Regional lithogeochemical synthesis of mafic-ultramafic volcanic and intrusive rocks in the Cape Smith Belt, Nunavik, northern Quebec

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ABSTRACT

More than a century of geological reconnaissance, mapping, and mineral exploration across the Cape Smith Belt has yielded a wealth of geochemical data. However, as is the case with much "big data" that span many years, sources, methodologies, and file types, the data have not been compiled in their entirety in a common format. This research component of the TGI-5 Ni-Cu-PGE-Cr Project was to compile, harmonize, and interpret publicly available lithogeochemical data for volcanic and associated intrusive rocks in the Cape Smith Belt. The current data set includes ~18,800 unique whole-rock analyses from the Cape Smith Belt (87%) and surrounding domains in Nunavik (13%) with major ± trace elements and accompanying metadata (drill-hole collars and depths, sample locations, rock descriptions, and references) from 130 sources. Duplications of records from different sources allowed cross-validation and identification of transcription errors, and preliminary QA-QC of data generated for the same rock units using multiple methods revealed differences in sample preparation and analytical methods employed at various laboratories.

Analysis of the collated data reveals significant differences in lithogeochemistry, and therefore petrogenesis, of several lithostratigraphic units. In the Southern Domain of the Cape Smith Belt, major and trace element contents can be used to readily distinguish between the major volcanic events; for example, the Povungnituk Group volcanic rocks have higher incompatible (e.g. Th, Nb, LREE, Zr, Ti) and lower compatible (e.g. Mg, Cr, Ni) element contents than those of the Chukotat Group, which have generally lower incompatible and higher compatible element contents. Fractionations in Th/Nb/Yb suggest that the Povungnituk Group formed from magmas derived by low-moderate degree partial melting of a depleted mantle source, whereas the Chukotat Group formed from magmas derived by higher degrees of partial melting of a depleted mantle source with variable degrees of contamination by crustally-derived sediments. Within the Povungnituk Group, coarser grained mafic (gabbroic) rocks of the Lac Bélanger Suite are geochemically indistinguishable from the surrounding finer grained mafic (basaltic) rocks of the Beauparlant Formation, consistent with the coarser grained Lac Bélanger units being thick flows or high-level synvolcanic sills that are geochemically related to but cooled more slowly than the finer grained Beauparlant volcanic rocks.

Similarly, thicker and coarser grained olivine orthocumulate-mesocumulate units of the Lac Esker Suite are geochemically related to thinner olivine- and pyroxene-phyric mafic (komatiitic basaltic) volcanic rocks of the Chukotat Group. The units of the Lac Esker Suite can be subdivided into an upper Raglan Trend, comprising poorly differentiated lava channels/invasive channels (Ni-Cu-PGE mineralized) and well differentiated sheet flows/sills (unmineralized), and a lower Expo Trend that includes poorly differentiated blade-shaped dykes (Cu-Ni-PGE mineralized) and well to poorly differentiated sills (unmineralized). Raglan units are characterized by higher Mg, Cr, and Th contents, higher La/Sm ratios, and generally higher Ni/Cu ratios than Expo units. Contrary to some previous interpretations, these geochemical differences suggest that the pyroxene peridotite/melagabbro blade-shaped dykes in the Expo Trend did not feed the peridotite/pyroxenite lava channels in the Raglan Trend. These lithogeochemical characteristics of the stratigraphic units provide important constraints on petrogenetic and metallogenic relationships and therefore the nature of the volcanic-subvolcanic-intrusive plumbing system, and should aid in categorizing potentially prospective units in areas along strike from known sulphide deposits.

INTRODUCTION

More than a century of activity by government, industry, and academia has generated a wealth of data through whole-rock and ore geochemical analyses, geophysical surveys, diamond drilling, and geological mapping. A major goal of this component of the

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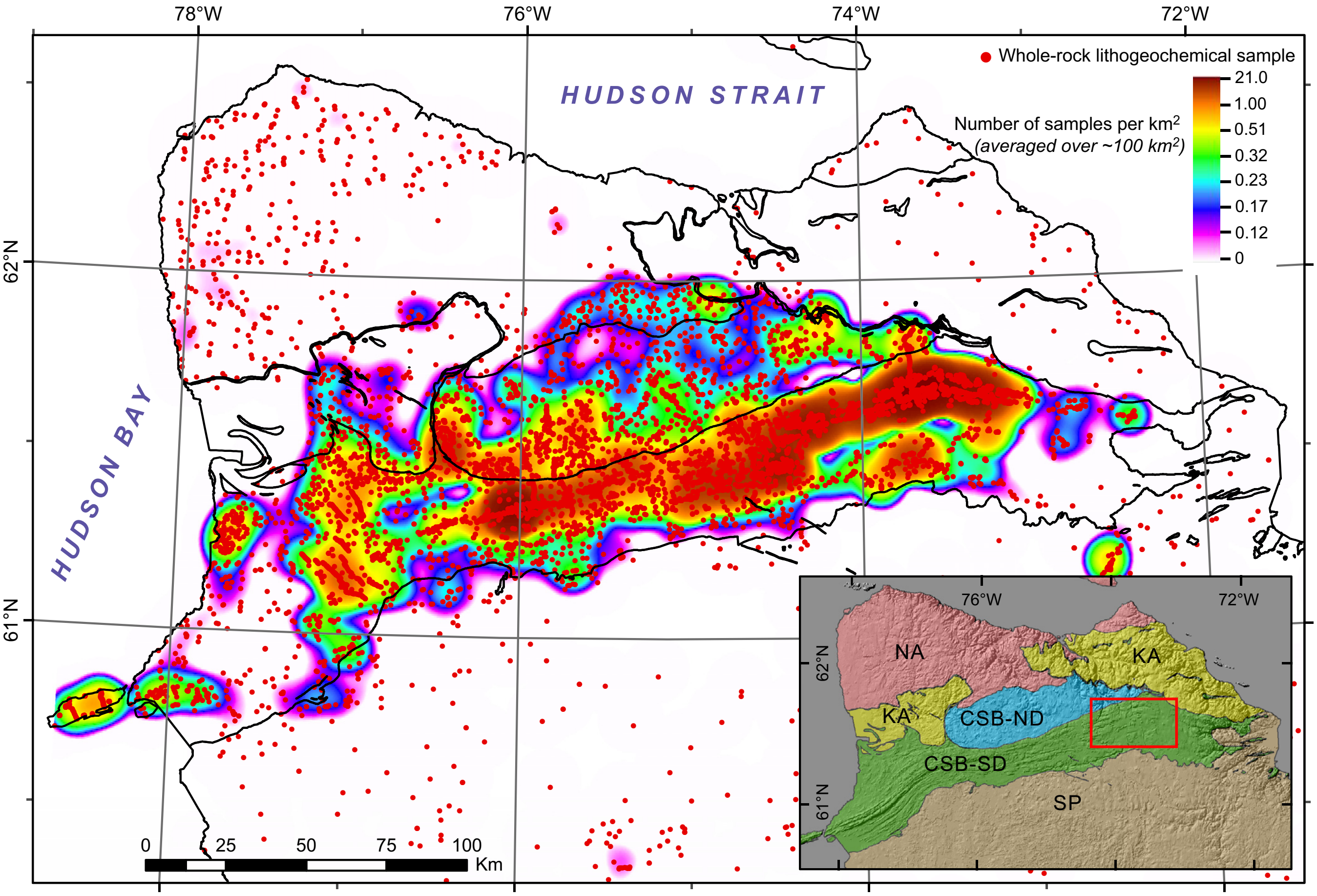

Figure 1. Locations of whole-rock samples in Nunavik, northern Quebec, for which lithogeochemical data are included in the present compilation. The colour scale shows sample density (samples per km^2, averaged over ~100 km^2; at a larger map scale, the largest number of samples per km^2 is ~160 and includes drill core and surface samples). Most samples come from the Cape Smith Belt. The red rectangle in the inset map outlines the map area shown in Figure 2. Abbreviations on inset map: CSB-ND = Cape Smith Belt, Northern Domain; CSB-SD = Cape Smith Belt, Southern Domain; KA = Kovik Antiform; NA = Narsajuaq Arc; SP = Superior Province.

research activity studying mafic and ultramafic magmatic architecture under the Ni-Cu-PGE-Cr Project of the Targeted Geoscience Initiative-Phase V (TGI-5) of the Geological Survey of Canada was to compile, harmonize, and interpret publicly available lithogeochemical data for rocks in the Cape Smith Belt.

Since the early geological reconnaissance, mapping, and exploration activity of A.P. Low by the Geological Survey of Canada (1898–1899) and the Cyril Knight Prospecting Company Ltd. (1931–1933) in the western end of the Cape Smith Belt, this Paleoproterozoic volcano-sedimentary succession has become well known for its Ni-Cu-PGE magmatic sulphide deposits (Dupras and Green, 1999). Currently, there are mining activities in the Southern Domain (Fig. 1, inset) of the eastern Cape Smith Belt by Glencore Canada Corp. in the Raglan area and by Canadian Royalties Inc. in the Expo area. Exploration for magmatic sulphide mineralization is ongoing throughout the region and along strike to the east and west (e.g. Orford Mining's West Raglan project), while exploration for shear-zone-hosted Au mineralization is progressing in the Cape Smith Belt's Northern Domain (e.g. Orford Mining's Qiqavik project).

This synthesis report presents preliminary results of the belt-scale compilation for mafic-ultramafic volcanic-subvolcanic-intrusive rocks in the eastern part of the Southern Domain of the Cape Smith Belt and is a part of a Ph.D. study at Laurentian University in Sudbury (Canada). For a description of the specific goals and fieldwork that was completed in the course of this study, the reader is referred to McKevitt et al. (2018, 2019).

RESULTS

Data Compilation Methodology

Types and sources

Compilation of whole-rock lithogeochemical data (excluding solely assay data) from both public and private sources began in September 2016. Previous compilations by government, academia, and industry (*see*

St-Onge et al., 2007 and SIGÉOM records; Ministère de l'Énergie et des Ressources naturelles du Québec, 2019) did not include some of the geochemical data from published and unpublished theses, scientific articles, and company reports. Additionally, these previous compilations often lacked metadata, including location and drilling information, analytical details, rock types/descriptions, and sources. Therefore, to obtain a more comprehensive, useful, and harmonized data set, original materials were obtained (including unpublished theses, digital reports, and scientific articles), and much of the data was extracted manually before comparison and integration with previous compilations. Table 1 lists the 130 sources that were used and the geological regions covered by this study.

Validation

A drawback of including so many sources was that many sample records were duplicated, however, this did facilitate the cross-validation and identification of multiple analytical methods and laboratories that had been used to analyze the same samples/rock units and individual elements; it also permitted the discovery of numerous transcription errors and some print/publication errors. Data quality assurance-quality control (QA-QC) was performed manually and with Excel, ArcGIS, and ioGAS software. Much older location data were reported in North American Datum 27 (NAD27); these coordinates were converted to NAD83 using the NRCan NTv2 National Transformation tool (https://www.nrcan.gc.ca/maps-tools-publications/tools/geodetic-reference-systems-tools/tools-applications/10925#ntv2). Duplicate sample records were identified both by element values and location coordinates. After the removal of duplicate sample records, the resulting data set comprises 17,000 public (or unpublished but public-pending) records, spanning all major geological domains in Nunavik, Quebec, north of latitude 60ºN (*see* Fig. 1 and Table 2).

Data Analysis

Classification

Samples were classified using a combination of original rock descriptions and locations (e.g. from drillhole logs) and geochemistry. They were categorized by geological domains, groups, and formations after the terminology of St-Onge et al. (2007) and Lamothe (2007). Mafic-ultramafic samples from units of exploration interest were classified using those same resources, detailed geological mapping that was undertaken as part of this current Ph.D. research (over the summers of 2017, 2018, and 2019), and publicly available mining exploration/assessment (GM) reports filed with the Ministère de l'Énergie et des Ressources naturelles du Québec, as well as validated with the aid of private Glencore Canada Corp. and Canadian Royalties Inc. geological maps. Samples from mineralized mafic-ultramafic lithologies of the Lac Esker Suite were subdivided into the "Raglan Trend" (after the informally defined Raglan formation of Lesher, 1999, 2007) and the "Expo Trend" (after the informally defined Expo intrusive suite of Mungall, 2007) based on the stratigraphic position, geometry of the units, and types of sulphide mineralization (Fig. 2). The geochemical data plotted in this article represent samples collected from the eastern Southern Domain of the Cape Smith Belt, east of longitude 75ºW, because this region is the main focus of the current research activity and contains the greatest concentration of lithogeochemical data (Fig. 1).

Geochemistry

Rocks in the Cape Smith Belt are generally metamorphosed from the lower greenschist facies to the lower amphibolite facies, but metamorphism is restricted to the greenschist facies in the eastern portion of the Southern Domain where this study is focused. Geochemical plots revealed that some elements are mobile during alteration (e.g. Cs, Rb, K, Na, Ba, Sr, Ca, Si, U) and show variable amounts of spread unrelated to magmatic processes; these elements are ignored here. Bivariate plots with MgO display geochemical variations in mafic-ultramafic rocks useful for the interpretation of petrogenetic processes.

Some of the geochemical variations observed in samples from the same rock unit result from differences in sample preparation (e.g. non-digestion versus 4-acid digestion versus alkali fusion) and variations in the lower limits of detection for individual elements by different analytical methods[1] (e.g. pressed-pellet XRF versus INAA versus ICP-AES versus ICP-MS) employed at various laboratories. Less reliable data, especially older analyses (e.g. from the 1980s) and cumulate rocks with abundances near lower limits of detection, have been flagged and filtered from the geochemical plots. In some cases, samples have been reanalyzed in recent years by alternate methods and/or improved techniques (e.g. samples collected from the western Cape Smith Belt by P.-D. Barrette and analyzed for trace elements by ICP-AES or XRF in 1987 were reanalyzed by ICP-MS and INAA in 2018). In such instances, the most recent, reliable, and complete data are utilized in plotting.

After considering and allowing for such analytical variations, the data revealed significant differences in the lithogeochemistry and therefore petrogenesis of some lithostratigraphic units and domains. In the east-

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[1] XRF = X-ray fluorescence, INAA = instrumental neutron activation analysis, ICP-AES = inductively coupled plasma-atomic emission spectroscopy, ICP-MS = inductively coupled plasma-mass spectrometry.

Table 1. Sources of whole-rock lithogeochemical data compiled for the region located north of latitude 60°N in Nunavik, Quebec.

Reference	Data Privacy	Number of Samples	CSB Southern Domain	*Raglan Trend*	*Delta Trend*	*Expo Trend*	CSB Northern Domain	Narsajuaq Arc	Kovik Antiform	Superior Province
Albino (1984) - Colorado State U.; M.Sc. thesis	public (unpub.)	69	X	X						
***Arndt et al. (1987)** - Geol. Society of London Spec. Pub. 33	public	1	X							
Barnes et al. (1982) - Economic Geology	public	25	X	X						
Barnes and Giovenazzo (1990) - The Canadian Mineralogist	public	17	X		X					
***Barnes (1979)** - U. of Toronto; M.Sc. thesis	public (unpub.)	53	X	X						
Bédard (1981) - McGill U.; M.Sc. thesis	public	116	X							
Burnham et al. (1998) - Camiro final report	public (unpub.-pending)	340	X	X		X				
***Ciborowski et al. (2017)** - Precambrian Research	public	25	X							
Clark (2008) - McGill U.; M.Sc. thesis	public	58	X	X						
Dionne-Foster (2007) - U. du Québec à Chicoutimi; M.Sc. thesis	public	71	X	X						
Dunphy and Ludden (1998) - Precambrian Research	public	76					X	X		
Dunphy (1995) - U. de Montréal; Ph.D. thesis	public	76					X	X		
Francis et al. (1981) - Contributions to Mineralogy and Petrology	public	19	X							
Francis et al. (1983) - Journal of Petrology	public	17	X							
Gillies (1993) - U. of Alabama; M.Sc. thesis	public (unpub.)	206	X	X						
Giovenazzo (1991) - U. du Québec à Chicoutimi; Ph.D. thesis	public	65	X		X					
Harvey (1995) - U. de Montréal; M.Sc. thesis	public (unpub.)	55							X	X
***Kastek et al. (2018)** - Lithos	public	86	X							
Lévesque (2000–2003) - Laurentian U.; unfinished M.Sc. thesis	public (unpub.-pending)	192	X	X						
McKevitt (2017-present) - Laurentian U.; pending Ph.D. thesis	public (unpub.-pending)	345	X	X	X	X				
Miller (1977) - U. of Western Ontario; Ph.D. thesis	public	72	X	X						
Modeland et al. (2003) - Lithos	public	156	X							
***Mungall (2007)** - Journal of Petrology	public	118	X			X				
Nadeau (1984) - U. de Montréal; M.Sc. thesis	public (unpub.)	78	X							
Picard (1989) - MERNQ publication ET 87-07	public	216	X							
Picard (1989) - MERNQ publication ET 87-14	public	163	X							
***Picard (1995)** - MERNQ publication MB 95-01	public	457	X		X					
Picard et al. (1994) - MERNQ publication MB 94-30	public	653	X	X	X	X				
Picard et al. (1990) - Precambrian Research	public	522	X				X			
Scott (1990) - Queen's U.; Ph.D. thesis	public (unpub.)	87					X			
Shepherd (1960) - U. of Toronto; Ph.D. thesis	public (unpub.)	5	X	X						
Stewart (2002) - McGill U.; M.Sc. thesis	public	118	X	X						
Stilson (2000) - U. of Alabama; M.Sc. thesis	public (unpub.)	197	X	X						
St-Onge et al. (2007) - GSC Open File 5117	public	2728	X	X	X	X	X	X	X	X
Thacker (1995) - U. of Alabama; M.Sc. thesis	public (unpub.)	68	X	X						
Thibert (1993) - U. de Montréal; M.Sc. thesis	public (unpub.)	73	X	X	X					
Tremblay (1990) - U. du Québec à Chicoutimi; M.Sc. thesis	public	27	X		X					
Van Hoof (2000) - U. of Ottawa; H.B.Sc. thesis	public	25	X	X						
Wilson et al. (1969) - Society of Economic Geologists, Monograph 4	public	59	X	X						
Glencore Canada Corp. Raglan Mine files (1981–2007), *including* Xstrata, Falconbridge, New Québec Raglan Mines records Talkington (1988) Falconbridge Ltd. Report Tremblay (1990) Falconbridge Ltd. Report	private	~1900	X	X	X	X	X			

Table 1 continued.

Reference	Data Privacy	Number of Samples	CSB Southern Domain	*Raglan Trend*	*Delta Trend*	*Expo Trend*	CSB Northern Domain	Narsajuaq Arc	Kovik Antiform	Superior Province
SIGÉOM, *including*	public	13,695	X	X	X	X	X	X	X	X
Barrette, P.-D. (1987)	public	384	X						X	
Budkewitsch, P. (1987)	public	36	X							
Carrier, J.A. (1988–1989)	public	87					X	X		
Giovenazzo, D. (1984–1985–1987)	public	543	X	X	X	X	X			X
Hervet, M. (1984)	public	293					X	X	X	
Lamothe, D. (1983–1984–1988–1989–1990)	public	1142	X				X	X	X	X
Lefebvre, C. (1986)	public	218	X				X	X		
Moorhead, J. (1986–1987)	public	460	X				X	X	X	X
Picard, C. (1984–1985–1987–1988)	public	805	X				X			
Roy, C. (1984)	public	165	X				X			
Tremblay, C. (1987)	public	115	X				X	X		
Tremblay, G. (1985–1986)	public	400	X				X	X	X	
Mining exploration/assessment reports filed with the Ministère de l'Énergie et des Ressources naturelles du Québec (# *samples in parentheses*):	public	7462	X	X	X	X	X	X	X	X
GM53072 (36); GM53312 (50); GM53313 (33); GM53314 (41); GM53966 (49); GM53968 (10); GM54025 (82); GM54774 (37); GM54904 (27); GM54911 (106); GM55418 (3); GM55652 (102); GM55666 (16); GM55667 (33); GM55835 (328); GM56016 (100); GM56017 (42); GM56057 (3); GM56113 (66); GM56137 (86); GM56228 (24); GM56643 (17); GM57830 (163); GM57914 (16); GM58002 (45); GM58098 (14); GM58155 (15); GM58329 (6); GM58535 (3); GM58538 (5); GM58539 (63); GM58541 (36); GM58542 (38); GM58543 (7); GM58544 (84); GM58561 (70); GM58565 (51); GM58566 (285); GM59703 (26); GM59704 (21); GM59705 (3); GM59708 (108); GM59709 (23); GM60528 (138); GM60665 (205); GM60677 (46); GM60678 (19); GM60679 (89); GM60680 (50); GM60977 (216); GM61450 (49); GM61451 (6); GM61458 (15); GM61459 (9); GM61624 (3); GM61628 (137); GM61828 (10); GM61982 (63); GM61990 (11); GM62276 (1); GM62288 (766); GM62602 (52); GM62619 (74); ***GM62809** (529); GM62855 (194); GM62857 (23); GM63002 (49); GM63073 (102); GM63115 (156); ***GM64449** (1118); ***GM64611** (136); GM64736 (10); GM64843 (118); GM64953 (389); GM65441 (306).										

NB: Many samples were found in numerous sources; after eliminating duplicates, the total number of samples is fewer than what is listed here (*see* Table 2).
***Reference:** Source of high-quality major, minor, and trace element data plotted in Figures 3 to 5 and discussed in the text.
Abbreviations: CSB = Cape Smith Belt, MERNQ = Ministère de l'Énergie et des Ressources naturelles du Québec, U. = University or Université.

Table 2. Summary of whole-rock lithogeochemical data compiled for the region located north of latitude 60°N in Nunavik, Quebec.

Geological Domain	**Number of sample records**		**Number of public sample records with particular group of elements analyzed**			
	All (private + public)	Public	majors ± traces	traces (no majors)	REEs	PGEs
Narsajuaq Arc	572 (3.1%)	572 (3.4%)	543 (3.7%)	29 (1.3%)	546 (5.2%)	8 (0.1%)
Kovik Antiform	271 (1.4%)	271 (1.6%)	180 (1.2%)	91 (4.0%)	234 (2.2%)	112 (1.5%)
CSB Northern Domain	1877 (10.0%)	1809 (10.6%)	1737 (11.8%)	72 (3.1%)	1429 (13.7%)	498 (6.8%)
CSB Southern Domain	14,453 (76.8%)	12,710 (74.8%)	11,134 (75.8%)	1553 (67.7%)	7432 (71.1%)	6283 (85.8%)
New Québec Orogen, Core Zone	25 (0.1%)	25 (0.1%)	16 (0.1%)	9 (0.4%)	17 (0.2%)	3 (0.04%)
New Québec Orogen, Labrador Trough	669 (3.6%)	669 (3.9%)	536 (3.7%)	133 (5.8%)	215 (2.1%)	214 (2.9%)
Superior Province	902 (4.8%)	902 (5.3%)	500 (3.4%)	402 (17.5%)	547 (5.2%)	176 (2.4%)
references + Franklin dyke swarm	44 (0.2%)	40 (0.2%)	37 (0.3%)	5 (0.2%)	28 (0.3%)	26 (0.4%)
Totals	18,813 (100.0%)	17,000 (100.0%)	14,683 (100.0%)	2294 (100.0%)	10,448 (100.0%)	7320 (100.0%)

NB: "Public" includes some records that are currently unpublished but are planned for release (*see* Table 1). "Majors" includes major + minor element oxides.
Abbreviations: PGEs = platinum group elements, REEs = rare earth elements.

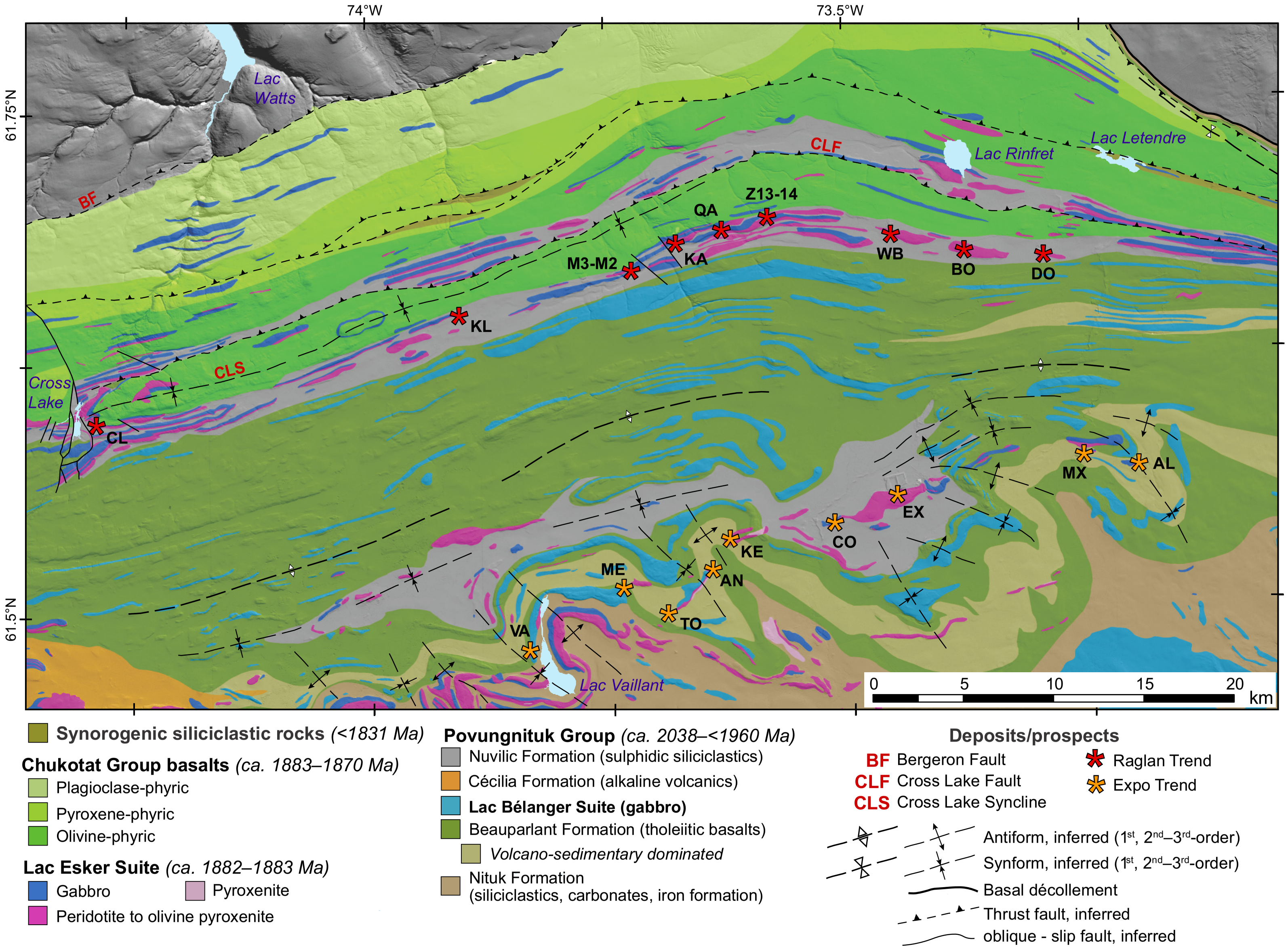

Figure 2. Regional geological map of the eastern part of the Southern Domain within the Paleoproterozoic Cape Smith Belt. The geology is *modified from* St-Onge et al. (2007) and Mungall (2007), and follows the structural interpretation of Bleeker and Kamo (2020). The underlying digital elevation model is from Porter et al. (2018). Deposits and prospects along the Raglan Trend, from west to east: CL = Cross Lake, KL = Kikialik, M3-M2 = Mine 3 and Mine 2, KA = Katinniq, QA = Qakimajurq, Z13-14 = Zone 13-14, WB = West Boundary, BO = Boundary, DO = Donaldson. Deposits and prospects along the Expo Trend, from west to east: VA = Vaillant, ME = Méquillon, TO = Tootoo, AN = Annie, KE = Kehoe, CO = Cominga, EX = Expo, MX = Mesamax, AL = Allammaq. Note: many lower order (2nd–3rd order), younger generation faults and folds are omitted for clarity.

ern portion of the Cape Smith Belt's Southern Domain, significant differences in major and trace element concentrations distinguish the various mafic-ultramafic volcanic and intrusive units. The following observations and discussion utilize a representative subset of 1,368 samples with high-quality major and trace element geochemical data from 9 sources (*see* Table 1).

Figure 3 shows major and trace element concentrations for volcanic and high-level intrusive rocks of the Povungnituk Group. The stratigraphically lowest and oldest volcanic rocks comprise the 1998–1991 Ma Beauparlant Formation tholeiitic basalt with continental flood basalt affinity and the associated microgabbro ("diabase") rocks (e.g. Picard et al., 1990, 1994; Modeland et al., 2003; Kastek et al., 2018), referred to as the Lac Bélanger Suite by Lamothe (2007). These samples contain 5–10 wt% MgO, 1–4 wt% TiO_2, and 20–300 ppm Cr. Primitive mantle-normalized rare earth element (REE) values of Beauparlant Formation and Lac Bélanger Suite samples average 10–30 for the light REEs (LREEs) and 5–7 for the heavy REEs (HREEs). The conformably overlying and slightly younger alkaline volcanic rocks of the Cécilia Formation (ca. 1959 Ma: Parrish, 1989; Gaonac'h et al., 1992), in comparison to Beauparlant Formation and Lac Bélanger Suite rocks, generally display similar concentrations of MgO and Cr, greater than 3 wt% TiO_2, similar or higher concentrations of high-field-strength elements (HFSEs) (e.g. >400 ppm Zr, >70 ppm Nb), and significantly higher concentrations of REEs (particularly greater La/Sm ratios). Phonolite samples from the Cécilia Formation contain ~2 wt% MgO, <20 ppm Cr, <1 wt% TiO_2, >500 ppm Zr, and Nb and REE concentrations similar to those of the other alkaline volcanic rocks.

The stratigraphically higher ca. 1883–1870 Ma Chukotat Group basalt transitions upward (in general) from olivine-phyric komatiitic basalt through pyroxene-phyric to plagioclase-phyric tholeiitic basalt, although different series are interlayered throughout the stratigraphy (Francis and Hynes, 1982; Hynes and Francis, 1982; St-Onge et al., 1992; St-Onge and Lucas, 1993; Bleeker and Kamo, 2018). Figure 3 displays the continuous geochemical variation of major and trace elements among these series in terms of MgO (~5–18 wt%; samples with >18 wt% represent channelized komatiitic basalt lava flows with cumulus olivine), TiO_2 (0.5–1 wt%), Cr (50–2000 ppm), Zr (30–90 ppm), and Nb (<10 ppm). Primitive mantle-normalized REE values average 4–5 for the LREEs and 3–4 for the HREEs.

Mafic to ultramafic dykes and sills[2], referred to as the Lac Esker Suite by Lamothe (2007), occur throughout the stratigraphy from the lower Povungnituk Group to the base of the Chukotat Group. Generally, non-mineralized samples from units hosting deposits/prospects/showings fall along similar trends on MgO bivariate plots, implying similar parental magma(s) and petrogenetic/magmatic processes for the Raglan Trend and Expo Trend units. However, Figure 4 shows some clear differences: 1) the most magnesian Raglan cumulate rocks range up to 44 wt% MgO, whereas the most magnesian Expo cumulate rocks only range up to 35 wt% MgO; 2) many Expo samples have lower TiO_2 and Cr concentrations than Raglan samples at >15 wt% MgO; 3) mineralized Raglan samples have higher Ni/Cu ratios than Expo samples; 4) Raglan samples have significantly higher La/Sm ratios and more positive primitive mantle-normalized Th and Zr-Hf anomalies than Expo samples.

Figure 5 utilizes Nb/Yb versus Th/Yb bivariate plots, which are ideal for identifying crustal input (i.e. direct crustal contamination or subduction-related crustal recycling in the magma source region) because Th and Nb behave similarly during most petrogenetic processes and are both immobile during lower amphibolite-facies metamorphism (Pearce, 2008). Sedimentary rock samples and Cécilia Formation alkaline volcanic/phonolite rocks plot at high values of Nb/Yb and Th/Yb, values typical of continental upper crust and ocean island basalt (OIB), respectively. Chukotat Group and Beauparlant Formation basaltic rocks plot in two distinct regions. The Chukotat field extends from low values of Th/Yb and Nb/Yb, located halfway between normal mid-ocean ridge basalts (N-MORB) and enriched mid-ocean ridge basalts (E-MORB), to higher Th/Yb and Nb/Yb values, outside of the oceanic basalt array. The Beauparlant samples plot in two fields located almost entirely within the oceanic basalt array: a "less-enriched" field between N-MORB and E-MORB comprising samples from the lower Beauparlant Formation and a "more-enriched" field between E-MORB and OIB comprising samples mostly from the middle-upper Beauparlant Formation. Ultramafic–gabbroic–basaltic samples from Raglan Trend and Expo Trend units together form an array that overlaps Chukotat samples and extends to high values of Th/Yb and Nb/Yb, similar to values for upper crustal rocks and sedimentary rocks derived from the upper continental crust. Raglan samples, classified as sedimentary "xenomelts" (Stilson, 2000) or "ultrahornfels" (*see* Fig. 6 in Bleeker and Kamo, 2020), plot within or close to the field of metasedimentary samples. We pre-

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[2] Units that belongs to the Lac Esker Suite have been classified as intrusive by Lamothe (2007), however, many of these, especially units at the interface between the Povungnituk and the Chukotat groups, are lava flows as suggested by the presence of polyhedral jointing and flow top breccias (*see* Lesher, 1999, 2007; Lesher and Houlé, 2017).

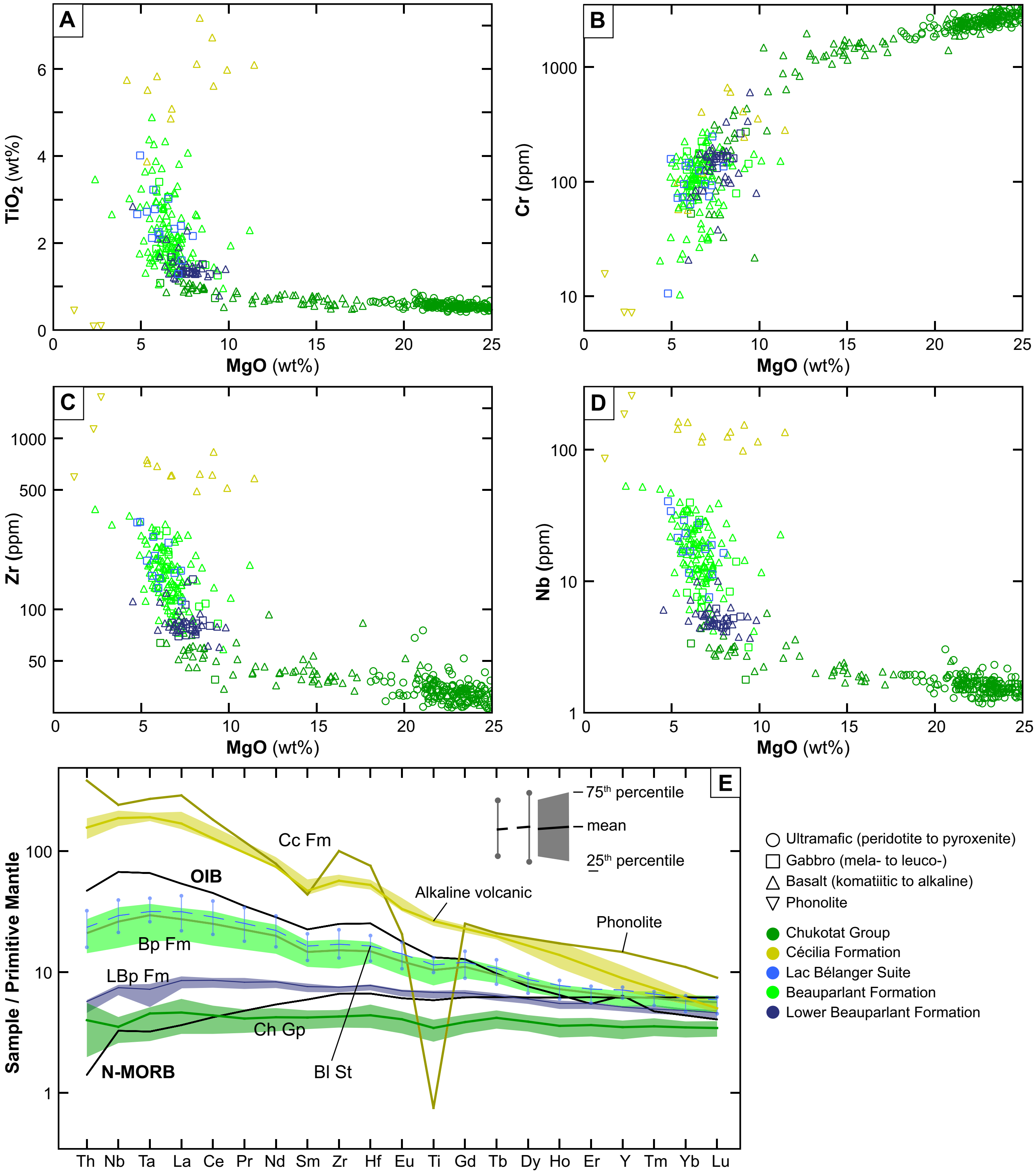

Figure 3. Geochemical plots for distinguishing volcanic-subvolcanic rocks of the Povungnituk and Chukotat groups in the Southern Domain of the eastern Cape Smith Belt (east of longitude 75ºW). bivariate plots of **(a)** MgO (wt%) versus TiO_2 (wt%); **(b)** MgO (wt%) versus Cr (ppm); **(c)** MgO (wt%) versus Zr (ppm); and **(d)** MgO (wt%) versus Nb (ppm) bivariate plot. **e)** High field strength elements (HFSE) and rare earth element (REE) primitive mantle-normalized diagram showing Povungnituk Group lower and middle to upper Beauparlant Formation basalt (LBp Fm and Bp Fm, n = 44 and 129, respectively), Cécilia Formation alkaline basalt (Cc Fm, n = 12) and phonolite (n = 7), Lac Bélanger Suite “gabbro” (Bl St, n = 14), and Chukotat Group basalt (Ch. Gp, n = 85). The thick, dark lines indicate the average values within the lighter coloured fields, which represent the 25th to 75th percentiles. All plotted data are publicly available (*see* text and Table 1). Chukotat Group basalts with >18 wt% MgO contain cumulus olivine in channelized lava flows or feeders; the samples averaged in (e) contain <18 wt% MgO. Abbreviations: N-MORB = normal mid-ocean ridge basalt, OIB = oceanic island basalt. Primitive mantle normalization and reference values are from Sun and McDonough (1989).

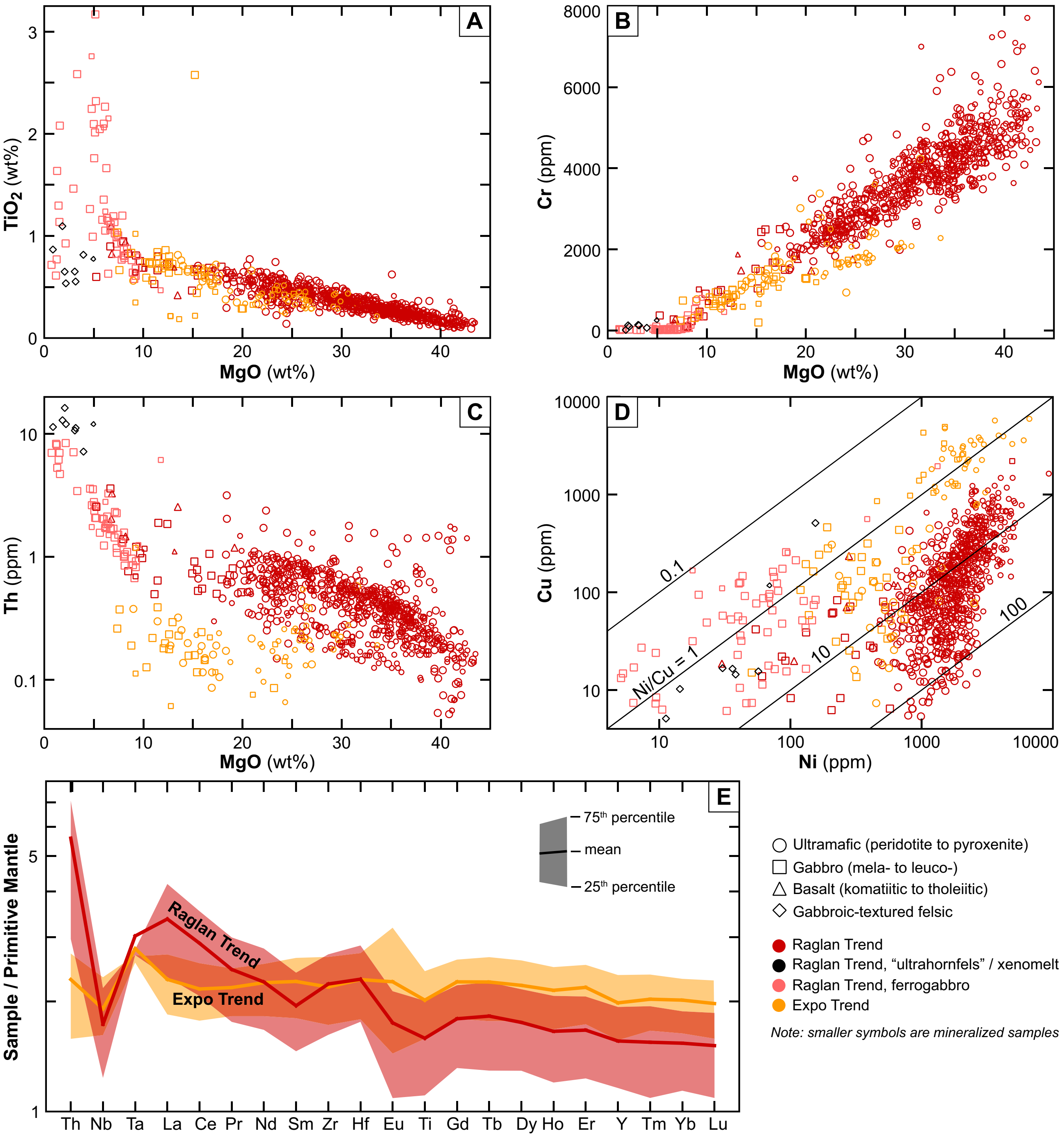

Figure 4. Geochemical plots for distinguishing volcanic-subvolcanic-intrusive units along the Raglan and Expo trends of the mafic-ultramafic Lac Esker Suite in the Southern Domain of the eastern Cape Smith Belt (east of longitude 75°W). Bivariate plots of **(a)** MgO (wt%) versus TiO_2 (wt%); **(b)** MgO (wt%) versus Cr (ppm); **(c)** MgO (wt%) versus Th (ppm); and **(d)** Ni (ppm) versus Cu (ppm) bivariate plot. **e)** High field strength elements (HFSE) and rare earth element (REE) primitive mantle-normalized diagram showing compositions of the Expo Trend (n = 70) and Raglan Trend (n = 665) for samples with >15 wt% MgO. The thick, dark lines indicate average values within the lighter coloured fields, which represent the 25th to 75th percentiles. All plotted data are publicly available (*see* text and Table 1). In plots (a) to (d), the smaller symbols represent mineralized samples with at least one value greater than 5000 ppm S, 2500 ppm Ni, 500 ppm Cu, and 250 ppb Pt+Pd. Primitive mantle normalization values are from Sun and McDonough (1989).

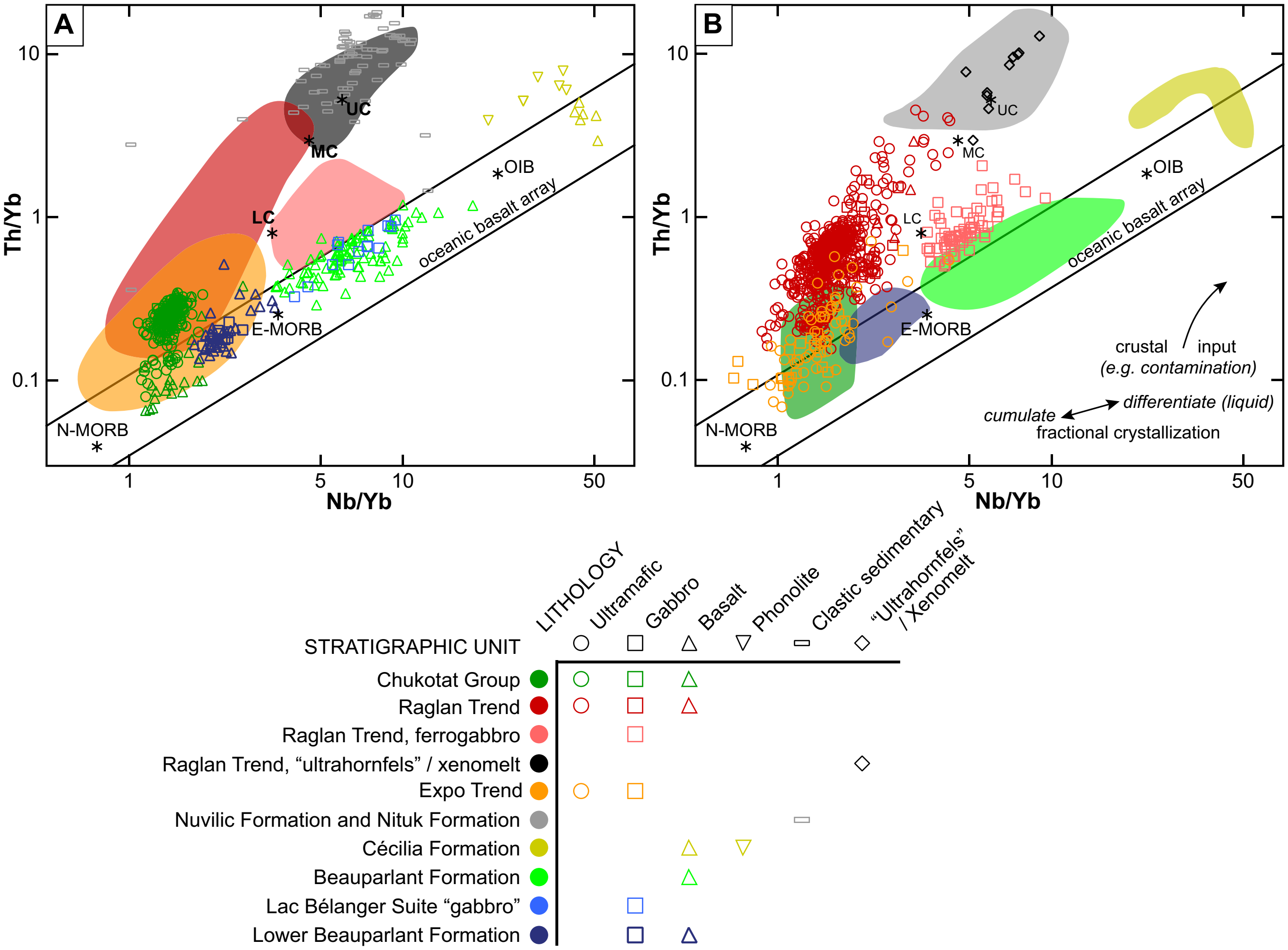

Figure 5. Geochemical plots of Nb/Yb versus Th/Yb (*after* Pearce, 2008) for characterizing magma source regions and crustal input. The legend applies to plots (a) and (b). **a)** Sedimentary and volcanic/high-level synvolcanic intrusive rock samples from the Povungnituk and Chukotat groups. Shaded fields correspond to samples plotted in (b). **b)** Volcanic/intrusive ultramafic-mafic rock samples from the Raglan Trend and Expo Trend units. Inset arrows indicate possible (but not exclusive) processes that may control trends. Shaded fields correspond to samples plotted in (a). All plotted data are publicly available (*see* text and Table 1). Abbreviations: E-MORB = enriched mid-ocean ridge basalt, N-MORB = normal mid-ocean ridge basalt, OIB = oceanic island basalt, LC = lower crust, MC = middle crust, UC = upper crust. Reference values are from Sun and McDonough (1989) and Rudnick and Gao (2003).

fer the former interpretation, as the most strongly hornfelsed rocks at Raglan are bleached, recrystallized, or spotted (*see* Fig. 4D in Lesher, 2007; Fig. 3E–H in Lesher, 2017), whereas these rocks have gabbroic igneous textures.

DISCUSSION

Volcanism in the eastern Cape Smith Belt

Povungnituk Group

Volcanic rocks in the Povungnituk Group have traditionally been separated into the Beauparlant Formation, with dominantly tholeiitic pillowed and massive basalt flows of continental-flood basalt geochemical affinity (Hynes and Francis, 1982; Modeland et al., 2003), and the concordantly overlying (in the central Cape Smith Belt area) Cécilia Formation alkaline basalt and lesser intermediate-felsic volcaniclastic rocks, characterized by high concentrations of LREEs and HFSEs such as Zr and Nb (Gaonac'h et al., 1992). These geochemical distinctions are evident in major and trace elements in the current geochemical compilation (Fig. 3). Modeland et al. (2003) and Kastek et al. (2018) note two end-member varieties within the Beauparlant basalts: enriched (highly incompatible lithophile elements: HILE, e.g. Th, LREE) and unenriched or depleted (lower HILE) basalt. Figure 3a–d shows relatively constant MgO concentrations (6–8 wt%) and a continuous variation between "enriched" and "unenriched" samples. Notably, some Beauparlant samples range up to ~10 wt% MgO (possibly a pyroxenephyric population), but they are readily distinguished from Chukotat Group basalt by higher TiO_2 (>1 wt%) and lower Cr (<200 ppm) contents at a given MgO concentration. The samples plotted in Figure 5a suggest two geochemically distinct magma source regions (unenriched or depleted and enriched); however, this is likely an artifact of sampling. Other data sets (e.g. Modeland et al., 2003), although less precise (not plotted), suggest that a continuum exists between these fields, possibly representing variable degrees of partial melting (more in less enriched samples, less in more enriched samples).

Numerous coarser grained units that often exhibit columnar jointing and stand in stark topographic relief relative to surrounding interflow sedimentary rocks and pillowed basalt within the Beauparlant Formation have been interpreted as subvolcanic microgabbro (“dolerite”) sills of the Lac Bélanger Suite (St-Onge and Lucas, 1993; Picard et al., 1994). Recent field observations (Mungall, 2007; McKevitt et al., 2019) have confirmed that these units are conformable with underlying and overlying massive and/or pillowed basalt flows. Additionally, what are often mapped at regional-scale (Fig. 2) as extensive, thick, entirely “gabbroic” units are, in fact, at outcrop scale units with rapid transitions in grain size with coarse-grained “gabbroic” columnar-jointed sections grading upwards into fine-grained, massive and/or pillowed basalt. Considering that the major and trace element concentrations of these gabbro units are indistinguishable from the surrounding basalt (Fig. 3, 5), this raises the possibility that at least some of the Lac Bélanger Suite intrusions are thick, coarse-grained texturally/compositionally differentiated basaltic flows.

Chukotat Group

The majority of the lower and middle Chukotat Group volcanic rocks (e.g. olivine-phyric and pyroxene-phyric basalts with >8 wt% MgO) are easily distinguished from Povungnituk Group volcanic rocks by higher MgO concentrations and a trend in Nb/Yb versus Th/Yb space that is oblique to the mantle array (and to the trend of Povungnituk basalt) but project to a point on the mantle array between N-MORB and E-MORB (Fig. 3, 5; Francis et al., 1983; Modeland et al., 2003). Although some Chukotat basalt samples have similar MgO contents to those of Beauparlant Formation basalt, they are distinguished by having lower TiO_2 and higher Cr concentrations (Fig. 3a,b) at equivalent MgO contents. Additionally, the averages of primitive mantle-normalized REE abundances of all Povungnituk Group volcanic and subvolcanic units are significantly higher than those of Chukotat Group basalt (Fig. 3e). Most of the more primitive Chukotat basalt and ultramafic cumulate rocks (from the lowermost series) plot outside of the MORB-OIB oceanic basalt array in Figure 5a, suggesting some degree of crustal input in the magma source region (less likely) and/or crustal contamination during flow through/over continental crust or sediments derived from continental crust (more likely) (Lesher et al., 2001; Lesher, 2007; *see* discussion by Pearce, 2008). The Chukotat basalt samples that plot within the oceanic basalt array between N-MORB and E-MORB are likely most representative of the primary magma source region (*see also* Lesher et al., 2001).

Mineralized Lac Esker Suite Units in the eastern Cape Smith Belt

The geometry of the host units and location and style of sulphide mineralization differ between the Expo and Raglan trends of the Lac Esker Suite: net-textured to disseminated Cu-Ni-PGE sulphide mineralization occurs along the lower margins and keels of blade-shaped dykes within the Expo Trend (Mungall, 2007), whereas massive to net-textured Ni-Cu-PGE sulphide mineralization occurs within embayments at the bases of channelized lava flows within the Raglan Trend (Lesher, 2007). As shown here, a combination of major and trace element geochemistry of mineralized or barren host rocks is useful in distinguishing between units of these two trends. They are also readily distinguished by the Ni and Cu concentrations of mineralized samples.

The geochemical differences in major and trace elements among samples from units throughout the Expo-Raglan transcrustal magmatic plumbing system(s) may result from a combination of factors: 1) differential evolution of magma(s) within different parts of the plumbing system(s) driven by variable pressure, temperature, flow dynamics, magma flux, assimilation of country rock, fO_2, and fS_2 (e.g. Lesher et al., 2001; Lesher, 2007, 2019); and 2) magma evolution within a rising mantle plume (Ciborowski et al., 2017; Bleeker and Kamo, 2018). Any explanation for the varying metal concentrations between ores of the Expo and Raglan trends should also consider the effective magma:olivine:sulphide ratios (R’ factors: *as modified by* Lesher and Burnham, 2001 *from* Campbell and Naldrett, 1979) and possible assimilation and subsequent upgrading of pre-existing sulphides from an upstream part of the system (*see* Barnes and Giovenazzo, 1990).

The similar HFSE-REE primitive mantle-normalized patterns in Figure 4e and the overlap of Expo and Raglan fields in Figure 5b suggest that the parental magmas of these two trends may have come from the same primary mantle source but with varying degrees of crustal contamination: the Raglan Trend samples ranging to more contaminated compositions. There is evidence of some crustal contamination in the Chukotat Group (Fig 5; *see also* Lesher et al., 2001; Lesher, 2007; Ciborowski et al., 2017), but it is minor compared to that in the Raglan and Expo units. The restriction of significant contamination to Raglan and

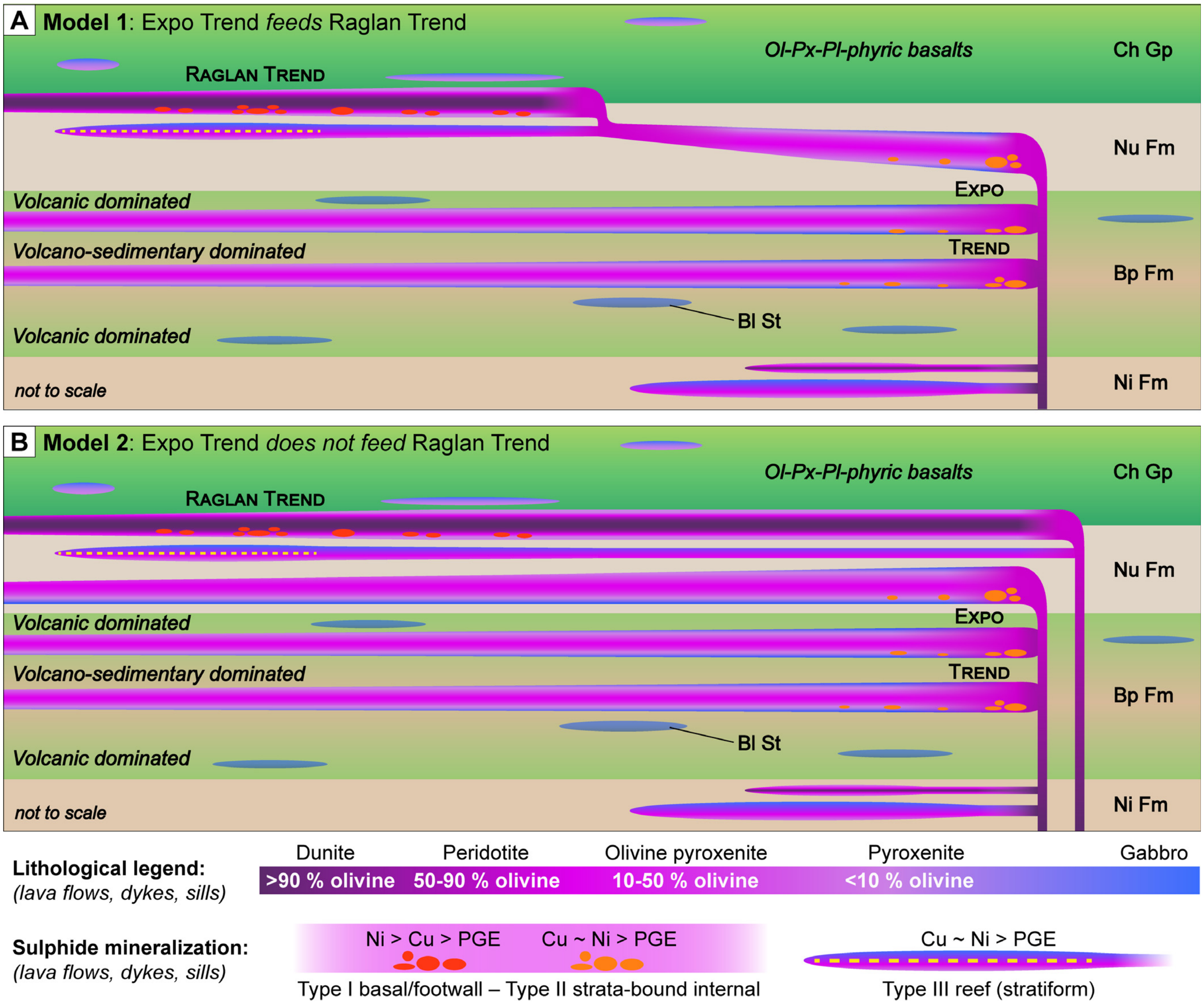

Figure 6. Schematic models of the magmatic plumbing systems (before deformation and erosion) for the Lac Esker Suite intrusive/extrusive mafic-ultramafic units of the eastern part of the Southern Domain of the Cape Smith Belt. **a)** Model 1 illustrates Expo Trend magmatism directly feeding the Raglan Trend units; **b)** model 2 illustrates Expo Trend magmatism *not* directly feeding Raglan Trend units. Specific deposits/prospects are not shown, but in the Expo Trend, those hosted by the lower to middle Beauparlant Formation include Vaillant, Méquillon, Tootoo, and Annie; those in the middle to upper Beauparlant Formation include Kehoe, Mesamax, and Allammaq; those in the Nuvilic Formation include Cominga and Expo. Deposits and prospects along the Raglan Trend include Cross Lake, Kikialik, Mine 3 and Mine 2, Katinniq, Qakimajurq, Zone 13-14, West Boundary, Boundary, and Donaldson. Abbreviations: Ch Gp = Chukotat Group, Bl St = Lac Bélanger Suite, Bp Fm = Beauparlant Formation, Ni Fm = Nituk Formation, Nu Fm = Nuvilic Formation.

Expo units, rather than the Chukotat Group as a whole, indicates that most of the contamination in those units was from Nuvilic sediments (which were derived by erosion of upper continental crust) and did not result from passage through upper continental crust (*see* discussion by Lesher and Arndt, 1995). After allowance for crustal contamination, there are no systematic variations in Th/Yb and Nb/Yb values in Raglan or Expo units—of the type observed in the Beauparlant Formation in Figure 5—that could be attributed to differences in the composition of the mantle source and/or degree of partial melting.

Figure 6 shows two possible models for the relationship between the magmatism of the Expo and Raglan trends, and Table 3 summarizes the criteria and actual observations by which the relative merits of these models can be tested. Model 1 (Fig. 6a), favoured by Francis et al. (1983), Bédard et al. (1984), Giovenazzo et al. (1989), Mungall (2007), and most recently by Bleeker and Kamo (2020), suggests that the subvolcanic parts (i.e. Expo) of the magmatic plumbing system fed the volcanic-dominated parts (i.e. Raglan). The models of Mungall (2007) and Bleeker and Kamo (2020), in particular, suggest that Expo represents a

Table 3. Summary of the key criteria expected and observed in each magmatic plumbing system model used to evaluate the relative merits of each model (*see* Fig. 6).

Criteria	**Expected Observations/Characteristics** (actual in **bold**)		**Actual Observations/Characteristics**	
	MODEL 1 Expo feeds Raglan	**MODEL 2** Expo DOES NOT feed Raglan	**RAGLAN**	**EXPO**
Age	must be the **same**	may be the **same** or different	1882–1883 Ma[1,2]	1882–1883 Ma[1,3]
Maximum MgO margins	Raglan ≤ Expo	**Raglan > Expo**, but may be different	18–20 wt%[4,5,7–8] pyroxenite	15-17 wt%[6,8–9] gabbro
Maximum MgO cumulates	Raglan ≤ Expo	**Raglan > Expo**, but may be different	44 wt%[4,5,7–9]	34 wt%[6–9]
$[La/Sm]_{MN}$ (proxy for crustal contamination)	Raglan ≤ Expo, but depends on flow rate[*see* 7]	**Raglan > Expo**, but depends on flow rate[*see* 7]	average ~1.8[4–9]	average ~1.0[6–9]
Primary magma source	must be the **same**	may be the **same** or different	between N-MORB and E-MORB[4–9]	between N-MORB and E-MORB[4–9]
Ni/Cu ratios of ores	Raglan ≤ Expo	**Raglan > Expo**, but may be different	average ~10[4–7,9]	average ~1[4–7,9]

References: [1]Bleeker and Kamo (2020), [2]Wodicka et al. (2002), [3]Randall (2005), [4]Lesher (1999), [5]Lesher (2007), [6]Mungall (2007), [7]Lesher et al. (2001), [8]McKevitt et al. (2019), [9]McKevitt et al. (this study).

Abbreviations: E-MORB = enriched mid-ocean ridge basalt, N-MORB = normal mid-ocean ridge basalt.

volcanic/intrusive centre that sits within the same sedimentary formation that underlies/hosts Raglan Trend units (i.e. that it is a southern synclinal outlier of the Nuvilic Formation sediments underlying Raglan units: *see* Fig. 2), and that Raglan units are "downflow" equivalents of Expo magmas. Model 2 (Fig. 6b), which has been favoured by Lesher (1999, 2007) and Lesher and Houlé (2017), suggests that the subvolcanic (i.e. Expo) and volcanic (i.e. Raglan) parts were fed separately. Although the criteria and observations, thus far, are insufficient to unequivocally prove or disprove either model, the current weight of evidence greatly favours Model 2 (Table 3). The less magnesian "chilled" margins and olivine cumulates of the host units combined with the lower Ni/Cu ratios of the ores at Expo indicate that the host units crystallized from and the ores equilibrated with cooler, less magnesian, and more evolved magmas, and could not have supplied the hotter, more magnesian, and more primitive magmas required to produce the more magnesian "chilled" margins and olivine cumulates of the host units and the higher Ni/Cu ratios of the ores at Raglan. Although the degree of crustal contamination increases then decreases with increasing magma/lava flux (*see* discussion by Lesher et al., 2001), the higher degree of contamination of Raglan host units—despite their higher magnesium contents—and the greater ore tonnages at Raglan are also consistent with higher temperatures, higher magma fluxes, and greater degrees of thermomechanical erosion.

Ongoing evaluation of these observations, models, and possible factors noted above will continue to yield insights into the source and evolution of this well exposed, well endowed Paleoproterozoic volcanic-subvolcanic-intrusive magmatic plumbing system. The findings may apply to Archean greenstone belts within the Superior Province, Circum-Superior Paleoproterozoic volcanic belts, and other Paleoproterozoic volcanic belts worldwide.

Geodynamic Setting

The geodynamic setting of the mafic-ultramafic magmatism in the Cape Smith Belt is not yet clear. Several authors have suggested that Chukotat magmas were generated in a mantle plume (e.g. Ciborowski et al., 2017; Kastek et al., 2018) that was "steered" toward the Superior Craton margin (Begg et al., 2010; *see also* Bleeker and Kamo, 2020), but Chukotat lavas have non-unique PRIMELT[3]-calculated compositions with 18–19% MgO that could also be generated by decompression melting of mantle peridotite in a hot rift (*see* Herzberg, 2004). It is not yet clear which model is more consistent with the presence of mafic-ultramafic magmas that extend more than 3500 km along the Circum-Superior Belt (Baragar and Scoates, 1981, 1987).

IMPLICATIONS FOR EXPLORATION

Important considerations during exploration for magmatic Ni-Cu-PGE sulphide mineralization include proximity to sulphur-rich horizons of country rock and magma flux in different parts of the magmatic plumbing system (Lesher, 2019; Fig. 6). These considerations especially apply in the eastern Cape Smith Belt, where

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[3] PRIMELT software, designed by Herzberg and O'Hara (2002) and Herzberg and Asimow (2008, 2015), can be used to determine the primary magma composition and mantle potential temperature from an observed lava composition.

deposits along the Expo and Raglan trends show stratigraphic control. The clear geochemical distinctions (in both major and trace elements) between the Povungnituk Group and Chukotat Group volcanic rocks thus may aid a surface or underground exploration program in establishing the relative stratigraphic position. Additionally, especially in examining drill core, some non-prospective gabbroic-textured units in the Povungnituk Group (i.e. Lac Bélanger Suite) may be mistaken for gabbro of prospective Lac Esker Suite units; however, the geochemical distinction between these two types of gabbro is possible by considering major elements (e.g. TiO_2) or trace element contents.

The major and trace element geochemistry of mineralized or barren samples from the Lac Esker Suite can be used to discriminate between units of the Expo or Raglan trends. Such data can aid in categorizing potentially prospective units as volcanic or intrusive (i.e. channelized flows or dykes/sills) and thereby improve targeting for sulphide mineralization within units.

The geochemical data shown here come from samples collected in the eastern Southern Domain of the Cape Smith Belt (east of longitude 75°W). However, the resulting distinctions may apply to similar lithologies located along strike to the west and east (e.g. West Raglan). Furthermore, as the rocks considered here are part of the Circum-Superior Large Igneous Province (e.g. Baragar and Scoates, 1987; Ciborowski et al., 2017), similar geochemical distinctions between prospective and less prospective units may be true in other parts of the Circum-Superior Large Igneous Province (e.g. western Cape Smith Belt and Labrador Trough).

ONGOING WORK

This research is part of a Ph.D. project, planned for completion in 2021. The project seeks to understand the temporal, geochemical, and architectural evolution of the transcrustal Expo-Raglan mineralized magmatic plumbing system. Additional geochemical data collection, QA-QC, classification, and interpretation will continue. Petrographic analyses, whole-rock and mineral geochemical analyses, and modelling are ongoing to evaluate the many possible factors and models that may explain the observed differences between the Expo Trend and Raglan Trend units. Compilation of regional mineral chemical data is also ongoing; hundreds of records have already been compiled from the same references sourced for the whole-rock lithogeochemical data presented here. Most of the whole-rock lithogeochemical data compilation referenced in this report, the largest and most comprehensive for this region, will be released as a GSC Open File.

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