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Preface

This Open File report provides petrographic information from a scanning electron microscope study of granules and small pebbles in four selected trawl samples from Flemish Cap. The mineral composition of the granules was determined by energy dispersive spectroscopy (EDS) and textures are shown in backscattered electron images (BSE). It complements Open File 8359 on the heavy mineral assemblage on Flemish Cap. Granules on the central shoals appear to be derived from outcropping Avalonian basement; those to the east and west are predominantly icerafted in origin. These data improve our understanding of the source of the voluminous sands on Flemish Cap and the characteristics of the Avalonian basement rocks on southern Flemish Cap.

Acknowledgments

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INTRODUCTION

Flemish Cap is promontory of continental crust marking the most easterly extent of the North American continent (Fig. 1). The Cap has a least depth of 126 m and has a relatively flat top, with a steeper continental slope in depths greater than 500–1000 m. The Cap is separated from the Grand Banks of Newfoundland by Flemish Pass, a flat-floored basin, 50 km wide and > 1000 m deep. Flemish Cap extends between 46 and 49°N and 43 and 47°W with a total area of approximately 27 000 km^2 above the 700 m isobath (Pérez Rodríguez et al. 2012).

The shallow area of south-central Flemish Cap is underlain by Neoproterozoic granodiorite, granite and associated low grade metasedimentary and metavolcanics rocks of the Avalon terrain, known only from a few short boreholes and from geophysical data (King et al., 1985; Pe-Piper, 1992; Broom and Cameron, 2021) (Fig. 2). ROV studies show that granitoid rocks also outcrop on the steep southern slope of Flemish Cap (Miles, 2018). The rest of Flemish Cap is underlain by Cretaceous to Cenozoic sedimentary rocks (Foster and Robinson, 1993). Seismic reflection profiles suggest that over much of Flemish Cap the bedrock is overlain by glacial till (Piper, 2018; Broom and Cameron, 2021). The till is overlain by up to a few metres of gravelly sand, that has been sculpted into a radiating series of sand ridges (Shaw, 2006; Broom and Cameron, 2021). The glacial till sheet was interpreted to date from the penultimate glacial period (Illinoian, MIS 6) (Stacey, 2011; Piper, 2018).

Piston core studies on core 2011031-59PC (Mao et al., 2014, 2017) have shown that most sediment supply on the northern edge of Flemish Cap through the last glacial cycle was a fine-grained suspended sediment or came as ice-rafted detritus (IRD) transported by the Labrador current. During glacial maxima, most sediment was derived from NE Newfoundland, Labrador and Hudson Strait, whereas during interstadials, the supply from Greenland was more important (Piper et al., 2021). Thus, potential provenance sources for the clastic sedimentary rocks of the Flemish Cap must be from both local erosion and ice rafting material. This interpretation was confirmed by a study of heavy minerals from surficial sands on Flemish Cap (Pe-Piper et al., 2018).

This study documents the petrography of granules and small pebbles from surficial grab samples in an east–west transect across Flemish Pass. There were two objectives: (1) to extend our understanding of the lithologies of the outcropping Avalonian rocks and (2) to determine if there were any prominent east to west variations in ice-rafted detritus.

Figure 1. Regional map of the eastern Canadian margin showing the physiographic and oceanographic setting of Flemish Cap. Also shows potential major sources of ice-rafted detrital carbonate rocks and red sandstones. Modified from Piper et al. (2021). AOSW = Arctic Ocean Surface Water; BC = Baffin Current; EGC = East Greenland Current; WGC = West Greenland Current.

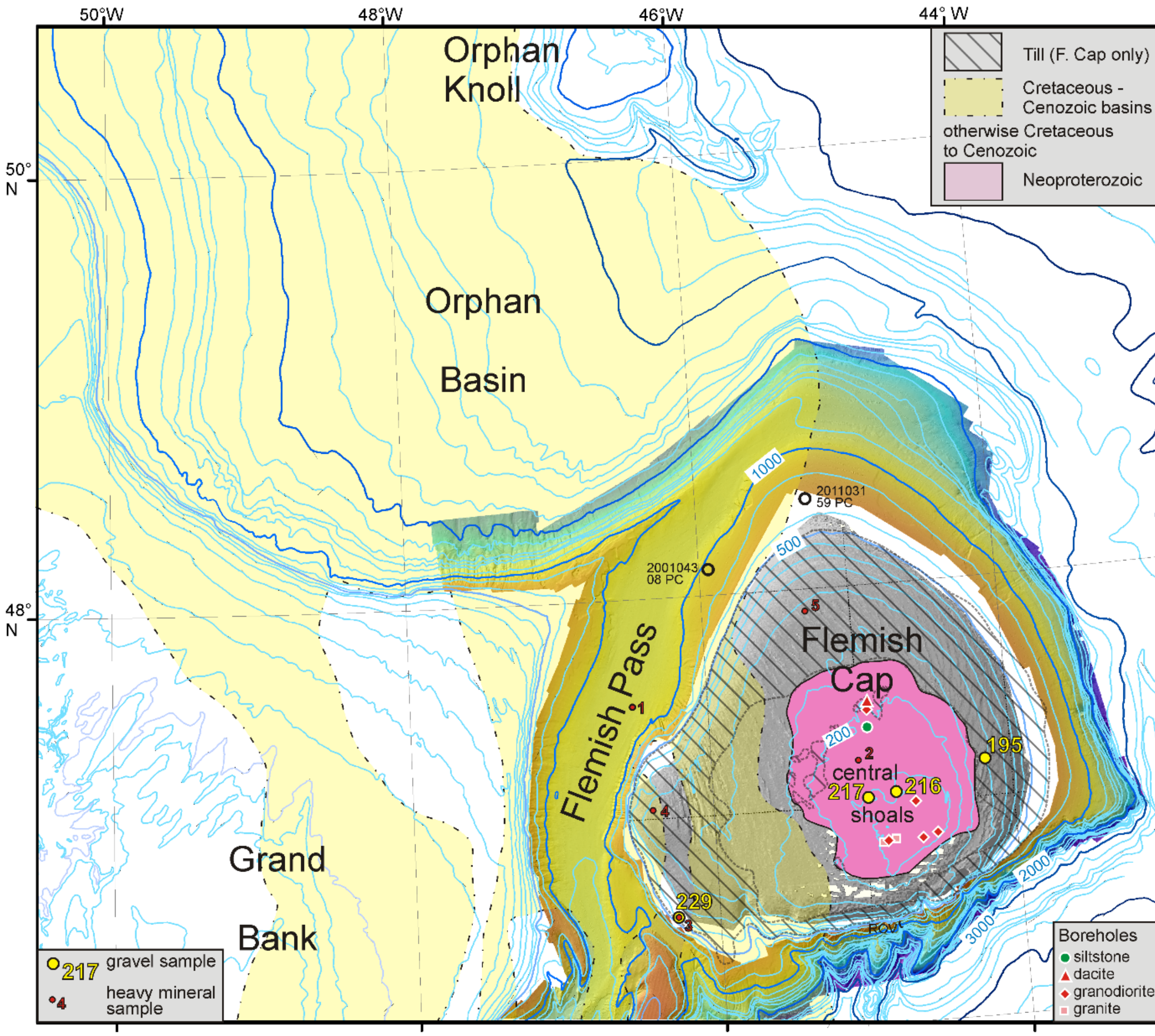

Figure 2. Bathymetric and geologic map of Flemish Cap and environs, showing location of samples mentioned in text. Base map from Piper et al. (2021)., geology from Broom and Cameron (2021), boreholes from King et al. (1985).

MATERIALS and METHODS

Material and sample preparation

A series of samples were collected from seabed trawls from the Spanish research vessel *Miguel Oliver* in 2008 (Murillo et al., 2016) on an expedition designated by the GSC as 2008NEREIDA. A small subset of these samples was used by Pe-Piper et al. (2018) for separation of heavy minerals in the 63–180 µm fraction. The coarser than 2 mm residues of four of these heavy mineral separates were assembled for further study (Table 1). Sample 229 was from the SW corner of Flemish Cap; 217 and 216 from the southern shoals north of most of the boreholes of King et al. (1985) and 195 from the eastern side of the Cap in 290 m water depth.

Table 1. Sample locations and reference to Appendix 1

Sample	Latitude	Longitude	Water depth (m)	Appendix
2008NEREIDA-229	46.5452	-46.2772	456	1-2A to 1-2D
2008NEREIDA-217	47.0332	-44.9673	149	1-3A
2008NEREIDA-216	47.0485	-44.7818	152	1-4A to 1-4D
2008NEREIDA-195	47.167	-44.1737	290	1-1A, 1-1B

The samples were rinsed, dried, and put into labeled plastic containers. The pebbles and granules were then sorted using tweezers according to grain size and put in small glass vials labeled for each sample and its grain size. The basis for separating the pebbles and granules by grain size was 2–4 mm (M = medium), and >4 mm (L=large). Similar lithologies were grouped using a binocular stereo microscope. All the samples were boxed up and sent to Van Petro Vancouver Petrographics Ltd, for impregnation and polished thin section preparation. Before Scanning Electron analysis, the thin sections were carbon coated in the Geology Department at Saint Mary's University.

Analytical Techniques

Scanning Electron Microscope (SEM)

SEM analysis was carried out at the Regional Analytical Centre at Saint Mary's University using a TESCAN MIRA 3 LMU Variable Pressure Schottky Field Emission Scanning Electron Microscope. This SEM has the capability of maximum resolution up to 1.2 nm at 30kV, and is paired with an INCA X-max 80mm² silicon drift detector (SDD) energy dispersive spectroscopy (EDS) system that has a detection limit of 0.1% and a beam size of ~10µm. Using this technology, excellent back scattered electron (BSE) images can be produced, and EDS chemical analyses of minerals can be acquired. In total 11 polished thin sections of granules and small pebbles were studied (Appendices 1-4). The abbreviations for mineral names that are 2 or 3 letters long are the IMA recommended abbreviations.

Optical Microscope

A Nikon Eclipse 50iPOL Petrographic Microscope was used to verify some of the EDS mineral analyses and obtain microphotographs of the pebbles at various magnifications in plane polarized light (PPL), crossed polarized light (XPL), and reflected light. All polished thin sections were examined by optical microscope and microphotographs of representative granules/pebbles were taken of seven samples (Appendix 2).

RESULTS

Data organisation

The data of this open file report are organized in two appendices. Appendix 1 includes the Back Scattered Electron (BSE) images and the EDS chemical analyses of the minerals identified in polished thin sections of granules from the bulk samples taken from the four stations 195, 229, 217, and 216 (Table 1). Different polished thin sections from the same station are assigned one of the letters A, B, C, D. Each thin section is referred to as a sample, and individual granules are numbered as sites 1, 2, 3 etc. Analytical sites within granule 1 are identified as sites 1.1, 1.2, 1.3 etc. These data are summarized in Table 2. This Appendix also includes some optical photomicrographs in both plane- and cross-polarized light.

Appendix 2 consists of optical photomicrographs in plane polarized light of seven additional thin sections containing a total of 53 granules. These data are summarized in Table 3.

SEM analyses

The petrography of ten thin sections with 63 granules from the four stations were studied by SEM. Colour in thin section and the identified mineral assemblage are summarized in Table 2, together with an identification of lithology. A more detailed description of each granule, including textures, is provided below as “Summary notes on petrography of lithic clasts”.

Table 2. Summary petrography of granules analysed by SEM

Thin section	Granule	Colour	Mineral assemblage	Lithology
195.1L	1	Colourless w/ grey and black patches	Qz, Hbl, Ap Ttn	Granodiorite
	2	Colourless	Qz, K-Fsp, Zrn, Ilm, Czo, Ab	Granite
	3	Colourless with some black patches	Qz, Ab, K-Fsp, Znc, Zrn	Granite
	4	Light grey	Andes, Brt, Chl, Ms, Qz, Mnz, Py	Deformed grain
	5	Sandy	Dol, Py	Dolostone
	6	Light grey to dark grey	K-Fsp, Dol, Py	Dolostone
	7	Colourless with greenish colouration	Qz, Ep, Ttn, Zrn, Ab, Ap	Metamorphic
195.2M	1	Colourless w/ grey and black patches	K-Fsp, Mag, Chl, Mnz, Ilm, Olig	Granitoid rock
	2	Colourless with some black patches	Ap, K-Fsp, Andes, Qz, Ilm, Olig, Zrn, Mnz, ?Ab	Igneous rock
	3	Colourless	Mnz, K-Fsp, Qz	Granitoid vein
	4	Black	Dol, Cal, Py, Qz	Carbonate
	5	Colourless with some black patches	Olig, K-Fsp, Ab, Ti-Mag	Feldspathic rock
	6	Colourless w/ grey and black patches	Opx, Qz, K-Fsp, Andes, Ap, Mag, llm	Diorite
	7	Colourless w/ grey and black patches	K-Fsp, Qz, llm, Andes, Bt, Ap, Olig, Ab	Granitoid
	8	Sandy	Ms, Qz, Ap, Zrn, Chl	Sandstone
	9	Dark brown	Dol, Cal, Ap	Dolostone
	10	Red orange and colorless patches	Qz, Ab, K-Fsp, Ti-Mag	Alkali granitoid rock
	11	Dark brown	Qz, Ap, Ti-Mag, K-Fsp	Mudstone
229.2L	1	Colourless w/ grey and black patches	Qz, Bt, Andes, Zrn, Chl, Cal, Mag, Ttn	Granitoid rock
	2	Pale green	Ep, Qz Cal, Ab, Olig, Chl, Act	Epidosite or Ep vein
	3	Colourless to light grey	Qz, Olig, K-Fsp, Bt, Ep, Ab, Ms, Ttn, Labrd, Zrn	Granodiorite
	4	Sandy	Chl, Zrn, Qz, Ank, Ms	Sandstone
229.3L	1	Pink and colourless	K-Fsp, Qz, Bt, Mag, Mnz, Ab, Ap, Zrn, Py, Olig, Chl, Feohy	Diorite (altered)
	2	Colourless w/ grey and black patches	llm, Opx, Cpx, Andes, Qz, Py, Mnz, Ap, Labrd, K-Fsp, Olig	Diorite (altered)

	3	Colourless	Qz, Andes, Chl, Mnz, Hbl, Olig, Ms, Cal	Igneous rock (altered)
	4	Colourless	Ank, Cal, Ab, Mag, Qz, Ap, Ms	Calcite
229.4L	1	Pinkish	Cal, Dol, K-Fsp, Mnz, Feohy, TiO_2, Ms, Ap	Limestone or Dolostone
229.6M	1	Colourless to light grey	Bytow, Ep, Znc, Qz, Bt, Chl, Hbl, K-Fsp, Adr	Diorite
	2	Red sandy	Mag, Qz, Zrn, Feohy, Znc, Ti-Mag, Bt, Py, Chl, Ab, Ep, Cal	Sandstone
	3	Red/brown	Qz, Mnz, Ab, Mag, Ap, K-Fsp, Feohy, Ms, Bt	Igneous rock
	4	Light green	Qz, Ep, K-Fsp, Ab, Mnz	Qz & Ep vein
	5	Colourless	Andes, Qz, K-Fsp, Mnz	Granodiorite
	6	Colourless to light grey	Ep, Ttn, llm, Chl, Qz, Ms, K-Fsp, Andes	Granodiorite
	7	Colourless with pale red patches	K-Fsp, Qz, Ti-Mag, Cal, Ap	Microgranite with xenolith
217.1M	1	Colourless w/ grey and black patches	K-Fsp, Qz, Chl, Ap, Mag, Ttn, Ep, Hbl, Zrn	Granitoid
	2	Colourless	K-Fsp, Qz, Ab, llm, Ttn	Igneous felsic rock
	3	Colourless	Qz, Ep, Cal, Zrn	Qz & Ep vein
	4	Colourless	Ep, Qz, Py	Qz & Ep vein
	5	Colourless	K-Fsp, Ep, Ab, Chl, Ttn	Granite
	6	Light grey	Ab, K-Fsp, Py, Act	Rhyodacite
	7	Colourless	Qz, K-Fsp, Andes, Ap, Bt, Chl	Granitoid
	8	Light brown/grey	Qz, Bt	Qz vein fragment
216.1L	1	Colourless w/ black and green patches	K-Fsp, Chl, Qz, Mag, Ab, Ap, llm	Granitoid
	2	Colourless w/ black and green patches	Ep, Ab, K-Fsp, Mag, Ttn, Qz, Chl, Act, Zrn	Epidotized granitoid rock
	3	Pink and colourless w/ black patches	Ab, Chl, Ap, Qz, Ti-Mag, Ms	?Alkali granite
	4	Pink and colourless	K-Fsp, Ab, Ap, Ms, Chl	Altered igneous rock
	5	Pale green	Ab, Cal, Chl, Ep, K-Fsp	Epidosite or Ep vein
	6	Pink and colourless w/ black patches	Qz, Chl, K-Fsp, Ab, Py, Ttn, Ap, Zrn	Granite
	7	Sandy and pink	K-Fsp, Qz, Ab, Ap, Chl	Fine-grained rhyolite
	8	Colourless	Ep, Qz, Ab, Ttn, Ms	Igneous rock

	9	Sandy	Qz, Ap, Chl, Feohy, Ab, K-Fsp, Ttn, Ms	Igneous rock
	10	Pink and colourless w/ black patches	Chl, Ab, Qz, Mag, Ap, K-Fsp, Zrn	Granite
	11	Pale green	Qz. Ep, Zrn, Chl, Ab	Epidosite or Ep vein
	12	Colourless w/ green veins	Ep, Qz, Cal, Chl, Ttn	Qz & Ep vein
	13	Sandy w/ black specs	K-Fsp, Ti-Mag, Ep, Ap, Andes, Qz	Igneous rock
	14	Very light tan	Ms, Qz, Mag, K-Fsp, Ep, Chl, Ab	Igneous rock (altered)
	15	Very light tan	Qz, Mag, Ep, Ap, K-Fsp, Ttn, Olig	?Metaigneous
	16	Pale green	Ab, Chl, Ep, Ttn, Ms, Ccp, Qz	Epidosite
216.3L	1	Colourless to grey with greenish patches	Hbl, Mag, Bt, Qz, Plag, Hem, K-Fsp, Ilm, Ap, Ep, Ttn, Sp	Hornblende Granodiorite
	2	Colourless to grey with greenish patches	Mag, Bt, Qz, Plag, K-Fsp, Ap, Mnz, Chl, Zrn, Chl, Ep	?Granodiorite
	3	Colourless to grey with greenish patches	Qz, Chl, Brt, TiO_2, Ms, Hem, Cal	Altered Quartzite
	4	Colourless to grey with greenish patches	Qz, Chl, Xen, Ap, Mnz, Ms, K-Fsp	Altered Quartz-rich Granitoid
216.4L	1	Grey/green	Ab, Ccp, Feohy, Ep, Ttn, K-Fsp, Qz, Chl	Fine-grained rhyolite

Key to mineral abbreviations: Ab = Albite; Act = Actinolite; Adr = Andradite (garnet); Andes = Andesine (plagioclase); Ap = Apatite; Brt = Barite; Bt = Biotite; Bytow = Bytownite (plagioclase); Cal = Calcite; Ccp = Chalcopyrite; Chl = Chlorite; Cpx = Clinopyroxene; Czo = Clinozoisite; Dol = Dolomite; Ep = Epidote; Feohy = iron (hydr)oxide undivided; Hbl = Hornblende; Hem = Hematite; Ilm = Ilmenite; K-Fsp = K Feldspar; Labrd = Labradorite (plagioclase); Mag = Magnetite; Mnz = Monazite; Ms = Muscovite; Olig = Oligoclase (plagioclase); Opx = Orthopyroxene; Plag = undivided plagioclase; Py = Pyrite; Qz = Quartz; Sp = Sphalerite; Ti-mag = Titanomagnetite; TiO_2 = undivided titania mineral (probably rutile); Ttn = Titanite; Xen = Xenotime; Znc = Zincite; Zrn = Zircon.

Table 3. Classification of granules and small pebbles of lithic clasts

	229			217		216			195		
Lithic clast type	SEM	Opt	TOTAL	SEM	TOTAL	SEM	Opt	TOTAL	SEM	Opt	TOTAL
Granitoid	1		1	3	3	2	3	5	4		4
Granite	1	5	6	1	1	4	1	5	3		3
Granite, altered		1	1		0	4	2	6			0
Granodiorite	4	2	6		0	1		1	1		1
Granodiorite, altered		1	1		0	1		1			0

Diorite			0		0			0	1		1
Diorite, altered	2		2		0			0			0
Rhyolite			0		0	3	3	6			0
Rhyodacite			0	1	1			0			0
Altered felsic or metamorphic	2		2		0	1	4	5	1		1
Epidote-dominated + Qz			0	2	2	4		4			0
Vein quartz			0	1	1			0			0
Dolostone	1	5	6		0			0	4	6	10
Limestone	1		1		0			0		9	9
Sandstone	2		2		0		1	1	1		1
Mudstone			0		0		3	3	1		1
Metamorphic (low grade)		1	1		0		2	2	1		1
Quartzite			0		0	1		1			0
TOTAL			**29**		**8**			**40**			**32**

SUMMARY NOTES ON PETROGRAPHY OF LITHIC CLASTS (refer to Appendix 1)

Sample 195.1L

Granule 1 (Sites 1, 1.1, 1.2) Microphotographs: Figures 1A.27, 1A.28.

Holocrystalline igneous rock made up of dominantly hornblende and quartz. There are also minor amounts of titanite and apatite (Figs.1A.3, 4).

Granule 2 (Sites 2, 2.1, 2.2, 2.3) Microphotographs: Figures 1A.29, 1A.30.

Holocrystalline granite. This granule consists of dominantly quartz, K-feldspar, and albite. Perthite can be seen between K-feldspar and albite. Rare zircon crystals. Late fractures and titania minerals are present.

Granule 3 (Sites 3, 3.1, 3.2, 3.3, 3.4, 3.5) Microphotographs: Figures 1A.31, 1A.32.

Holocrystalline granitic rock. This granule consists of mainly quartz, K-feldspar, and albite. Minor minerals include biotite, labradorite, oligoclase, and chlorite. Rare zircon and zincite are also present. Chlorite and dissolution voids appear to be late.

Granule 4 (Sites 4, 4.1, 4.2) Microphotographs: None.

Deformed granitic rock, highly chloritized, possibly metamorphosed. Main minerals include K-feldspar, quartz, andesine, and chlorite. Late minerals are chlorite, and rare barite, monazite, titania, and pyrite.

Granule 5 (Sites 5, 5.1, 5.2) Microphotographs: Figures 1A.33, 1A.34.

Porous dolostone. This granule consists mostly of dolomite. There is also rare K-feldspar, and late possible diagenetic pyrite.

Granule 6 (Sites 6, 6.1, 6.2) Microphotographs: None.

Porous dolostone similar to Granule 5. Consists of mainly dolomite and K-feldspar, although detrital minerals are more common. In the thin section (Fig. 1A.1) the granule appears concentric, with possible growth rings. Late possibly diagenetic minerals include pyrite, and probable iron oxides.

Granule 7 (Sites 7, 7.1, 7.2) Microphotographs: Figures 1A.35, 1A.36.

Possible metamorphic granule or highly altered granite. Main minerals include quartz, albite, and epidote. Epidote is most likely secondary and appears as veins in the granule. Rare zircon, titanite, and apatite are usually found in association with epidote.

Sample 195.2M

Granule 1 (Sites 1, 1.1, 1.2) Microphotographs: Figures 1B.24, 1B.25

Holocrystalline granitoid rock or andesite. Quartz is more of an accessory mineral along with biotite and magnetite. Andesine, albite, K-feldspar, and magnetite are present. Smaller inclusions of quartz can be seen in Figure 1B.3 in andesine. Muscovite is partially replaced by chlorite (Fig. 1B.4).

Granule 2 (Sites 2, 2.1) Microphotographs: Figures 1B.26, 1B.27

Largely intermediate size feldspar crystals (K-feldspar, albite and oligoclase). Apatite crystals are commonly seen with monazite rims. Zircon and K-feldspar are present, and ilmenite tends to fill voids. There are vacant voids present as well.

Granule 3 (Site 3) Microphotographs: Figures 1B.28, 1B.29

Probably quartz granitoid vein with some K-feldspar filling fractures and some large independent K-feldspar crystals.

Granule 4 (Sites 4, 4.1) Microphotographs: None

Carbonate rock with what must be diagenetic pyrite and some quartz that seemed to have suffered some dissolution due to contrast from outer edges of crystals inward.

Granule 5 (Sites 5, 5.1) Microphotographs: Figures 1B.30, 1B.31

Holocrystalline feldspathic rock. Oligoclase and K-feldspar are the dominant minerals present, with some albite and titanium-magnetite.

Granule 6 (Sites 6, 6.1, 6.2) Microphotographs: Figures 1B.32, 1B.33

Holocrystalline rock with intergrowths of orthopyroxene, andesine, K-feldspar, and quartz. Some ilmenite and apatite are also present. Voids are common.

Granule 7 (Sites, 7, 7.1) Microphotographs: Figures 1B.34, 1B.35

Holocrystalline rock of granitoid composition. Common minerals include K-feldspar, quartz, and andesine. Some ilmenite and apatite are also present. Myrmekitic texture is observed between quartz and feldspar.

Granule 8 (Site 8) Microphotographs: None

Sandstone with mostly quartz and minor chlorite, apatite, and muscovite. Zircon is also present.

Granule 9 (Sites 9, 9.1) Microphotographs: None

Dolostone made up of dolomite and some calcite with minor apatite. Very porous.

Granule 10 (Sites 10, 10.1) Microphotographs: Figures 1B.36, 1B.37

Large crystals of quartz surrounded by K-feldspar. Small grains of titanium-magnetite are very dispersed in the K-feldspar. There are patches of albite in the K-feldspar. The rock is very red in colour and the composition suggests that it is an alkaline granitoid rock.

Granule 11 (Sites 11, 11.1) Microphotographs: None

Very fine-grained rock made up of quartz, K-feldspar, titanium-magnetite, and other fine grained undetermined minerals. This is most likely a mudstone judging from the dark colour in thin section.

Sample 229.2L

Granule 1 (Sites 1, 1.1) Microphotographs: Figures 2A.15, 2A.16

Holocystalline granitic rock. Igneous textures of intergrowths between andesine, quartz, and biotite. Biotite is chloritized in some parts of the granule. Zircon is partially filling a void (Fig. 2A.2).

Granule 2 (Sites 2, 2.1) Microphotographs: Figures 2A.17, 2A.18

Epidosite. Fine-grained rock composed largely of epidote and lesser quartz. Metamorphic rock with fabric can be seen in Figure 2A.4. Small amounts of calcite, albite, chlorite, and actinolite can be seen with 1.57 kx magnification (Fig. 1.5).

Granule 3 (Sites 3, 3.1, 3.2, 3.3) Microphotographs: Figures 2A.19, 2A.20, 2A.21, 2A.22

If extrusive, could be dacite, or if intrusive, granodiorite. Holocrystalline igneous rock with a 2:1 oligoclase to K-feldspar ratio. Dominant minerals are oligoclase, K-feldspar, quartz, with small amounts of biotite. Muscovite and epidote are in smaller amounts and are found as smaller crystals. There is also zircon present (Fig. 2A.9).

Granule 4 (Sites 4, 4.1) Microphotographs: Figures 2A.23, 2A.24

Sandstone. Largely composed of quartz grains. Ankerite appears to be the cement. Smaller amounts of titanium oxide, chloritized biotite, and zircon are present. Chlorite is probably the result of altered ferromagnesian minerals. This sandstone contains lithic clasts of similar mineral constituents.

Sample 229.3L

Granule 1 (Sites 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6) Microphotographs: Figures 2B.21, 2B.22, 2B.23, 2B.24, 2B.25, 2B.26.

Largely made up of albite, oligoclase, quartz, and K-feldspar. This granule may have come from an altered rock as some of the minerals show alteration in the granule such as biotite and magnetite. There are large spots of monazite with relation to magnetite. An odd texture between chlorite and magnetite is observed that seems to be bordered by TiO_2 (Fig.2B. 5).

Granule 2 (Sites 2, 2.1, 2.2, 2.3) Microphotographs: Figures 2B.35, 2B.36.

This is a similar granule to that seen in 195.2M (granule 6). Holocrystalline igneous texture with andesine, quartz, and orthopyroxene, the three main minerals of the granule. There is also some apatite, monazite, ilmenite, labradorite, and pyrite present. Some orthopyroxene crystals contain clinopyroxene inclusions.

Granule 3 (Sites 3, 3.1, 3.3, 3.3) Microphotographs: Figures 2B.31, 2B.32, 2B.33, 2B.34.

Quartz and andesine make up a large portion of this rock. There is some hornblende that seems to have been chloritized. There is muscovite, calcite, and oligoclase in lesser abundance. This could be metamorphic although no fabric is evident. The large andesine crystals are showing alteration to possible sericite. Voids are present in the rock and the crystal texture indicates igneous origin.

Granule 4 (Sites 4, 4.1, 4.2, 4.3, 4.4) Microphotographs: Figures 2B.27, 2B.28, 2B.29, 2B.30.

This granule is mostly a carbonate vein composed of calcite and it is cutting a fine-grained igneous rock. The vein is porous and also contains magnetite and TiO_2 (probably rutile) filling some pores. The host rock consists mostly of albite, quartz, rare muscovite and TiO_2 again filling voids (Figs. 2B.18, 19) .

Sample 229.4L

Granule 1 (Sites 1, 1.1, 1.2) Microphotographs: None.

The granule appears to be composed of mostly calcite and dolomite. There are rare detrital minerals such as K-feldspar, apatite, and muscovite, however, it is unclear if the granule represents a vein cutting through the host rock or if is a carbonate rock with some detrital minerals.

Sample 229.6M

Granule 1 (Sites 1, 1.1, 1.2, 1.3) Microphotographs: Figures 2D.28, 29

Probably a plutonic rock. Quartz, and biotite are present and voids are scattered throughout the granule. Epidote is late, zincite precipitated in voids and biotite is partly chloritized. The mineral assemblage suggests that this may be a hornblende gabbro as it is dominated largely by plagioclase feldspar (bytownite) and has approximately less than 10% mafic minerals (biotite, hornblende, and magnetite). The minerals epidote, zincite, quartz, chlorite, and rare garnet and magnetite appear to be secondary.

Granule 2 (Sites 2, 2.1, 2.2 , 2.3) Microphotographs: Figures 2D.30, 2D.31, 2D.32, 2D.33

Sandstone. Quartz grains dominate and are cemented by calcite. Lithic clasts may contain epidote grains, some with quartz veining, albite, magnetite, biotite, and chlorite. Zircon is a rare detrital mineral and zincite and iron oxy(hydr-)oxide (Feohy) also may be late diagenetic minerals.

Granule 3 (Sites 3, 3.1, 3.2, 3.3) Microphotographs: Figures 2D.34, 2D.35

Fine-grained mineralized rock. Quartz-rich vein crosscuts the granule. Observation in thin section suggests it has been altered and possibly oxidized to yield the reddish colouration (iron is present as Fe^{3+}). This is a late phase as it crosscuts other minerals. Mineral assemblage: quartz, albite, monazite, magnetite, muscovite, altered biotite, and calcite. Hydrothermally altered felsic igneous rock or metasedimentary rock.

Granule 4 (Sites 4, 4.1, 4.2, 4.3) Microphotographs: Figures 2D.36, 2D.37

Probably a piece of an epidote vein. Very epidote rich with quartz present. Other minerals occur in minimal amounts and in grains smaller than ~15μm. Mineral assemblage: epidote, quartz, monazite, albite, zincite.

Granule 5 (Sites 5, 5.1, 5.2, 5.3) Microphotographs: Figures 2D.38, 2D.39

Probably a granodiorite. Composed entirely of feldspars and quartz. Holocrystalline igneous rock. Some perthitic texture observed in thin section. Mineral assemblage: andesine, quartz, monazite, some K-feldspar.

Granule 6 (Sites 6, 6.1, 6.2, 6.3) Microphotographs: Figures 2D.40, 2D.41

Holocrystalline igneous rock (granodiorite) with large andesine crystals that make up more than 90% of rock. The rest of the rock is made up of quartz, altered K-feldspar crystals (Fig. 2D.25), and rare muscovite (Fig. 2D.24). Ilmenite, chlorite, and epidote occur later (Fig. 2D.23) and may be the result of hydrothermal alteration.

Granule 7 (Sites 7, 7.1) Microphotographs: Figures 2D.42,2D. 43

Holocrystalline igneous rock (microgranite?) with xenoliths made up of calcite surrounded by apatite. Mineral assemblage: K-feldspar, and subhedral quartz with xenoliths made up of calcite and apatite.

Sample 217.1M

Granule 1 (Sites 1, 1.1) Microphotographs: Figures 3A.19, 3A.20

Holocrystalline, possibly altered. granitoid rock Mineral assemblage: K-feldspar, quartz, chlorite, apatite, magnetite, titanite, epidote, hornblende, zircon

Granule 2 (Sites 2, 2.1) Microphotographs: Figures 3A.21, 3A.22

K-Feldspar in intergrowths with albite, holocrystalline and rhyolitic in composition. Mineral assemblage: K-feldspar, quartz, albite, altered ilmenite, titanite

Granule 3 (Sites 3, 3.1) Microphotographs: Figures 3A.23, 3A.24

Quartz-epidote vein with minor calcite

Granule 4 (Sites 4, 4.1) Microphotographs: Figures 3A.25, 3A.26

Quartz-epidote vein with minor pyrite

Granule 5 (Sites 5, 5.1) Microphotographs: Figures 3A.27, 3A.28

Holocrystalline rock with granitic composition with epidote forming as an alteration product. Mineral assemblage: K-feldspar, epidote via alteration, albite, chlorite, minor titanite

Granule 6 (Sites 6, 6.1) Microphotographs: Figures 3A.29, 3A.30

Fine grained rhyodacite. Mineral assemblage: absence of quartz? Albite and K-feldspar patchy, abundant pyrite, minor hornblende

Granule 7 (Sites 7, 7.1) Microphotographs: Figures 3A.31, 3A.32

Holocrystalline rock with granitic composition. Mineral assemblage: quartz, K-feldspar, andradite, apatite, biotite, chlorite altering biotite

Granule 8 (Sites 8, 8.1) Microphotographs: Figures 3A.33, 3A.34

Probably a piece of quartz vein. Mineral assemblage: quartz and biotite

Sample 216.1L

Granule 1 (Sites 1, 1.1, 1.2) Microphotographs: Figures None

Holocrystalline granitic rock that may have been altered. It contains some magnetite. K-feldspar, albite, and quartz make up the dominant minerals. Chlorite and minor apatite are present in what seems to be an altered grain (Fig. 4A.3). The same crystal also contains bright exsolution lamellae.

Granule 2 (Sites 2, 2.1, 2.2, 2.3) Microphotographs: Figures 4A. 48, 4A.49

Composed of larger crystals of epidote, albite, and K-feldspar. Albite and epidote seem to be intergrown. There is chlorite present that may be a result of alteration. Zircon is present, as well as magnetite. Titanite occurs in the chlorite masses and in epidote (Fig. 4A.6). Quartz is accessory. Perhaps an altered syenite.

Granule 3 (Sites 3, 3.1) Microphotographs: Figures None

Igneous rock that may be from an alkali granite. It is composed of albite, chlorite, apatite, and some quartz. Some Ti-rich minerals occur in chlorite as does the apatite. The dominant mineral in the granule is albite. Muscovite is present in lesser amounts.

Granule 4 (Sites 4, 4.1, 4.2) Microphotographs: Figures None

Fine-grained rock made of albite and K-feldspar that shows interlocking texture. There is some apatite, muscovite, and TiO_2 present but in lesser amounts and tend to occur together. This may be a rock that was subjected to low grade metamorphism or a fine-grained igneous rock.

Granule 5 (Sites 5, 5.1, 5.2) Microphotographs: Figures None

Probably epidosite or a fragment from an epidote vein. Very porous rock composed almost entirely of epidote, at least >90%. Other minerals present are albite, chlorite, minor Kfeldspar, and very minor calcite.

Granule 6 (Sites 6, 6.1, 6.2) Microphotographs: Figures None

Holocrystalline granitic rock. Composed of large quartz crystals, K-feldspar crystals, and with large amounts of chlorite that contain interesting textures (Fig. 4A.18). Zircon is also present.

Granule 7 (Sites 7, 7.1) Microphotographs: Figures None

Fine-grained rhyolite, composed of K-feldspar, quartz, and albite. Some chlorite alteration seems to be present.

Granule 8 (Sites 8, 8.1) Microphotographs: Figures 4A.50, 4A.51

Holocrystalline igneous rock. The main minerals are quartz, albite, and epidote. There are lesser amounts of muscovite, and titanite.

Granule 9 (Sites 9, 9.1, 9.2) Microphotographs: Figures None

Likely an igneous rock. Composed of quartz, albite, and K-feldspar as the main mineral assemblage. Minor titanite, magnetite, muscovite, and apatite are present. Very small specs of chalcopyrite are also present.

Granule 10 (Sites 10, 10.1, 10.2) Microphotographs: Figures None

Igneous rock, granite. It is composed of K-feldspar, quartz, and albite. Large amount of chlorite probably derived from alteration. Minor magnetite and zircon are also present.

Granule 11 (Sites 11, 11.1) Microphotographs: Figures 4A.52, 4A.53, 4A.54, 4A.55

Epidosite. Fine-grained roc composed of epidote and quartz with minor albite, chlorite, and calcite.

Granule 12 (Sites 12, 12.1, 12.2, 12.3, 12.3, 12.4, 12.5) Microphotographs: Figures None

Probably a piece of a quartz-epidote vein.

Granule 13 (Sites 13, 13.1) Microphotographs: Figures None

Fine-grained rock. Quartz, andesine, and K-feldspar are making up most of the granule. Some well-preserved crystals of epidote, apatite, and Ti-magnetite are present.

Granule 14 (Sites 14, 14.1, 14.2) Microphotographs: Figures None

Very fine-grained rock with possible fabric (Fig.4A. 41). It is mainly composed of quartz and K-feldspar, with some muscovite, magnetite, and epidote.

Granule 15 (Sites 15, 15.1) Microphotographs: Figures None

Common magnetite throughout the granule. Quartz grains and oligoclase make up most of the granule with larger scattered grains of epidote and apatite.

Granule 16 (Sites 16, 16.1, 16.2) Microphotographs: Figures None

Fine-grained rock that is composed of quartz, epidote, and albite. The epidote is riddled with quartz and albite relics. This is likely to be epidosite that may have formed in a slightly different environment than the previous two granules named epidosite. To note, there was a chalcopyrite grain analyzed in this granule, but none found in the previous epidosite granules.

Sample 216.2L

Granule 1 (Sites 1, 1.2, 1.3) Microphotographs: None.

This granitic granule appears to be highly chloritized. The most common minerals include quartz, K-feldspar, albite and minor biotite. Accessory minerals include chalcopyrite, and titanite. Epidote and chlorite are most likely late and/or secondary minerals.

Granule 2 (Sites 2, 2.1, 2.2) Microphotographs: None.

This granule appears to be a chloritized granite, with common magnetite. The main minerals are K-feldspar, quartz, muscovite and biotite. Accessory minerals include apatite and monazite. Chlorite is abundant throughout the granule.

Granule 3 (Sites 3, 3.1, 3.2) Microphotographs: None

This granitic granule is composed of mainly K-feldspar, albite, and quartz. Other minerals present include calcite, zircon, apatite, synchysite. Chlorite and epidote appear late.

Granule 4 (Sites 4, 4.1) Microphotographs: None

This granitic granule is speckled with magnetite. Common minerals include magnetite, altered ilmenite, and quartz. Rare minerals are present such as synchysite. Chlorite is abundant.

Granule 5 (Sites 5, 5.1, 5.2) Microphotographs: None

This granule is similar to the other granules except magnetite is uncommon.

Granule 6 (Sites 6, 6.1) Microphotographs: None

This granitic granule is similar to granule 4. Main minerals include quartz, oligoclase, feldspar, altered ilmenite, magnetite, and rare monazite. Chlorite is a very common alteration mineral.

Sample 216.3L

Granule 1 (Sites 1, 1.1, 1.2) Microphotographs: None.

Hornblende granodiorite. This granule consists of hornblende, magnetite, labradorite, andesine, oligoclase, biotite, and minor apatite and titanite. Epidote is most likely late.

Granule 2 (Sites 2, 2.1, 2.2) Microphotographs: None.

This granule is similar to Granule 1 except that it contains more chlorite. It contains albite, quartz, K-feldspar, oligoclase, biotite, and rare zircon and monazite. Epidote and monazite appear to be late.

Granule 3 (Sites 3, 3.1, 3.2) Microphotographs: None.

This granule consists of mostly quartz and chlorite + muscovite. It is an altered quartzite. Rare or secondary minerals include barite, magnetite, and titania.

Granule 4 (Sites 4, 4.1) Microphotographs: None.

Altered quartz-rich granitoid. This granule contains quartz, K-feldspar, and apatite. Chlorite and xenotime may be secondary.

Sample 216.4L

Granule 1 (Sites 1, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6) Microphotographs: Figures 4D.9, 4D.10, 4D.11, 4D1.12, 4D.13, 4D.14, 4D.15, 4D.16, 4D.17.

Very fine-grained rock with a greenish tint of colour in thin section. No evident texture seen. The mineral assemblage of this rock consists of albite, chlorite, epidote, some K-feldspar, and minor amounts of titanite and chalcopyrite. The epidote is riddled with albite relics (Figs.

4D.6, 8). There is relatively little quartz present in the granule. In thin section, there seems to be mineralization filling a fracture that is red in colour (does not yield a good analysis).

This granule is probably a fine-grained rhyolite (?intrusive) with strong secondary alteration and some mineralization (chlorite, epidote, chalcopyrite). The Fe-oxide/hydroxide vein (Fig. 4D.13, 15 microphotographs) may also be hydrothermal

Additional optical microscope analyses

Additional lithologic determinations of granules were made by petrographic optical microscope alone. These results are summarized in Table 4 and the photomicrographs are presented in Appendix 2.

Table 4. Summary petrography of additional granules based on optical microscopy

Thin section	Granule	Grain size	Mineral Assemblage	Lithology
195.3M	1	very fine	Qz, Plag, Ms, Dol	Sandy dolostone
	2	very fine	Cal	Limestone
	3	fine-coarse	Cal, Ms	Limestone
	4	fine-coarse	Dol	Dolostone
	5	fine-coarse	Dol, Cal	Dolostone
	6	fine-coarse	Dol	Dolostone
	7	very fine-coarse	Cal	Limestone
	8	micrite	Carbonate	Limestone or Dolostone
	9	fine	Dol	Dolostone
	10	fine-coarse	Cal	Limestone
	11	fine-coarse	Cal	Limestone
	12	fine-medium	Cal	Limestone
	13	very fine	Cal	Limestone
	14	fine	Cal, Qz	Limestone
	15	fine	Cal	Limestone
229.1L	1	fine	Dol	Dolostone

	2	fine	Dol, Qz	Dolostone
	3	fine	Qz, Ep, Ms, Clays	?Low grade metamorphic rock
	4	fine	Cal	Limestone
	5	medium-coarse	Qz, Plag	Granite (altered)
229.4L	4	fine	Qz, Dol	Dolostone
229.5M	1	fine, fabric	Qz, Hbl, Plag	Granodiorite
	2	coarse	Bt, K-Fsp, Plag, Qz	Granite
	3	medium-coarse	Chl, Qz, K-Fsp, Plag, Ep	Granodiorite (altered)
	4	coarse	Qz, K-Fsp, Bt, Plag	Granite
	5	medium	Qz, Plag, K-Fsp, Ms, Py	Granite
	6	coarse	Bt, Qz, K-Fsp, Plag	Granite
	7	very fine	Dol	Dolostone
	8	very fine	Cal	Limestone
	9	very fine	Dol	Dolostone
	10	coarse	Plag, K-Fsp, Hbl, Opx, Qz	Granodiorite
	11	medium-coarse	Qz, K-Fsp, Plag	Granite
216.2L	1	N/A	N/A	N/A
	2	fine	Plag, Qz, Ep	Igneous rock
	3	fine	Chl, ?Plag	?Igneous rock
	4	fine	Ms, Qz	Igneous rock
	5	fine	Qz, Ms, Hbl	Igneous rock
	6	fine	Qz, Hbl	Igneous rock
216.3L	1	coarse	Qz, K-Fsp, Bt, Chl, Rt, Mag	Granite
	2	coarse	Plag, Qz, Hbl	Granodiorite
	3	fine	Qz, Chl	?Mudstone
	4	fine	Qz, Chl	?Mudstone
216.5M	1	fine	Qz, Plag, Chl, K-Fsp	Igneous rock
	2	fine	Ms, Qz, Chl, Ap	Igneous rock
	3	very fine	Qz, Ms	?Low grade metamorphic rock
	4	fine-medium	Qz, Ms, Chl	?Low grade metamorphic rock
	5	fine	Qz, Plag, Ms	Rhyolite
	6	fine-medium	Qz	Sandstone

	7	fine-large crystals	Ms, Chl, Ap, Qz	Igneous rock
	8	very fine	Qz, Ms, Chl	Sandy mudstone
	9	fine	Chl, Qz, Bt, Plag	Granodiorite
	10	fine	Ms, Plag, Qz	Rhyolite
	11	very fine	Qz, Ms	?

Mineral abbreviations as in Table 2

DISCUSSION

The most striking feature of the relative abundance of different granule lithologies (Fig. 3) is that detrital carbonate rocks predominate on eastern Flemish Cap (195: 59 %), are common in the west (229: 24 %) but are absent in samples from the central shoals (216, 217). The detrital carbonate rocks are characteristic of ice-rafted supply in the Labrador Current (Piper and de Wolfe, 2003; Mao et al., 2014) and no significant sources of carbonate rocks are to be expected in the Avalonian basement at Flemish Cap.

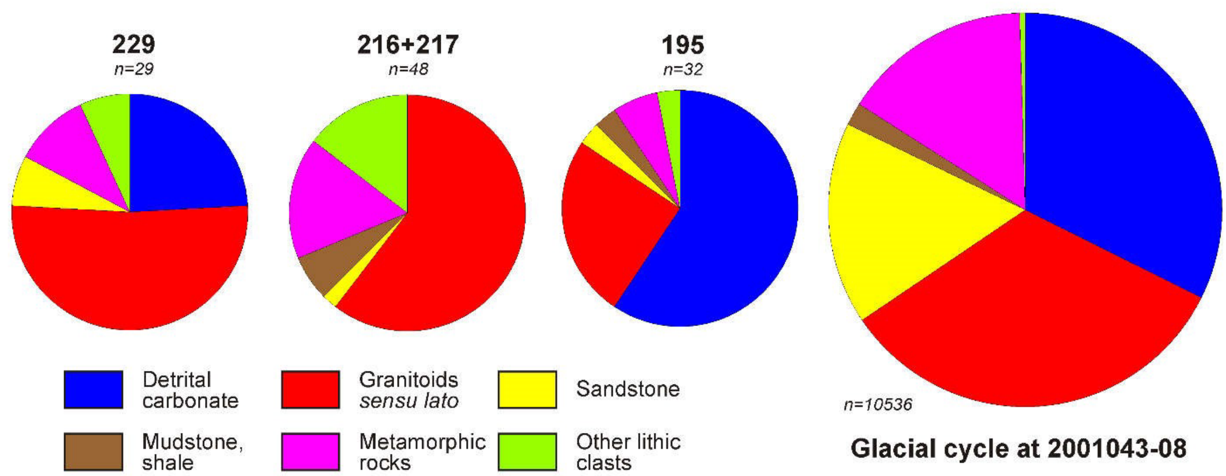

Figure 3. Summary of types of lithic clasts in the granule-small pebble fraction of the studied samples. For comparison, the cumulative abundance through a glacial cycle is illustrated for core 2001043-08 in northern Flemish Pass.

The most comprehensive assessment of detrital ice-rafted granules in the Labrador Current through much of a glacial cycle is available from core 2001043-08PC in northern Flemish Pass (Fig. 3; Appendix 3). Granules in this core were identified by binocular microscope. The data represent a continuous channel sample through almost an entire glacial cycle and thus correspond to the average supply by the Labrador Current to the region. In addition, Mao et al. (2014) used a similar procedure in core 2011031-59PC for core intervals between Heinrich layers, which are rich in detrital carbonate (Piper and deWolfe, 2003).

The data from both studied cores show that lithic clasts of granitoid rocks make up about one-third of ice-rafted lithic clasts, and they are predominantly sourced from Precambrian Shield areas of Canada and Greenland. Such granitoid rocks include granitic gneiss and are of a wide range of compositions. The granitoid lithic clasts from the central shoals are distinctive in having common alteration to chlorite. They include hornblende granodiorite and some contain the REE mineral synchysite. In contrast, chlorite is almost absent in granitoid rocks except as a minor alteration phase in biotite from samples 229 and 195. The exceptions are granule 195-1L-4 and four granules from sample 229 that resemble granules from the central shoals, namely 229-2L-2, 3L-3, 6M-1 and 6M-6.

A previous study of heavy minerals from Flemish Cap (Pe-Piper et al., 2018; Fig. 2) showed that 63–177 mm (fine sand sized) heavy minerals on the central shoals were derived in equal proportions from local bedrock and from ice rafting from distant sources. Other samples from sand ridges in the north and west were predominantly from ice-rafting, with a small central shoal component, particularly in their sample #3, corresponding to sample 229 of the present study.

The principal transport direction for sand during storms is to the SE (Li et al., 2017), so that the presence of central shoal heavy minerals and chlorite-bearing granitoid granules in sample 229 is likely due to erosion of locally exposed glacial till (Stacey, 2011) rather than transport of sand during storms. The higher proportion of ice-rafted heavy minerals in the central shoals, compared to the paucity or lack of ice-rafted granules, is likely the result of greater mobility of fine sand during storm transport.

An approximate sediment budget can be developed for the sorted sands on Flemish Cap. Olex bathymetry data shows that sand ridges make up about 50% of the seafloor between the 250 and 400 m isobaths and Huntec sparker data suggest a mean thickness of 20 m for the sand ridges (Piper, 2018). The flux of ice-rafted sand and gravel to core 2011031-59PC is about 10% of the total sediment accumulation, with a mean total sedimentation rate of 0.1 m/ka (Mao et al., 2017). Thus, within the 1 Ma of major ice advances since the mid-Pleistocene transition, the flux of ice-rafted sediment would be sufficient to account for the observed sand and gravel in the sand ridges of Flemish Cap.

CONCLUSIONS

1. Lithic clast granules from the central shoals of Flemish Cap are locally derived, probably mostly through glacial till, from a wide range of local Avalonian basement rocks including hornblende granodiorite, granite and rhyolite that have experienced low grade greenschist metamorphism. Granules of similar lithologies at the southwestern edge of Flemish Cap were likely eroded out of the local till, which is exposed at the seabed.
2. Lithic clast granules from the sand ridges of western and eastern Flemish Cap are predominantly derived from ice rafting; they include detrital carbonate rocks and granitoid rocks lacking pervasive chlorite alteration.

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