New constraints on the age, geochemistry, and environmental impact of High Arctic Large Igneous Province magmatism: Tracing the extension of the Alpha Ridge onto Ellesmere Island, Canada

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ABSTRACT

The High Arctic Large Igneous Province (HALIP) represents extensive Cretaceous magmatism throughout the circum-Arctic borderlands and within the Arctic Ocean (e.g., the Alpha-Mendeleev Ridge). Recent aeromagnetic data shows anomalies that extend from the Alpha Ridge onto the northern coast of Ellesmere Island, Nunavut, Canada. To test this linkage we present new bulk rock major and trace element geochemistry, and mineral compositions for clinopyroxene, plagioclase, and olivine of basaltic dykes and sheets and rhyolitic lavas for the stratotype section at Hansen Point, which coincides geographically with the magnetic anomaly at northern Ellesmere Island. New U-Pb chronology is also presented.

The basaltic and basaltic-andesite dykes and sheets at Hansen Point are all evolved with 5.5–2.5 wt% MgO, 48.3–57.0 wt% SiO₂, and have light rare-earth element enriched patterns. They classify as tholeiites and in Th/Yb vs. Nb/Yb space they define a trend extending from the mantle array to northern Ellesmere Island. New U-Pb crystallization ages for the HPTS and SFI Formation volcanic rocks may link and influence major changes in Earth climate-ocean systems.

INTRODUCTION

Widespread Cretaceous magmatism reported throughout the circum-Arctic borderlands and within the Arctic Sea (Alpha-Mendeleev Ridge) is characteristic of a large igneous province (LIP) (Fig. 1) (Coffin and Eldholm, 1994; Tarduno et al., 1998; Maher, 2001; Bryan and Ernst, 2008; Buchan and Ernst, 2006, 2018; Oakey and Saltus, 2016; Jackson and Chian, 2019). A LIP is defined as a region where greater than 100,000 km³ of typically basaltic magma is emplaced over a relatively short duration of time (e.g., Ernst and Bleeker, 2010).
Figure 1. Bathymetric map of the High Arctic region showing the extent of on-land and offshore areas with mafic rocks ascribed to the High Arctic Large Igneous Province (HALIP), and the location of the study area at Hansen Point, northern coast of Ellesmere Island, Canada. The expressions of HALIP magmatism includes lavas, sills, and dykes of the Canadian Islands (Trettin and Parrish, 1987; Estrada et al., 2016; Buchan and Ernst, 2018), the De Long Islands (Nikishin et al., 2020), Franz Josef Land, Svalbard, the Barents Sea (Polteau et al., 2016), North Greenland (Thorarinsson et al., 2015), and the High Arctic Magnetic High Domain interpreted as the geophysical manifestation of magmatic intrusions and extrusions associated with the Alpha-Mendeleev ridge (Oakey and Saltus, 2016). Also shown are the approximate locations of offshore samples (black squares) from the Alpha Ridge by Jokat (2003; labeled 1) and Van Wagoner et al. (1986, labeled 2). Bathymetry and topography from Jakobsson et al. (2008).
The geology of northern Ellesmere Island is divided into three major tectono-stratigraphic units: (1) the Mesoproterozoic to upper Silurian exotic Pearya Terrane, (2) the Neoproterozoic to Devonian Franklinian Basin, and (3) the Carboniferous to Eocene Sverdrup Basin (as numbered in Fig. 2; Trettin, 1991). The Sverdrup Basin is divided into several phases of development with volcanism on northern Axel Heiberg and Ellesmere islands occurring during phases 6 and 7 as described by Embry and Beauchamp (2019) (Fig. 2A). These phases are characterized by Early Cretaceous to Late Cretaceous rift-related sedimentation with interbedded volcanism. The beginning of Phase 6 of Embry and Beauchamp (2019), corresponding to the base of the Hauterivian (ca. 136 Ma), is marked by rifting and extension of the basin and coincides with deposition of volcanic and sedimentary rocks of the Isachsen and Christopher formations. Phase 6 ended abruptly at the end of the Albian (ca. 99.6 Ma), with widespread uplift and a major transgression that marked the initiation of Phase 7. The beginning of Phase 7 during the Cenomanian (ca. 99.6–93.5 Ma) is marked by renewed high rates of subsidence and transgression, and with deposition of the Hassel and Strand Fjord (SFF) formations, the latter dominated by tholeiitic volcanic rocks and interbedded sedimentary rocks. The later part of Phase 7 is marked by a new uplift episode and major fault zones (after Harrison et al., 2015). The main occurrences of Cretaceous volcanic rocks of northern Ellesmere Island are labeled: (1) Audhild Bay, (2) Philips Inlet, (3) Yelverton Bay West, and (4) Yelverton Bay East that includes Hansen Point itself. Also shown is the location of the dated hornblende syenite sample 17HSB-40A to the north of Audhild Bay.

The SFF is composed of variably fractionated, low-Ti tholeiitic continental flood basalts (Estrada and Henjes-Kunst, 2004; Dostal and MacRae, 2018; Kingsbury et al., 2016). The volcanic rocks of SFF are followed upsection by mudstones of the Kanguk Formation deposited from upper Turonian to Campanian (ca. 93–71 Ma) (Fig. 3A) (Embry and Beauchamp, 2019). This unit includes numerous alkaline, silicic ash beds (bentonites) up to 50 cm thick that are interbedded with mudstone (Fig. 3A) (Davis et al., 2017; Pounton et al., 2019).

Trettin and Parrish (1987) first gave the informal name “Hansen Point volcanics” to volcanic outcrops at either side of Yelverton Bay, including the stratotype on the Hansen Point peninsula to the east (Fig. 2B). Subsequently, Embry and Osadetz (1988) described Late Cretaceous volcanic rocks between Emma Fiord and Audhild Bay; and in the Philips Inlet area (Fig. 2B). Based on biostratigraphy, Embry and Osadetz (1988) correlated the intra-volcanic sedimentary rocks with the Kanguk Formation (Fig. 3A). They also correlated the volcanic units at Audhild Bay and Philips Inlet to the Hansen Point volcanic rocks at Yelverton Bay (Trettin and Parrish, 1987). Subsequently, Estrada et al. (2006) referred to all of these Late Cretaceous volcanic units of northern Ellesmere Island as the Hansen Point Volcanic Complex. However, our results show that this nomenclature is unfortunate for two reasons. First, it includes both alkaline and tholeiitic suites. Second, it encompasses a wide range of ages (ca. 104–73 Ma) that overlap with the ages of both the Strand Fiord and Kanguk formations. As discussed below, we conclude that it is useful to divide the volcanic occurrences of northermmost Ellesmere Island into two suites: the Hansen Point tholeiitic suite (HPTS), typified by the volcanic rocks of the stratotype section at Hansen Point and the Audhild Bay alkaline suite (ABAS). To establish the case for this suggestion, we refer in the following to the main outcrop areas of volcanic rocks on northern Ellesmere Island (as numbered in Fig. 2B) from SW to NE as: Audhild Bay (1), Philips Inlet (2), Yelverton Bay West (3), and Yelverton Bay East (4) that includes Hansen Point itself.
The volcanic rocks of the northern coastal areas of Ellesmere Island occur in scattered outcrops stretching over ~200 km and are in tectonic or depositional contact with rocks of the Neoproterozoic basement, the Paleozoic Franklinian Basin, or the Paleogene Sverdrup Basin (Trettin and Parish, 1987; Embry and Osadetz, 1988; Estrada and Henjes-Kunst, 2004; Estrada et al. (2006); Embry and Beauchamp, 2019) (Fig. 2B). The fault-bounded outcrops are associated with the SW-NE striking Mitchell Point fault zone and Emma Fiord fault zone. These are mainly Paleozoic strike-slip faults that were re-activated in the Paleogene during the Eurekan orogeny (Estrada et al., 2006; Piepjohn et al., 2019) (Fig. 2B). The fault-bounded outcrops are associated with the SW-NE striking Mitchell Point fault zone and Emma Fiord fault zone. These are mainly Paleozoic strike-slip faults that were re-activated in the Paleogene during the Eurekan orogeny (Estrada et al., 2006; Piepjohn et al., 2019).

The exposed volcanic rocks vary considerably. At Yelverton Bay West and Yelverton Bay East, they are typically dominated by pyroclastic deposits, volcanic breccias, lava flows, and dykes (Trettin and Parrish, 1987; Embry and Osadetz, 1988; Estrada and Henjes-Kunst, 2004). The Yelverton exposures are compositionally bimodal with silicic rocks (e.g., rhyodacitic) dominating over basaltic rocks. Basaltic compositions are mainly found in the dykes, but also as occasional flows and breccias (Trettin and Parrish, 1987; Estrada et al., 2006, 2016). At Audhild Bay, a ~200 m stratigraphic section of mainly basaltic flows is overlain by ~250 m of trachytic and more silicic pyroclastic units (Embry and Osadetz, 1988). In the Phillips Inlet area, basaltic lava flows dominate the volcanic pile that is at least 650 m thick but also includes silicic flows and pyroclastic deposits (Embry and Osadetz, 1988; Estrada and Henjes-Kunst, 2004).

MATERIAL AND METHODS

Field Work and Samples

A complete 2.5-km-long traverse of the Hansen Point stratotype section was sampled along an unnamed creek at Hansen Point; starting at the head, near an unnamed glacier, to the end of the exposed section near the shore of the Arctic Ocean (Figs. 4 and 5). All GPS coordinates are recorded in reference to NAD 83.
The starting position for the sampling transect is 82.45631497N; −82.43058002W (elevation 184 m), and the end coordinate is 82.469148N; −82.53214697W (elevation 27 m). Forty-eight in situ samples were collected from this section. Ten of these samples have been selected for this study (nine dykes and one sheet), with a main focus on the basaltic rocks. The Hansen Point samples are described in Supplementary Data File 1 and their GPS positions are given in Supplementary Data File 2. In addition, two samples were selected for U-Pb geochronological analysis; one is from the Hansen Point area (Fig. 4) and one is from Audhild Bay (location 1; Fig. 2B) (see below).

**Analytical Methods**

Polished thin sections were prepared at Vancouver Petrographics Ltd., Langley City, British Columbia, Canada. Petrographic descriptions were completed using transmitted and reflected polarized light optical microscopy on a Zeiss Axioplan microscope. Mineral percentages were visually estimated. The mineral chemistry of clinopyroxene, plagioclase, and olivine was characterized using wavelength dispersive spectroscopy using a JEOL JXA-8200 electron microprobe at the University of Calgary, Calgary, Canada. The analytical conditions were an accelerating voltage of 15 kV, a current of 30 nA, a beam diameter of 5 µm, and counting times of 20 s on peak and 10 s on both positive and negative background. Calibration was achieved using natural mineral standards of albite, anorthite, augite, chromite, fluorapatite, grunerite, hornblende, orthoclase, and rhodonite. For clinopyroxene, only analyses with cation sums between 3.95 and 4.05 were accepted. For plagioclase and olivine, we accepted analyses with cation sums between 4.95 and 5.05 and 2.99 and 3.01, respectively.

For whole rock geochemistry, samples were cut using a diamond saw to remove weathered surfaces. Using a steel hammer and plate, samples were broken into gravel-sized pieces, then pow-

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**Supplemental Material.** Supplementary Data Files: (1) Sample list and description; (2) GPS positions of samples; (3) Accuracy of major and trace element bulk rock compositions and precision of repeat analyses; (4) Photomicrographs; (5) Clinopyroxene, plagioclase and olivine compositions; (6) SHRIMP U-Pb methods and results; (7) Nb-Zr-Y tectonic discrimination diagram; (8) Ti-Zr-Y tectonic discrimination diagram; (9) Ti-V tectonic discrimination diagram; (10) MgO-FeO<sub>tot</sub>-Al<sub>2</sub>O<sub>3</sub> tectonic discrimination diagram; (11) AFM diagram; and (12) Th/Nb vs. SiO<sub>2</sub> diagram. Please visit https://doi.org/10.1130/GSAB.S13217810 to access the supplemental material, and contact editing@geosociety.org with any questions.
dered using an agate mortar and pestle for 30 min at the Geological Survey of Canada (GSC), Calgary. Standard lithogeochemistry was completed by Acme Labs in Vancouver, British Columbia, Canada for major element oxides by X-ray fluorescence, and trace elements by inductively coupled plasma–mass spectrometry. The accuracy and precision of the bulk rock data are evaluated in Supplementary Data File 3. This shows that the major and trace element compositions described here are accurate within 2 and 8%, respectively.

Two additional samples were selected for U-Pb geochronological analysis. The mineral separates for Trettin and Parrish’s tholeitic rhyodacite sample 82-TM-212A from the stratotype locality (Fig. 4) was revisited using the sensitive high resolution ion microprobe (SHRIMP) at the GSC in Ottawa, Canada. A new sample of “hornblende syenite” (17HSB-40A) was collected along the western shore of Audhild Bay (Fig. 2B) in 2017. This new sample was disaggregated using standard crushing/pulverizing techniques followed by density separation using the Wilfley table and heavy liquids and purification into a zircon separate using a Frantz Isodynamic separator. Zircron grains were cast in 2.5 cm diameter epoxy mounts along with fragments of the GSC laboratory standard zircon (z10493, with \( ^{206}\text{Pb} / ^{238}\text{U} \) age = 417 Ma, Black et al., 2003). The analytical details are provided together with the results in Supplementary Data File 6. The mid-sections of the zircons were exposed using 9, 6, and 1 mm diamond compound and internal features of the zircons (such as zoning, structures, alteration, etc.) were characterized in cathodoluminescence (CL) and back-scattered electron (BSE) mode utilizing a Tescan field emission scanning electron microscope. SHRIMP analytical procedures followed those described by Stern (1997), with standards and U-Pb calibration methods following Stern and Amelin (2003). Eleven masses including background were sequentially measured with a single electron multiplier on the SHRIMP. Off-line data processing was accomplished using SQUID2 (version 2.50.11.10.15, rev. 15 October 2011). The 1σ external errors of \( ^{206}\text{Pb} / ^{238}\text{U} \) ratios reported in Supplementary Data File 6 incorporate the error in calibrating the reference material. Common Pb correction utilized the Pb composition of the surface blank (Stern, 1997). Details of the analytical session, including spot size, number of scans, error, and the requirement for an isotopic mass fractionation correction are given in the footnotes of Supplementary Data File 6. Isoplot v. 4.15 (Ludwig, 2003) was used to generate concordia plots and calculate weighted means of the \( ^{206}\text{Pb} / ^{238}\text{U} \) ages. The error ellipses on the concordia diagrams and the weighted mean errors are reported at the 95% confidence level.

RESULTS

Field Observations

The southeastern portion of the section studied is dominated by felsic flows, tuffs, agglomerates, breccias, and dykes, but also includes basaltic dykes (Supplementary Data File 1). In the northwestern part of the section mafic dykes, sheets, and flows are more abundant (Figs. 4 and 5). Overall, most of the dykes strike east to west and have near vertical to steep dips to the north or south. Chilled margins were observed on some of the contacts. Individual mafic dykes range from ~3 m to roughly 30 m thick and are typically fine- to medium-grained, some are sparsely plagioclase- and clinoxyroxene-phryic. Both dykes and sheets are often amygdaloidal. Rusty surface weathering varies from mild to strong. Toward the center and northwestern end of the section, several fine-grained mafic sheets display columnar jointing. The sheet included in this study (17C-74) is ~30 m thick and dips ~45° to the north. The contacts are not exposed and it remains unclear whether this sample represent a dyke or a lava flow.

 Petrography

The samples are composed of a fine-grained, planeretic groundmass dominated by plagioclase laths, clinopyroxene, and interstitial mesostasis showing sub-ophitic textures (Supplementary Data File 4 shows typical textures). Four samples are porphyric with phenocrysts of plagioclase (up to 7% and up to 4 mm) and clinopyroxene (up to 6% and up to 1 mm) that often occur together as glomerocrysts. The plagioclase phenocrysts range from euhedral laths to equant grains with highly serrated rims. Three samples also contain microphenocrysts of olivine (up to 3% and up to 0.3 mm) that are fresh in two samples, but completely pseudomorphed in the third sample. Clinopyroxene crystals often show zoning from core to rim; this is seen in both groundmass and phenocrysts. Ilmenite and magnetite either form anhedral to euhedral grains in the groundmass, or skeletal grains associated with the glassy mesostasis. Three samples also contain interstitial, granophyric intergrowth of quartz and alkali feldspar; these samples are also distinct in terms of bulk rock major element compositions where they classify as basaltic andesite (see below). The rock samples often contain a minor amount of circular amygdules (up to 5% and up to 0.6 mm) that are commonly filled in with radial aggregates of chlorite and anhedral to euhedral quartz. Most of the rocks are weakly to moderately altered including sericite, chlorite, and grungy red-brown clays or mica associated with the mesostasis. One sample (17C-51) is, however, heavily altered. Here the alteration minerals include chlorite, sericite, calcite, albite, and sporadic anhedral pyrite strings.

Clinopyroxene, Plagioclase, and Olivine Chemistry

Ninety-one analyses of clinoxyroxene from eight Hansen Point samples are shown in the pyroxene quadrilateral and all classify as augite (Fig. 6) (all microprobe data are reported in Supplementary Data File 5). Approximately half of the analyses are from the cores of grains and they show the highest Mg# (100 Mg/[Mg + Fe]) ranging from 73 to 52. The Mg# of rims is generally lower and ranges from 67 to 26. The wollastonite endmember Wo% (100 Ca/[Ca + Fe + Mg]) ranges from 30 to 45. The TiO\(_2\) contents range from 0.8 to 2.8 wt% for cores and are slightly lower for the rims (0.3–2.5 wt%). The Al\(_2\)O\(_3\) contents range from 1.2 to 5.7 wt% in the cores, and from 0.4 to 4.0 wt% in the rims. Both TiO\(_2\) and Al\(_2\)O\(_3\) correlate positively with Mg#. The Cr\(_2\)O\(_3\) contents are always below detection limit (<0.02 wt%). In a few cases pigeonite (not shown) is present in the rims of groundmass crystals. The plagioxyroxene compositions (n = 95) are listed and shown in the plagioxyroxene classification diagram in Supplementary Data File 5. The cores of phenocrysts (samples 17C-39, 17C-63) classify as labradorite and the anorthite contents [Ca/(Ca + Na)] range from An66–52. The rim com-

![Figure 6. Pyroxene quadrilateral showing the compositions of clinoxyroxene from basaltic dykes and sheets at Hansen Point, Ellesmere Island, Canada. Also shown is the classic tholeiitic differentiation trend from the Skaergaard intrusion (Wager and Brown, 1968). Cpx—clinoxyroxene; Di—diopside; Hd—hedenbergite; En—enstatite; Fs—ferrosilite.](http://pubs.geoscienceworld.org/gsa/gsabulletin/article-pdf/133/7-8/1695/5353972/b35792.1.pdf)
positions of the phenocrysts stretch into andesine compositions to lower anorthite (An60–34). The cores of groundmass plagioclase also span from labradorite to andesine to An14–40. The compositions of rims of the groundmass grains partly overlap with the cores, but extend to oligoclase compositions and An24. Groundmass olivine in sample 17C-70 (n = 11) was also analyzed and has Fo% [Mg/(Mg + Fe)] of 45–59 in the cores, and down to 30 in the rims (Supplementary Data File 5). The Supplementary Data File 5 also includes analyses of interstitial alkali feldspar (n = 20) and albite alteration products in 17C-51 (n = 8).

**Whole Rock Geochemistry**

The wt% of major element oxides and loss on ignition (LOI) of the samples are presented in Table 1. The LOI is less than 1 wt%, with the exception of sample 17C-51 with 2.24 wt%. In the following we describe and plot the major element oxide values normalized to 100% volatile-free compositions. The samples in this study range from 48.3 to 57.0 wt% SiO₂, with most samples falling between 49.5 and 52.2 wt%. The alkali oxides range from 0.76 to 2.77 wt% K₂O, and from 2.51 to 3.64 wt% Na₂O. In the total alkali versus silica (TAS) diagram (Fig. 7) all samples, with one exception, plot in the subalkaline field. The sample (17C-51) plotting in the alkaline field is, however, also the most strongly altered sample. In terms of the immobile element contents, this same sample is comparable to the other basalts (see below) and does not yield nepheline in the CIPW norm. We therefore ascribe the high alkali content of this sample to alteration. Otherwise, we assume the measured whole rock data represent the primary igneous compositions. The studied samples can therefore be classified as basalt (n = 7) and basaltic andesite (n = 3, including 17C-51). The TiO₂ contents of the samples range from 2.44 to 3.45 wt%, and MgO contents range from 2.53 to 5.53 wt% (Fig. 8). TiO₂ is highest for intermediate MgO (4.10–4.30 wt%) and decreases toward lower and higher MgO.

The trace element compositions of the ten samples are presented in Table 1. The immobile elements Nb (25–36 ppm; R² = 0.54) and Zr (56–96 ppm; R² = 0.77) correlate negatively with MgO, whereas Ni (5–38 ppm; R² = 0.89) correlates positively with MgO (Fig. 8). In the Zr/Ti versus Nb/Y discrimination diagram (Pearce, 1996), our Hansen Point samples show similar Nb/Y (0.58–0.64), but more variation in Zr/Ti (0.01–0.02) (Fig. 9). All Hansen Point samples

### TABLE 1. MAJOR AND TRACE ELEMENT BULK ROCK COMPOSITIONS FOR HANSEN POINT AND AUDHILD BAY, ELLESMERE ISLAND, CANADA

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**Notes:** HP = Hansen Point; AB = Audhild Bay; bas-and. = basaltic andesite; LOI = loss on ignition.

*From Trettin (1966b) Open File 3274, Geological Survey of Canada.
plot in the subalkaline field, consistent with the inference from the TAS diagram (Fig. 7).

Rare earth element (REE) chondrite-normalized and multielement primitive mantle-normalized diagrams are presented in Figure 10. These samples show near-parallel REE patterns that are enriched in the light relative to the heavy elements, and all show a minor negative Eu anomaly. The three samples of basaltic andesite (17C-39, 17C-51, and 17C-79) are the most enriched samples, in particular for the light-REEs. The light-REEs (La to Eu) show patterns that are similar to ocean island basalts (OIB), whereas the mid- to heavy-REEs (Gd to Lu) display flatter patterns that are enriched relative to OIB (Fig. 10A). The patterns of the Hansen Point samples are also sub-parallel in the multielement spider diagram and show increasing concentrations relative to primitive mantle with increasing incompatibility from right to left (Fig. 10B). The three basaltic andesites are generally the most enriched samples, but show negative Ti anomalies. All samples show marked negative Sr anomalies. Most samples also show positive Rb and Th anomalies and negative Nb anomalies. The multielement patterns are also comparable to OIB for the most incompatible elements (left side of the diagram), but they are enriched and display flatter patterns in the right side of the diagram (Fig. 10B).

The whole rock compositions of the two dated samples and a rhyodacite flow (17C-38) from the sample section at Hansen Point (Figs. 2B and 4) are also listed in Table 1. The dated sample from Hansen Point (82-TM-212A; Trettin and Parrish, 1987, Trettin, 1996b) has 69.1 wt% SiO$_2$ and plots in the dacite field. Finally, the sample from our sample section (17C-38) contains 70.8 wt% SiO$_2$ and falls in the rhyolite field of Figure 7. This rhyolite sample is enriched in the REEs, apart from Eu that shows a stronger negative anomaly, relative to the basalts and basaltic andesites of Hansen Point (Fig. 7).

In the multielement spider diagram, the pattern for 17C-38 mimics the most enriched basaltic andesites of Hansen Point but at higher values, apart from distinct negative anomalies for Sr, Ti, and Eu. The three silicic samples all have low TiO$_2$. The whole rock compositions of the two dated samples and a rhyodacite flow (17C-38) from the sample section at Hansen Point (Figs. 2B and 4) are also listed in Table 1. The dated sample from Hansen Point (82-TM-212A; Trettin and Parrish, 1987, Trettin, 1996b) has 69.1 wt% SiO$_2$ and plots in the dacite field. Finally, the sample from our sample section (17C-38) contains 70.8 wt% SiO$_2$ and falls in the rhyolite field of Figure 7. This rhyolite sample is enriched in the REEs, apart from Eu that shows a stronger negative anomaly, relative to the basalts and basaltic andesites of Hansen Point (Fig. 10A). In the multielement spider diagram, the pattern for 17C-38 mimics the most enriched basaltic andesites of Hansen Point but at higher values, apart from distinct negative anomalies for Sr, Ti, and Eu. The three silicic samples all have low TiO$_2$. 

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Figure 7. The Na$_2$O + K$_2$O (wt%) vs. SiO$_2$ (wt%) classification diagram showing the bulk rock compositions of basaltic and basaltic andesite dykes and sheets from Hansen Point, Ellesmere Island, Canada. Also shown are the compositions of three silicic samples of this study: 17C-38 (rhyolite), 82-TM-212A (dacite), and 17HSB-40A (hornblende syenite).

Figure 8. The bulk rock compositions of immobile elements TiO$_2$, Nb, Ce, and Ni vs. MgO for basaltic samples of Hansen Point of this study, Ellesmere Island, Canada. Also shown are published compositions for basaltic rocks (<54 wt% SiO$_2$) of: (i) Auduhild Bay/Emma Fjord area (Estrada and Henjes-Kunst, 2004), Philips Inlet area (Estrada and Henjes-Kunst, 2004), outcrops west of Yelverton Bay West (Estrada et al., 2006, 2016), and Hansen Point east of Yelverton Bay (Estrada et al., 2006, 2016); and (ii) a field for Strand Fiord Formation (SFF) (Estrada and Henjes-Kunst, 2004; Kingsbury et al., 2016; Dostal and MacRae, 2018), and (iii) Alpha Ridge (Van Wagoner et al., 1986). Note that the dredged samples of Alpha Ridge are highly altered and the Ti and trace element compositions were reported for four samples, whereas the MgO content was only reported for one sample; these samples are therefore plotted at the same MgO content. Panel (A) also shows a MELTS algorithm fractional crystallization model of the most primitive Hansen Point sample with 5.53 wt% MgO (sample 17C-57), assuming it contained 0.25 wt% H$_2$O and fractionated along the fayalite-magnetite-quartz oxygen buffer. This was calculated using rhyolite-MELTS code release 1.0.2 (Ghiorso and Sack, 1995; Gualda et al., 2012).
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Figure 9. Zr/Ti versus Nb/Y discrimination diagram (Pearce, 1996) showing the bulk rock compositions of basaltic samples of this study from Hansen Point (Ellesmere Island, Canada), together with published data for basalt and basaltic andesite from Audhild Bay, Phillips Inlet, Yelverton Bay West, Alpha Ridge, and the Strand Fjord Formation (SFF). Key and data sources are given in Figure 8.

(0.41–0.45 wt%) and high Zr (356–584 ppm) relative to the basalts and basaltic andesites. They therefore have Zr/Ti ratios that are much higher than can be shown in Figure 9. However, the Nb/Y ratio ranges from 0.32 in 82-TM-212A, over 0.77 in 17C-38 to 2.53 in 17HSB-40A.

U-Pb Chronology

A plagioclase and microcline porphyritic rhyodacite sample from Hansen Point (82-TM-212A, Fig. 4) was originally dated by zircon U-Pb isotope dilution–thermal ionization mass spectrometry (Trettin and Parrish, 1987). These analyses of large, multi-grain fractions returned an intercept age of 88 ± 20 Ma and demonstrated the presence of a significant proportion of xenocrystic zircon. The original mineral separates of this sample were reanalyzed using SHRIMP in order to avoid the mixing of igneous and inherited zircons that plagued the earlier analyses. Transmitted light (Figs. 11A and 11B) and CL (Fig. 11C) images of the zircons show considerable variation in color and shape. There is a subpopulation of zircon grains that are subrounded/resorbed (Fig. 11A) and appear xenocrystic, whereas other grains are clear, colorless, and well-faceted and are inferred to be igneous (Fig. 11B). In CL, most grains are composed of a single phase of oscillatory-zoned zircon, although a small number have internal core/rim structures (Fig. 11C, e.g., grain 76). Twenty-four analyses were carried out on 24 zircon grains (Fig. 11D, Supplementary Data File 6). Seventeen analyses of the dominant, euhedral, oscillatory zoned population present as both discrete grains and rims yield a concordia age of 95.5 ± 1.0 Ma (Fig. 11B) which is interpreted as the crystallization age of the rhyodacite. An additional six analyses demonstrated inheritance ranging from 110 to 1060 Ma, primarily from the population of subrounded/resorbed grains, but not exclusively (e.g., grain 66, Fig. 11C).

Sample 17HSB-40A collected along the western shore of Audhild Bay (Fig. 2B) is a medium-grained, hornblende-porphyritic syenite from a unit inferred to be the “hornblende syenite” unit on Trettin’s map (1996a), which previously yielded a Cretaceous K-Ar age interpreted to reflect a younger thermal overprint. Zircon recovered from the syenite are clear, colorless, anhedral fragments (Fig. 11E). The zircons have extremely poor CL response owning to very high U contents (Supplementary Data File 6), thus their faint internal zonation is best seen in BSE images (Fig. 11F). Eighteen analyses on separate zircon grains, returned 206Pb/238U ages between 78.6 and 90.7 Ma. With the exception of the oldest analysis (spot 12199-26.1, 90.7 Ma, Supplementary Data File 6), there is a linear relationship between SHRIMP Pb/U age and U concentration. This is a known analytical artifact of ion probe analyses related to differences in the matrix of high U zircon relative to the reference material used to calibrate the ion sputtering and instrumental Pb-U mass fractionation (Williams and Hergt, 2000; White and Ireland, 2012). The weighted mean 206Pb/238U age of seven analyses of zircon with less than 2000 ppm U is 79.5 ± 0.5 Ma (Fig. 11G) and is interpreted as the crystallization age of the hornblende syenite. One additional low U zircon returns an age of ca. 90 Ma and is interpreted as an inherited component.

DISCUSSION

Classification of Basalt and Basaltic Andesite at Hansen Point

The analyzed samples of basalt and basaltic andesite from Hansen Point form coherent trends for the immobile elements (Fig. 8) and have near-constant ratios of incompatible elements, e.g., Nb/Y (Fig. 9) and Zr/Nb (8.0–9.6, Table 1). The Nb/Y (0.60–0.64) plots in the subalkaline field, consistent with the classification in the TAS diagram with the exception of one highly altered sample (Fig. 7). In several tectonic discrimination diagrams (Nb-Zr-Y, Ti-Zr-Y, Ti-V, MgO-FeO*-Al2O3), the Hansen Point samples classify as intraplate volcanism (Supplementary Data File 7–10). In the AFM diagram they follow a trend of iron enrichment similar to tholeiitic basalts (Supplementary Data File 11). Similarly, the clinopyroxene compositions plot in the subalkaline field of the Ti-Ca discrimination diagram (Fig. 12) and compare to the tholeiitic Skaergaard differentiation trend in the pyroxene quadrilateral (Fig. 6). The plagioclase and olivine compositions are also typical of evolved, tholeiitic basalts. We therefore conclude that the basalts and basaltic andesites of Hansen Point follow tholeiitic trends and represent intraplate rift volcanism, corroborating previous inferences (Trettin and Parrish, 1987; Estrada et al., 2006; 2016; Bédard et al., 2019).
Petrogenesis of Basalt and Basaltic Andesite at Hansen Point

The TiO$_2$ of the Hansen Point basalts and basaltic andesites (Fig. 8) can be explained by fractional crystallization. The change-over at maximum TiO$_2$ witness the first appearance of FeTi oxides as a fractionating phase at 4.3–4.1 wt% MgO. This is confirmed by a MELTS (code release 1.0.2) fractional crystallization model Ghiorso and Sack, 1995; Gualda et al., 2012) starting with the most primitive Hansen Point sample with 5.53 wt% MgO (sample 17C-57), assuming it contained 0.25 wt% H$_2$O and fractionated along the fayalite-magnetite-quartz oxygen buffer (Fig. 8A). The trends of decreasing Ni, and increasing Ce and Nb with decreasing MgO (Fig. 8) are also qualitatively consistent with fractional crystallization. However, the increasing SiO$_2$ up to 57 wt% in the basaltic andesites (Fig. 7) may also indicate significant crustal assimilation, in addition to fractional crystallization. Similarly, the positive Th and negative Nb anomalies in the primitive mantle-normalized...
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Figure 12. Clinopyroxene (Cpx) compositions from basaltic dykes and sheets of Hansen Point (Ellesmere Island, Canada) plotted in the Ti vs. Ca per formula unit (p.f.u.) discrimination diagram of Leterrier et al. (1982). Also shown are the clinopyroxene compositions from the dredge samples of the Alpha Ridge (Van Wagoner et al., 1986).

Figure 13. Th/Yb vs. Nb/Yb showing the Hansen Point basalt, basaltic andesite, and silicic rocks of this study, other basaltic rocks of northern Ellesmere Island, Canada, and the Strand Fiord Formation (SFF) (see caption to Fig. 8), the oceanic mantle array of Pearce (2008), the average composition of upper and lower continental crust (AUC, and ALCC, respectively) from Willbold and Stracke (2006), the average composition of Pearya basement gneisses in the Hansen Point area (Succession I, Estrada et al., 2018) and a Cretaceous sediment (sandstone) from Axel Heiberg Island (Evenchick et al., 2015). The composition shown for the Pearya basement is the average of three samples of leucogranite and gneiss and is very similar to AUCC, also in terms of Th, Nb, and Yb concentrations (Estrada et al., 2018). In this average we have not included metamorphic mafic rocks in the Pearya Terrane as these are less fusible during assimilation processes and have intermediate compositions between mantle and crust.

The Hansen Point trend in Figure 13 is best explained by crustal contamination assuming a starting composition for the uncontaminated basalt between E-MORB and OIB. For illustration, we have calculated trends for bulk mixing (not shown) and for coupled assimilation and fractional crystallization (AFC) assuming that (i) the uncontaminated basalt was a simple mixture of 85% E-MORB and 15% OIB (constructed to fit the uncontaminated end of the trend) and (ii) the assimilated material had the composition of AUCC. Results are very similar for calculations using the average leucocratic Pearya basement rocks as the assimilated material (not shown). The bulk mixing model explains the Hansen Point basalts by ~8–20% assimilation of bulk crust, whereas the basaltic andesites requires up to 35% assimilation of bulk crust. Similarly, the AFC calculations suggest the basalts of Hansen Point can be explained by 10–17% assimilation, and up to 38% assimilation is required to explain the basaltic andesite with the highest Th/Yb (Fig. 13). Supplementary Data Figure 12 shows that the high SiO2 and high Th/Nb of the basaltic andesites (52–57 wt%) can also roughly be explained by mixing with up to 35% AUCC (Willbold and Stracke, 2006). The omnipresent influence of continental crust in the petrogenesis of the basalts and basaltic andesites of Hansen Point is supported by Sr and Nd isotopic compositions (Estrada et al., 2016; Bédard et al., 2019).

multielement plot (Fig. 10B) are hallmarks of crustal assimilation.

To examine this further we have plotted the Hansen Point samples in Th/Yb versus Nb/Yb space (Fig. 13). This plot was developed by Pearce (2008) to distinguish basaltic samples that were influenced by continental crust relative to uncontaminated basaltic samples of the oceans. The latter forms a mantle array encompassing depleted normal mid-ocean ridge basalts (N-MORB), enriched mid-ocean ridge basalts (E-MORB), and OIB that formed with little or no influence from continental crust. Continental crust plots above the mantle array at relatively high Th/Yb for a given Nb/Yb. For illustration, we have shown average compositions of upper and lower continental crust (AUC, and ALCC, respectively) from Willbold and Stracke (2006). All Hansen Point samples plot above the mantle array in a trend stretching toward the composition of AUCC. Clearly, the ALCC cannot provide a satisfactory explanation for crustal contamination of the Hansen Point trend. Figure 13 also shows published compositions for local crustal rocks that may be potential contaminants. These are (i) local Pearya basement rocks (Succession I) occurring within 12 km to the SE of Hansen Point (Fig. 4) (Estrada et al., 2018) and (ii) a Cretaceous sandstone from Axel Heiberg Island (Evenchick et al., 2015). The composition shown for the Pearya basement is the average of three samples of leucogranite and gneiss and is very similar to AUCC, also in terms of Th, Nb, and Yb concentrations (Estrada et al., 2018). In this average we have not included metamorphic mafic rocks in the Pearya Terrane as these are less fusible during assimilation processes and have intermediate compositions between mantle and crust. In contrast, the Cretaceous sandstone has lower Th/Yb that is comparable to the basaltic andesite samples (Fig. 13). Moreover, the Th concentration of this sandstone (4.2 ppm) is comparable to the basaltic andesites (3.7–5.9 ppm) and lower than the basaltic andesites (6.5–9.6 ppm) at Hansen Point. Rocks of this particular composition are therefore not likely candidates to explain crustal contamination in the Hansen Point samples, unless it is assumed that partial melts of the sandstone were assimilated.

The Hansen Point trend in Figure 13 is best explained by crustal contamination assuming a starting composition for the uncontaminated basalt between E-MORB and OIB. For illustration, we have calculated trends for bulk mixing (not shown) and for coupled assimilation and fractional crystallization (AFC) assuming that (i) the uncontaminated basalt was a simple mixture of 85% E-MORB and 15% OIB (constructed to fit the uncontaminated end of the trend) and (ii) the assimilated material had the composition of AUCC. Results are very similar for calculations using the average leucocratic Pearya basement rocks as the assimilated material (not shown). The bulk mixing model explains the Hansen Point basalts by ~8–20% assimilation of bulk crust, whereas the basaltic andesites requires up to 35% assimilation of bulk crust. Similarly, the AFC calculations suggest the basalts of Hansen Point can be explained by 10–17% assimilation, and up to 38% assimilation is required to explain the basaltic andesite with the highest Th/Yb (Fig. 13). Supplementary Data Figure 12 shows that the high SiO2 and high Th/Nb of the basaltic andesites (52–57 wt%) can also roughly be explained by mixing with up to 35% AUCC (Willbold and Stracke, 2006). The omnipresent influence of continental crust in the petrogenesis of the basalts and basaltic andesites of Hansen Point is supported by Sr and Nd isotopic compositions (Estrada et al., 2016; Bédard et al., 2019).

and for coupled assimilation and fractional crystallization (AFC) curves assuming that (i) the uncontaminated basalt was a simple mixture of 85% enriched mid-ocean ridge basalt (E-MORB) and 15% ocean island basalt (OIB) and (ii) the assimilated material had the composition of AUCC. The AFC equations are from DePaolo (1981) and the calculations assume the bulk partition coefficients are 0.1 for all elements, and the r value, i.e., the ratio of the rate of mass assimilated to the rate of mass crystallized, is 0.3 (Tegner et al., 1999). N-MORB—normal mid-ocean ridge basalt.
We also emphasize that the steep trend of the Hansen Point rocks in Figure 13 cannot easily be explained by crustal components mixed into the mantle. This could, for example, result from situations where continental sediments were translated to the mantle via subduction zone processes. Such mechanisms are known from island arc volcanism (Pearce, 2008), but also from some LIPs such as the Central Atlantic Magmatic Province (Whalen et al., 2015; Marzoli et al., 2018, 2019). However, in the case of crustal components mixed into the mantle, the mantle melting trends have been shown to be sub-parallel to the mantle array in Figure 13 (Pearce, 2008; Tegner et al., 2019), and thus almost orthogonal to the Hansen Point trend.

In summary, the analyzed basalts and basaltic andesites of Hansen Point show coherent geochemical trends that are best explained by fractional crystallization coupled with ubiquitous assimilation of upper continental crust. A parental magma of tholeiitic basalt with trace element compositions intermediate between E-MORB and OIB provides a good fit. The tectonic setting was one of continental intraplate, rift-related volcanism, in agreement with previous studies (e.g., Estrada et al., 2006, 2016; Dockman et al., 2018).

Petrogenesis of Silicic Rocks at Hansen Point and Audhild Bay

It is beyond the scope of the present contribution to discuss the petrogenesis of the silicic rocks in detail. We note, however, that the composition of the rhyolite flow of the Hansen Point section (17C-38) is enriched in the incompatible trace elements and depleted in the compatible trace elements relative to the basaltic andesites, and shows a very similar pattern in the multi-element plot (Fig. 10). Moreover, in Figure 13 this rhyolite sample plots on the Hansen point trend at slightly higher Th/Yb (2.1) compared to the basaltic andesites (up to 1.8). We therefore conclude that this rhyolite composition is well explained by further AFC processes relative to the tholeiitic basalts and basaltic andesites. In other words, the extrusive silicic rocks are petrogenetically linked to the tholeiitic basaltic dykes. This result corroborates the analysis of Estrada et al. (2016).

Although the available trace element data for the dated dacite sample from Hansen Point (82-TM-212A; Trettin and Parrish, 1987, Trettin, 1996b) is sparse, its Th/Yb is distinctly higher (3.9) than the 17C-38 rhyolite and comparable to the AUCC (Fig. 13). This sample therefore has a strong crustal signature, consistent with the abundance of inherited zircons as discussed below. Hence, this dacite potentially could represent a crustal melt involved as a contaminant in the AFC processes discussed above for the Hansen Point samples. Finally, the dated sample of hornblende syenite (17HSB-40A) is distinct from the two other silicic samples discussed. The alkali-rich composition (12.1 wt% Na₂O + K₂O and Nb/Y of 2.53) shows this sample is alkaline. This is confirmed by (Na⁺K)/Al of 1.01 and an aluminum saturation index (Al/[Ca + Na⁺K]) of 0.90 which suggest it is borderline to being peralkaline. Also, in Figure 13 this sample plots at the upper bound of the mantle array close to OIB and at much higher Nb/Yb (24.6) compared to the two other silicic samples (7.1 and 5.4). We therefore conclude that the dated hornblende syenite from Audhild Bay formed from a mantle-derived magma that evolved to trachytic compositions mainly by fractional crystallization without much interaction with the continental crust.

Geochemical Correlation of Basaltic Rocks of Northern Ellesmere Island, the Strand Fiord Formation on Axel Heilberg Island, and Alpha Ridge

As outlined above, the Hansen Point Volcanic Complex nomenclature has hitherto been used collectively as reference for volcanic rocks in the four areas referred to here as Audhild Bay, Philips Inlet, Yelverton Bay West, and Yelverton Bay East (that includes the Hansen Point stratotype area) (Fig. 2B) (Estrada et al., 2006, 2016). In the following we critically discuss this usage and the correlations to the Strand Fiord Formation on the basis of geochemistry and, in the next section, from geochronology. The published compositions for basaltic and slightly more evolved rocks with up to 56 wt% SiO₂ from these areas are also plotted in Figures 8 and 9 (Estrada and Henjes-Kunst, 2004; Estrada et al., 2006, 2016). Clearly, the samples from Audhild Bay, Philips Inlet, and Yelverton Bay West have higher Nb (up to 143 ppm) and Ce (up to 140 ppm) concentrations for a given MgO content relative to the Hansen Point rocks (Fig. 8). Similarly, in the Zr/Ti vs. Nb/Y discrimination diagram these rocks form a separate trend in the alkaline field with Nb/Y values from 0.88 to 3.81 (Fig. 9), distinctly higher than the tholeiitic rocks from Hansen Point. The exceptions are two samples (SE161/01A and SE135/01 from Estrada et al., 2016) from Yelverton Bay West that overlap with the Hansen Point samples in terms of Ce and Nb vs. MgO (Fig. 8), and plot at intermediate Nb/Y (0.72–0.76) close to the division line between the tholeiitic and alkaline fields (Fig. 9). Unfortunately, the nature of the outcrops of these two samples is not given. We also note that the previously published values for basalts and basaltic andesite for the stratotype at Hansen Point (Estrada et al., 2016) overlap perfectly with our results (Figs. 8 and 9).

Figures 8 and 9 also show a field for published values for basaltic rocks of the Strand Fiord Formation (Estrada and Henjes-Kunst, 2004; Kingsbury et al., 2016; Dostal and MacRae, 2018). Figure 8 shows that the compositions of Hansen Point samples largely overlap with the compositions of SFF. In Figure 9, they also mostly overlap, although the trend of near-constant Nb/Y and variable Zr/Ti for the Hansen Point samples is comparable to the broad positive correlation of Zr/Ti and Nb/Y shown by the SFF. Variation of Zr/Ti ratio, however, can be ascribed to effects of fractional crystallization of Fe-Ti oxide that preferentially removes Ti relative to Zr. Moreover, Figures 8 and 9 also show the compositions of four basalts dykes cutting Pearya basement in the vicinity of Hansen Point; two are located ~5 km to the south in a fault block of the Mitchell Point fault zone, and two are NE-SW striking dykes located ~10 km to the northeast across Petersen Bay (Fig. 4) (Estrada and Henjes-Kunst, 2013). As can be seen in Figures 8 and 9, their compositions are similar to tholeiitic rocks from both Hansen Point and SFF. This was also the conclusion of Estrada and Henjes-Kunst (2013).

Finally, the published results for the dredge samples of the Alpha Ridge (Van Wagoner et al., 1986) are shown in Figures 8 and 9. The Alpha Ridge samples are similar to the samples from Audhild Bay, Philips Inlet, and Yelverton Bay West and have similar incompatible element concentrations (Figs. 8 and 9). In contrast, the clinopyroxene compositions of Alpha Ridge are different from the Hansen Point samples (Fig. 12). There is also a marked difference in whole rock compositions in Figure 13. Here, the Alpha Ridge samples plot close to OIB within the mantle array whereas the Hansen Point samples form a vertical trend that can be explained by contamination of upper continental crust and points to a mantle-derived composition distinct from both OIB and from the Alpha Ridge samples as discussed above. Unfortunately, the available data for basalts from Audhild Bay and Philips Inlet are lacking in Yb and thus cannot be shown in this plot. However, the dated hornblende syenite from Audhild Bay plots close to OIB and the Alpha Ridge samples in Figure 13. Finally, data from basalts and basaltic andesite of Yelverton Bay West (Estrada et al., 2016) also plot close to OIB and Alpha Ridge samples across the upper bounds of the mantle array.

In summary, we have shown that the basaltic rocks (lavas and dykes) at Hansen Point (Yelverton Bay East) are tholeiitic and compositionally akin to (i) dykes cutting Pearya basement in the vicinity of Hansen Point and to (ii) lavas and
intrusions of the Strand Fiord Formation on Axel Heiberg Island. Notably, the tholeiitic compositions of the Hansen Point rocks are distinct from the alkaline compositions of basaltic dykes and lavas of the other areas of northern Ellesmere Island (Audhild Bay, Philips Inlet, and Yelverton Bay West), and to the alkaline basalts dredged from the Alpha Ridge.

Age of the Hansen Point Volcanic Complex, the Strand Fiord Formation, and Alpha Ridge

Assessing the chronology of the magmatism of northern Ellesmere Island is challenging for several reasons. Firstly, geological and structural age control is hampered by the fault contacts with much older Paleozoic or Proterozoic rocks (Figs. 2 and 4). Secondly, the ubiquitous interaction with crustal rocks in the petrogenesis of both basalts and silicic rocks (Fig. 13; Estrada et al., 2016), renders zircon inheritance a major challenge for U-Pb chronology, as discussed above and by Trettin and Parrish (1987) and Estrada et al. (2016). Thirdly, resetting of Ar-Ar systematics has been ascribed to hydrothermal activity associated with the Eurekan orogeny both for HALIP rocks of northern Ellesmere Island (Estrada and Henjes-Kunst, 2013) and for North Greenland (Tegner et al., 2011). Notwithstanding these challenges, we have summarized recently published Ar-Ar and U-Pb chronology argued to represent crystallization ages for volcanic rocks of northern Ellesmere Island, and basalts of SFF and Alpha Ridge in Figure 14.

In the Hansen Point area (Yelverton Bay East), recent chronology is restricted to four Ar-Ar ages and the U-Pb age presented here. Ar-Ar plateau ages of 93.9 ± 1.3 Ma and 83.0 ± 1.8 Ma were given for two, compositionally similar, basaltic dykes cutting the volcanic rocks at Hansen Point close to our sample transect (Estrada and Henjes-Kunst, 2013). On the grounds that the younger age overlapped with the preferred emplacement age for volcanic rocks of Yelverton Bay West, it was concluded that the 83.0 ± 1.8 Ma age likely represented the age of magmatism at Hansen Point itself. The older age was regarded as spurious or unexplained. The older 93.9 ± 1.3 Ma age, however, is based on a robust Ar-Ar plateau age that just overlaps within error of our U-Pb crystallization age of 95.5 ± 1.0 Ma (Figs. 11 and 14) for a rhyodacite sample of Hansen Point (Trettin and Parrish, 1987). Moreover, two basaltic dykes cutting Pearya basement ~5 km to the south in a fault block within the Mitchell Point fault zone, and a NE-SW striking dyke located ~10 km to the northeast across Petersen Bay (Fig. 4), also yielded Ar-Ar plateau ages in this range (94.3 ± 2.8 Ma and 96.6 ± 1.6 Ma; Estrada and Henjes-Kunst, 2013) (Fig. 14). The ages of SFF basalts range from ca. 102–95 Ma (Fig. 14) with the most recent U-Pb ages (95.56 ± 0.24 Ma, 95.18 ± 0.35 Ma; Kingsbury et al., 2018) overlapping with the Hansen Point ages. As discussed above, the compositions of the dykes in the vicinity of Hansen Point are tholeiitic and similar to the dykes and lavas of this study, and to the basalts of SFF (Figs. 8 and 9). We therefore conclude that both the chronology and geochemistry of the Hansen Point dykes and lavas can be correlated with the basalts of SFF, suggesting they were part of the same magmatic system.

The chronology of Audhild Bay and Philips Inlet is more straightforward (Fig. 14).

Three published Ar-Ar ages for basalt flows and an ignimbrite at Audhild Bay have similar ages of 78.4 ± 0.1 Ma, 78.8 ± 0.1 Ma, and 79.2 ± 1.9 Ma (Dockman et al., 2018; Estrada and Henjes-Kunst, 2013). A similar Ar-Ar age of 76.6 ± 3.7 Ma is reported for a basaltic flow at Philips Inlet (Fig. 14). The new U-Pb age of the plutonic rock from Audhild Bay with an age of 79.5 ± 0.5 Ma (Fig. 11) shows that this hornblende syenite can be linked to the volcanic rocks outcropping between Audhild Bay and Emma Fjord (Fig. 2). Hence, the rocks of Audhild Bay and Philips Inlet are ~18 m.y. younger than the Hansen Point rocks. Moreover, their alkaline compositions are distinct from the tholeiites of Hansen Point (Figs. 8 and 9).

While the alkaline Wootton intrusive complex (WIC) that extends across Wootton Peninsula from Philips Inlet to Yelverton along the Mitchell Point fault zone (Trettin and Parrish, 1987; Saumur et al., 2016) (Fig. 2) gives consistent U-Pb and Ar-Ar ages of 93–92 Ma (Fig. 14) (Estrada and Henjes-Kunst, 2013), the ages reported for Yelverton Bay West are disparate. Two Ar-Ar plateau ages that are interpreted to represent crystallization ages gave 82.3 ± 2.0 Ma and 73.5 ± 2.4 Ma for alkali basalt and trachyandesite flows, respectively (Estrada and Henjes-Kunst, 2013). In contrast, zircon U-Pb chronology of three samples of rhyodacite flows from the same volcanic area yielded highly diverse age populations resulting from inheritance (Estrada et al., 2016). The three samples are dominated by zircons with ages ranging from ca. 88–120 Ma, i.e., HALIP ages, but all three samples also contained Proterozoic zircons. As pointed out by Estrada et al. (2016), it is obviously a challenge to determine the emplacement age for these. For one sample (SE162/01) they interpreted the twelve youngest and concordant grains as the emplacement age (103.6 ± 1.0 Ma). However, if concordance is assessed using the probability of concordance of individual Concordia ages (Ludwig, 1998) (rather than the difference between the 206Pb/238U and 207Pb/206Pb ages), the data reveals that there are also discordant ages in the 98–95 Ma range for this sample. The two other samples have populations around 99–98 Ma and 106–105 Ma, and individual dates down to 88 Ma. In our view, it therefore remains a possibility that the rhyodacites of Yelverton Bay West were emplaced at the same time as the rhyodacite units at Hansen Point. However, more high-resolution chronology is required to resolve crystallization ages from xenocrystic/autochryotic material. We also note that the younger Ar-Ar ages obtained for basaltic and trachyandesitic flows at Yelverton Bay West (82.3 ± 2.0 Ma and 73.5 ± 2.4 Ma; Estrada and Henjes-Kunst, 2013) are comparable, but not identical to the ages.
obtained at Audhild Bay (79–78 Ma; Estrada and Henjes-Kunst, 2013; Dockman et al., 2018; this study) (Fig. 14). Moreover, in terms of compositions, the basaltic and trachyandesitic rocks of Audhild Bay, Philips Inlet, and Yelverton Bay West are comparable (Figs. 8 and 9). Hence, we surmise that these rocks may have formed part of an alkaline magmatic province that was active perhaps from ca. 83 to 73 Ma, as also suggested by Estrada et al. (2016).

Another part of the volcanic puzzle for Ellesmere and Axel Heiberg islands are the alkaline, silicic ash beds (bentonites) that are interbedded in the Kanguk Formation (Fig. 3). Their ages range from 93–83 Ma (Fig. 14) (Davis et al., 2017; Pointon et al., 2019). Compositionally, they are similar to the alkaline silicic volcanic rocks and WIC of northern Ellesmere Island, and the initial phase (ca. 93–91 Ma) therefore fits very well with WIC, as pointed out by these authors. However, the later ashes from ca. 90–83 Ma are not readily matched by any known ages (Fig. 14). Davis et al. (2017) argued that the thickness of the ash beds (10–50 cm) can be explained by plinian eruptions up to 1000 km away and, therefore, pointed to the volcanic rocks of northern Ellesmere Island or the Alpha Ridge as the likely source areas. The recent Ar–Ar age obtained for the dredge samples of alkaline basalts from Alpha Ridge (90.40 ± 0.26 Ma; Williamson et al., 2019a), and the explosive character of these samples (Williamson et al., 2019b; Massey et al., 2019), therefore, supports this speculation. However, so far only explosive basaltic samples have been recovered from the Alpha Ridge.

In summary, our new U–Pb crystallization age of 95.5 ± 1.0 Ma for Hansen Point (Fig. 11) is consistent with Ar–Ar ages for dykes in the vicinity of Hansen Point (Estrada and Henjes-Kunst, 2013), and is coeval with the basalts of the Strand Fiord Formation. The other dated occurrences of northern Ellesmere Island (Audhild Bay, Philips Inlet, and Yelverton Bay West) and Alpha Ridge are considerably younger, including our 79.5 ± 0.5 Ma age for a hornblende syenite at Audhild Bay.

**Revised Nomenclature for the Volcanic Rocks of Northern Ellesmere Island**

The geochemical and chronological correlations reviewed above pose serious questions to the usage of the Hansen Point Volcanic Complex (Estrada et al., 2006, 2016) as a collective term for the Cretaceous volcanic rocks of northwestern Ellesmere Island. Instead, we propose to divide these rocks into tholeiitic and alkaline suites. The analyzed basaltic to rhyolitic rocks from the Hansen Point area (Yelverton Bay East) are all tholeiitic (Trettin and Parrish, 1987; Estrada et al., 2006, 2016; this study). We view these rocks as the stratotype of the tholeiitic suite of northwestern Ellesmere Island and therefore propose that it is called the Hansen Point tholeiitic suite (HPTS). We note that this suite is not restricted to Hansen Point. Estrada et al. (2016), for example, reported tholeiitic compositions from Yelverton Bay West. Based on the present knowledge, the HPTS was mainly emplaced from 97 to 93 Ma and can be correlated with the SFF volcanic rocks of Axel Heiberg Island.

As discussed above (Figs. 8, 9, and 13), the volcanic rocks of Audhild Bay, Philips Inlet, and Yelverton Bay West are all alkaline. We propose the large outcrops of alkali basaltic to rhyolitic extrusives and intrusions (e.g., the syenite reported here) of the Audhild Bay area (Fig. 2) and described by Embry and Osadetz (1988) is used as the stratotype. Hence, the alkaline suite of northwestern Ellesmere Island is denoted as the Audhild Bay alkaline suite (ABAS). Based on the present knowledge, the alkaline suite is considerably younger (83–73 Ma) than the tholeiitic suite (97–93 Ma).

**Potential Linkage to OAE2**

While long debated, the causes of Cretaceous Ocean Anoxic Events (OAEs) are increasingly linked to volcanic eruptions. Numerous studies have suggested a linkage of one of the most intense OAEs, the late Cenomanian OAE2 (=94 m.y.), to either (or both) the HALIP and Caribbean LIP (e.g., Kuroda et al., 2007, Turgeon and Creaser, 2008; Adams et al., 2010; Tegeter et al., 2011; Zheng et al., 2013; Lühr and Kennedy, 2014; Du Vivier et al., 2015; Schröder-Adams et al., 2019; O’Connor et al., 2020). Several studies have used geochemical proxies to link OAE2 to a purported submarine LIP eruption, including: isotopic records of Os (Turgeon and Creaser, 2008; Du Vivier et al., 2015; Schröder-Adams et al., 2019), S (Adams et al., 2010), Nd (Zheng et al., 2013), and Hg (Percival et al., 2018). This has important implications for how climate and environmental impacts during OAE2 are modeled, as it implies deleterious volatiles of the LIP eruption are released directly into marine waters rather than into the atmosphere (e.g., O’Connor et al., 2020; Joo et al., 2020; Percival et al., 2018). However, it has been argued that the release and distribution of magmatic volatiles is greatly reduced in submarine environments compared to subaerial eruptions (e.g., Percival et al., 2018). Furthermore, a submarine LIP erupting through ocean crust would not generate the additional volatiles compared to a LIP erupting through a sedimentary basin, through thermal metamorphism of sediments (e.g., CO₂, CH₄, Cl, Br, CO, and Hg) (Svensen et al., 2018a; 2018b; Grasby et al., 2019).

The studies invoking a submarine LIP at OAE2 do not account for reported evidence for subaerial eruption occurring during that time, that includes Pb isotope (Kuroda et al., 2007) and clay minerals data (Lühr and Kennedy, 2014). In addition, direct evidence of subaerial eruption of the SFF phase of HALIP, including basalt flows and pyroclastic deposits, have long been recognized (Ricketts et al., 1985; Souther, 1963). Likewise, it is recognized that the tholeiitic suite (HPTS) of the Hansen Point stratotype section is composed of interbedded basaltic and rhyolitic extrusive units that erupted subaerially (Trettin and Parrish, 1987; Estrada et al., 2006). Moreover, amygdaloidal textures in the studied dykes cutting the volcanic rocks witness degassing and these dykes thus most likely represent near-surface feeders for subaerial eruptions. Our work links the subaerial eruptions of SFF and HPTS to the same late Cenomanian age magmatic event. These results imply a much broader subaerial eruption event, than previously recognized to have occurred at that time, one that could have been even more extensive depending on the extension of the poorly characterized Alpha Ridge. Although volcanism of HALIP spread over a long period (130–60 Ma), the stratigraphy shows subaerial volcanism was pulsed (Fig. 3) and recent chronology suggests that two, short major volcanic events took place at ca. 122 and 95 Ma (e.g., Corfu et al., 2013; Estrada et al., 2016; Kingsbury et al., 2018; Dockman et al., 2018; this study). The subaerial ca. 95 Ma HALIP event correlates well with age estimates for the onset of OAE2, and as such we suggest that this event is the best candidate for driving that OAE. Similarly, the subaerial ca. 122 Ma HALIP event correlates well with age estimates for the onset of OAE1a and a causal relationship has been proposed (Midtkandal et al., 2016). In both cases it can be argued that the subaerial nature of the HALIP events are more likely to have caused major global environmental perturbations given deleterious volatiles being released directly to the atmosphere, affecting climate and allowing rapid global dispersion. Additionally, HALIP volcanics intruded through sediments of the Sverdrup Basin causing thermal metamorphism of organic rich shales and further volatile generation (Goodarzi et al., 2018). Submarine LIPs of similar age (e.g., Caribbean and Ontong Java oceanic plateaus) would have directly impacted local marine systems and would explain some geochemical anomalies (Os, S, Nd) in sedimentary records, but given more rapid marine sequestration processes of...
released volatiles, along with much slower ocean circulation, global impacts would likely be more limited compared to the HALIP events.

CONCLUSIONS

This study aimed to better understand the geochemistry, chronology, and petrogenetic history of Cretaceous mafic and felsic volcanic rocks located at Hansen Point, and how they compare to the basalts from other locations of northern Ellesmere Island, the Strand Fiord Formation of Axel Heiberg Island, and the Alpha Ridge, in order to clarify their relationships to overall HALIP volcanism and to environmental perturbations.

At Hansen Point mafic magmatism includes lavas interbedded with silicic volcanic rocks (e.g., rhyodacite), dykes, and sheets. The analyzed basalts, basaltic anidesites, and rhyolites of Hansen Point are distinct both in terms of age and composition from other occurrences of magmatism of northern Ellesmere Island, that hitherto all have been described the Hansen Point Volcanic Complex. We therefore propose this nomenclature is abandoned. Instead, we suggest the volcanic rocks of northern Ellesmere Island are divided into two suites: the Hansen Point tholeiitic suite (HPTS) that were emplaced at ~97–93 Ma and mainly is represented at the Hansen Point stratotype section; and the Audhild Bay alkaline suite (ABAS) that is considerably younger (83–73 Ma) and includes volcanic and intrusive rocks at Audhild Bay, Philips Inlet, and Yelverton Bay West.

Finally, our study supports the view that rocks of ABAS are related to those of the Alpha Ridge. We emphasize that the lack of direct geochronological correlation of the volcanic rocks at Hansen Point and the few available samples from the Alpha Ridge does not preclude a relationship. The deeper parts of the Alpha Ridge could easily include HPTS and Strand Fiord Formation equivalents, as suggested by the on-land extension of the Alpha Ridge geophysical signatures on the Canadian Arctic islands. In the broader scope, understanding the connections of Alpha Ridge to Canada’s continental crust contributes to the research needed for the definition of territorial boundaries in international waters under UNCLOS (United Nations, 1982). Understanding the onland-offshore connections can also help resolve total eruptive volumes during HALIP events and the potential global environmental change they may have driven.

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