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## 2019

Permanent link: https://doi.org/10.4095/314659

**Recommended citation**
Dockman, D.M., Hadlari, T., and Dewing, K., 2019. Geochemistry of the Neoproterozoic to Cambrian mafic volcanic rocks of the Jaeger Lake assemblage and the Yelverton Formation, Nunavut; Geological Survey of Canada, Open File 8555, 13 p. https://doi.org/10.4095/314659

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# Abstract

Basaltic rocks of the Jaeger Lake assemblage of Axel Heiberg Island and the Yelverton Formation of Ellesmere Island are Neoproterozoic to Cambrian in age and outcrop in a stratigraphic package dominated by carbonate. A lack of modern geochemical data on these basalts has limited the ability to correlate the two assemblages and to comment on the tectonic setting from which they were generated.

Major, Trace, and Rare Earth Element (REE) geochemistry was performed on three samples collected by the Geological Survey of Canada (GSC) during the 2015-2017 field seasons. Trace element analysis indicates that volcanic flows of the Jaeger Lake assemblage and sills within the Yelverton Formation are sub-alkaline basalts that form a geochemical array along a garnet-lherzolite petrogenetic trend. One sample from each assemblage has an REE pattern indicative of a magma derived from a garnet-bearing, EMORB source, while one Jaeger Lake sample has a strongly depleted, NMORB-like REE pattern.

We hypothesize that all 3 samples are from the same EMORB source and that the strongly depleted sample is the result of extreme, iterative partial melting. Trace elements alone cannot determine if this hypothesis is correct, so an ongoing Sr-Nd and U-Pb study is being undertaken to comment on the age and source characteristics of these understudied basalts.

# Introduction

The Jaeger Lake assemblage is a 425 m thick package of interbedded carbonates and volcanics that outcrops in the Northern Heiberg Fold Belt of Axel Heiberg Island (Figure 1a). The carbonates contain stromatolites indicating the volcanic rocks were extruded in a shallow marine shelf setting. The Yelverton Formation has a total thickness of 1000 m of interbedded carbonates, sills, volcanics, with minor chert and mudrock (Trettin, 1998), which outcrops in the Clements Markham Fold Belt on northwest Ellesmere Island (Figure 1a). The Yelverton Formation was deposited in a deep marine basin called the Hazen Trough (Trettin, 1998). The formations have been subject to variable metamorphism up to greenschist facies.

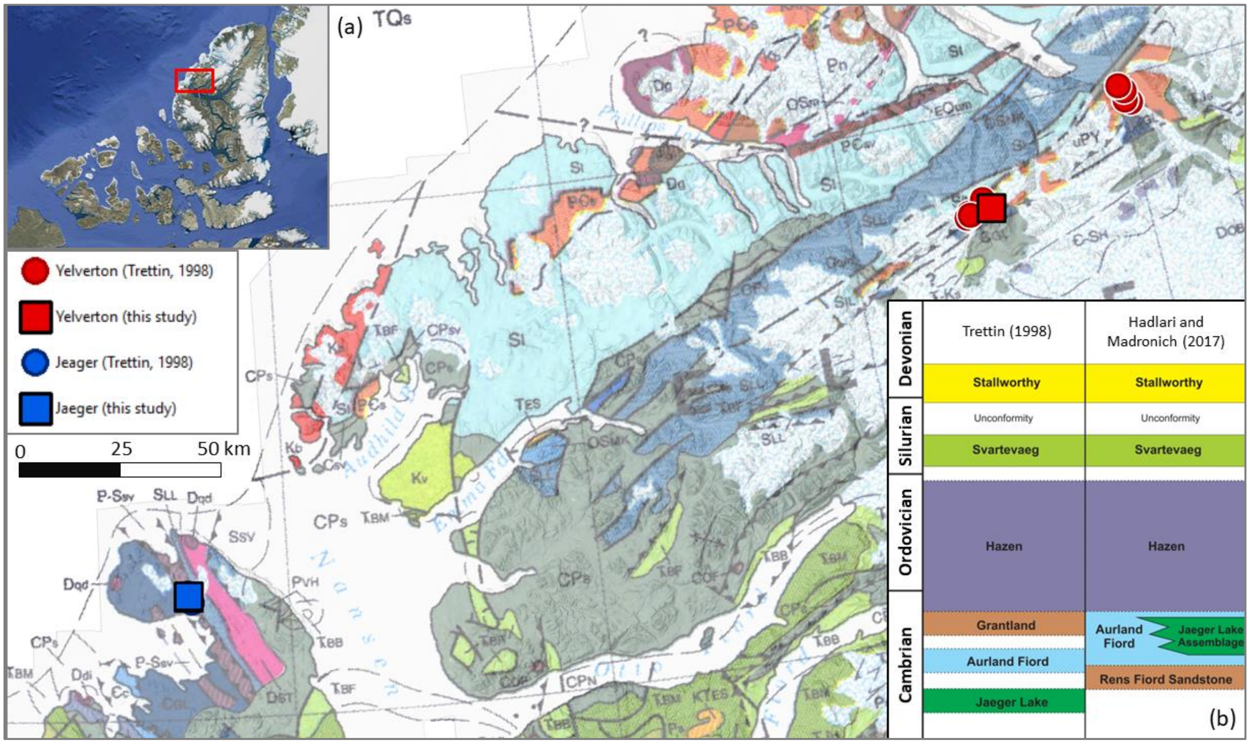

Figure 1—(a) Geological map showing the basalt sample locations. Jaeger Lake assemblage in blue; Yelverton Formation in red. See Okulitch (1991) for formation codes and stratigraphic descriptions. Geochemistry from this study and Trettin (1998). (b) Updated stratigraphic chart adapted from Hadlari and Madronich (2017). Colours of stratigraphy do not match the map in (a)

There are no radiometric ages of these volcanics; they are classified as Neoproterozoic to Early Cambrian age based on their being thrust on top of the Cambrian siliciclastic Grantland formation (Figure 1b; Trettin, 1998). The basalts of the assemblages are stratigraphically correlated (Trettin, 1987), yet are separated by 200 km without outcropping of lower Paleozoic bedrock. Recently, Hadlari and Madronich (2017) re-established that the Jaeger Lake assemblage basalts lie within the Aurland Fiord Formation (Figure 1b).

## Study area and previous work

The majority of the work to date on the volcanics of the Jaeger Lake assemblage and Yelverton formation basalts has been completed by Trettin (1991, 1998), who published reports on their major and trace element geochemistry. Classification by an older immobile trace element diagram place both volcanic assemblages in an array between andesite/basalt and subalkaline basalt (Figure 2).

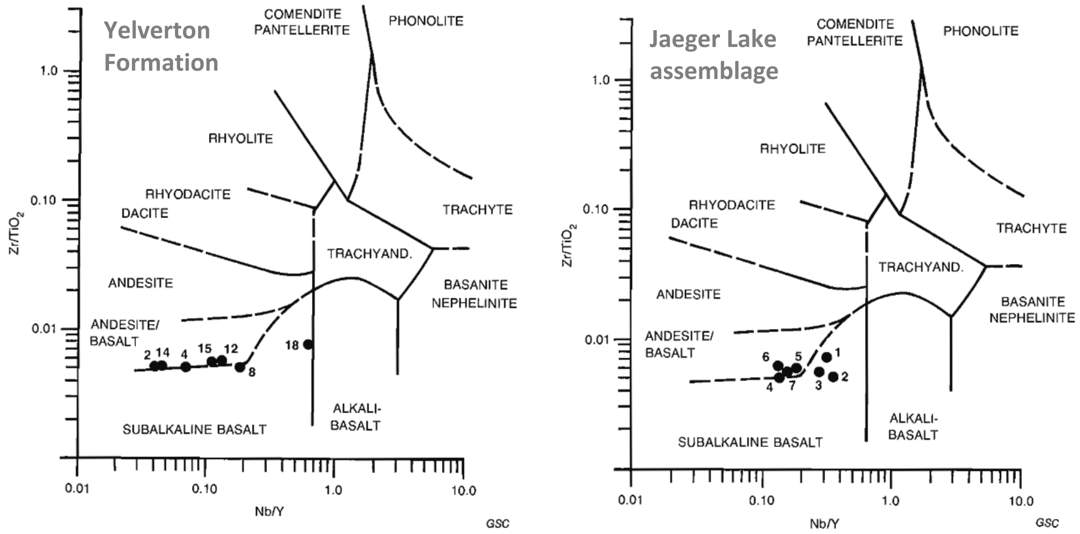

Figure 2—Immobile trace element ratio classification diagrams from reproduced from Trettin (1998) using an old discrimination diagram by Winchester and Floyd (1977).

Previous geochemical analysis methods were limited and did not include a full suite of trace elements or rare earth elements. Three of the samples were collected in the 2015-2017 field seasons. From the Jaeger Lake assemblage, sample 15-DTA-16-1 is from the massive portion at the base of a pillowed flow, whereas 16-HSB-26-A1 was selected from a thicker massive interval for geochronology and could be intrusive. 17-HSB-08-A1 is sampled from the Yelverton Sill Complex (see Hadlari et al., 2019), within the carbonates of the Yelverton Formation. Our volcanic rocks have been analyzed by modern techniques to acquire the full suite of trace elements and will be compared with the published geochemistry from Trettin (1998)

# Methods

Two hand samples from the Jaeger Lake assemblage and one from the Yelverton Formation were sawn into blocks weighing 39-48 g. Care was taken during sawing to exclude epithermal veins and weathering that were visible to the naked eye. The samples blocks were polished with 400-grit sand paper to remove saw marks, then rinsed in deionized water, and left to air dry under cover before they were shipped to Washington State University, Pullman, for analysis at the Peter Hooper GeoAnalytical Lab.

The lab chipped and handpicked sample to achieve a consistent 28 g for powdering using an agate shatter box Agate was used to eliminate tungsten and hafnium contamination. The sample material is weighed to 3.5 g and fused with 7.0 g of dilithium tetraborate, which was analyzed for major elements and 17 trace elements on a thermo-ARL automated X-ray fluorescence spectrometer (XRF). For detailed XRF methods and precision see Johnson et al. (1999).

A parallel Inductively Coupled Plasma Mass Spectrometry (ICP-MS) analysis was undertaken at the same lab, where 2 g of sample was fused with 2 g of dilithium tetraborate before multi-acid dissolution. The fusion minimizes the effect of trace elements being retained in undissolved accessory phases (e.g. zircon, rutile, etc.). After a two-stage digestion and evaporation at 110 °C in a multi-acid bath, the samples were diluted to 1:4800 the original fused amount and measured on an Agilent model 4500 ICP-MS. Tuning is optimized to minimize isobaric interference of the light rare earth elements (REE) on the heavy REE by keeping the CeO/Ce ratio below 0.5%. The method results in 14 REEs (5% RSD) and 13 trace elements (10% RSD). For detailed methods see the School of Environment, Washington State University website (Data accessed: January 28, 2019).

## Results

Major elements for the two of the three samples plot in basalt field of the Total Alkali Silica (TAS) diagram, overlapping with previously published data (Figure 3). One Jaeger sample (15-DTA-16-1) plots within the picro-basalt field, outside of previously published results for the Jaeger Lake assemblage volcanics. Overall, the Jaeger Lake assemblage volcanics are higher in alkalis, lower CaO, and have slightly higher MgO content (Figure 4). As these samples have experienced up to greenschist facies metamorphism (Trettin, 1991) and variable alteration (LOI = 0.1 to 11.2, average = 4.0), the major elements were likely mobilized and are not reliable for geochemical classification.

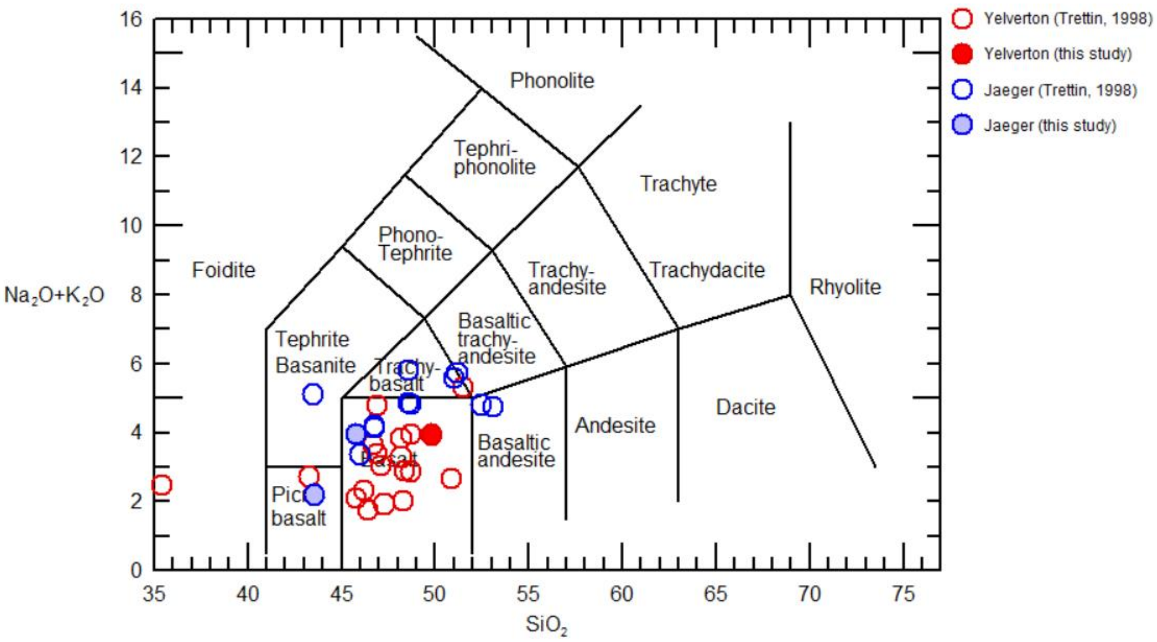

Figure 3—Total alkali versus silica (TAS) plot after LeBas et al. (1986). Previously published data (open circles) from Trettin (1998)

Trace element results for the three samples are found in the Appendix (Table 1). When plotted on the updated immobile trace element classification diagram (Figure 5a; Pearce, 1996), both assemblages plot in the basaltic field and form an overlapping array with previously published results. This array encompasses both normal and enriched mid-ocean ridge basalt (NMORB and EMORB) fields. On a ternary plot that discriminates potential tectonic settings, mafic volcanics

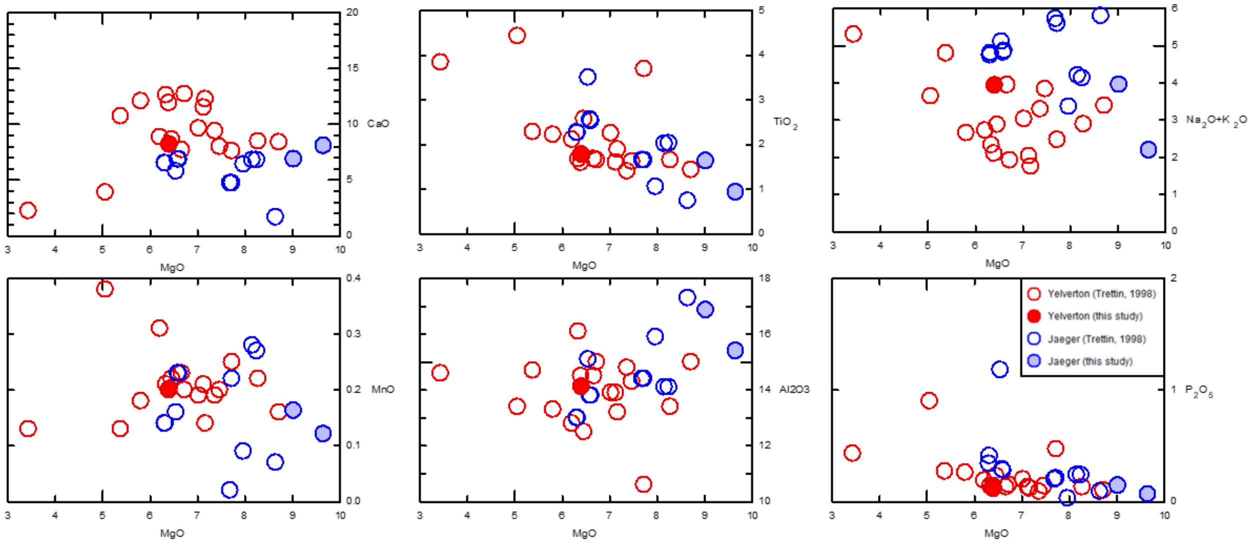

Figure 4—Major element versus MgO variation diagrams. Previously published data (open circles) from Trettin (1998)

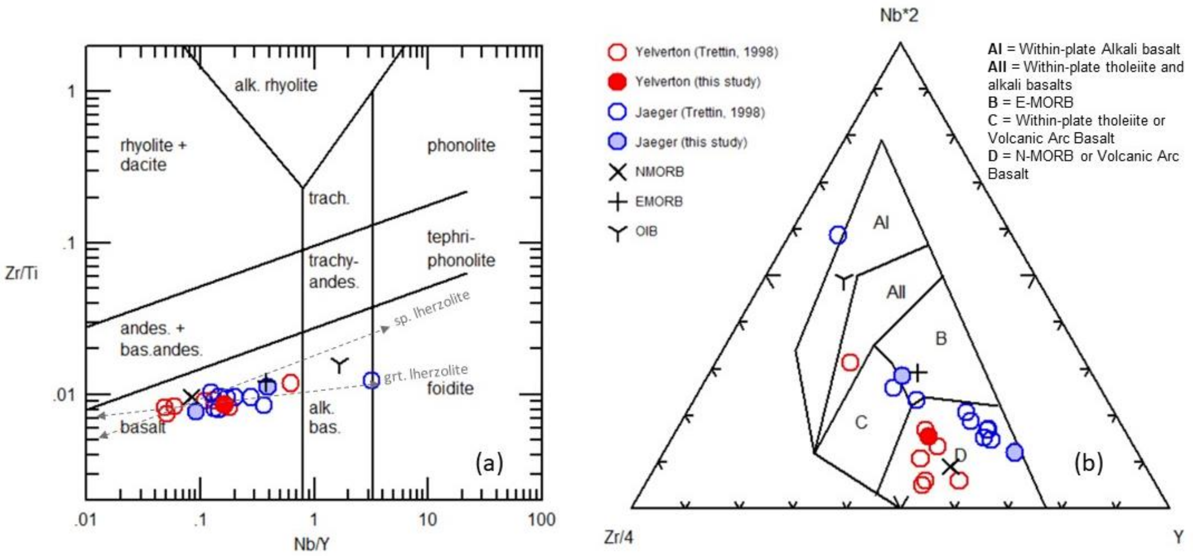

Figure 5 – Immobile trace element diagrams. (a) modern basalt discrimination diagram after Pearce (1996). Jaeger Lake assemblage basalts and Yelverton Formations basalts form an overlapping array in the sub-alkaline basalt field that follows the garnet lherzolite petrogenetic vector (Pearce, 1996). There is one outlier from the Trettin (1998) data. (b) Ternary immobile element discrimination diagram that indicates which tectonic setting basalts are derived from, after Meschede (1986). Previously published data (open circles) from Trettin (1998)

of the Jaeger Lake assemblage and Yelverton Formation plot in distinct groupings within in the NMORB/Volcanic Arc Basalt field, with some Jaeger samples plotting in the EMORB field (Figure 5b; Meschede 1986).

Rare Earth Elements (REEs) measured in this study are the first full suite of REEs for the volcanics of these assemblages (to the best of our knowledge). As such, there are no previously published samples to compare the results with. A REE diagram of the three samples (Figure 6) indicates a slightly enriched light REE (LREE) for sample 16-HSB-26-A1, a slight LREE depletion in 17-HSB-08-A1, and strong depletion of LREE and mid-REE in 15-DTA-16-1.

# Discussion

The new geochemical results presented on the updated basalt discrimination diagram (Figure 2; Pearce 1996) demonstrate that the Jaeger Lake assemblage and Yelverton Formation basalts overlap geochemically. The data forms an array in Zr/Ti v Nb/Y space that follows the garnet lherzolite petrogenetic line, implying the magmas are derived from a deep source where garnet is present (Pearce, 1996).

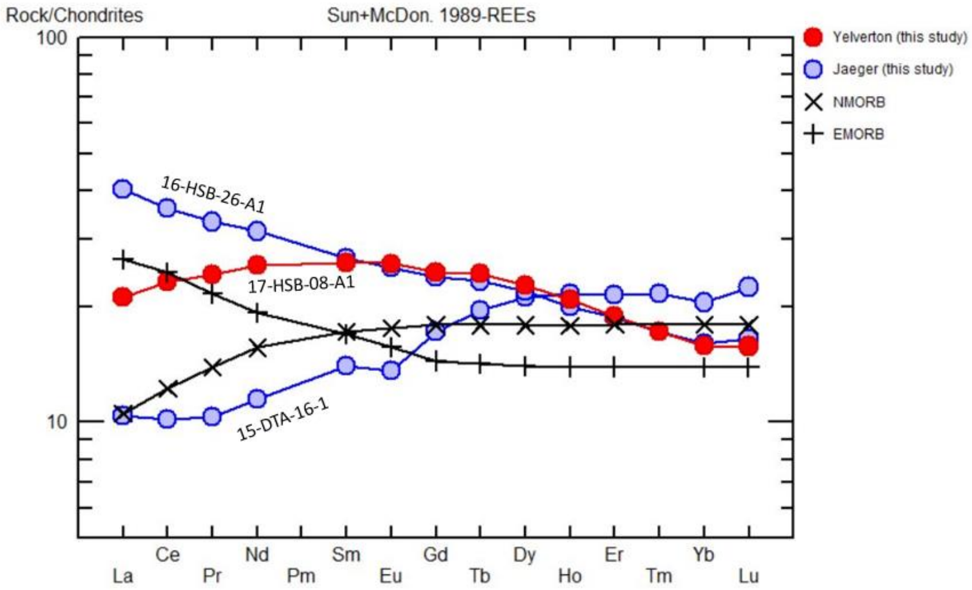

Figure 6—Chondrite normalized REE diagram. Chondrite, EMORB, and NMORB values from Sun and McDonough (1989).

In Nb-Zr-Y geochemical space (Figure 5b), the two assemblages group into distinct populations, with Yelverton basalts potting in the volcanic arc/mid-ocean ridge field and Jaeger Lake basalts forming an array between volcanic arc/mid-ocean ridge and the EMORB/within-plate fields. Trettin (1991; p. 230) disregarded the mid-ocean ridge tectonic setting as the interbedded marine carbonates included in each assemblage are incompatible with a mid-ocean ridge setting. The Jaeger Lake array moves directly away from the Y apex, which strongly partitions into garnet and amphibole (Winter, 2001), indicating the array forms from either continuous partial melting of a garnet-bearing mantle source or amphibole fractional crystallization (or both).

The MREE and heavy REE (HREE) for 16-HSB-26-A1 and 17-HSB-08-A1 (Figure 6) are nearly identical and become more depleted towards Lu, indicating that they could be from the same, deep source that has garnet in the residue (e.g. Mckenzie and Bickle, 1988). The difference in LREE of these 2 samples could be due to degree of partial melt, with the LREE-enriched pattern of 16-HSB-26-A1 being from an earlier, small degree partial melting event from an EMORB-like mantle source in the garnet stability field. The slightly depleted LREE pattern of 17-HSB-08-A1 could be from subsequent, higher-degree partial melting of the same source, from which LREE were extracted in earlier melt generations.

The positive LREE and MREE pattern of 15-DTA-16-1 (Figure 6) indicates partial melting of a depleted mantle source (NMORB) or possibly a high-percent partial melting event of an EMORB source. The negative Eu anomaly of this sample supports the latter hypothesis, as the anomaly is indicative of magma chamber evolution and plagioclase removal at crustal levels (above 40 km depth). A larger REE dataset is needed as well as measurement of Sr-Nd isotopic ratios to comment further on whether there are one or two mantle sources for the Jaeger Lake assemblage and Yelverton Formation basalts.

## Conclusions and future work

Three basaltic rock samples of the Jaeger Lake assemblage and Yelverton Formation were analysed for major and trace element geochemistry. The results were compared with only other published data (Trettin, 1998). The immobile trace elements of both assemblages overlap and form an array, indicating a similar genesis and tectonic setting.

The LREE patterns for the two Jaeger Lake assemblage basalts vary from enriched to strongly depleted, indicating two distinct mantle sources—EMORB and NMORB—formed samples 16-HSB-26-A1 and 15-DTA-16-1, respectively. If they are genetically related magmas, one would expect that they would have the same mantle source. Evidence of melting from two distinct mantle sources complicates the petrogenetic history of the Jaeger Lake assemblage, as these samples erupted into the same stratigraphic package in the same location. Another possibility is that the NMORB-like sample (15-DTA-16-1) is the result of extreme partial melting of an EMORB source.

Trace element geochemistry alone cannot determine which is the most likely mantle source for these assemblages, so a Rb/Sr and Sm/Nd isotopic analysis of these samples is ongoing at the University of Alberta. Once the analyses are complete, differing source characteristics and relationship of the Yelverton Formation basalts to the Jaeger Lake basalts can be addressed in more detail.

U-Pb analysis of samples 15-DTA-16-1 and 17-HSB-08-A1 is also being performed at the University of Alberta. If successful, these will be the first U-Pb ages from the basaltic rocks of the Jaeger Lake assemblage and Yelverton Formation. This will provide a benchmark age for the Aurland Fiord formation (assuming that both samples are roughly the same age), the putative age of Cambrian magmatism on Axel Heiberg and Ellesmere islands, and will give temporal constraints on the length of time that passed between EMORB and NMORB magma generation.

## Acknowledgments

We thank the Peter Hooper GeoAnalytical Lab, University of Washington (Pullman) for their excellent XRF and ICP-MS data. We thank Kalin McDannell for his thorough review of this manuscript. This project was funded by the Geo-mapping for Energy and Minerals (GEM-II) initiative.

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# Appendix

## Table 1 – Major and trace element geochemsitry

| Sample | **15-DTA-16-1** | **16-HSB-26-A1** | **17-HSB-08-A1** |
|---|---|---|---|
| C-Number | C-601197 | C-625022 | C-626857 |
| Data Source | GSC, ongoing | GSC, ongoing | GSC, ongoing |
| Formation | Jaeger Lake assemblage | Jaeger Lake assemblage | Sill in the Yelverton Fm. |
| Latitude | 81.235703 | 81.238666 | 81.796024 |
| Longitude | -93.335290 | -93.333355 | -82.174375 |
| Unit type | flow | flow | sill |
| $SiO_2$ (wt %) | 43.55 | 45.79 | 49.84 |
| $TiO_2$ | 0.930 | 1.632 | 1.775 |
| $Al_2O_3$ | 15.40 | 16.87 | 14.12 |
| $Fe_2O_3$ | 13.52 | 11.46 | 14.28 |
| FeO | 12.16 | 10.31 | 12.86 |
| MnO | 0.121 | 0.163 | 0.202 |
| MgO | 9.66 | 9.03 | 6.41 |
| CaO | 8.07 | 6.88 | 8.19 |
| $Na_2O$ | 1.64 | 3.16 | 3.58 |
| $K_2O$ | 0.55 | 0.79 | 0.35 |
| $P_2O_5$ | 0.066 | 0.145 | 0.116 |
| Total | 92.15 | 94.77 | 97.45 |
| LOI | 7.37 | 5.01 | 2.24 |
| Eu*/Eu | 0.88 | 1.00 | 1.02 |
| Cr* (ppm) | 374 | 255 | 182 |
| Ni* | 178 | 115 | 74 |
| Zn* | 106 | 77 | 103 |
| Sc* | 45 | 39 | 42 |
| V* | 274 | 206 | 359 |
| Cu* | 39 | 27 | 221 |
| Ga* | 15 | 16 | 17 |
| Pb | 0.65 | 0.82 | 0.42 |
| Rb | 10.2 | 11.6 | 8.2 |
| Cs | 0.88 | 0.75 | 0.37 |
| Ba* | 155 | 285 | 41 |
| Sr | 128 | 251 | 460 |
| Ta | 0.22 | 0.70 | 0.36 |
| Nb | 2.85 | 11.03 | 4.80 |
| Hf | 1.33 | 2.99 | 2.66 |
| Zr | 43 | 110 | 91 |
| Y | 31.05 | 28.17 | 29.39 |
| Th | 0.29 | 0.82 | 0.36 |
| U | 0.08 | 0.20 | 0.13 |
| La | 2.46 | 9.56 | 5.02 |
| Ce | 6.23 | 22.07 | 14.21 |
| Pr | 0.98 | 3.15 | 2.30 |
| Nd | 5.35 | 14.64 | 11.98 |
| Sm | 2.14 | 4.09 | 3.97 |
| Eu | 0.79 | 1.46 | 1.50 |
| Gd | 3.53 | 4.89 | 5.04 |
| Tb | 0.73 | 0.87 | 0.91 |
| Dy | 5.38 | 5.57 | 5.76 |
| Ho | 1.22 | 1.13 | 1.18 |
| Er | 3.55 | 3.10 | 3.13 |
| Tm | 0.55 | 0.44 | 0.44 |
| Yb | 3.48 | 2.72 | 2.69 |
| Lu | 0.57 | 0.42 | 0.40 |

*trace elements reported from XRF analysis, as they are more accurate from this method vs ICP-MS