd and Sr Isotopes

Rock powders were spiked with a mixed ^{148}Nd – ^{149}Sm spike before being dissolved in a mixed solution of ~29 M HF and ~16 M HNO_3 . The samples were then dried down on a hotplate before being redissolved with 8 M HNO_3 and 6 M HCl sequentially. The dried residue of each sample was finally dissolved in 2.5 M HCl prior to being loaded onto 14-ml Bio-Rad borosilicate glass chromatography columns containing 3.0 ml of Dowex AG50W–X8 cation resin. Strontium and REE were eluted with 2.5 N HCl and 6 M HCl, respectively. REE fractions were then dissolved in 0.26 M HCl and loaded onto Eichrom Ln Resin chromatographic columns containing Teflon powder coated with HDEHP [di(2-ethylhexyl) orthophosphoric acid], (Richard et al., 1976). Nd was eluted with 0.26 M HCl, followed by Sm with 0.5 M HCl.

The isotope ratios were measured using a Thermo Finnigan Triton thermal ionization mass spectrometer (TIMS) housed at the Isotope Geochemistry and Geochronology Research Centre, Carleton University, Ottawa Canada. Nd and Sm fractions were loaded with H_3PO_4 onto one side of a double rhenium filament assembly. The isotope ratios were measured at temperatures of 1700–1800°C and are normalised to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. An Isotope Geochemistry and Geochronology Research Centre (IGGRC)'s in-house Nd standard was routinely measured and an average value of the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio was 0.511826 ± 0.000007 (1σ) over a period of three

years; this value is equivalent to $^{143}\text{Nd}/^{144}\text{Nd} = 0.511855$ reported for the La Jolla Nd standard. Sm and Nd concentrations were measured precisely within 1%, whereas $^{147}\text{Sm}/^{144}\text{Nd}$ ratios are reproducible to 0.5%. Analyses of the USGS standard BCR–1 yield Nd = 29.02 ppm, Sm = 6.68 ppm, and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512668 \pm 0.000010$ (1σ , $n = 4$). Total procedural blanks for Nd were less than 100 pg. Sr fractions were loaded onto single tantalum filaments with H_3PO_4 and ionised at filament temperatures of 1350–1400°C. Strontium isotope ratios were normalised to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$. NBS987 was routinely measured and an average of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio = 0.710245 ± 0.000020 (2σ) for a period of three years. Total procedural blanks for Sr were less than 250 picograms.

Results

Petrography

Thin-section analyses of samples reveal that rocks from South Fiord intrusions and Isachsen Formation lavas show primary igneous textures and igneous mineral assemblages typical of mafic rocks. In terms of primary igneous mineralogy, the bulk of the volume (>90 vol.%) consists of plagioclase feldspar and clinopyroxene (Fig. 5). Olivine is either absent or rarely present in trace amounts in less differentiated samples. Free quartz exists in trace amounts in more chemically evolved samples, particularly the sample collected from the top of the >50 m-thick sill (Fig. 5A). Ilmenite and magnetite are present in varying quantities. South Fiord intrusive rocks typically display subophitic textures (Fig. 5C, D) whereas lavas are characterised by mm-sized plagioclase phenocrysts in a groundmass of plagioclase and clinopyroxene (Fig. 5D–E). Whereas many samples are fresh (Fig. 5B, D, E), some show some degree of secondary alteration, saussuritised plagioclase and amphibole-after-clinopyroxene replacement (Fig. 5C, F). Such evidence of alteration likely caused varying degrees of mobility of large ion lithophile elements and silica. Therefore, this study relies on the systematics of the more immobile high field strength elements and REE rather than total-alkali silica systematics (cf., LeBas et al., 1986).

Major and trace elements

With one exception, all samples collected near South Fiord, Camp Five Creek and Geodetic Hills (raw data available in Electronic Supplement 1) are chemically classified as subalkaline basalts on the basis of Nb/Y vs. Zr/Ti systematics (Fig. 6A; Pearce & Norry, 1979). The exception plots as basaltic andesite (Fig. 6A) and was collected from the upper portion of a ~50 m-thick sill near South Fiord. When the intrusive rocks collected in the South Fiord locality are compared with Isachsen

South Fiord intrusives

Isachsen Formation lavas

Figure 5. Crossed-polar photomicrographs of samples from the South Fiord intrusives (A–C) and Isachsen Formation lavas (D–F) with sample ID numbers included. (A) sample of gabbro of basaltic andesite composition from the >50 m sill, (B) representative sample of fresh subophitic dolerite, (C) representative subophitic dolerite showing alteration of primary mineralogy; (D–E) representative unaltered lavas showing phenocrysts of plagioclase within a groundmass of plagioclase and clinopyroxene, (F) Isachsen Formation lava showing extensive alteration of plagioclase phenocrysts and in the groundmass to clay. Key to mineral ID: Pl – plagioclase, Cpx – clinopyroxene, Qtz – quartz, Ox – oxides.

Formation lavas from Camp Five Creek and Geodetic Hills, the two suites not only plot largely as subalkaline basalts, but display nearly identical Nb/Y vs. Zr/Ti compositional ranges. Furthermore, in a Nb/Yb vs. Th/Yb plot, the South Fiord intrusions along with Isachsen formation lavas plot slightly above the E–MORB section of the MORB–OIB diagonal array (Fig. 6B; Pearce, 2008). This indicates that the parental magmas and lavas (a) had chemistries consistent with E–MORB and (b) that there has been some degree of interaction with crustal material.

The ratio Tb/Yb normalised to primitive mantle values (McDonough & Sun, 1995, herein symbolised as Tb/Yb_N) can be used to elucidate depth of partial melt (Wang et al., 2002). $Tb/Yb_N > 1.8$ are interpreted to signify melting of the mantle within the garnet stability field, whereas $Tb/Yb_N < 1.8$ signify melting in shallower (<75 km) spinel lherzolite although values close to 1.8 likely melted both garnet and spinel lherzolitic components (Wang et al., 2002). Tb/Yb_N of intrusive samples from the South Fiord region cluster tightly between ~1.3 and ~1.5 with one sample having a lower Tb/Yb_N of 1.1 (Fig. 7). The Tb/Yb_N values of Isachsen Formation lavas from the South Fiord area largely overlap with those from Camp Five Creek and those from Geodetic Hills with the South Fiord intrusives, but there are a significant number of

samples with higher ratios (1.6–1.8). Collectively, these data indicate that both the South Fiord intrusions and the Isachsen Formation lavas were derived by melting in shallow spinel lherzolite mantle. However, the higher Tb/Yb_N displayed by many samples from the Isachsen Formation lavas indicate that melting likely occurred over a wider range of depths, some of which approach the spinel–garnet stability transition of ~75 km.

Fig. 8 shows the relationship between Gd/Yb (higher values signify melting in the garnet stability field) and La/Sm (higher values signify greater source enrichment, crustal assimilation and/or a lower degree of partial melting) (e.g., Pearce, 2008). The Isachsen Formation basalts can be divided into two groups: one displaying low La/Sm and a second displaying higher La/Sm. These two groups show little variation of La/Sm and a wide variation of Gd/Yb within each group. This suggests the Isachsen Formation lavas formed during melting of the mantle at varying depths (see also Fig. 7) and additionally suggests little change in the degree of partial melting. Conversely, intrusive rocks from the South Fiord locality display a comparatively narrow Gd/Yb range (occupying the lower half of the Isachsen Formation basalt array) and a wider range in La/Sm, suggesting that South Fiord magmas formed in a relatively restricted depth range.

Figure 6. (A) Nb/Y vs. Zr/Ti classification of lavas and intrusive rocks in this study based on the scheme of Pearce & Norry (1979). Data normalised on a volatile-free basis. The one sample in the andesite field is the highly differentiated gabbro whereas the Strand Fiord Formation lavas plot with the South Fiord intrusives and Isachsen lavas but are hidden from view. (B) Nb/Yb vs. Th/Yb classification systematics of Pearce (2008). Note that all samples plot above E-MORB signifying magma-crust interaction. Key to reference footnote: [1] – Jowitt et al. (2014).

Figure 7. Mg# vs. Tb/Yb(N) diagram. Note that the Isachsen Formation lavas display chemical evidence of deeper melting than those of the South Fiord intrusives and the Strand Fiord Formation lavas. Tb/Yb values are normalised to McDonough & Sun (1995) and the spinel-garnet transition line is from Wang et al. (2002). Symbols used herein are the same as in Fig. 6.

Fig. 9 compares the chondrite-normalised REE patterns (Sun & McDonough, 1989) of the South Fiord intrusives (Fig. 9A) with the Isachsen Formation lavas (Fig. 9B). Both suites show enrichment of light REE relative to the heavy REE, with patterns similar to those of E-MORB (Sun & McDonough, 1989), in addition to small negative euro-

pium anomalies that signify fractionation of plagioclase. Whereas the ranges of La/Sm in rocks of the South Fiord intrusives and the Isachsen Formation lavas are similar, the South Fiord intrusive rocks exhibit a smaller range in La/Sm. Both the South Fiord intrusives and the Isachsen formation lavas have low Gd/Yb indicative of shallow

Figure 8. Gd/Yb vs. La/Sm plot showing the evolutionary trends of Isachsen Formation lavas, the South Fiord intrusives and Strand Fiord Formation lavas (data from Jowitt et al., 2014). Note the wider range of Gd/Yb of the Isachsen Formation lavas when compared to the South Fiord intrusives and Strand Fiord Formation lavas, signifying a greater range of melting depth. Conversely, the wider range of La/Sm on the part of the South Fiord intrusives and Strand Fiord formation lava would suggest an enrichment trend. Full discussion in the text. Symbols used herein are the same as in Fig. 6.

Figure 9. Chondrite-normalised REE diagrams normalised following the values given in Sun & McDonough (1989). (A) South Fiord intrusives and (B) Isachsen Formation lavas.

melting in the spinel stability field, but there is a subpopulation of Isachsen Formation lavas that has slightly higher Gd/Yb ratios, indicating that a portion of Isachsen magmatism may have formed in the garnet stability field. Primitive mantle-normalised (Sun & McDonough, 1989) incompatible element patterns in Fig. 10 show that the South Fiord intrusions (Fig. 10A) and Isachsen Formation lavas (Fig. 10B) have broadly similar patterns. They both show negative anomalies in Sr and P. Furthermore, some samples of the South Fiord Intrusive rocks and the Isachsen Formation lavas show small negative Nb–Ta anomalies but there is a population of samples of both having negative K anomalies (adjacent to Ta) which masks the overall appearance for those samples dis-

playing the Nb–Ta anomaly. One feature in which the Isachsen Formation lavas as a group diverge from the South Fiord intrusions is that the Isachsen Formation lavas have more prominent negative anomalies in the large-ion lithophile elements (Rb, K, Sr) as well as less prominent positive Pb anomalies.

With the exception of a chemically evolved gabbro (MgO = 1.5 wt.%), MgO contents in the South Fiord intrusions range from 3 to 5 wt.% (Fig. 11). Isachsen Formation lavas have MgO contents from 1.5 to 6 wt.%. Relative to oceanic basalts, these MgO contents are indicative of chemically evolved rocks that have experienced fractionation of mafic minerals. All but one sample of the South

Figure 10. Trace-element ratio diagrams normalised to primitive mantle of Sun & McDonough (1989). (A) South Fiord intrusives and (B) Isachsen Formation lavas.

Figure 11. (A) MgO (wt.%) vs. Sc (ppm) variation plot showing how South Fiord intrusives, Isachsen formation lavas and Strand Fiord formation lavas evolve with respect to clinopyroxene fractionation. Note that Isachsen formation and Strand Fiord formation lavas show a moderate fractionation trend. (B) MgO (wt.%) vs. Ni (ppm) variation plot showing how South Fiord intrusives, Isachsen formation lavas and Strand Fiord formation lavas evolve with respect to olivine fractionation. Note strong olivine fractionation trend for the South Fiord intrusives and Strand Fiord formation lavas, but no obvious olivine fractionation detectable for the Isachsen formation lavas. Key to reference footnote: [1] – Jowitt et al. (2014).

Fiord intrusive rocks and all Isachsen lavas have Sc contents from 29 to 59 ppm (Fig. 11A) (the evolved gabbro contains 21 ppm Sc). Most of the Isachsen Formation lavas have lower Sc in more evolved (lower MgO) lavas suggesting that clinopyroxene was a major fractionating phase. The Strand Fiord Formation lavas (Jowitt et al., 2014) also show a clinopyroxene fractionation pattern like the Isachsen Formation lavas. The South Fiord intrusions, however, show no obvious clinopyroxene fractionation trend. Ni contents (Fig. 11B) for the South Fiord intrusions are <50 ppm whereas higher concentrations of up to 80 ppm are recorded for the Isachsen Formation lavas, and would indicate that the Isachsen Forma-

tion lavas are less evolved. Furthermore, in these Isachsen lavas there is no consistent correlative trend between Ni and MgO. On the other hand, the Strand Fiord formation lavas (Jowitt et al., 2014) have Ni contents largely overlapping with the South Fiord intrusions (20–55 ppm) and in both cases show a clear positive correlation (increasing Ni with commensurate increase in MgO).

Fig. 12 shows the relationship between Ba/Th and Ba/Th. The South Fiord intrusive rocks have Ba/Nb ratios between 0.5 and 16 whereas the Isachsen Formation lavas display a much wider range of 0.5–39. Most of the Isachsen Formation lavas are enriched in Ba compared to

Nb and especially Th when compared to the South Fiord intrusions. Furthermore, the Isachsen Formation Lavas display a strong positive correlation between Ba/Nb and Ba/Th whereas the South Fiord intrusions show a positive correlation, yet are more clustered as a reflection of the limited range in Ba/Nb and Ba/Th values. Compared to average E–MORB (Ba/Nb = 7; Ba/Th = 95; Sun & McDonough, 1989), the South Fiord intrusions are low in Ba/Th whereas Isachsen Formation lavas are both low and high in Ba/Th. A majority of the South Fiord intrusions and the Isachsen Formation lavas are enriched in Ba/Nb compared to average E–MORB values. Finally, when compared with the weighted compositional average of Sverdrup Basin sedimentary rocks (Ba/Nb = 36; Ba/Th = 40; Patchett et al., 2004), most samples from both South Fiord intrusives and Isachsen Formation

Lavas are high in Ba/Th whereas all samples except for two Isachsen Formation lavas are low in Ba/Nb.

Fig. 13 is a plot showing the relationship between Th/La and Ba/Th in the South Fiord intrusions, Strand Fiord Formation lavas (Jowitt et al., 2014) and Isachsen Formation lavas. The South Fiord intrusions, Strand Fiord Formation lavas (Jowitt et al., 2014) and a part of the Isachsen Formation lavas show a wide range in Th/La (0.13–0.25) with near uniform Ba/Th ratios (~60). Furthermore, these data plot between E–MORB (Sun & McDonough, 1989) and the weighted average composition of sedimentary rocks of the Sverdrup Basin (Patchett et al., 2004). The remainder of the Isachsen Formation lavas (about half of the total Isachsen Formation sample set herein presented) have near uniform Th/La ratios

Figure 12. Ba/Nb vs. Ba/Th plot showing distribution of data for the South Fiord intrusives, the Isachsen Formation lavas as well as the Strand Fiord Formation lavas. E–MORB point derived from Sun & McDonough (1989) whereas the Sverdrup Basin point is a weighted average (described in the text) from Patchett et al. (2004). Key to reference footnote: [1] – Jowitt et al. (2014).

Figure 13. Th/La vs. Ba/Th plot showing distribution of data for the South Fiord intrusives, the Isachsen Formation lavas as well as the Strand Fiord Formation lavas. E–MORB point derived from Sun & McDonough (1989) whereas the Sverdrup Basin point is a weighted average (described in the text) from Patchett et al. (2004). Key to reference footnote: [1] – Jowitt et al. (2014).

(~0.14) but have a comparatively wide range in Ba/Th (60–220).

Nd Isotopes

For this study, we performed Nd Isotopic analyses on 8 samples from the South Fiord intrusions, two samples from an Isachsen lava flow exposed in the South Fiord region, and 10 samples of Isachsen Formation lavas collected in Geodetic Hills and Camp Five Creek (Williamson, 1988) (Electronic Supplement 2).

The South Fiord rocks range in present-day $^{143}\text{Nd}/^{144}\text{Nd}$ from 0.51265 to 0.51285, $^{147}\text{Sm}/^{144}\text{Nd}$ from 0.145 to 0.160, and display a modestly-scattered positive correlation on a $^{147}\text{Sm}/^{144}\text{Nd}$ vs. $^{143}\text{Nd}/^{144}\text{Nd}$ diagram (Fig. 14). When age-corrected to 105 Ma (average of expected range main pulses between c. 95 and 120 Ma), ϵNd_t ranges from +1 to +4.5. Relative to the Isachsen Formation lavas (described below), less scatter exists in either $^{147}\text{Sm}/^{144}\text{Nd}$ or $^{143}\text{Nd}/^{144}\text{Nd}$ as one moves from high to low $^{143}\text{Nd}/^{144}\text{Nd}$ for the South Fiord intrusions. The South Fiord intrusive rocks overlap with the Strand Fiord formation lavas (Estrada & Henjes-Kunst, 2004) suggesting a common source and common evolutionary processes. In contrast, the Isachsen formation lavas show a high degree of scatter in $^{147}\text{Sm}/^{144}\text{Nd}$ (0.14–0.17) in lavas with the highest $^{143}\text{Nd}/^{144}\text{Nd}$. The most primitive South Fiord intrusive sample (13_WJA_C032A, MgO = 4.9 wt.%) has a $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.512808 whereas the most primitive Isachsen Formation lava selected for Nd isotopic analyses (AX85–263, MgO = 5.9 wt.%) has an $^{143}\text{Nd}/^{144}\text{Nd}$ of 0.512896 (Fig. 14).

The South Fiord intrusions, along with the Strand Fiord Formation lavas (Estrada & Henjes-Kunst, 2004), appear to form a scattered Sm–Nd errorchron in Fig. 14. Using equation 4.11 of Faure & Mensing (2005), we calculate an Sm–Nd errorchron age of 1.318 ± 0.6 Ga (2σ , MSWD = 38) for the South Fiord intrusions [2σ uncertainties from Ludwig (1991)]. This age is significantly older than the 130–90 Ma emplacement ages obtained from U–Pb studies on HALIP intrusions and thus at best constitutes an errorchron. We also calculated Sm–Nd model ages, using a modern depleted mantle $^{143}\text{Nd}/^{144}\text{Nd} = 0.513115$ and $^{147}\text{Sm}/^{144}\text{Nd} = 0.2140$ and assuming a linear mantle depletion beginning at 4.5 Ga, and then plotted model ages against ϵNd_t (Fig. 15). The South Fiord intrusions have Sm–Nd model ages between 800 and 1000 Ma, and we note a general increase in Sm–Nd model age with ϵNd_t in these samples. Sm–Nd model age determinations for the Isachsen formation lavas range from 600 to 1100 Ma, which is a wider age range than that of the South Fiord intrusions. Our South Fiord Nd model age determinations are similar to previously published values (Estrada & Henjes-Kunst, 2004) with the exception of one having a model age of ~2200 Ma. The range in model ages for the Isachsen Formation lavas from this study and that of Estrada & Henjes-Kunst (2004) are also similar.

Discussion

We have established that all Isachsen Formation lavas and nearly all South Fiord intrusive rock samples are subalkaline basalts based on the Pearce & Norry (1979) classification (Fig. 6A). A coarse-grained gabbroic

Figure 14. Sm–Nd whole-rock errorchron diagram. Annotated samples (circled) represent the highest MgO concentration amongst analysed South Fiord intrusives (Sample 13_WJA_C032A) and Isachsen formation lavas (Sample AX85–263). The best-fit Sm–Nd errorchron for the South Fiord intrusive rocks was calculated using Eq. 4.11 of (Faure & Mensing (2005)). Note the more even spread of the South Fiord intrusives data in contrast to the clustering of Strand Fiord Formation lava data. Also note the greater scatter of the Isachsen Formation lava data relative to that of the South Fiord intrusive rocks and Strand Fiord lavas, which is discussed in the text. Key to reference footnote: [1] – Estrada & Henjes-Kunst (2004).

sample from the exposed top of a >50 m sill plots in the basaltic andesite field using this scheme. The evolved nature of the gabbro likely reflects within-sill crystal settling processes, rather than injection of a wholly more evolved magma into the sedimentary sequence. This is based on the assumption that the thick sill underwent in situ chemical differentiation by way of crystal settling of mafic minerals to the base of the sill, thereby making the exposed top not a chilled margin and resulting in silica enrichment in the interior portion. Differences in other trace-element ratios and isotopic signatures between the intrusive rocks of South Fiord and the Isachsen Formation lavas (described below) are a reflection of different chemical evolutionary processes within each suite. We discuss examples of such divergent chemical trajectories below based on the results we presented previously, in order to elucidate potential magmatic source and crustal assimilation differences.

Based on our results, we observe that the trace-element and isotopic compositions of the South Fiord intrusions are distinct from those of the Isachsen Formation. This is consistent with the Strand Fiord Formation being stratigraphically younger than the Isachsen Formation (Embry & Osadetz, 1988) and thus representing two distinct magmatic events possibly from different sources, depths and degrees of partial melting. Furthermore, the chemistry of South Fiord intrusions suggests that they were likely feeders for the Strand Fiord Formation lavas (Jowitt et al., 2014).

We have established that, in general, the intrusive rocks from South Fiord display evidence of a more restricted melting depth interval along with a wider range of La/

Sm compared to the Isachsen Formation lavas (Figs. 7 & 8). As stated in the previous section, the elevated La/Sm may be related to initial enrichment of the source in LREE, crustal assimilation, or varying degrees of partial melting. The South Fiord intrusive rocks, along with the Strand Fiord Formation lavas, show a strong correlation of decreasing Ni with lower MgO suggestive of strong olivine fractionation in both suites. Olivine fractionation, however, is not as important in the evolution of the Isachsen Formation lavas since no correlation of MgO with Ni is observed (Fig. 11). We propose, based on trace and isotopic data, that South Fiord intrusive rocks likely originated from a more chemically homogeneous mantle source than that of the Isachsen Formation lavas, a conclusion that also is evident in the isotopic data from Estrada & Henjes-Kunst (2004). Based on heavy and light REE slopes (Fig. 9), we suggest that the Isachsen Formation lavas may have been sourced from a wider range in depths with varying degrees of isotopic enrichment than the South Fiord intrusive rocks. Finally, the linear correlation of ϵNd_t with the Sm–Nd model age (Fig. 15), in tandem with decreasing Mg# with decreasing ϵNd_t for the South Fiord intrusions (Fig. 16), suggest strongly that the apparent errorchron (Fig. 10) of the South Fiord intrusions is instead a mixing line between a parental magma with relatively high ϵNd , and a contaminant with lower ϵNd . We now turn to understanding (1) what might have caused heterogeneity within the mantle source(s) for HALIP magmas and mantle processes, and (2) the particulars of potential crustal assimilation.

Figure 15. Sm–Nd depleted mantle (DM) model age vs. ϵNd_t plot showing that South Fiord intrusive rocks and most Strand Fiord formation lavas, along with the Isachsen Formation lavas, increase in DM model age as ϵNd_t decreases, which suggests mixing between a parental magma enriched in radiogenic lead relative to CHUR (having low model ages) and an assimilant that is less enriched in radiogenic Nd relative to CHUR (having higher model ages). Model ages were determined using the CHUR method of Jacobsen & Wasserburg (1980), modified for depleted mantle. Note also the wider spread in model ages for the Isachsen Formation than the South Fiord intrusives data, potentially implying more heterogeneity in the latter. Key to reference footnote: [1] – Estrada & Henjes-Kunst (2004).

Mantle plume head as the driver for HALIP:

We suggest that the source material for the Isachsen Formation lavas and the South Fiord intrusions was the upper mantle under the influence of a mantle plume head. We base this interpretation on 3 factors: (1) both the South Fiord intrusions and the Isachsen Formation lavas are less radiogenic than MORB; (2) the presence of a giant radiating dyke swarm of Cretaceous age extending ~500 km in a radiating pattern from a focal point at the southernmost extent of the Alpha Ridge just northeast of Ellesmere Island (Buchan & Ernst, 2013) along with a tectonically reconstructed HALIP radial dyke swarm in Svalbard and Franz Josef Land (Buchan & Ernst, 2006) provides magmatic evidence of plume head activity. Finally, (3) sedimentary evidence in the form of regional unconformities in Svalbard which suggest Cretaceous domal uplift towards the Alpha ridge (Maher, 2001) as well as southward prograding Barremian clinoforms on the Barents Shelf (Polteau et al., 2016) indicate regional domal uplift, a phenomenon associated with plume-head impingement (Rainbird & Ernst, 2001).

Crustal assimilation

We next investigate the potential role of crustal assimilation and if so, which potential packages of crustal material most strongly modified the chemistry of the magmas. One way of investigating the role of crustal assimilation is by plotting $Mg\#$ vs. ϵNd_t . As Fig. 16 shows, the intrusive rocks from South Fiord show a strong positive correlation between $Mg\#$ and ϵNd_t which suggests that assimilation of crustal material played a role in modulating the magma chemistry for these rocks and for the Isachsen formation lavas, while still demonstrating a positive trend in $Mg\#$ vs. ϵNd_t , shows

more scatter when compared with the South Fiord intrusions (notwithstanding the gabbroic sample at $Mg\# \sim 0.2$) and furthermore, show a generally shallower slope, suggesting that magma evolution was more prominently affected by the fractional crystallisation process with crustal assimilation playing a more minor role.

Crustal assimilation modelling assumptions

Crustal assimilation appears to have had a major influence in the chemical evolution of South Fiord intrusive rocks but only a minor influence in the case of the Isachsen Formation lavas. We next turn our attention to understanding the degree to which the chemical evolution of the intrusive rocks from South Fiord in tandem with the Isachsen formation lava samples from South Fiord, Camp Five Creek and Geodetic Hills is controlled by interaction with the continental crust. As part of this section, we employ two-component modelling with an E-MORB end member and three possible crustal components as specified below.

In the Nb/Y vs. Th/Yb classification diagram (Pearce, 2008), all samples plot above the E-MORB component of the diagonal N-MORB – OIB basalt array (Fig. 6B). On this basis we assume that the parental melt had chemical and Sm–Nd isotopic characteristics that, if no lithospheric interaction had occurred, would be similar to modern E-MORB. Sm–Nd isotopic assumptions are based on the arithmetic mean of samples identified as E-MORB (Waters et al., 2011). Trace-element concentrations and all calculated trace-element ratios are based on average E-MORB values (Sun & McDonough, 1989).

Magmas ascribed to HALIP ascended through three chemically and isotopically heterogeneous packages of crustal material. The basement of Canada's Arctic islands consists of Archaean–Proterozoic metasedimentary

Figure 16. $Mg\#$ vs. ϵNd_t diagram showing crustal influence in the South Fiord intrusives and the Isachsen Formation lavas. With the exception of the chemically evolved gabbro ($Mg\# \sim 0.2$), all South Fiord intrusive analyses show a clear and fairly cohesive correlation of lower $\epsilon Nd(t)$ with more chemically evolved rocks (lower $Mg\#$). This trend suggests that mixing with crust is an important factor in the evolution of these magmas. A similar trend exists with the Isachsen formation lavas but with much greater scatter.

Figure 17. Two-component mixing curves in a Th/La vs. ϵNd_t plot. Mixing curves connect an assumed E–MORB parent with possible crustal assimilants along with subducted sediment mixing. In this plot, both Isachsen formation lavas and South Fiord intrusive rocks most closely follow the Sverdrup Basin curve. Discussion about the subducted sediment model can be found in the text. E–MORB Sm–Nd data are from Waters et al. (2011) and trace elements taken from Sun & McDonough (1989). Sverdrup Basin crustal data weighted averages were calculated from Patchett et al. (2004), and the same for the Franklinian Mobile Belt and cratonic data from Patchett et al. (1999). The subducted sediment data were calculated from Plank & Langmuir (1998). Tick intervals in evolution curves are 10%.

and metavolcanic rocks that, in northern Ellesmere Island, constitute the Pearya terrane (Trettin, 1987; Malone, 2012). Lying unconformably above the cratonic basement is the Cambrian–Devonian Franklinian Mobile Belt with sediments derived from underlying cratonic (>450 Ma) as well as Caledonian sources from the northeast (<450 Ma) on the basis of Nd and trace-element geochemistry (Patchett et al., 1999). The final package is the sedimentary sequence of the intracratonic Carboniferous–Late Cretaceous Sverdrup Basin (Embry & Beauchamp, 2008).

Whereas geochemical data strongly suggest that crustal assimilation has chemically modified the composition of intrusive magmas from South Fiord as well as to a lesser extent the Isachsen Formation lavas, it is important to establish the level(s) within the crustal column where the assimilation occurred. Taking Sm–Nd isotopic and trace-element data from the Sverdrup Basin (Patchett et al., 2004) and the underlying Franklinian Mobile Belt (Patchett et al., 1999), which represents a proxy for the cratonic basement, we calculate a weighted average of the compositions of (a) the Sverdrup Basin, (b) the Franklinian Mobile Belt and (c) the underlying Archaean–Proterozoic shield. Because of the paucity of S-type granites in Canada's High Arctic and noting that sedimentary rocks older than ~450 Ma from the Franklinian Mobile Belt show shield-like chemical and isotopic signatures, we assume that these signatures represent a best-case 'fit' for the chemical nature of the underlying craton owing to erosive and deposition processes from disparate source regions.

Two-component mixing

Three trace-element ratios that can be used to elucidate the degree of crustal involvement are Th/La , Ba/Nb and

Nb/U . Thus, we plot each of these ratios against ϵNd_t and, through two-component modelling, we use these plots in order to understand which first-order crustal package (Sverdrup Basin, Franklinian Mobile Belt and/or cratonic basement, $\pm$ subducted sediments) had the greatest influence in chemically altering magma with a probable starting E–MORB composition.

Th/La is a useful first-order discriminant in the level of crustal involvement in that Th/La ratios in oceanic rocks are <0.1 , in continental crust ~ 0.3 , with some marine sediments up to ~ 0.4 (Plank, 2005). In Th/La vs. ϵNd_t space, both the South Fiord intrusions and the Isachsen lavas display a wide variance in Th/La (0.13–0.21) and have largely overlapping chemical trajectories (Fig. 17). In this chemical space, the South Fiord intrusive rocks follow most closely the Sverdrup Basin mixing curve (where assimilation of up to 20% is modelled). The trend of the Isachsen Formation lavas also tends to follow the Sverdrup Basin mixing line. Conversely, the South Fiord intrusions and Isachsen Formation lavas diverge most strongly from the cratonic mixing curve, suggesting little cratonic involvement.

A second plot that can be used to understand the role of crustal assimilation is Nb/U vs. ϵNd_t (Fig. 18). Here, both the South Fiord intrusions and the Isachsen formation lavas again overlap substantially (much like in the Th/La system) and range in Nb/U from 10 to 30 with no correlation between ϵNd_t and Nb/U . Two-component mixing models show that the HALIP data closely follow the Sverdrup Basin curve as well as the Franklinian Mobile Belt curve, suggesting that $\sim 10\%$ of crustal material was assimilated. Again, like the Th/La data (Fig. 17), there is a strong divergence between the data and the cratonic mixing curve, indicating further that cratonic

basement did not play much of a role as an assimilant in HALIP magmas (see also previous paragraph).

One trace-element ratio in which the South Fiord Intrusions diverge strongly from that of the Isachsen formation lavas is Ba/Nb (Fig. 19). Whereas the South Fiord suite has Ba/Nb values of 8–11, the Isachsen formation lavas display much wider ranges in values (0.8–37). Furthermore, in a Ba/Nb vs. ϵNd_t plot, the South Fiord intrusions show a tight, strongly negative correlation between ϵNd_t (+1.2 – +4.5) and Ba/Nb. The Isachsen Formation lavas, on the other hand, show increasing Ba/Nb with no systematic change in ϵNd_t , commensurate with the trace-element ratio increase.

In our modelling, the negative Ba/Nb and ϵNd_t correlation displayed by the South Fiord intrusions follows the mixing curves that connect E-MORB with both Sverdrup Basin and cratonic basement, signifying that the Sverdrup Basin and/or cratonic basement rocks are likely candidates for assimilation. Owing to the shallower model path connecting E-MORB with the Franklinian Mobile Belt, the Franklinian rocks likely did not play a substantial role in the chemical evolutionary pathway of the South Fiord intrusive rocks. The apparent assimilation of the South Fiord intrusive rocks with the Franklinian Mobile Belt in Nb/U is more likely a function of Sverdrup Basin and Franklinian Mobile Belt model pathways sharing essentially identical trajectories. The Isachsen Formation lavas display a chemical trend that diverges significantly from the chemical evolution curves involving the three crustal packages, suggesting little crustal assimilation overall.

Crustal interaction levels

Taking in the above two-component modelling using Th/La, Ba/Nb and Nb/U (Figs. 13–15), it seems that the first-order crustal package that played the greatest role as a contaminant for the South Fiord intrusions is that of the sedimentary rocks from the Sverdrup Basin. In both Th/La and Nb/U vs. ϵNd_t plots (Figs. 17 & 18), the modelled curve from E-MORB to cratonic values diverges significantly from the trend of both the Isachsen Formation lavas and the South Fiord intrusions. Although the South Fiord intrusions appear to follow both the Sverdrup Basin and cratonic tie-lines in Ba/Nb space (Fig. 19), the Sverdrup Basin and the cratonic curves essentially overlap. The importance of Sverdrup Basin rocks supports the idea that magma storage prior to any associated eruptive events occurred within the shallow continental crust, above the level of both Franklinian and cratonic rocks. We now turn our attention to explaining the divergence of the Isachsen Formation lavas from the three first-order packages of crustal material in Ba/Nb space (Fig. 19). We invoke the following hypothesis: that the plume head which fed Isachsen Formation lavas incorporated sediments transported to the mantle from

subductions zones ancestral to the present-day Aleutian and Alaska subduction zones.

Subducted sediment as a driver for mantle heterogeneity

As mentioned above based on trace-element and isotopic parameters, a heterogeneous mantle is invoked for the Isachsen Formation magmas. What might have been the cause of this heterogeneity? Based on time-integrated tomographic modelling, multiple north-verging paleo-subduction zone fronts have been hypothesised to have existed beneath Canada's Arctic Islands (Shephard et al., 2013, 2014). An issue to address here is whether there is evidence to suggest the chemistry of magmas feeding either the South Fiord intrusions (which we suggest are linked with the younger Strand Fiord Formation lavas) or the older Isachsen Formation lavas were affected by subducted sediment in the upper mantle.

Subducted sediments are heavily enriched in Ba that, in the case of the modern Aleutian Arc, is the result of Ba precipitates and crusts derived from Ba-rich fluids from cold seeps (Suess et al., 1998) whereas the continental crust is a Th reservoir (Plank & Langmuir, 1998; Plank, 2005). Therefore, the ratio Ba/Th may be used in part to discriminate between effects from crustal involvement and possible influences from subducted sediments. In Fig. 12, as well as stated in the Results section, both E-MORB and Sverdrup Basin sedimentary rocks have Ba/Th ratios of 95 and 40, respectively (Sun & McDonough, 1989; Patchett et al., 2004). Whereas a population of Isachsen Formation lavas plots close to the values of E-MORB and Sverdrup Basin sedimentary rocks, a number of samples plot significantly higher than these (up to Ba/Th = 220). Therefore, magmas which fed the Isachsen Formation lavas must have drawn Ba from either a chemical reservoir other than continental crust or a direct melt of an E-MORB composition. We therefore propose that the mantle plume head intersected a batch of sediment entrained in the mantle in extinct subduction zones. In terms of certain ocean island basalts (from Gough Island, for example), Ba/Th along with Ba/Nb ratios are significantly higher when compared with data from Ascension, St. Helena, Bouvet and Tristan da Cunha islands, and Weaver et al. (1986) have used this, in part, to suggest that Gough Island magmas incorporated small amounts of ancient subducted sediment. Furthermore, certain lavas in Hawaii also show evidence of incorporation of small amounts of subducted carbonate-rich sediment (Huang et al., 2009, 2011) a small Hawaiian volcano on the Loa trend, exhibit major and trace element abundance variations exceeding those in lavas from large Hawaiian shields, such as Mauna Loa and Mauna Kea. Mahukona lavas define three geochemically distinct groups of tholeiitic shield basalt and a transitional group of postshield basalt. At 10% MgO the tholeiitic groups range from 9 to 12% CaO;

Figure 18. Two-component mixing curves in a Nb/U vs. $\epsilon\text{Nd}(t)$ plot. In this plot, both Isachsen formation lavas and South Fiord intrusive rocks are consistent with Sverdrup Basin and/or Franklinian Mobile Belt curves but not consistent with mixing cratonic basement. Discussion about subducted sediment can be found in the text. Plot mixing line colours and symbols along with data sources are identical to those in Fig. 17.

Figure 19. Two-component mixing curves in a Ba/Nb vs. $\epsilon\text{Nd}(t)$ plot. In this plot, South Fiord Intrusive rocks show a clear mixing trend involving Sverdrup Basin crustal material, whereas Isachsen Formation lavas appear to be primarily affected by a heterogeneous source defined in part by incorporation of subducted sediments. Plot and mixing line colours and symbols along with data sources are identical to those in Fig. 13 with the exception of the phlogopite mantle mixing line addition. Plot mixing line colours and symbols along with data sources are identical to those in Fig. 17.

such differences in CaO can reflect partial melts derived from garnet pyroxenite (low CaO).

In contrast to the Isachsen Formation samples, those from the South Fiord intrusions and lavas (Jowitt et al., 2014) have uniformly low Ba/Nb and Ba/Th, and with respect to Ba/Th plot between E–MORB and Sverdrup Basin sedimentary rocks, possibly suggesting that these rocks did not incorporate entrained ancient subducted sediment but rather have a signature of upper crustal contamination by sedimentary rocks.

For the purposes of modelling subducted sediment, we use the closest modern subduction zone to Axel Heiberg Island: the Alaska–Aleutian subduction zone, about

3,000 km WSW. For modelling purposes, we take the relevant Sm–Nd along with Ba, Nb and Th concentration data from the ‘Aleut’ and ‘Alaska’ datasets from (Plank & Langmuir (1998) and apply a weighting equal to the length of each arc as a percentage of the combined length of the two arcs.

Fig. 19 (Ba/Nb vs. ϵNd_t) shows that the trend of the Isachsen Formation is not consistent with crustal assimilation models. Isachsen Formation lavas thus require a potential assimilant that remains within approximately 5 time-integrated epsilon Nd units from chondritic values. Our trench-length-weighted average ϵNd_t for Aleutian and Alaska subduction zones is $\sim +2.5$. This, coupled with our weighted average Ba/

Figure 20. Two-component mixing curve between E-MORB and subducted sediments in a Ba/Nb vs. Ba/Th plot. E-MORB point derived from Sun & McDonough (1989), The Sverdrup Basin point is a weighted average (described in the text) from Patchett et al. (2004), and the weighted average composition of Aleut and Alaskan subducted sediments from Plank & Langmuir (1998). Key to reference footnote: [1] – Jowitt et al. (2014).

Nb (Plank & Langmuir, 1998) of ~ 240 , makes a plausible mixing line describing the chemical behaviour of the Isachsen Formation lavas. Furthermore, Fig. 12 shows that a substantial number of samples from the Isachsen Formation have Ba/Th ratios substantially higher than those of E-MORB and Sverdrup Basin sedimentary rocks, necessitating a source other than E-MORB or Sverdrup Basin crust to explain these high ratios. Based on a weighted average of the modern Aleutian and Alaska arcs (Plank & Langmuir, 1998), the Ba/Th and Ba/Nb ratios are 356 and 0.29, respectively. This Ba/Th ratio is substantially higher than E-MORB and Sverdrup Basin sedimentary rocks as shown above. Simple two-component modelling between E-MORB and the weighted average of subducted sediments on a Ba/Nb vs. Ba/Th plot (Fig. 20) shows that a substantial number of Isachsen Formation lavas follow the mixing curve between the two end-members and therefore require addition of subducted sediments of up to 10%. Our major assumption in constructing the subducted sediment mixing model is that the Ba/Nb, Ba/Th and time-integrated Sm–Nd isotopic compositions that have been compiled for the Aleutian and Alaska subduction zone (Plank & Langmuir, 1998) remained essentially constant from ~ 200 Ma to the present-day in the north Pacific Ocean (Shephard et al., 2013). As Fig. 19 (Ba/Nb vs. ϵNd_t) and Fig. 20 (Ba/Nb vs. Ba/Th) show, the Isachsen Formation lavas follow the mixing curve between E-MORB and the weighted average of the Aleutian and Alaska subducted sediment compositions. However, the South Fiord intrusive rocks do not follow this trend. Thus, Isachsen Formation magmas may have included a subducted sediment component whereas the magmas feeding the South Fiord intrusions did not.

It has been speculated that the downgoing slab imaged in tomographic models represents the remains of the

Farallon, Izanagi and Cache Creek slabs (depending on specific locations: Shephard et al., 2013, 2014) which are precursors to the present-day Juan de Fuca and Aleutian subduction zones. Based on seismic and numerical modelling, only about 15–30% of sediment gets accreted onto accretionary wedges at subduction zones, the balance (70–85%) being subducted into the Earth's interior (e.g., von Huene & Scholl, 1991). Furthermore, of those sediments that are subducted, about 20% are entrained into magmatic-arc systems leaving 80% of the remaining sediment being fully incorporated into the mantle (Plank & Langmuir, 1993). Thus, we conservatively calculate that if 70% of sediments go down into subduction zones and that 80% of that 70% also bypassed a volcanic arc system, then slightly more than half ($\sim 55\%$) of the sediment that encounters a subduction zone trench ultimately makes it into the mantle. Furthermore, recent geophysical modelling of subducted sediment shows that these sediments may detach from the subducting slab via a buoyant, horizontal, sediment plume intruding into the back-arc mantle and laterally propagating 100s of km from the subduction front (Currie et al., 2007), thereby providing the sediment signature required for high Ba/Nb and Ba/Th as well as comparatively low Th/La for some of the Isachsen Formation lavas. We therefore speculate that enroute to the base of the lithosphere, the plume head responsible for the production of HALIP magmas intersected subducted sediments transported into the mantle via extinct subduction zones. This plume then scavenged Ba from the sediments at depth and subsequently transferred high-Ba material to the source region of the magmas feeding the Isachsen Formation lavas. However, this slab and sediments were not apparently intersected during the time period associated with the South Fiord intrusions, potentially

due to a breach in a possible sediment-bearing plume (see discussion above). Another possible mechanism whereby sediments could interact with the ascending plume involves thermal conduction, as models predict that plumes are hotter than the surrounding mantle (Campbell & Griffiths, 1990). The centre of the plume would be hot enough to interact with and assimilate any subducted sediment plume in the mantle, thereby releasing Ba (and other large-ion lithophile elements) from the sediment. An alternative idea is that possible subducted sediment-bearing material that had detached from the slab was present at the plume site only during certain time intervals, and those magmas that did not incorporate subducted sediment signatures instead acquired a crustal assimilation signature such as is shown by some of the Isachsen Formation lavas (Fig. 13).

Conclusions

Whereas both the South Fiord and the Isachsen suites have subalkaline compositions, new trace element and isotopic data reported here show that the South Fiord intrusions are chemically distinct from the Isachsen Formation rocks. Furthermore, we suggest that the South Fiord intrusions likely have chemical affinities with the Strand Fiord Formation. Trace-element and isotopic results indicate a homogeneous upper mantle source coupled with a strong Sverdrup Basin assimilation signature for the South Fiord intrusive rocks (matching Strand Fiord Formation lavas). Conversely, using the same plots, older Isachsen Formation lavas probably originated from a chemically heterogeneous mantle source with less crustal assimilation. We suggest that mantle heterogeneity in the Isachsen Formation lavas is strongly defined by the interaction with a subducted sediment component (Fig. 19) derived from extinct, Jurassic–Cretaceous subduction zones (see previous section). Furthermore, the presence of a subducted sediment signature in the Isachsen Formation lavas and the lack thereof in the South Fiord intrusions, coupled with a strong crustal assimilation signature in the South Fiord intrusions are likely a result of a subducted slab impacting two features of the Isachsen lavas. Firstly, the down-going subduction slab provides the sediments necessary for higher Ba/Nb and especially Ba/Th, and such sediments may detach from the subducting slab and laterally propagate 100s of km in the back-arc (Currie et al., 2007), thereby providing the sediment signature required for high Ba/Nb, Ba/Th and comparatively low Th/La ratios. Secondly, and more speculatively, the presence of subducted sediment at the base of the crust diminishes the thermal anomaly of the plume head — providing a lower temperature ‘lid’ — to such a degree that crustal assimilation efficiency on the part of magmas feeding Isachsen Formation lavas was very low. Without a subducted sediment ‘lid’ during the time-frame of

magmatism leading to emplacement of the South Fiord intrusions, the thermal anomaly of the HALIP plume facilitated hotter magmas capable of greater degrees of crustal assimilation, perhaps with increasing degrees of assimilation through time as the surrounding crust was heated by repeat-injection episodes. Further isotopic work (e.g., Sr) will help clarify the nature of contaminants discussed above.

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