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Critical review

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Ultramafic cumulates east of Kingnait Fiord, Cumberland Peninsula, Nunavut: possible origin and mineral potential

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Abstract: An occurrence of ultramafic rocks on central Cumberland Peninsula of Baffin Island consists of coarse-grained, variably layered peridotite with an assemblage of Mg-rich olivine (Fo_{65-85}), chromite, ilmenite, and Mg-amphibole. Olivine is transected by serpentine-filled fractures that are truncated by secondary tremolite and chlorite. Bulk compositions correspond closely to those of unaltered wehrlitic cumulates. Trace-element profiles show enrichment in incompatible elements relative to primitive mantle, and predict a parental magma compositionally resembling ocean island basalt. Intrusive phases related to such plume-related magmatism are known elsewhere for their nickel and PGE potential. Accordingly, although the Kingnait Fiord ultramafic rocks likely relate to rift magmatism of Paleoproterozoic age, exploration models developed for intrusion-hosted nickel sulphide and platinum-reef mineralization in younger systems of similar composition should be applied.

Résumé : Dans le centre de la péninsule Cumberland, dans l'île de Baffin, une occurrence de roches ultramafiques se manifeste sous forme de péridotite à grain grossier et à stratification variable avec une association d'olivine riche en Mg (Fo_{65-85}), de chromite, d'ilménite et d'amphibole magnésienne. L'olivine est recoupée par des fractures remplies de serpentine, elles-mêmes tronquées par de la trémolite et de la chlorite secondaires. Les compositions globales correspondent étroitement à celles de cumulats wehrlitiques non altérés. Les spectres des éléments traces montrent un enrichissement en éléments incompatibles par rapport au manteau primitif et laissent supposer un magma parental qui ressemble en composition aux basaltes d'îles océaniques. Des phases intrusives liées à un magmatisme de panache sont reconnues ailleurs pour leur potentiel en nickel et en ÉGP. Par conséquent, bien que les roches ultramafiques du fjord Kingnait soient probablement associées à un magmatisme de rift du Paléoprotérozoïque, on devrait recourir à des modèles d'exploration conçus pour des minéralisations de sulfures de nickel et de platine sous forme d'horizons minéralisés dans des intrusions associées à des systèmes plus récents de composition semblable.

INTRODUCTION

This report describes an occurrence of ultramafic rocks from Cumberland Peninsula, Nunavut, discovered during a Geo-mapping for Energy and Minerals project (Sanborn-Barrie et al., 2011a,b,c; Sanborn-Barrie and Young, in press a, b, c; Sanborn-Barrie et al. in press a, b). The rocks are notable for their coarse grain size and preservation of apparent primary textures in a map area that typically exposes highly strained, metamorphic rocks. In an effort to better understand the origin and mineral potential of these rocks, several samples were collected and analyzed for whole-rock and mineral compositions, accompanied by petrographic examination.

This investigation contributes to the general aim of the GEM Cumberland project to improve on the geoscience knowledge base for this underexplored frontier region through acquisition of high-resolution aeromagnetic data (Coyle, 2009), surficial (Dyke, 2011a,b,c,d,e,f; Gammon et al., 2011) and bedrock (Sanborn-Barrie et al., 2010, 2011a,b,c; Sanborn-Barrie and Young, in press a, b, c; Sanborn-Barrie et al., in press a, b) mapping. New integrated information on supracrustal and intrusive rocks (e.g. Sanborn-Barrie and Young, 2011; Keim et al., 2011; Whalen et al., 2012) forms the basis of interpretation of Archean and Paleoproterozoic sequences on the peninsula which allows regional correlations with other major tectonic elements of northeastern Laurentia (cf. St-Onge et al., 2006a, b, 2009; Sanborn-Barrie et al., 2008; Corrigan et al., 2009).

Early reconnaissance mapping had interpreted much of Cumberland Peninsula to be underlain by metasedimentary rocks and undifferentiated paragneiss, interpreted as a Paleoproterozoic cover sequence designated the Hoare Bay Group (Jackson and Taylor, 1972). However, more recent mapping highlighted extensive regions of Archean (ca. 2.97–2.77 Ga) metaplutonic rocks and lesser associated supracrustal rocks (Rayner et al., 2012) that form the structural basement to much more restricted cover rocks of the Paleoproterozoic Hoare Bay group (Sanborn-Barrie et al., 2011a,b,c; Sanborn-Barrie and Young, in press a, b, c; Sanborn-Barrie et al., in press a, b). The Hoare Bay group comprises minor, isolated exposures of lowermost quartzite and carbonate (marble±calc-silicate), overlain by extensive semipelite and psammite (Fig. 1). Ultramafic-mafic metavolcanic rocks, associated iron-formation, and chert form laterally contiguous interstratified units across eastern Cumberland Peninsula (Fig. 1). Metavolcanic rocks include both bright-green-weathering komatiitic units, best exposed on Totnes Road Fiord (Keim et al., 2011), and black-weathering tholeiitic fragmental rocks, interpreted to occur in a parallel, stratigraphically higher, northeast-trending belt. Collectively, these volcanic rocks were designated the Totnes Road formation based on their petrological, stratigraphic, and geochemical characteristics (Keim, 2013).

Gabbro, leucogabbro, diorite and lesser pyroxenite are generally interlayered with Archean tonalite-trondhjemite and are known, or inferred, to be Archean. In contrast, ultramafic sills, up to 200 m thick, cut both basement and cover rocks, establishing them as Paleoproterozoic. Ultramafic sills are commonly observed to be spatially associated with ultramafic metavolcanic rocks, with which they are locally transitional.

Intermediate to felsic plutonic rocks, dominated by charnockite and granodiorite, cut basement and cover rocks, forming a belt that extends more than 300 km from Pangnirtung to Qikiqtarjuaq (Fig. 1). Designation of this belt as the Qikiqtarjuaq plutonic suite is based on extensive exposures of compositionally similar rock types, that yield U-Pb ages between ca. 1.88 and 1.895 Ga from seven localities (Rayner et al., 2012; N. Rayner unpub. data, 2011). This suite is ~35 Ma older than the 1845–1865 Ma Cumberland batholithic complex (Whalen et al., 2010) exposed to the west and formerly predicted to underlie this region.

At least two strongly penetrative deformation events have affected the rocks of Cumberland Peninsula, resulting in transposed and commonly tightly infolded contacts between Archean crystalline basement and overlying Paleoproterozoic supracrustal rocks. Deformation was accompanied by medium- to high-grade metamorphism (Hamilton et al., 2012). Assemblages in the Kingnait Fiord area suggest metamorphism to the lower-amphibolite facies.

ULTRAMAFIC ROCKS OF THE KINGNAIT FIORD AREA

A till-covered region east of Kingnait Fiord is characterized by isolated exposures of resistive, black-weathering ultramafic rock, which may represent part of a large, compositionally layered igneous body. One of the largest exposures from this region, located 16 km east of Kingnait Fiord (Fig. 1), was investigated in order to elucidate the age, origin, and economic potential of these rocks through petrographic and geochemical studies.

Petrography and mineral chemistry

In the area of study, three zones of mafic-ultramafic rock are exposed (Fig. 2). In area 1, large (300–400 m³), black, erratic boulders were observed from a distance but not sampled. Area 2 consists of a single outcrop of medium- to coarse-grained ultramafic schist from which sample C-110 was taken. Area 3 is a large outcrop from which several texturally and compositionally variable samples (C-112A, B, D) were collected. Area 3 exposes i) massive, coarse-grained, equigranular, brown-weathering peridotite (Fig. 3a); ii) massive peridotite with olivine grains up to 5 cm separated by interstitial amphibole (Fig. 3b); iii) layers up to 4 cm thick of medium-grained, green and rusty-weathering, ilmenite- and

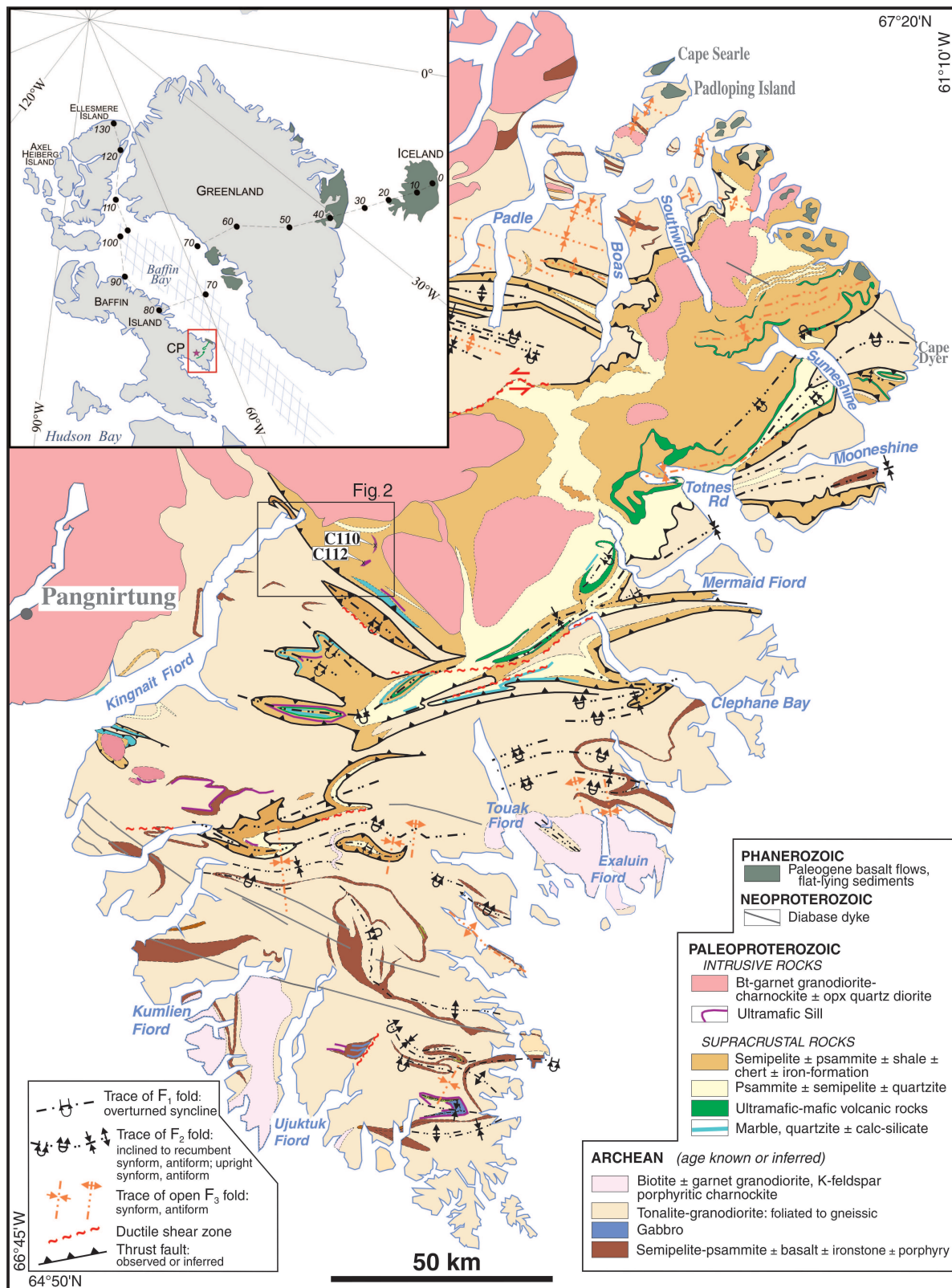


Figure 1. Bedrock geology of Cumberland Peninsula, eastern Baffin Island after Sanborn-Barrie et al., 2011a, b, c, in press a, b, Sanborn-Barrie and Young in press a, b). Black outline highlights location of Kingnait ultramafic plutonic occurrence, this study. Inset map shows distribution of Paleogene basalt and related intrusive rocks (grey-green); path for the Iceland hotspot (dashed line) summarized in 10 Ma intervals from 130 Ma to present day after Lawver and Müller (1994); hatched lines denote new crust formed during extension across Baffin Bay; CP - Cumberland Peninsula.

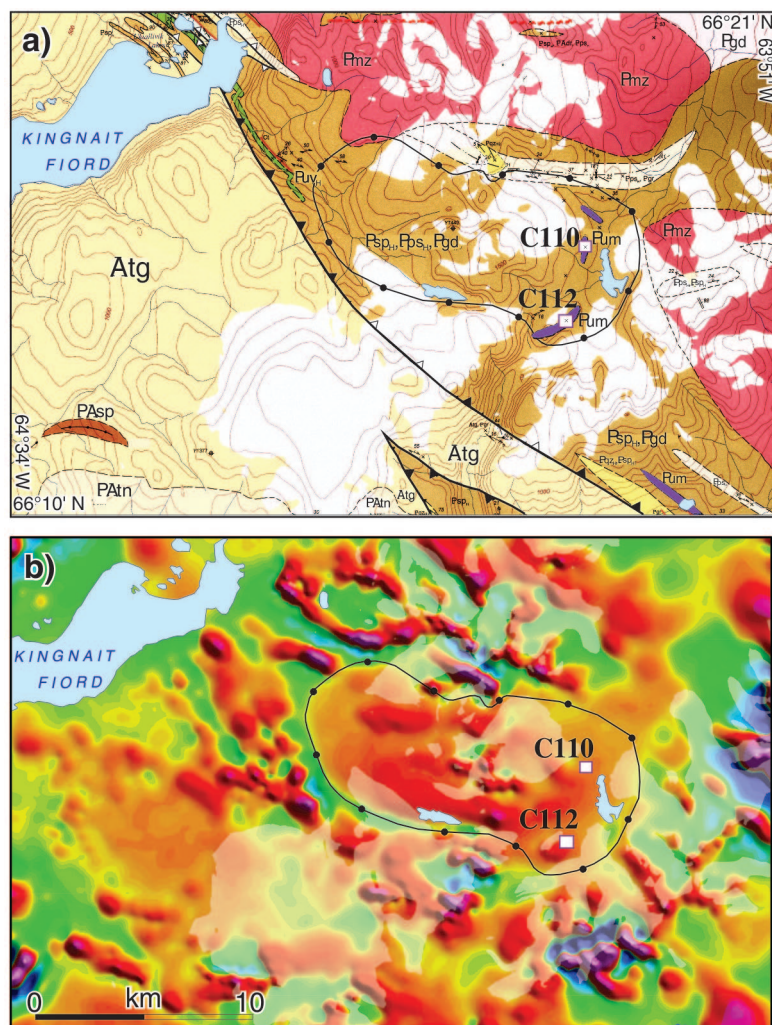


Figure 2. Geology in the vicinity of ultramafic plutonic exposure C112. **a)** Bedrock geology from Sanborn-Barrie and Young (in press a). Archean rocks coded as: Atg - tonalite gneiss. Paleoproterozoic rocks coded as: Pum - ultramafic intrusive rocks; PuvH - ultramafic volcanic rocks; PspH - semipelite; PpsH - psammite; PqzH - quartzite; Pmz - monzogranite; Pgd - granodiorite. Rocks of uncertain age coded as: PAsp - semipelite; PAtn - tonalite. Regions of permanent ice cover are shown in white. **b)** total magnetic field in the vicinity of C112.

spinel-rich peridotite (Fig. 3c); and iv) green-weathering peridotite breccia consisting of rounded fragments in a medium- to coarse-grained peridotite matrix (Fig. 3d). Minor rusty-weathering layers, up to a few centimetres thick, contain small amounts of sulphides. Six samples from areas 2 and 3 are described in further detail below with mineral analyses presented in Tables 1 through 5.

C-110A: This sample is an altered peridotite consisting of isolated, optically continuous remnants of olivine (30%; Fo_{64} ; Table 1) with aligned, serpentine-filled fractures. The fractures are truncated by an enclosing groundmass of fine tremolite (60%; Table 2) with elongate ilmenite (8%; Table 3) and randomly oriented chlorite (2%; Table 4). Traces of rutile are present.

C-112A-1: The rock is an altered peridotite (Fig. 3a) made up dominantly of coarse (to 3 cm), optically continuous olivine (70%; Fo_{83} ; Table 1) and chlorite (25%; Table 4), with minor ilmenite (1%; Table 3) and chromite (tr; Table 3). Serpentine replaces olivine along polygonal fractures. Chlorite occurs in irregular-shaped patches up to 5 mm in size and contains minor remnant olivine and ilmenite.

C-112A-2: This peridotite (Fig. 3b) consists dominantly of coarse (to 1.5 cm), optically continuous olivine (60%; $Fo_{83.5}$; Table 1) with scattered ilmenite (1%; Table 3) and chromite (tr; Table 3). Serpentine (3%) replaces olivine along polygonal fractures. Patches of tremolite (20%; Table 2) and chlorite (16%; Table 4) truncate the serpentine-filled fractures (Fig. 4d).

C-112A-3: This peridotite consists of large (2–3 cm), optically continuous olivine grains (60%; Fo_{84} ; Table 1), dissected by two sets of serpentine-filled fractures. Olivine contains fine chromite (1%; Table 2). Patches of chlorite (10%; Table 4) and tremolite (5%; Table 2), up to 1 cm diameter, truncate the altered olivine grains. A few grains of pentlandite (Table 3) within tremolite contain 32 wt% Ni and minor Co and Cu.

C-112B: This altered peridotite consists of coarse (to 2 cm) olivine (50%; $Fo_{71.5}$; Table 1) with fine Fe-Mg-Al spinel (hercynite; 5%; Table 3) inclusions. Serpentine (5%) occurs along polygonal fractures. Ovoid patches of Mg-hornblende (40% Table 2), up to 1 cm in diameter, truncate fractures in olivine and contain isolated olivine and spinel remnants.

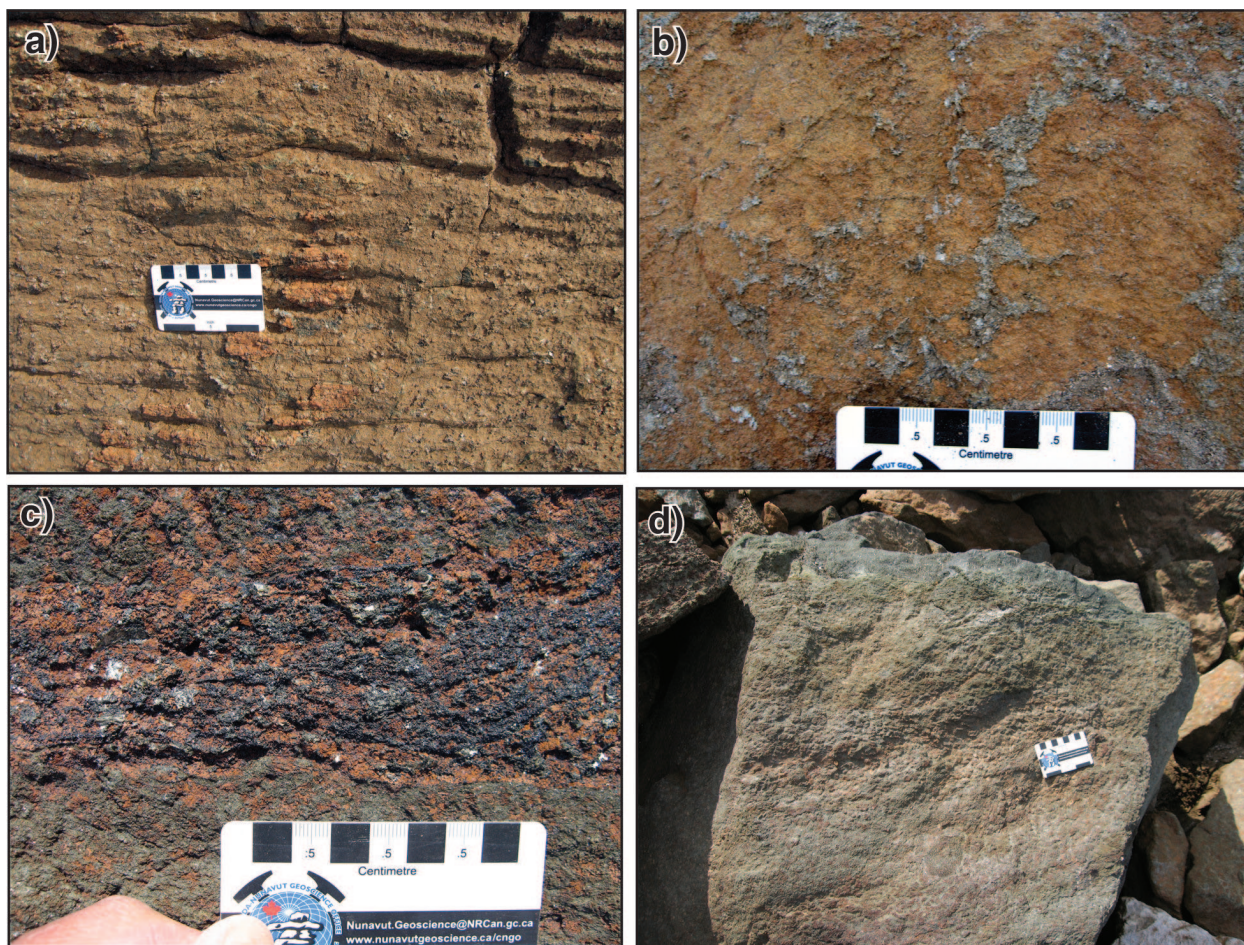


Figure 3. Outcrop photographs of Kingnait Fiord ultramafic rocks: **a)** massive, equigranular peridotite (C-112A-1). 2012-182; **b)** porphyritic cumulate peridotite (C-112A-2) showing large olivine phenocrysts (brown) separated by intercumulus amphibole (green). 2012-184; **c)** layer of medium-grained, ilmenite- and spinel-rich peridotite (C-112D-1) within more massive peridotite. 2012-188; **d)** peridotite breccia consisting of rounded fragments in a medium-to coarse-grained peridotite matrix (not sampled). 2012-185. All photographs by J.A. Percival.

Table 1. Olivine analyses.

Sample	C-110A	C-112A-1	C-112A-2	C-112A-3	C-112B	C-112D-1	C-112D-2
SiO ₂	36.7	39.0	38.5	39.9	36.9	36.7	36.7
TiO ₂	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Al ₂ O ₃	0.0	0.0	0.1	0.0	0.0	0.1	0.0
Cr ₂ O ₃	0.1	0.1	0.0	0.0	0.0	0.1	0.0
V ₂ O ₃	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FeO	30.3	15.5	15.0	14.8	25.6	28.2	30.1
MnO	0.3	0.2	0.2	0.2	0.3	0.4	0.6
MgO	31.9	44.6	44.1	44.2	36.6	34.7	32.8
NiO	0.3	0.3	0.3	0.3	0.1	0.1	0.0
CaO	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Na ₂ O	0.1	0.0	0.0	0.0	0.0	0.0	0.0
K ₂ O	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	99.6	99.8	98.3	99.6	99.6	100.4	100.3
Fo	64.8	85.0	83.5	83.8	71.5	68.3	65.6

Table 2. Amphibole analyses.

Sample	C-110A	C-112A-2	C-112A-3	C-112B	C-112D-1	C-112D-2
	Mg-Hb	Tr	Tr	Tr	Mg-Hb	Mg-Hb
SiO ₂	49.3	57.1	56.3	52.4	48.9	45.7
TiO ₂	0.3	0.1	0.2	0.3	0.4	0.5
Al ₂ O ₃	8.0	1.6	2.3	5.8	8.3	12.2
Cr ₂ O ₃	0.3	0.3	0.5	0.0	0.1	0.2
V ₂ O ₃	0.1	0.0	0.0	0.1	0.0	0.0
FeO	6.7	2.7	2.9	5.1	6.6	7.9
MnO	0.2	0.1	0.1	0.1	0.2	0.2
MgO	18.5	22.8	22.6	31.7	18.0	15.9
NiO	0.1	0.0	0.0	0.2	0.0	0.1
CaO	12.0	12.6	12.3	12.5	11.7	12.4
Na ₂ O	1.6	0.3	0.4	0.3	0.8	1.3
K ₂ O	0.1	0.1	0.0	0.1	0.1	0.2
Total	97.6	98.2	98.0	96.8	95.3	96.8

Table 3. Chromite, spinel, ilmenite, pentlandite analyses.

Sample	C-110A	C-112A-1	C-112A-1	C-112A-2	C-112A-2	C-112A-3	C-112A-3	C-112B	C-112D-1	C-112D-1	C-112D-2	C-112D-2
	ilm	chr	ilm	ilm	chr	pent	chr	cr-herc	ilm	herc	ilm	herc
SiO ₂	0.0	0.0	0.0	0.0	0.1	na	0.0	0.0	0.0	0.0	0.0	0.0
TiO ₂	52.3	1.3	53.0	53.3	0.7	na	0.9	0.3	52.4	0.0	51.9	0.1
Al ₂ O ₃	0.0	11.5	0.1	0.1	12.6	na	1.3	39.0	0.1	59.1	0.0	59.1
Cr ₂ O ₃	0.1	43.6	0.1	0.1	45.8	na	54.6	18.9	0.0	1.9	0.0	1.0
V ₂ O ₃	0.2	0.6	0.1	0.1	0.4	0.0	0.4	0.6	0.1	0.2	0.1	0.1
FeO	44.8	36.8	42.0	41.3	34.7	31.8	37.6	31.5	44.1	23.5	44.4	25.6
MnO	0.6	0.6	1.0	1.0	0.6	0.0	0.6	0.3	0.7	0.3	1.0	0.2
MgO	2.3	3.2	3.3	3.8	3.5	na	1.6	7.0	2.4	13.0	2.3	12.4
NiO	0.1	0.1	0.1	0.0	0.1	32.9	0.1	0.2	0.0	0.2	0.0	0.2
S						32.8						
Total	100.4	97.7	99.7	99.7	98.5	97.5	97.1	97.8	99.8	98.2	99.7	98.7

Table 4. Chlorite analyses.

Sample	C-110A	C-112A-1	C-112A-2	C-112A3	C-112D-1	C-112D-2
SiO ₂	28.3	28.7	28.3	28.9	27.8	27.7
TiO ₂	0.0	0.1	0.1	0.1	0.0	0.0
Al ₂ O ₃	19.4	19.2	19.2	18.2	20.6	21.0
Cr ₂ O ₃	0.6	1.1	1.0	1.3	0.1	0.1
V ₂ O ₃	0.0	0.0	0.0	0.0	0.1	0.1
FeO	7.8	4.4	4.3	4.1	8.0	8.0
MnO	0.1	0.0	0.0	0.0	0.1	0.1
MgO	28.7	31.5	31.7	31.0	28.4	28.3
NiO	0.2	0.2	0.2	0.2	0.1	0.1
CaO	0.0	0.0	0.0	0.0	0.0	0.0
Na ₂ O	0.0	0.0	0.0	0.0	0.0	0.0
K ₂ O	0.0	0.0	0.0	0.0	0.0	0.0
Total	85.5	85.3	85.1	83.8	85.5	85.8

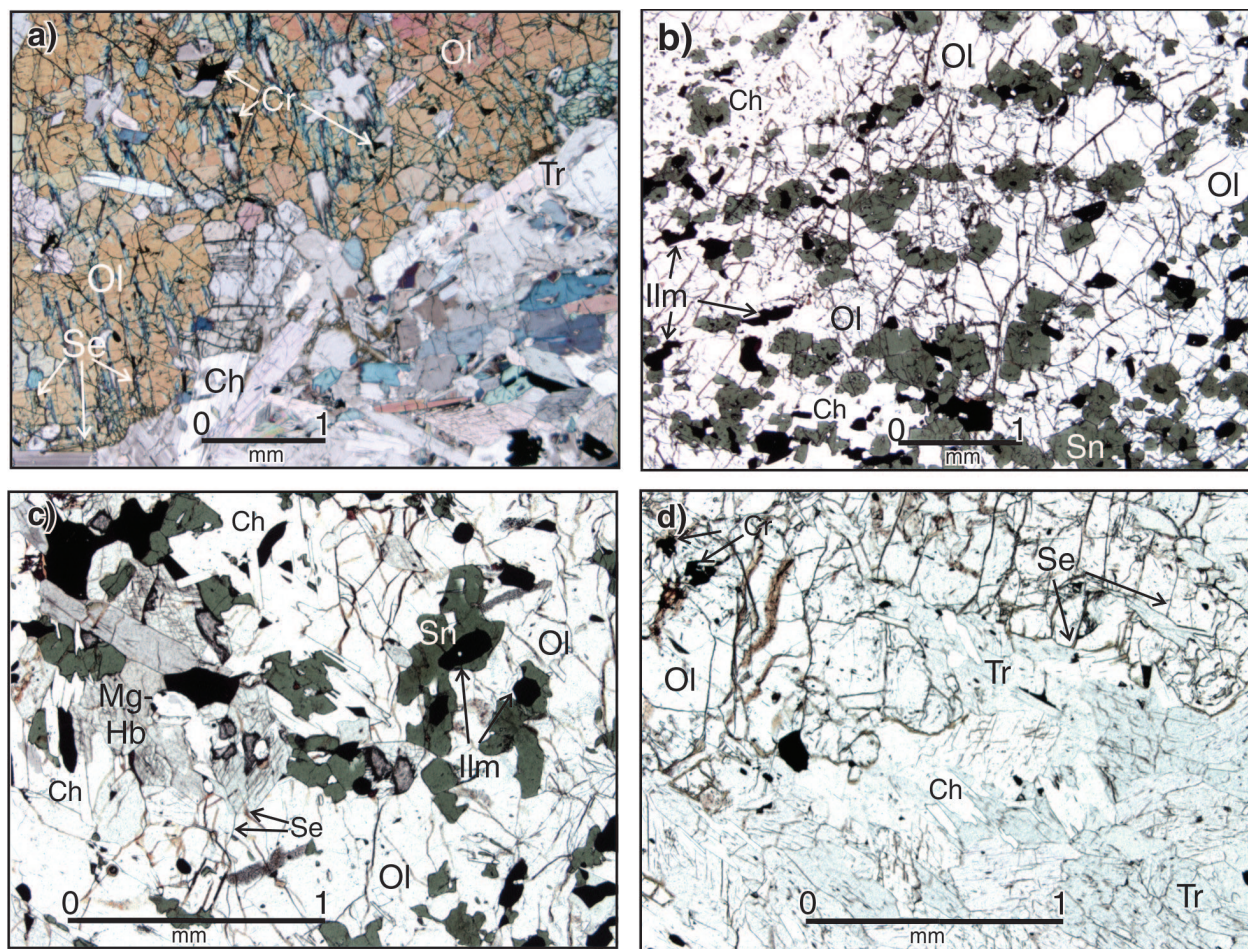


Figure 4. Photomicrographs illustrating textural relationships. **a)** Large olivine crystal (Ol) with chromite (Cr) inclusions, cut by serpentine-filled fractures (Se), truncated by tremolite (Tr) and chlorite (Ch), sample C-112A-1; cross-polarized light. 2012-186. **b)** Spinel (Sn), ilmenite (Ilm)-rich layers as inclusions in olivine, in peridotite C-112D-1. 2012-187. **c)** Fracture continuity and high-temperature composition (Mg-hornblende; Mg-Hb) suggest a primary origin for this amphibole, whereas cross-cutting chlorite (Ch) suggests a metamorphic origin, sample C-112D-2. 2012-189. **d)** Olivine with chromite (Cr) inclusions shows serpentine-filled fractures, truncated by tremolitic amphibole (Tr) and chlorite (Ch) of inferred metamorphic origin, sample C-112A-2. 2012-183

C-112D-1: This rock exhibits subtle, irregular, centimetre-scale layering defined by differing abundances of spinel and ilmenite (Fig. 3c). It consists of coarse (to 2 cm) olivine (70%; Fo_{68} ; Table 1), with finely disseminated hercynite (20%; Table 3) and ilmenite (3%; Table 3). Olivine is transected by serpentine-filled fractures and these are truncated by Mg-hornblende (5%; Table 2) and chlorite (2%; Table 4).

C-112D-2: This sample consists of two layers: layer 1 has coarse (to 1 cm) olivine (40%; Fo_{65} ; Table 1) and medium-grained (1–2 mm) pargasite (30%; Table 2), both with fine (0.5 – 1 mm) inclusions of hercynitic spinel (29%; Table 3) and ilmenite (1%; Table 3), transected by serpentine-filled fractures; layer 2 consists dominantly of pargasite (90%) with isolated olivine (5%), spinel (4%) and ilmenite (1%) relics.

Collectively, the olivine-bearing ultramafic rocks at this locality are characterized by coarse to very coarse grain size, variably developed compositional layering, and breccia phases. These macroscopic characteristics, in concert with microscopic textural observations and olivine compositions with up to 0.3 wt% NiO_2 , are consistent with preserved primary igneous features. Serpentine-filled fractures in olivine are inferred to result from an early alteration or metamorphic event, whereas crosscutting, fracture-free chlorite and tremolite likely formed during the regional, lower-amphibolite-facies metamorphism. The two generations of secondary features observed in the peridotites may reflect regional D_1 and D_2 events of Paleoproterozoic age.

Calculated equilibria

Spinel compositions range from chromite to hercynite and pleonaste (Table 3), and plot in the fields of both continental mafic intrusions and high-grade metamorphic rocks (Barnes and Roeder, 2001). The olivine-spinel thermometer (Ballhaus et al., 1991) was applied to three samples with appropriate assemblages. Apparent temperature results (350–490°C) are well outside the calibrated range for the thermometer (>1000°C). Accordingly, it remains uncertain whether the temperature estimates reflect cooling from regional metamorphic conditions in this area, or whether they are meaningless.

WHOLE-ROCK GEOCHEMISTRY

Six samples were analyzed for major and trace elements (Table 5). All rocks are rich in MgO (20.7–37.3 wt%) with Mg numbers (100 MgO/MgO+FeO) between 65 and 88.7. MgO and Mg# vary proportionally with both Cr (1690–3570 ppm) and Ni (584–2160 ppm). SiO₂ ranges from 34.4 to 44.2 wt% and iron from 11.4–22.0 wt% (total iron as Fe₂O₃). Al₂O₃ generally falls in the range 2.5 to 6.75 wt%, with the exception of the spinel-rich sample (C-112D-2) with Al₂O₃ = 13.5 wt%. CaO (2.7–7.5 wt%) is proportional to amphibole content. TiO₂ varies from 0.3 wt% in the most magnesian rocks, to 2.9 wt% in more iron-rich compositions. Alkali contents are low, ranging from 0.1–1.1 wt% for Na₂O and 0.01 to 0.43 wt% for K₂O. The major-element compositions correspond well with wehrlitic cumulates (e.g. *see* comparative analysis from Holm and Prægel (2006) in Table 5). Calculations of CIPW norm indicate dominant olivine, ortho- and clinopyroxene, plotting in the lherzolite field.

Trace-element contents are moderate for chalcophile elements (101–137 ppm Co; 3–19 ppb Pt) and low for lithophile elements (Table 5). Gold contents are generally low (maximum 105 ppb). Concentrations of the relatively immobile incompatible trace elements are moderate, with Zr ranging from 8.4 to 182 ppm, Y from 3.4 to 13.5 ppm and Nb from 1.2 to 19.4 ppm. Hf values are low (<0.1 to 4.8 ppm).

Rare-earth element (REE) contents vary inversely with MgO and Mg#, and vary proportionally with Ca, Al, and Ti. All rocks show sinusoidal chondrite-normalized REE patterns (Fig. 5), with variable heavy REE (HREE) fractionation (Tb/Yb)_n = 1.2 to 3.4. Patterns of the more enriched samples (i.e. C-110A, C-112D-2) are comparable to those of ocean island basalt (OIB; Sun and McDonough, 1989).

Abundance and fractionation features are assessed using PRIM-normalized trace element data (Fig. 6). The Kingnait samples generally display positive Nb, Ti anomalies, with pronounced negative Zr, Hf anomalies exhibited only in C-112A peridotites (i.e. A1, A2 and A3). With respect to average OIB (Fig. 6b), the Kingnait Fiord cumulates have similar overall patterns, but much lower abundances, particularly

in large-ion lithophile elements (Rb, Ba). Spinel-rich sample C-112D2, which is enriched in aluminum, is the only rock with a very slight Th-Nb-La trough. This may reflect some degree of assimilation by the magma of aluminous sedimentary rocks of continental derivation.

DISCUSSION

Age and origin

Two notable features of the Kingnait Fiord ultramafic plutonic rocks are their coarse grain size and their mineral assemblages, which are dominated by olivine. Olivine-rich cumulates are generally considered coarse at 5 mm, whereas the present suite exhibits crystals up to 5 cm (Fig. 3b). Possible factors in the growth of coarse olivine include large magma volumes, typical of thick, periodically replenished magma chambers, conduit settings, or hydrous magma compositions. Preservation of apparent primary cumulate textures suggests that the Kingnait ultramafic rocks record considerably less strain than their enveloping host rocks. Evidence at the microscopic scale supports some degree of sub-solidus deformation and metamorphic mineral growth. Accordingly, these olivine-dominated rocks are interpreted to have been rheologically strong relative to surrounding quartz-bearing felsic plutonic rocks during deformation, focusing strain in the more ductile host rocks and leaving the ultramafic rocks relatively weakly deformed.

Comparison to ultramafic-mafic extrusive rocks in the region

In the vicinity of the Kingnait Fiord ultramafic plutonic occurrence, several sequences of Paleoproterozoic volcanic (extrusive) rocks are exposed. A comparative study was undertaken in order to assess whether any of these are related to the Kingnait plutonic occurrence, and whether they may represent a proxy for parental liquid compositions. The most proximal extrusive rocks include ultramafic-mafic metavolcanic rocks within the Hoare Bay group (Fig. 1). As previously noted, these constitute two main types. Komatiitic rocks of the Totnes Road suite have typical MgO contents of 15–20 wt% (Keim et al., 2011) and are classified geochemically as enriched to normal mid-ocean ridge basalt (E- to N-MORB) type (Whalen et al., 2012). The Totnes Road volcanic sequence could be derived from a Mg-rich parental magma from which olivine-rich cumulates settled; however, two of the cumulate rock samples, C-110A and C-112D2, have higher MgO contents (21.14 and 20.75 wt% MgO respectively) than analyzed Totnes volcanic rocks, with more enriched incompatible-element concentrations than the komatiitic compositions (Fig. 6a). This implies that their parental magma should be even more enriched. Black-weathering basaltic volcanic rocks on Cumberland Peninsula are classified geochemically as being of alkali continental rift (ACR) affinity (Whalen et al., 2012). They have lower

Table 5. Whole-rock geochemical analyses.

Sample	C-110A	C-112A-1	C-112A-2	C-112A-3	C-112B	C-112D-2	428003	428006
SiO ₂	43.5	41.2	44.2	41.6	43.4	34.4	45.47	41.86
TiO ₂	2.3	0.3	0.3	0.3	1.0	2.9	0.51	0.82
Al ₂ O ₃	6.8	3.2	2.5	2.7	6.8	13.5	0.91	2.53
Fe ₂ O ₃	16.1	12.0	11.4	11.6	15.3	22.0	12.13	14.18
MnO	0.2	0.2	0.2	0.2	0.2	0.3	0.16	0.18
MgO	21.1	37.3	34.5	36.5	24.9	20.8	28.93	31.91
CaO	7.6	2.7	4.8	2.9	7.5	5.8	10.40	4.64
Na ₂ O	1.1	0.1	0.2	0.1	0.2	0.5	0.30	0.69
K ₂ O	0.4	0.0	0.0	0.0	0.0	0.1	0.06	0.14
P ₂ O ₅	0.2	0.0	0.0	0.0	0.0	0.1	0.02	0.07
Cr ₂ O ₃	0.2	0.5	0.5	0.5	0.3	0.3	0.28	0.49
LOI	0.7	3.1	1.7	4.1	0.7	0.1	nd	nd
Sum	100.0	100.1	99.9	100.0	100.0	100.4	99.2	97.5
Total C	0.0	0.1	0.0	0.1	0.0	<0.02	nd	nd
Total S	<0.02	0.2	<0.02	0.1	<0.02	<0.02	nd	nd
Trace elements in ppm								
	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	XRF	XRF
Ba	75	2	2	2	1	19	20	51
Be	<1	<1	<1	<1	<1	4	nd	nd
Co	101.5	121	112.6	129.2	102.6	136.8	129	144
Cs	19.7	0.2	<0.1	<0.1	<0.1	<0.1	nd	nd
Ga	14.9	5.6	4	5.4	10.4	22.5	nd	nd
Hf	4.3	0.1	0.2	<0.1	1.1	4.8	nd	nd
Nb	19.4	1.2	2.2	2.9	4.4	16.6	1.1	8.3
Rb	15.2	<0.1	0.3	<0.1	0.4	0.4	1.9	2.3
Sn	1	<1	<1	<1	<1	<1	nd	nd
Sr	179.5	49.1	111.5	56	60.8	93	nd	93
Ta	1.4	0.5	<0.1	0.6	<0.1	1.5	nd	nd
Th	1.8	<0.2	<0.2	<0.2	0.3	2.5	nd	nd
U	0.5	<0.1	<0.1	<0.1	<0.1	0.3	nd	nd
V	292	119	110	98	215	335	97	130
W	0.5	0.9	<0.5	<0.5	<0.5	<0.5	nd	nd
Zr	158.3	10.9	9.3	8.4	49.3	182	12	51
Y	13.5	3.5	5.6	3.4	9.1	13.4	5.2	5.8
La	18.3	1.1	1.2	0.7	2.4	22.2	1.6	8.4
Ce	43.1	3.5	4.2	2.9	7.7	51.3	4.78	16.3
Pr	5.79	0.42	0.71	0.34	1.15	6.15	0.81	nd
Nd	25.3	3.1	4.1	2.4	6.3	26.3	4.28	11.7
Sm	5.32	0.45	1.27	0.63	1.79	4.98	1.28	nd
Eu	1.07	0.24	0.43	0.27	0.52	2.77	0.4	nd
Gd	4.34	0.77	1.32	0.72	2.11	4.59	1.34	nd
Tb	0.65	0.14	0.27	0.1	0.33	0.55	0.19	nd
Dy	3.16	0.68	1.13	0.43	1.91	2.93	0.95	nd
Ho	0.56	0.1	0.29	0.09	0.27	0.51	0.18	nd
Er	1.35	0.34	0.7	0.34	0.97	1.5	0.42	nd
Tm	0.16	0.04	0.08	0.04	0.13	0.17	0.05	nd
Yb	1.09	0.26	0.36	0.37	0.63	1.31	0.3	nd
Lu	0.14	0.04	0.07	0.04	0.12	0.22	0.04	nd
Mo	<0.1	<0.1	0.1	<0.1	0.1	<0.1	nd	nd
Cu	132	7	15	7	100	129	36	nd
Pb	1	0.4	0.2	0.1	0.2	0.6	4	4
Zn	49	39	22	33	5	6	82	89
Ni	584	2154	1845	2160	764	650	1366	1497
As	<0.5	49	7.2	8.8	0.6	<0.5	nd	nd
Cd	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	nd	nd
Sb	<0.1	0.4	<0.1	<0.1	<0.1	<0.1	nd	nd
Bi	<0.1	0.5	0.2	0.2	<0.1	<0.1	nd	nd
Ag	<0.1	<0.1	<0.1	<0.1	0.2	0.1	nd	nd
Hg	<0.01	0.02	0.01	<0.01	<0.01	<0.01	nd	nd
Tl	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	nd	nd
Se	<0.5	0.5	<0.5	<0.5	<0.5	<0.5	nd	nd
Trace elements in ppb								
	FA	FA	FA	FA	FA	FA		
Au	4	3	3	5	42	105	nd	nd
Pt	11	<3	8	6	19	12	nd	nd
Pd	<2	4	7	6	9	7	nd	nd
All samples numbers except 428003, 428006 prefixed by 09SRB- Analysis for samples 428003, 428006 from Holm and Prægel (2006) FA = Fire assay; nd = not determined								

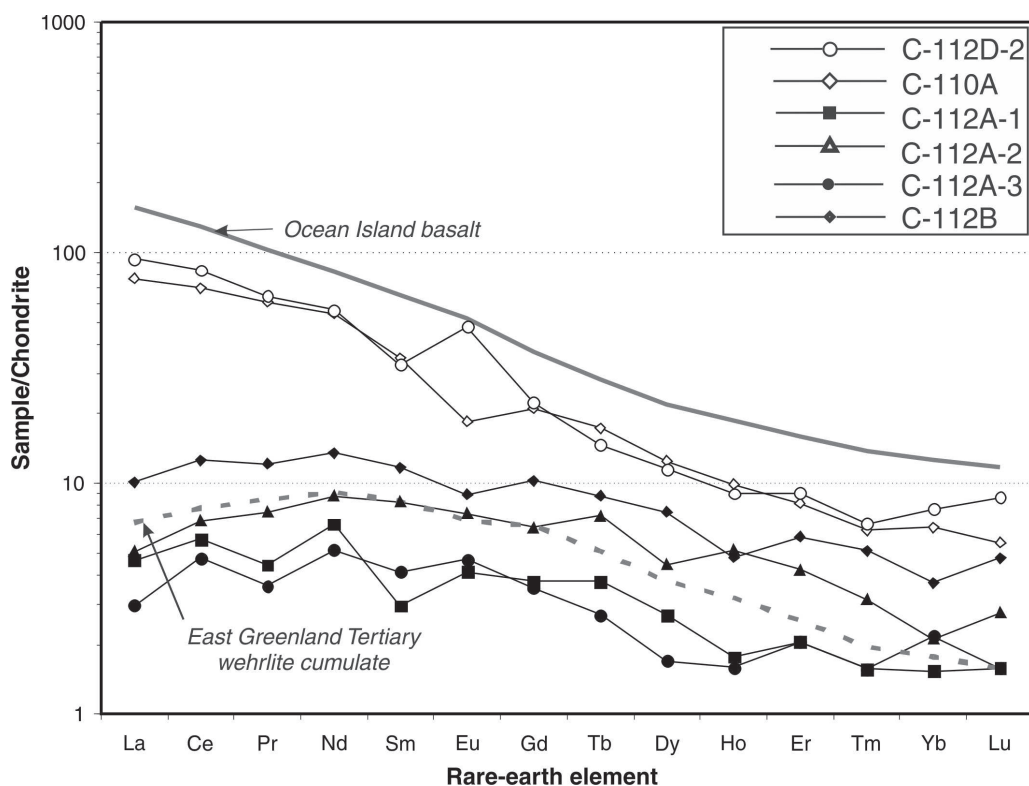


Figure 5. Rare-earth element diagram for seven Kingnait Fiord peridotites. Chondrite-normalized (Sun and McDonough 1989) analyses are plotted along with ocean island basalt for reference.

MgO contents (up to 15.6 wt%) and more enriched incompatible trace-element patterns (Fig. 6a), parallel to those of samples C-110A and C-112D2. Accordingly, they provide a plausible parental magma for the cumulates.

Two hundred kilometres northwest of Cumberland Peninsula, the Paleoproterozoic Bravo Lake Formation comprises mafic flows of dominantly alkali basaltic composition (Johns et al., 2006). These mafic volcanic rocks have MgO contents typically between 5 and 10 wt% (maximum 18 wt%), and enriched trace-element patterns (Johns et al., 2006; Fig. 6a). Cumulate sills and peridotite intrusions are thought to be related (St-Onge et al., 2005). However, the Bravo Lake basalts have steeper LREE patterns (higher La/Sm) than the Kingnait Fiord rocks.

We also investigated the possibility that the Kingnait Fiord cumulates might have been derived from parental magmas of more recent age. Nearby candidates include Paleogene (ca. 55 Ma) picrites exposed along the northeastern coast of Cumberland Peninsula (Fig. 1b) and Cretaceous (ca. 100 Ma) flood basalts of northern Ellesmere and Axel Heiberg islands. Olivine-rich picritic lavas of Paleogene age are exposed across northeastern Cumberland Peninsula, from Padloping Island (Clarke 1970; Clarke and Upton, 1971) to Cape Dyer (Francis, 1985), and are inferred to underlie Baffin Bay (Clarke, 1977). These Mg-rich lavas, with up to 22 wt% MgO, are considered to represent high-temperature magmas (Gibson, 2002) generated in a hot mantle plume

(e.g. Baffin Bay plume, Gill et al., 1995) during opening of Baffin Bay (Fig. 1; Clarke, 1970; 1977; Clarke and Upton 1971; Francis, 1985). Given the olivine-rich character and low strain state of the Kingnait samples, we considered whether magma, which erupted mainly in Baffin Bay, could have been channelled along rift-related structures to inland locations (i.e. east of Kingnait Fiord). The Baffin Island picrites have trace-element contents consistent with N- and E-type MORB (Robillard et al., 1992; Kent et al., 2004), with patterns (Fig. 6b) significantly flatter than the Kingnait Fiord rocks.

More plausible parental magmas from the compositional standpoint are products of Iceland hot-spot magmatism. Some reconstructions propose that the Icelandic hot spot may have tracked southward along the edge of eastern Baffin Island 90–75 Ma ago (Fig. 1), prior to migrating eastward across Greenland (Lawver and Müller, 1994). Least-contaminated basalts of East Greenland have high MgO contents and primitive mantle-normalized profiles (Fig. 6b) resembling ocean island basalt (Peate et al., 2003). Related cumulates have remarkably similar major- and trace-element compositions (Holm and Prægel, 2006) to the Kingnait Fiord rocks (Table 5; Fig. 6b). However, in light of textural evidence for deformation and a low-grade metamorphic overprint in the Cumberland Peninsula cumulates, a Paleogene-Cretaceous age is unlikely for the Kingnait suite. Involvement of a plume is, however, supported by the geochemical data.

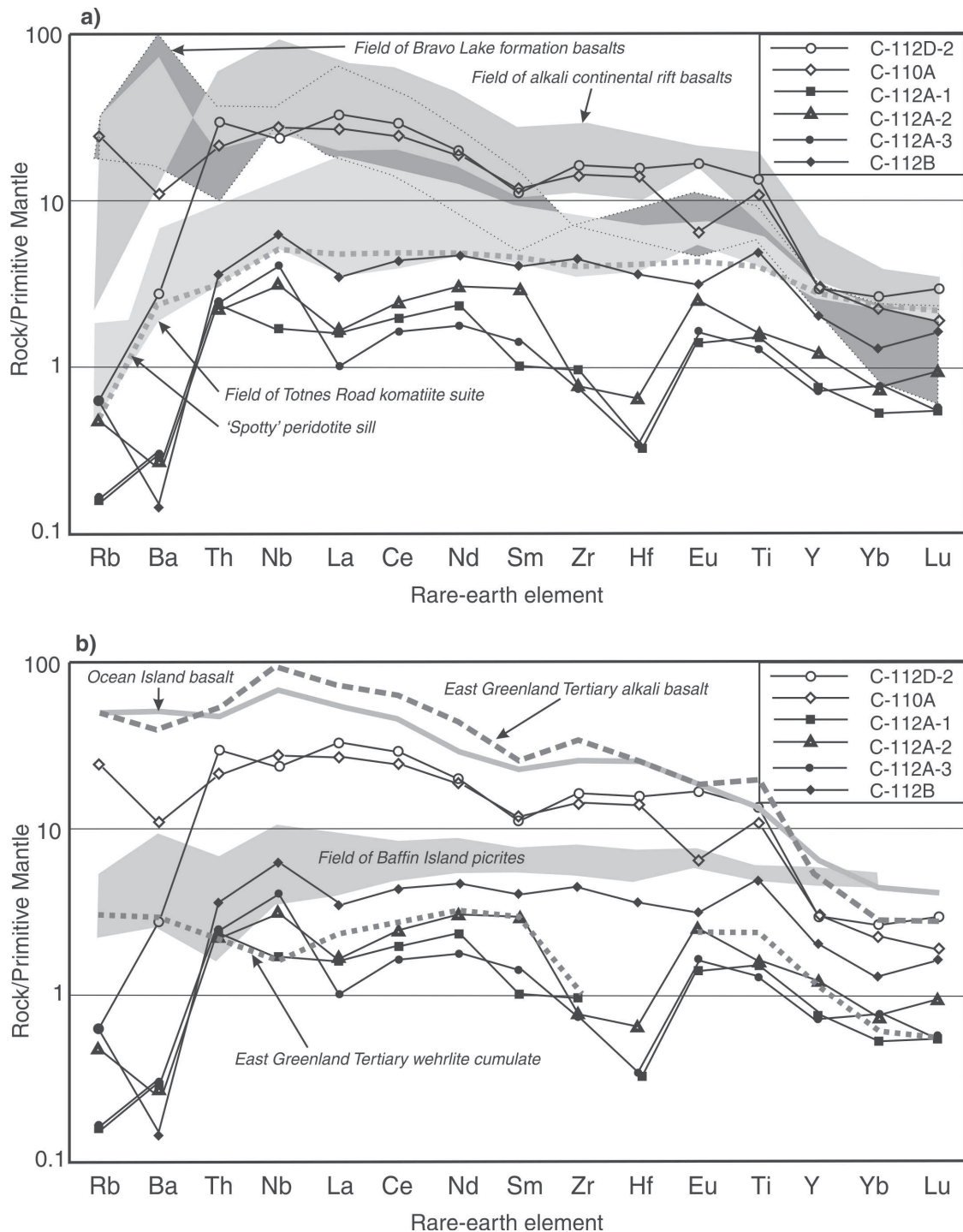


Figure 6. Primitive mantle-normalized (Sun and McDonough 1989) analyses for Kingnait Fiord peridotites (solid patterns); **a)** for comparison, compositional fields are shown for other Paleoproterozoic mafic-ultramafic sequences from southern Baffin Island; **b)** comparative data for compositional fields of North Atlantic Tertiary province volcanic and intrusive units.

In summary, Paleoproterozoic mafic volcanic rocks showing geochemical affinity to alkali continental-rift basalt represent the most likely parental magmas for the Kingnait Fiord cumulates. These rocks have experienced Paleoproterozoic deformation and metamorphic events. Their trace-element contents provide plausible magmatic compositions from which olivine-rich cumulates could have been derived. Compositionally similar magmas of the Tertiary North Atlantic Igneous Province have been comprehensively studied and provide guidance in terms of mineralization potential associated with plume-head magmatism.

Economic geology implications

Geochemical data for the Kingnait Fiord ultramafic rocks point to an enriched basaltic source: high-temperature, rift-related magmatism that was active in the region at various times in the geological past. Specifically, the compositions fall into the field of high-Fe magnesian suites characteristic of plume starting-heads (Gibson, 2002), and show many features of fertile large igneous provinces of all ages (Zhang et al., 2008; Tao et al., 2007). Accordingly, these rocks should be considered in terms of their potential to host Ni-Cu-PGE mineralization, based on the known characteristics of deposits of different geological ages.

For example, PGE mineralization is common as platinum reefs within Tertiary intrusions of East Greenland (Skaergaard; Andersen et al., 1998; Kap Edvard Holm; Arnason and Bird, 2000; Kruse Fiord; Arnason et al., 1997; Miller and Andersen, 2002) and Scotland (Mull, Skye; Pirrie et al., 2000). Lightfoot et al. (1997) drew attention to Tertiary mafic-ultramafic intrusions of West Greenland as potential analogues of Noril'sk-type Ni-PGE mineralization (cf. Naldrett and Lightfoot, 1999). A common characteristic of these intrusions, mirroring large, economic deposits (Bushveld, Stillwater), is concentration of platinum-group elements with chromite, in ultramafic layers. The ultramafic rocks east of Kingnait Fiord are presumed to represent exposures of a mafic-ultramafic complex of unknown size, shape, or orientation. Their coarse grain size (e.g. Fig. 3b) suggests slow crystallization, implying that high temperatures were sustained over a long period, possibly within a thick intrusion. Alternatively, high temperatures may have been maintained within a magmatic conduit, as hot material periodically flowed through to the magma chamber. Such environments are highly prospective for Ni-sulphide PGE mineralization (Naldrett and Lightfoot, 1999).

Several conditions are required for potential for magmatic Ni-sulphide PGE deposits (Brooks et al. 1999):

1. passage of large quantities of hot, primitive magma (i.e. fertile, plume-related magma);
2. magmas that were sulphur-undersaturated during segregation and ascent;
3. magmas that assimilated crustal sulphur near the surface, in order to form and concentrate sulphide minerals.

The Kingnait Fiord ultramafic plutonic rocks may have been derived from a fertile magma, by virtue of their enriched incompatible trace-element signatures (cf. Zhang et al., 2008). Given that these rocks were emplaced into metasedimentary rocks of the Hoare Bay group (Fig. 1), the magma could have assimilated sulphur-bearing material of Paleoproterozoic age during ascent (Fig. 2). Alternatively, if the magma did not interact with crustal sulphur, low-S deposit types such as PGE reefs could have formed. The mineral sperrylite (PtAs_2), which has been identified in anomalous quantities in association with elevated nickel-copper-cobalt-PGE in regional till samples on Cumberland Peninsula (Peregrine Diamonds Ltd. 2011), is a common PGE mineral in mineralized zones of the Paleogene layered intrusions of East Greenland and Scotland (Andersen et al., 1998; Pirrie et al. 2000). It may be an indicator of platinum reef-style mineralization on eastern Baffin Island. The Platinova reef of the well exposed Skaergaard intrusion went undetected despite years of academic research (Nielsen et al. 2005). Precious metal analyses of the Kingnait Fiord peridotites (Table 5) show some anomalous values. In particular, sample C-112D-2, with 105 ppb Au, 12 ppb Pt, and 7 ppb Pd indicates enrichment above background levels of unmineralized peridotites.

In conclusion, the presence, composition and geochemical affinity of ultramafic plutonic rocks on Cumberland Peninsula highlight potential for both Ni-sulphide and platinum reef-style mineralization, which should be assessed through more detailed mapping and exploration.

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