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Heavy Mineral Partitioning in Sedimentary Facies: Lac Baby Esker, Lac Timiskaming Region, Canada

J.-E. Lesemann, D.I. Cummings, B.A. Kjarsgaard, H.A.J. Russell, and D.R. Sharpe

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Abstract

Sampling protocols for heavy minerals (HM) and kimberlite indicator minerals (KIM) in glacifluvial sediments generally follows those established for sampling in fluvial environments. These protocols emphasize sampling of gravely facies. The transfer of this protocol to glacifluvial sediments (especially eskers) assumes that fluvial and glacifluvial systems operate in similar manners. Though they share process similarities, they also have significant differences. Consequently the existing protocol used to sample eskers is largely untested and is not constrained by understanding of glacifluvial processes. In the Lac Baby glacifluvial complex in the Lac Timiskaming region, various esker facies were sampled for KIM in order to assess how these minerals may be partitioned and concentrated in an eskerine depositional environment. The main finding of this study is that gravely esker facies are not necessarily the prime sampling medium in an esker, and that medium to coarse sand facies may be a better choice. However, this does not mean that sampling gravely facies should be abandoned. Near Notre Dame du Nord, heavy mineral (HM) grain counts are elevated within an esker segment where a cobble-boulder bedform occurs. In this bedform, HM grain counts are only slightly lower than the highest HM concentration reported from Lac Baby. Many esker gravely facies record mass flow deposits and poor sorting. These are poor sampling media for KIM due to a lack of density sorting in dynamic flows. Nevertheless, other gravel facies have similar KIM concentrations to those reported in medium to coarse sand facies. Consequently, to select the optimum sample medium requires more testing of sedimentary facies, and also the identification of the depositional controls on the facies to optimize sampling strategies based on facies interpretations.

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Appendix A. Mass Heavy Mineral and KIM counts for small sedimentary facies samples. MSExcel file name : OF-7425 Appendix A (small samples).xls

Appendix B. Mass Heavy Mineral and KIM counts for small sedimentary facies samples. MSExcel file name : OF-7425 Appendix B (large samples).xls

1. Introduction

Sampling for indicator minerals in glaciated terrain has traditionally focused on till (c.f. McClenaghan et al. 2001, Paulen and McMartin 2010 and references therein) and the abundant literature on drift prospecting reflects the emphasis placed on sampling these glacial sediments. Eskers have been sampled extensively by industry e.g. Lac de Gras (Kjarsgaard and Levinson, 2002), but have received comparatively little attention regarding process controls on indicator mineral (IM) concentration within the esker landform, bedforms, and sedimentary facies. The tacit assumption in sampling of eskers has been that eskers are fluvial deposits and that standard fluvial protocols are appropriate. The basis for this premise has never been demonstrated nor documented in the literature (Cummings et al., 2011).

One of the complexities of sampling eskers for heavy minerals (HM), including Kimberlite Indicator Minerals (KIM), is related to an incomplete understanding of how esker sedimentary deposits form. Eskers are sediment casts of conduits formed within the ice (subglacial; Brennand, 2000), or as part of ice-walled open-air conduits formed in re-entrants at the ice margin (subaerial; Warren and Ashley, 1994). Eskers tend to be dominated by coarse sand and gravel as a result of high flow velocities within (sub)glacial conduits, and some esker sediments resemble those found in fluvial environments, owing to similarities in their transport processes by turbulent water flows. For this reason, sampling of esker sediments has followed protocols established for HM in river bed deposits, where indicator grains tend to concentrate within gravely deposits (Afanasev et al., 1984, Muggeridge, 1995, Carling and Breakspear, 2006). In addition architectural elements of eskers include macro-scale bedforms that influence the morphology of esker ridges (Brennand, 1994, 2000). Thus, hydraulic conditions within eskers exert a first-order control on their morphologic and sedimentologic characteristics over a broad scale range extending from individual clast characteristics to facies architecture. Consequently, esker-forming flows likely also control how indicator minerals may be transported and where they may preferentially concentrate within sedimentary facies. It is therefore reasonable to expect that HM/KIM will be partitioned

according to flow dynamics related to channel-conduit geometry, sedimentary architecture and sedimentary facies.

Although some elements of esker hydraulics, and the resulting sedimentary facies, may be similar to those found in fluvial settings, there are also fundamental differences between fluvial flows and esker-forming flows. These differences are related to the sediment supply which may to be more abundant within eskers, and especially the spatio-temporal scale of meltwater production and delivery to subglacial conduits: eskers may represent time-transgressive landforms built my multiple sequential drainage events, or fewer but more 'catastrophic' drainage events (c.f. Brennand, 2000 and references therein). Consequently, esker facies and macro-scale architectural elements can vary greatly from those found in fluvial settings. To date, it remains unclear how individual facies relate to specific hydraulic conditions and how these flow conditions might affect dispersal and concentration of HM and KIM

Irrespective of process similarities between fluvial and glaciofluvial systems, there are fundamental differences between the sampling protocols of most diamond exploration programs in fluvial and glaciofluvial deposits. In fluvial settings, the preferred sampling media are cobble and boulder lags forming a sediment trap, often in the lee of clast clusters (Muggeridge, 1995). In esker deposits, the typical sampling medium is sand and gravel at the top or on the side of the esker. These sampling approaches largely reflect the ease of site access and sampling in the field, rather than process-based protocols based on understanding of depositional controls on eskers and their sedimentary facies.

1.1. Objectives

This report examines HM concentration within different esker sediment facies, emphasizing grain count results and 'first-order' patterns in HM distribution, specifically 5 KIMs. Results provide the basis for development of process-based interpretation of HM partitioning based on glacial meltwater hydraulics. It provides a basis to improve understanding of mineral distribution/dispersal processes within glaciofluvial systems and their deposits in order to better target and execute exploration efforts in glaciated terrains.

2. Field area:

Field work was carried out in the Lac Timiskaming region of Quebec with sampling focussed on north-south trending eskers south of the Roulier moraine and east – northeast of Lac Timiskaming. (Fig. 1, 2). The bedrock in the area is predominantly Archean age volcanic, turbidite and granitoid rocks of the Superior Province, with minor Paleoproterozoic metasedimentary rocks (Gowganda and Lorrain formations) with outliers of Paleozoic carbonate sequences along Lac Timiskaming. Surficial sediment consists of discontinuous till patches over bedrock high points. In lowlands, till, sand , and gravel, overlain by up to 40 m of glacilacustrine mud from Lake Barlow are common (Daigneault and Prichonnet, 1988).

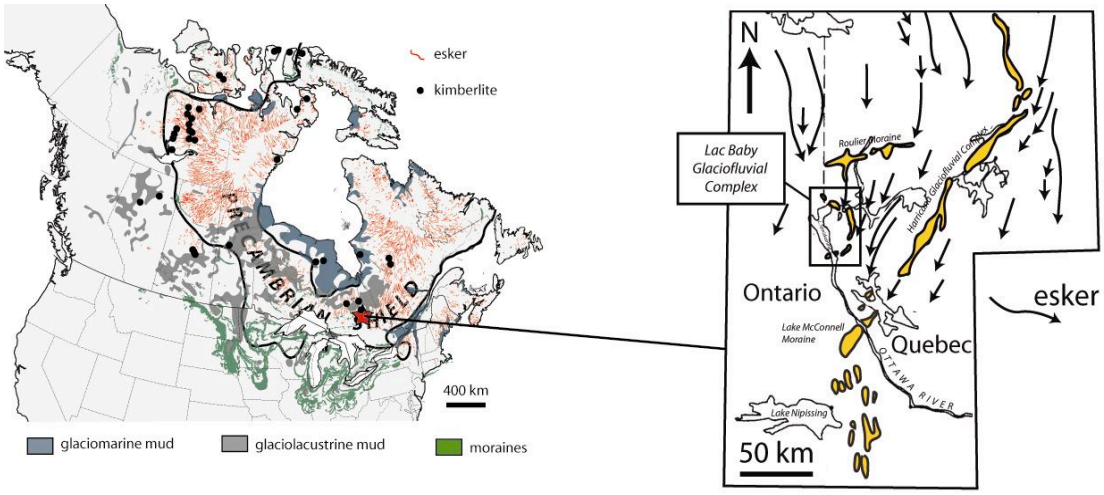


Figure 1: Location map of the Lac Baby glacifluvial complex near Lake Timiskaming.

Within the study area a number of exposed and buried glacifluvial deposits have been mapped (Veillette, 1996). These include esker segments (Roulier esker, Guiges esker, Lac Baby esker, La des Quinze esker, and Laverlochère esker, Fig. 2) extending downflow (~south) of the Roulier Moraine (Fig.2). Due to the continuity of esker segments, in this report we generically refer to these landforms as the Lac Baby glacifluvial complex. Limited work has been completed on these deposits. The Lac Baby glacifluvial complex has been interpreted as an interlobate moraine (Laverlochère Moraine, Veillette, 1996). The same area has been interpreted as an esker (Vincent, 1971;

Daigneault & Prichonnet, 1988; Averill, 1996). This latter interpretation seems most robust as it relies on extensive mineralogic and paleoflow measurements (Daigneault and Prichonnet, 1988; Averill, 1996).

2.1. KIM sources in the field area

The field area is particularly well-suited for examination of KIM dispersal within eskers due to the presence of a number of kimberlite pipes to the north (upflow) of the landforms examined herein (McClenaghan et al. 2006). These include one kimberlite pipe crossed by the Lac Baby glacifluvial complex (Kjarsgaard et al. 2004), north of the Lac Baby esker exposure, and the SC118 kimberlite occuring 9 km north of Lac Baby (McClenaghan et al. 2006) (Fig. 3). Two additional kimberlites (NDN-1 and NDN-2) (not shown on Figure 3) occur 18 km northwest of Lac Baby (McClenaghan et al. 2006). Within the objectives of this study the kimberlite pipes provide know point sources for indicator minerals in glacigenic sediment, and have defined mineralogical assemblages (e.g. Kjarsgaard et al., 2004).

2.2. KIM signatures in Glacial sediment of the region

The Lac Baby esker area is a well known site for elevated KIM values and was first reported to contain kimberlite fragments over 30 years ago (e.g. Veillette, 1996). Exploration work for kimberlites indicated elevated KIM concentrations from borehole samples to the west of the Lac Baby esker segment and from surface sampling of the esker (Fig. 2; Averill, 1996).

Kimberlite clasts occur frequently within glacifluvial deposits in this region (Sage, 1996; Veillette, 1996). Kjarsgaard et al. (2004) presented mineralogy and chemistry results for a number of esker-derived kimberlite clasts which can be used as a baseline for kimberlite chemistry, and also for comparative purposes. This context-supported reconnaissance-scale sampling of sedimentary facies in the Lac Baby esker that

documented elevated KIM concentrations with various sedimentary facies and sample locations (McClenaghan et al., 2006).

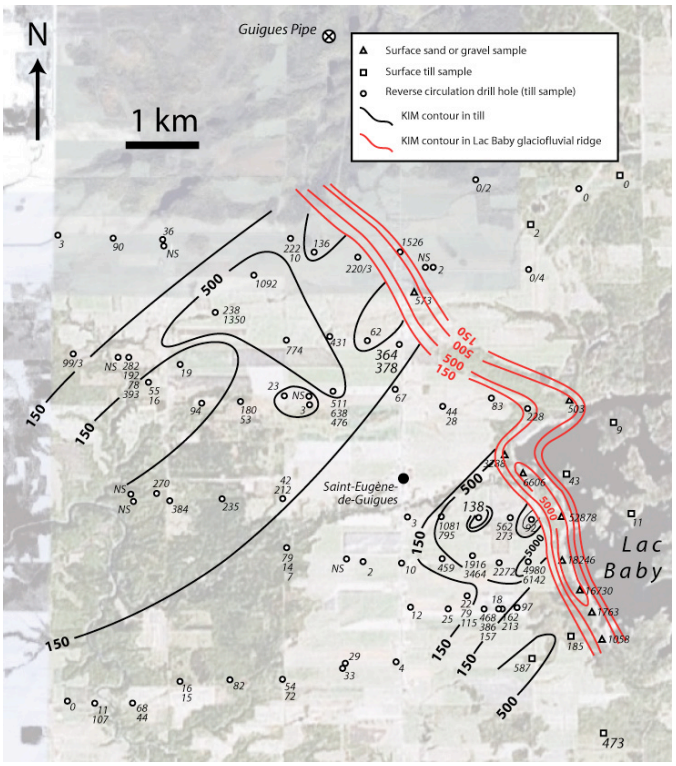


Figure 2. Kimberlite indicators in the Lac Baby esker and adjacent till (modified from Averill, 1996). Numbers refer to total KIM counts.

3. Study Sites and Sampling Scheme

Four glacifluvial landforms, including the Roulier esker, the Lac Baby esker, the Lac des Quinze esker, and deposits in the Paulson pit, were targeted for sampling and sedimentologic studies based on the availability and lateral extent of exposures, and on the stratigraphic position of these exposures within the landforms. Nine sites were visited, with two sites only having sedimentological observations (Fig. 3, sites 1 and 2) and 7 sites sampled for heavy minerals (Fig. 3, sites A – F). Two sites are located in the Roulier esker near the town of Notre Dame du Nord, Quebec (Asphalt Pit – AP, and Municipal Refuse pit – MRP; Fig. 3 sites 1 and D). Four sites (Fig. 3. Sites C, E, F - two sites occur at C) are located in the Lac des Quinze esker, east of the Lac Baby esker. Two sites are

located in the Lac Baby esker (Fig. 3), A single sedimentological site is located in the Paulson pit (PP; Fig 3, site 2).

Two sampling objectives were completed during the field visit in September 2010. The primary objective was detailed sediment facies sampling of two sites. The secondary objective was more regional sampling to provide a baseline dataset of KIM concentrations in glacifluvial deposits that are upflow of known kimberlite pipes in the area. A third field objective was data collection to permit sedimentological characterization of the different esker landforms.

Sampling for KIM and HM in different sediment facies was completed at two sites in the Lac Baby esker (Fig. 3: site A and site B). At site A in the Lac Baby esker, a total of 48 small sand samples (1.5-4.5 kg) were collected. In detail, six samples were collected from each of eight different sedimentary facies. To maximize the volume of sand per sample, sediment coarser than 1.2 cm was screened in the field with a wire mesh. Most samples therefore have two fractions, one <1.2 cm (the "sand" fraction) and one >1.2 cm (the "pebble" fraction). Nine bulk samples (nominally 15 kg) were collected. Seven were collected from regional sites. Two samples were collected from the Lac Baby esker (site A) to verify that the 1 kg samples were representative with respect to KIM counts and mineral assemblages (Table 1). These large samples yielded between 1.1 and 2.3 kg of <2 mm size fraction. Small samples, ranged in bulk weight from 1.5 to 4.5 kg and yielded 0.7 to 2.7 kg of <2 mm size sand fraction.

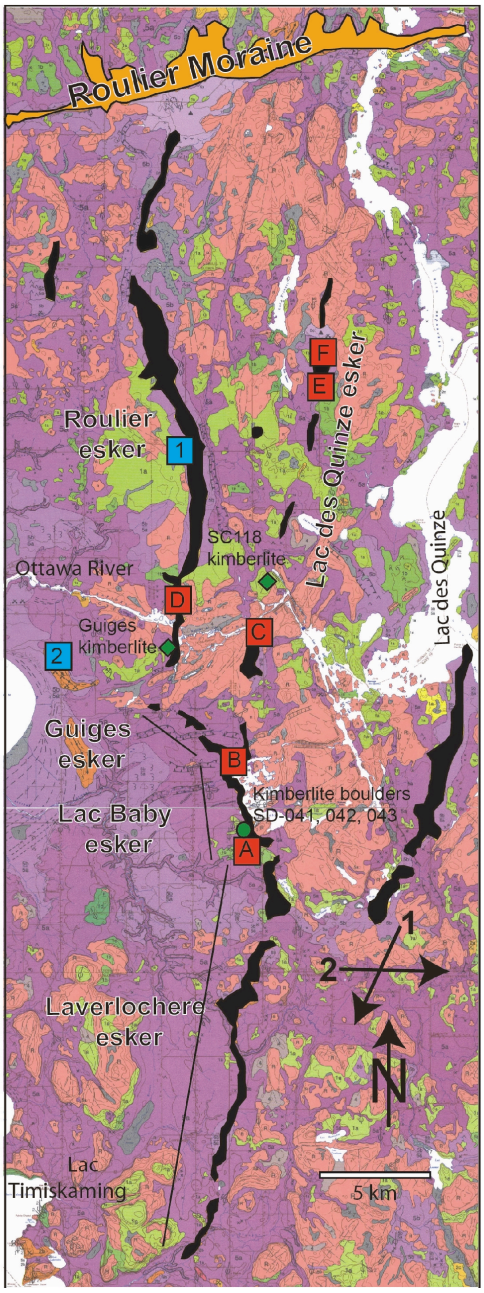


Figure 3: Regional map of the studied glacifluvial complex and its subdivisions (black polygons): Roulier esker, Lac de Quinze esker, Guiges esker, Lac Baby esker, and Laverlochère esker. Sedimentologic, and sample sites for KIM and HM studies are denoted by red square boxes. Blue squares denote sedimentological analysis and sampling sites. Green diamonds locate known kimberlites (McClenaghan et al., 2006). Green circle locates occurrence of kimberlite boulders within the Lac Baby esker (McClenaghan et al., 2006). Surficial geology base map from Veillette (1983). Map legend colours are bedrock is pink, till is green, purple is mud.

Table 1. Sample sites referenced in Figure 2 and nature of sampling.

Site	Esker location	Sample size kg.	Number samples	comments
A	Lac Baby camping	3 15	1 -48 / 25-26	6 samples from each of 8 sedimentary facies 1 samples from 2 different sedimentary facies
B	Lac Baby hilltop	3	58 - 64	7 samples from 4 facies
C-1	Lac des Quinze (S)	15	53	Slumped section
C-2	Lac des Quinze (N)	15	51 - 52	Slumped section,
D	Roulier	3 15	65 – 69 57	5 samples from matrix of boulder bedform 1 sample from main face
E	Lac des Quinze	15	54	Roadside sand sample
F	Lac des Quinze	15 3	55 56	Borrow pit at <2 m depth in sand Borrow pit at <2 m depth in sand

3.1. Heavy Minerals

The sampling objective was to collect sediment for heavy mineral separation and analysis of five common KIMs (olivine, pyrope garnet, Cr-diopside, chromite, magnetite, ilmenite) that are commonly separated from the sand fraction (Appendix A and B).

3.2. Laboratory Process

The bulk samples and the small "sand" samples were sent to Overburden Drilling Management, Ottawa for analysis. Samples were wet sieved at 2.0 mm. The pebbles in the >2.0 mm fraction were subsequently examined, classified, and counted (Appendix A). The <2.0 mm fraction was processed on a concentrating table, twice (i.e. two runs). The table concentrate was then dried, weighed, and sieved to 0.25 mm. The 0.25 to 2.0 mm concentrate material was processed using heavy liquids (acetone diluted methylene iodide, specific gravity of 3.2) to produce a heavy mineral concentrate, which then underwent ferromagnetic separation to remove magnetite. The retained nonferromagnetic heavy concentrate was cleansed with oxalic acid to remove limonite stains that would otherwise impede mineral identification. The samples were subsequently sieved at 0.25 mm, 0.5

mm, and 1.0 mm. The 0.25 to 0.5 mm fraction was further sorted electromagnetically into mineralogically simpler non-paramagnetic and weakly, moderately, and strongly paramagnetic fractions to assist with indicator mineral picking. The <0.25 mm heavy mineral fraction of all samples was archived. The mineral processing flow diagram is shown in Figure 4.

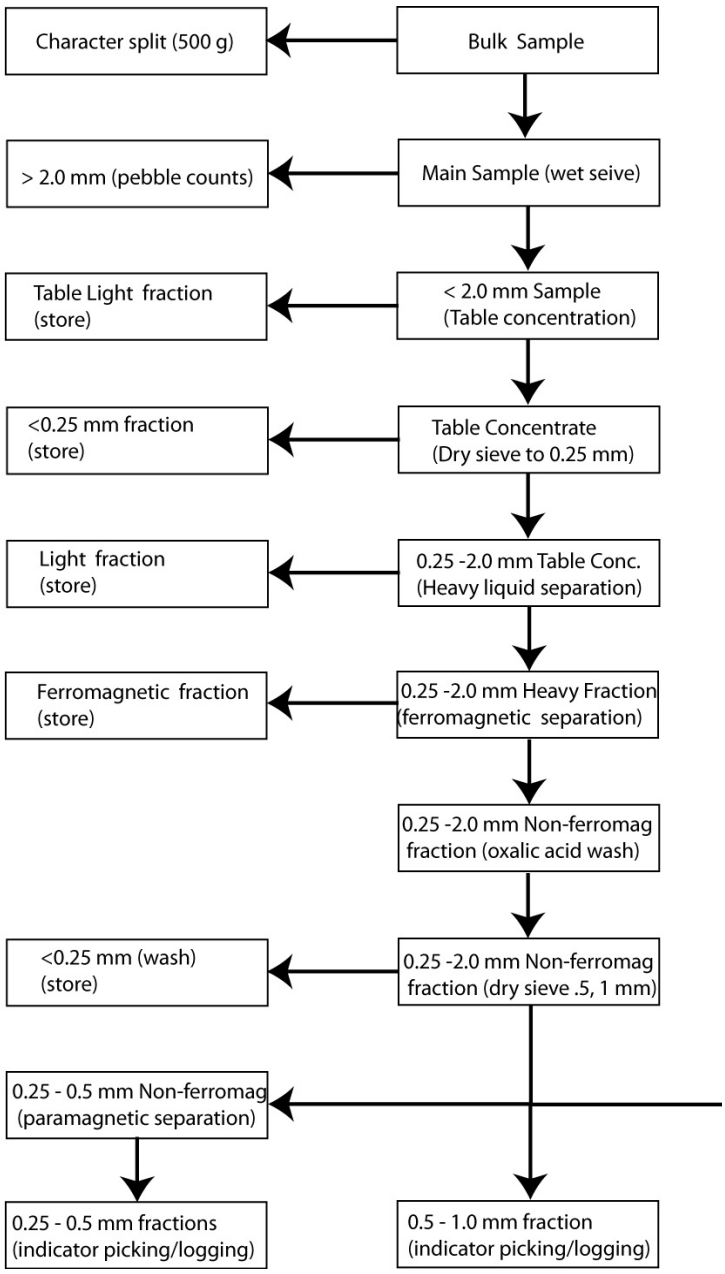


Figure 4: Indicator mineral processing flow diagram.

All fractions were picked for kimberlite indicator minerals and the picked grains were stored in labelled vials according to size and species. Any difficult or ambiguous grains were identified with the aid of scanning electron microscope (SEM) energy dispersive spectrometry (EDS) analysis. Indicator mineral counts for all esker samples in the 0.25–0.5 mm, 0.5–1.0 mm, and 1.0–2.0 mm fractions are listed in Appendix A.

3.3. Quality Control

Two samples (one ~3 kg and one ~15 kg) of clean beach sand were spiked with KIM and diamonds. The KIM were from heavy mineral concentrate from kimberlite, or extracted from mantle xenoliths. In general, the picking results from the spiked samples are identical, with the numbers of grains picked identical to the spiked quantity. In some instances, the picked grain counts are higher, which is thought to be due to breakage of large grains into smaller grains (e.g. olivine in RAZ-2010-42; P-type garnet in RAZ-2010-43). However, ilmenite grain counts are low in RAZ-2010-42; and E-type garnet, cpx, and chromite grain counts are low in RAZ-2010-43 (Table 2).

4. Sedimentological Sites

Detailed sedimentological descriptions were collected at six sites that had adequate depth and breadth of exposure. Two sample sites in the northern part of the Lac des Quinze esker segment consisted of roadside sand exposure with less than one metre slumped sections. Standard sedimentologic descriptions (c.f. Tucker, 1988; Evans and Benn, 2004) were performed at each site. For continuity, sedimentological observations for sites with heavy mineral samples are presented in companion with the heavy mineral results.

4.1. Paulson Pit

The Paulson Pit occurs on the edge of a sedimentary plateau rising from the shores of Lake Timiskaming to localized escarpments where gravel pits have been developed. Sand and gravel dominate the sedimentary package and these sediments are overlain by rhythmically bedded glacilacustrine mud from the former Lake Barlow. (Veillette, 1996).

Table 2: Information on spikes inserted in individual samples as a control on KIM recovery and identification.

Sample	size	Diamond	P-type garnet	E-type garnet	Clino pyroxene	ilmenite	Chromite	Olivine
RAZ - 2010-42	Spike	**2**	**7**	**7**	**7**	**5**	**2**	**4**
RAZ - 2010-42 picked	1-2mm	1	7	8	4	1	1	4
	.5-1	1	0	0	2	0	0	2
	.25-.5	0	0	0	0	0	0	4
	total	**2**	**7**	**8**	**6**	**1**	**1**	**10**
RAZ - 2010-43	Spike	**1**	**14**	**13**	**19**	**6**	**7**	**15**
RAZ - 2010-43 picked	1-2mm	1	14	6	11	5	2	10
	.5-1	0	3	0	1	0	0	1
	.25-.5	0	0	0	0	0	0	2
	total	**1**	**17**	**6**	**12**	**5**	**2**	**13**

NOTES:

1.) Diamonds are synthetic yellow cubo-octahedrons

2.) P-type garnet, Cpx, chromite, ilmenite from kimberlite concentrate

3.) E-type garnet, olivine from mantle peridotite xenoliths

Sand and gravel dominate within the Paulson Pit. Sediments generally fine upward. There also appears to be lateral textural changes within the pit, though these are more difficult to assess given the availability of exposures. Sand-rich beds are commonly planar-bedded and are often intercalated between normal graded gravel-sand beds. In some instances, coarse sand-granule beds exhibit dune-scale cross-stratification. Bedsets of climbing dunes also occur in this material (Fig. 5A). Gravel-rich beds are commonly cross-stratified and range from clast-supported with little grading, to normal-graded with pebbly bed tops (Fig. 5 B). Cross-stratified gravel sets are seldom, if ever, overlain by planar-bedded material. Clasts are commonly sub-angular to sub-rounded. Most cobble-sized (and smaller) clasts are sub-rounded while boulders are commonly sub-angular. Near the top of the exposure, faulted normal-graded beds of coarse to fine sand occur

(Fig. 5 C). These are overlain by rhythmically bedded and laminated mud. Deformation and decimetre-scale sediment clasts characterize the transition between these facies. Sediments within the Paulson Pit have very little surface expression. However, concentrations of boulders (many over 1 m diameter) occur on the landscape in the vicinity of the Paulson Pit (Fig. 5 D)

The lack of a distinct geomorphic expression for the pit area limits genetic interpretations of the sediments. However, the stratigraphic context of these deposits, occurring below the Lake Barlow mud, suggest that Paulsen Pit sediment predate or were contemporaneous with Lake Barlow and likely have a glacigenic origin. Clast rounding, sedimentary structures, abundant bedforms, and a dominance of sorted sediments all suggest that sediments record transport and deposition by glaciofluvial processes. Cross-stratified gravel, and cross-sets of graded gravel couplets might suggest a deltaic depositional environment. However, the absence of topset beds overlying cross-sets speaks against this possibility. Instead, gravel cross-sets are interpreted as m-scale bedforms. This interpretation is consistent with the presence of coarse sand and pebble dunes. The textural difference reflects fluctuating depositional energy as a result of proximal-distal relationships relative to the sediment input point, or an overall decrease in meltwater supply. The gravel couplets also occur in different parts of the Paulsen Pit at a higher stratigraphic position than the dunes, suggesting that meltwater supply remained sufficient for gravel transport beyond the period of dune deposition.

Overall, sedimentary facies of the Paulson Pit record abundant sediment delivery by highly energetic flows. In addition, rapid and frequent vertical and lateral facies changes record pulsations within the flows delivering sediments. These characteristics are typical of glaciofluvial systems where flow hydrographs are characterized by flashy discharges at a range of temporal scales (Marren, 2005). In addition, possible episodic meltwater release from supraglacial and subglacial sources also contributes to flashy discharge characteristics (Zwally et al. 2002; Marren 2005).

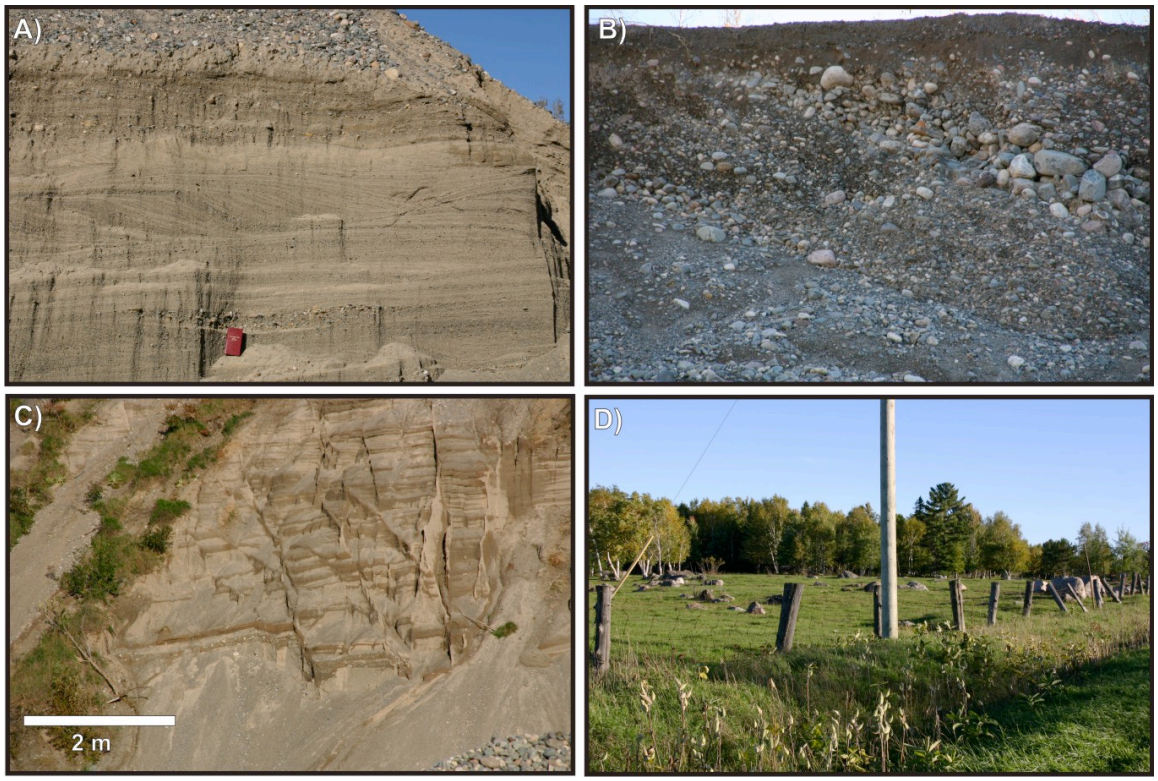


Figure 5: Sediments of the Paulson Pit. A) Bedsets of climbing dunes occur in coarse sand. B) Cross-stratified gravel commonly occur in the lower portions of the pit. C) Faulted medium to find sand beds near the pit top. D) Boulder concentrations on the land surface adjacent to and above the Paulson Pit.

Based on these preliminary examinations, it is unclear if the Paulson Pit records subaerial (e.g. outwash plain) or subaqueous (e.g. subaqueous fan) depositional conditions. The presence of Lake Barlow sediments overlying the sands and gravels most likely supports an interpretation of subaqueous deposition of the coarse sediments. Diffusely-stratified sands are a typically documented sedimentary facies of subaqueous depositional settings (c.f. Russell and Arnott, 2003), and are associated with rapid deposition of sediment-laden flows as ice tunnels exit into a water body. However, no diffusely stratified sands were identified in the Paulson Pit, which could be suggestive of a subaerial depositional setting, although this interpretation is equivocal (since a subaqueous depositional setting could occur without deposition of diffusely stratified sand facies). For examples, the absence of diffusely stratified sands could be rationalized if sediments were delivered

beyond the confines of subglacial tunnels, such as ice marginal re-entrants or short-distance outwash plains terminating in a deep glacilacustrine basin where abundant accommodation space precludes progradation of a fan/deltaic system. Therefore, further detailed sedimentologic and geomorphologic work is necessary to refine the depositional environment at the Paulson Pit.

Reported concentrations of KIM in the Paulson Pit area are (Averill, 1996; McClenaghan et al., 2006) much lower (1-6 grains/kg) than for the Lac Baby glacifluvial complex (see section 5.2). For this reason, the Paulson Pit is unlikely to yield significant insights into KIM concentrations within sedimentary facies.

4.1.1. Notre Dame du Nord, Asphalt Plant Pit Sedimentology

The asphalt pit (AP) site is one of four pits located along ~1 km of the Roulier esker. Two textural elements characterize the glacifluvial ridge of the AP pit: a gravel and coarse sand lower element, and an upper medium to fine sand element (Fig. 6 A). The coarse lower element consists of planar-bedded, and cross-stratified coarse sand, granules, and cobble to boulder gravel (Fig. 6 A). Diffusely stratified coarse sand occurs in places (Fig. 6 B). The lower element can be up to 25 m thick. The architecture of this lower element consists of cross-stratified sediments near the ridge flanks. These beds dip away from the ridge axis and the dip angle is roughly conformable with the ridge flanks. The central ridge portion consists mainly of planar-bedded sand and cobble to boulder gravel with local occurrence of diffusely-stratified coarse sand packages containing internal scours. The upper contact of this lower element is very sharp and laterally continuous, forming a distinct sub-horizontal surface truncating the cross-stratified beds. Boulders and cobble concentrations occur at this contact (Fig. 6 A).

The finer-grained upper-element immediately overlies the sharp basal contact with the lower element (Fig. 6 A). It consists of sub-horizontal to weakly undulating rhythmic beds of medium sand, extending laterally over 10's m distance (Fig. 6 C). These beds vary in thickness between 5-25 cm and contain low-angle bedforms grading into sub-

horizontal planar laminations and beds (Fig. 6 D). Stoss-erosional climbing ripples are common as are dune-scale and antidune cross-stratification in the thickest beds. Fine sand to silty sand beds capping coarser sand beds enhance the rhythmic appearance of this upper element (Fig. 6 D).

The lateral continuity of planar-bedded gravel passing into cross-stratified gravel beds near the ridge flanks suggests that these beds were deposited contemporaneously. More significantly, the fact that ridge flanks are conformable to the dip angle of cross-stratified gravel suggests that a broadly anticlinal sedimentary architecture partly defines the ridge form. Brennand (1994) identified pseudo-anticlinal macroforms within eskers and proposed that undulating, mound-like esker morphology is in large part dictated by these architectural elements. Such forms result from complex helicoidal flow structures within the subglacial conduit (Brennand, 1994). Local occurrence of diffusely-stratified coarse sand records rapid deposition by sediment-laden flows in zones of flow expansion (Russell and Arnott, 2003). These deposits can be rationalized within a model of macroform deposition.

Local scours or simply zones of flow separation are expected near the ridge axis or in the lee of bedform crests as helicoidal flow structures converge near the crests and plunge toward the flanks (c.f. Brennand, 1994). Rapid filling of such scours is expected as flow expands in these zones and the presence of diffusely stratified coarse sand suggests that high concentrations of sediments were transported in suspension within the subglacial conduit. The sharp upper contact of the lower element is interpreted as an erosional surface. Within this context, boulder concentrations represent lag material.

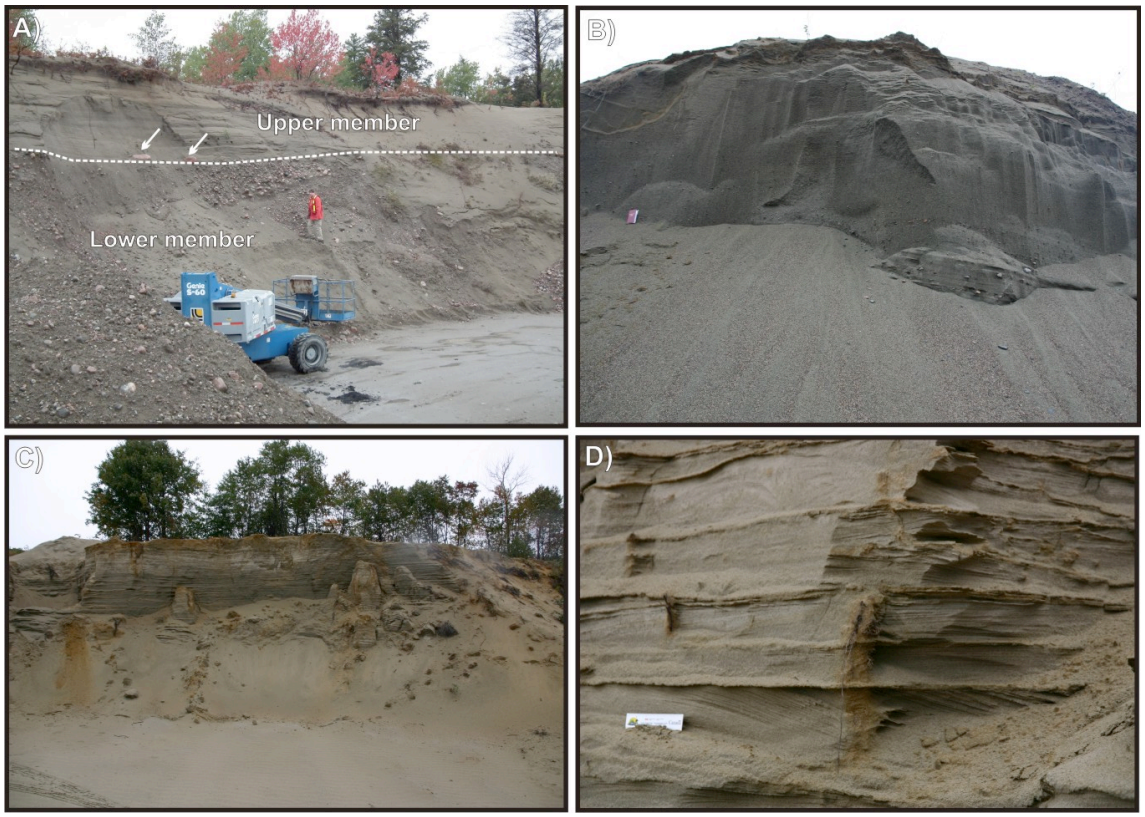


Figure 6: Sediments of the Asphalt Plant Pit, Roulier esker, northeast of Notre Dame du Nord, Quebec. A) Sharp contact (dashed line) between the Lower and Upper textural members. Boulder concentrations (arrowed) occur at the contact. B) Diffusely graded sands occur within the coarse Lower Member. C) Rhythmic subhorizontal beds of medium to fine sand in the Upper Member. D) Low angle bedforms and planar-bedded medium sand of the Upper Member. The rhythmic pattern is enhanced by fine sand beds and laminations near the bed tops.

The occurrence and spatial transitions between low-angle climbing ripples, dunes, antidunes and planar-laminated beds are associated with flow conditions oscillating between subcritical to supercritical flow conditions (so-called transcritical flows; Grant, 1997; Fielding, 2006, Duller et al. 2008). The textural difference between the lower and upper element could suggest an overall decrease in flow energy toward the ridge top. However, the erosional surface at the lower-upper element contact clearly illustrates that flows were sufficiently competent (at least initially) to erode cobbles and boulders. The dominance of sand (and absence of boulders) immediately above the contact suggests that most of the coarse eroded material by-passed this erosional surface. Furthermore, the lateral continuity of this surface indicates that flows, and sediment by-passing occurred

over most of the conduit width as a single-event rather than as a series of more localized flows. This should result in distinct and possibly cross-cutting erosional surfaces within the lower element. The trans-critical flow conditions recorded by dunes, antidunes, and low-angle to planar laminations and beds suggest that only sand was transported during this depositional episode, reflecting selective longitudinal sediment sorting and/or remobilization of previously sorted sand beds further upflow.

5. Heavy Mineral Sample Sites

A total of 58 samples were collected for grain size analysis and KIM extraction. The majority of samples (46/58) were collected at the Lac Baby esker camping site (Fig. 3, site A) due to the presence of a known kimberlite source to the north of the exposure (Averill, 1996), the quality of the exposure offering a cross-sectional view of the esker segment, and a range of facies of variable texture lending themselves to hypothesis testing of KIM concentration within facies. Although no known kimberlites occur upflow (north) of the Notre Dame du Nord pits, samples were collected at the MRP to assess regional background heavy mineral concentrations.

5.1. Notre Dame du Nord pit: Municipal Refuse Pit (MRP)

Sediments in this pit consist of two separate exposures of cobble and boulder gravels. Matrix supported boulder gravel cross-sets reaching up to 8 m height and dipping at ~15-25 degrees (Fig. 7A) form the most prominent feature. Boulders and cobbles are sub-angular to rounded. The matrix typically consists of pebble gravel and coarse sand. Local clusters are common and consist of clast-supported and weakly imbricate small cobbles and pebbles (Fig. 7 B). Sample 57, a 15 kg sample was collected from the lower part of the section illustrated in Figure 7A. As was the case in the AP pit, the height of the cross-sets defines most of the ridge topography. Cross-sets pass vertically into cross-stratified coarse sand, pebbles, and cobbles. A second 3 m high exposure consists of rounded, tightly packed cobbles and boulders with local sandy matrix-rich areas (Fig. 7). Transitions between packed boulders and matrix-rich zones are gradational: tightly

packed boulder clusters with little matrix pass into matrix-rich zones exhibiting lone matrix-supported clasts (Fig. 7 C, D).

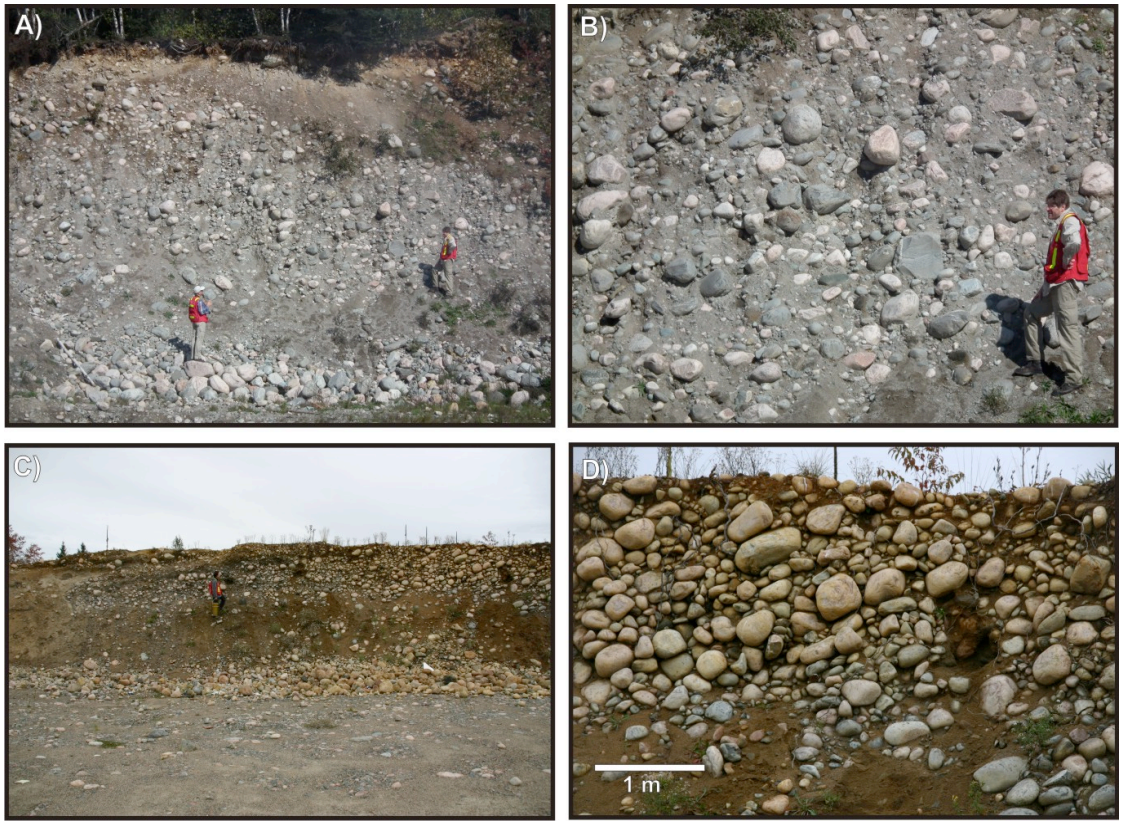


Figure 7: Sediments of the Municipal Refuse Pit, Roulier esker, east of notre Dame du Nord, Quebec. A) Weakly stratified cross-sets of cobbles and boulders within a large depositional macroform defining the esker ridge; B) Close-up view of boulders and matrix-rich zones within weakly stratified cross-sets; C) Low angle dipping beds of rounded cobbles and boulders. This possibly represents a barform or a climbing bedform; D) Close-up view of tightly packed cobbles and boulders arranged within dipping beds.

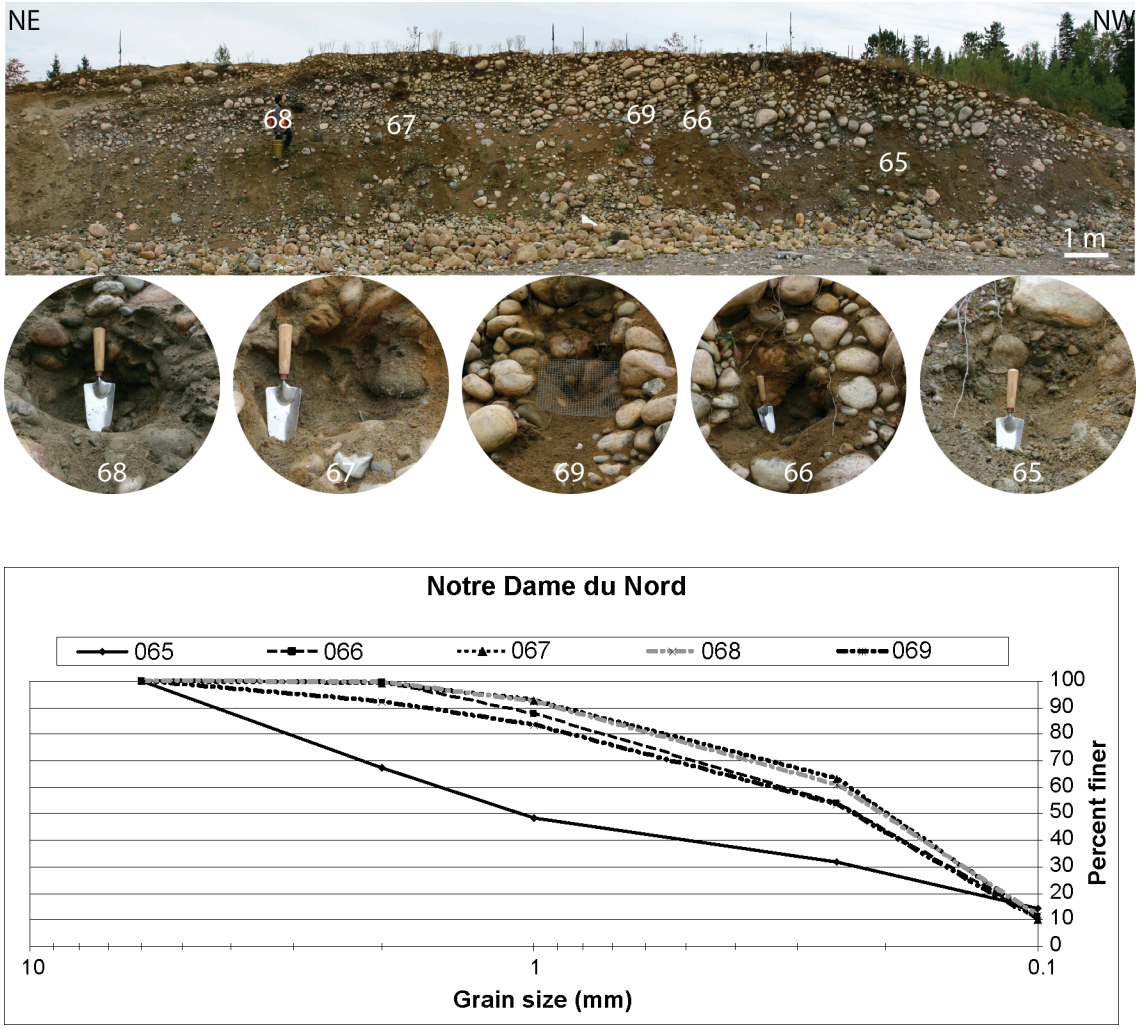


Figure 8: Location of samples in gravel bedform and grain size graph of matrix sampled between the gravel clasts of the bedform at the Municipal Refuse Pit, east of Notre Dame du Nord, Quebec. All sample numbers prefixed by 2010-RAZ.

Boulder clusters tend to be linear and produce weak stratification with a gently up-flow (north) dipping surface. Linear clusters become more tightly packed and matrix-poor as the bed climbs. Weak downflow-dipping stratification occurs beyond the zones of maximum packing. Overall, dipping beds define an asymmetric form with a gentler upflow side.

The two landforms in the Municipal Refuse Pit are interpreted as constituent architectural elements of the Roulier esker. In the case of the bouldery cross-sets, it is difficult to

ascertain the degree to which the entire deposit defines a single bedform. However, given the height of the cross-sets and the fact that they account for most of the esker ridge relief at this locality, we consider them to be a major architectural element of the esker. Boulder cross-sets record traction transport and deposition on an avalanching surface producing cross-stratification. The size of the material within cross-sets requires extremely high flow velocities for mobilization, while the relatively poor sorting and matrix-rich zones suggest high sediment concentrations with a relatively low degree of sorting, though some matrix-rich zones may result from deposition by reversing (return) flows in a flow separation zone in the lee of the cross-set brink point.

The second landform (Fig. 8 C, D) may represent a gravel bedform (although the possibility that this is a channel bar has not been excluded). Linear boulder clusters defining stoss-side stratification record traction transport. On the stoss-side, upslope decrease in matrix and concomitant increase in the packing efficiency of boulders may result from flow acceleration and increasing entrainment of matrix material toward the bedform crest. Stoss-side clusters result from avalanching, and matrix-rich zones suggest deposition of bypassing matrix material within a flow separation zone.

5.1.1. Municipal Refuse Pit : Heavy mineral (HM) concentrations

Kimberlites have not been identified in the vicinity of the Notre Dame du Nord pits. Consequently, HM and KIM concentrations were expected to be lower than at Lac Baby (section 5.1). A single 15 kg sample from a cobble gravel of the main esker face yielded 17 g/kg of heavy minerals. Samples from the boulder gravel bedform (Fig. 7), approximately one hundred metres away yielded 4 to 6.5 g/kg of heavy minerals (Fig. 9). The matrix grain size was similar for four of the samples (samples #66 - #69); sample #65 was from a finer cobble gravel with a coarser and more heterogeneous matrix (Fig. 8). These results suggest that HM were strongly concentrated by hydrodynamic conditions within the gravel form. Based on our preliminary results, it is unclear if sampled sand grains were deposited pene-contemporaneously with the clast-supported cobble gravel, or if they later infilled interstices. Further sedimentologic work and sampling will be

required to elucidate formative mechanisms for these gravel bedforms and the HM segregation processe(s). Visually picked KIM grains consisted of two chromite grains from samples 065 and 066, however, in the absence of mineral chemistry data, these may not be true KIM, but could be derived from Archean mafic or ultramafic rocks.

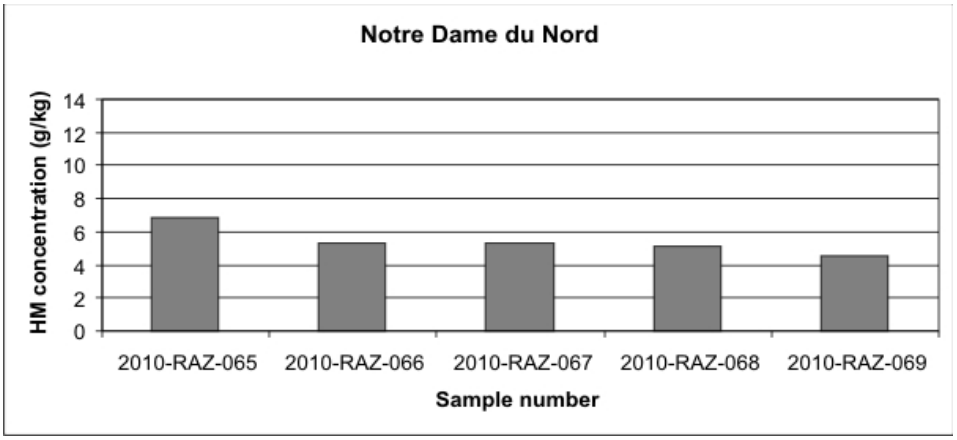


Figure 9: Heavy mineral concentration of samples from a cobble-gravel bedform in the Municipal Refuse Pit.

5.1.2. Roulier esker, south of Municipal Refuse Pit : Heavy mineral (HM) concentrations

A ~17 kg coarse sand and gravel sample was taken on the Roulier esker immediately south of the river, and just to the north of the Guige kimberlite locality (Fig. 3). Visually picked KIM grains consisted of two chromite grains and one chrome diopside grain. These results are very similar to those from samples 065 and 066 from the Municipal Refuse Pit (Fig. 9) on the north side of the river, and strongly suggest that input of kimberlite detritus occurred downflow.

5.2. Lac Baby Esker:

Samples were collected at two sites in the Lac Baby esker segment. At the camping site (Fig. 3, site A) five of the facies were sandy with few to no pebbles and three were framework supported gravel with sandy matrices. At the hilltop site, seven ~3kg samples

were collected from 4 sedimentary facies (Fig. 3, site B). In addition, five kimberlite cobbles were collected along the esker between sites A and B.

5.2.1. Lac Baby kimberlite clast mineralogy

Of the five collected kimberlite cobbles, one clast (*Outlet-1*) was collected in glacifluvial sediments near the outlet of Lac Baby. The remaining clasts (*Camp-2* through *Camp-5*) were collected within the main esker exposure described in this report (section 5). Determining regional kimberlite and kimberlite clast mineralogy is critical to establishing the relative abundance of each indicator mineral in order to help assess whether KIM concentrations in sediments are controlled by kimberlite source(s) and their respective mineral abundance, and/or whether they reflect transport and hydrodynamic processes leading to grain sorting and concentration within certain facies.

Indicator grains in the Lac Baby kimberlite boulders reach the tens of thousands. Plots of raw grain counts (Fig. 10) and normalized grain counts (Fig. 11) show a clear dominance of olivine and/or Mg-ilmenite grains (Figs. 10, 11). Inversely, Cr-diopside and chromite make up a minor fraction of the total grains. Inter-sample differences in grain counts vary by a factor of two and up to twelve. For example, both types of garnets exhibit the least amount of variability. In contrast, Mg-ilmenite and olivine are most variable. (Fig. 10). Intra-sample variability in the abundance of each indicator mineral also occurs. For example, the Outlet-1 and Camp-2 samples contain some of the highest total KIM counts, yet the variability is also amongst the highest. The Outlet-1 boulder exhibits an almost 20-fold difference in Mg-ilmenite and olivine counts. The same degree of variability is not seen in other samples. High variability of indicator grains within kimberlite boulders was noted by earlier studies in this area (McClenaghan et al., 2002a; Kjarsgaard et al., 2004).

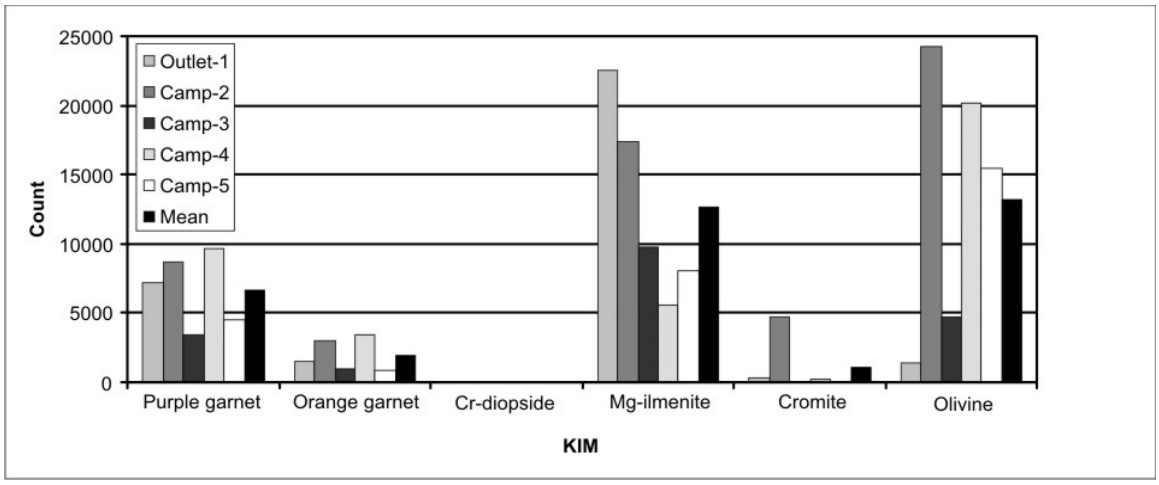


Figure 10: KIM count and mineralogic characteristics of five kimberlite cobbles collected in the vicinity of the Lac Baby esker.

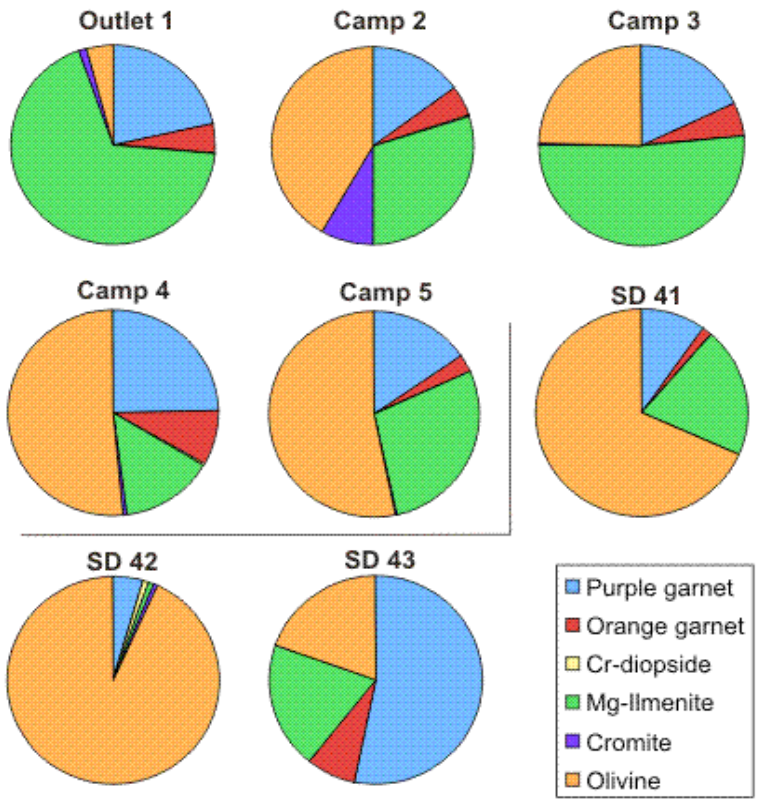


Figure 11: Pie charts of normalized mineralogical counts from five cobbles collected in the vicinity of Lac Baby. Samples SD41, SD42, and SD43 are shown for comparison (from Mclenaghan et al., 2006).

Comparing KIM data from cobbles collected at Lac Baby (McClenagan et al., 2006; Fig. 11) to those collected for this study show no apparent pattern in relative abundance of each KIM in each boulder. The variability may therefore reflect highly heterogeneous kimberlitic source rocks, and/or multiple kimberlite sources. This latter possibility was also invoked by McClenaghan et al. (2006) to explain sample variability and rationalized by the known occurrence of two kimberlite sources along the esker network connecting to Lac Baby (Fig. 2).

5.2.2. Lac Baby hilltop: sedimentology and HM/KIM counts

A 3 m high exposure of the Lac Baby esker occurs ~ 3 km upflow of the main Lac Baby pit (section 5.2). Exposed sediments consist of cross-sets composed of normally graded beds of coarse sand and gravel (up to cobble size) (Fig. 12 A, B). These sand-gravel beds overlie low-angle to planar beds of well sorted coarse sand and granules (Figs. 12A, B). HM concentrations at this site are comparable to some of the highest concentrations observed at the Lac Baby pit (section 5.2). However, in the hilltop exposure, HM concentrations vary strongly between facies. The highest concentrations occur in the sandy matrix filling interstices between gravel clasts at the base of normally graded beds (samples 061-063, Fig. 10C). A well-sorted sand bed (sample 064) occurring within gravel beds also yielded elevated HM concentrations. In contrast, samples taken in less well sorted coarse sand below the gravel cross-sets (samples 058, 059, 060) yielded HM concentrations that were almost 50 % less than the neighbouring samples (Fig. 12C). Similar to samples from the Notre Dame du Nord pit, KIM were absent, or present only in negligible amounts (0-2 grains of chromite present) for most samples. The single exception is sample 064 where 60 KIM grains were identified (7 purple garnets, 1 Cr-diopside, 12 Mg-ilmenite, 40 olivine). Although the types of observed KIMs are similar to those within kimberlite cobbles in this area (Fig. 10, 11), and within facies in the Lac Baby pit (section 5.2), the total number of KIM is low and is at least one order of magnitude less than the lowest KIM counts in the Lac Baby pit.

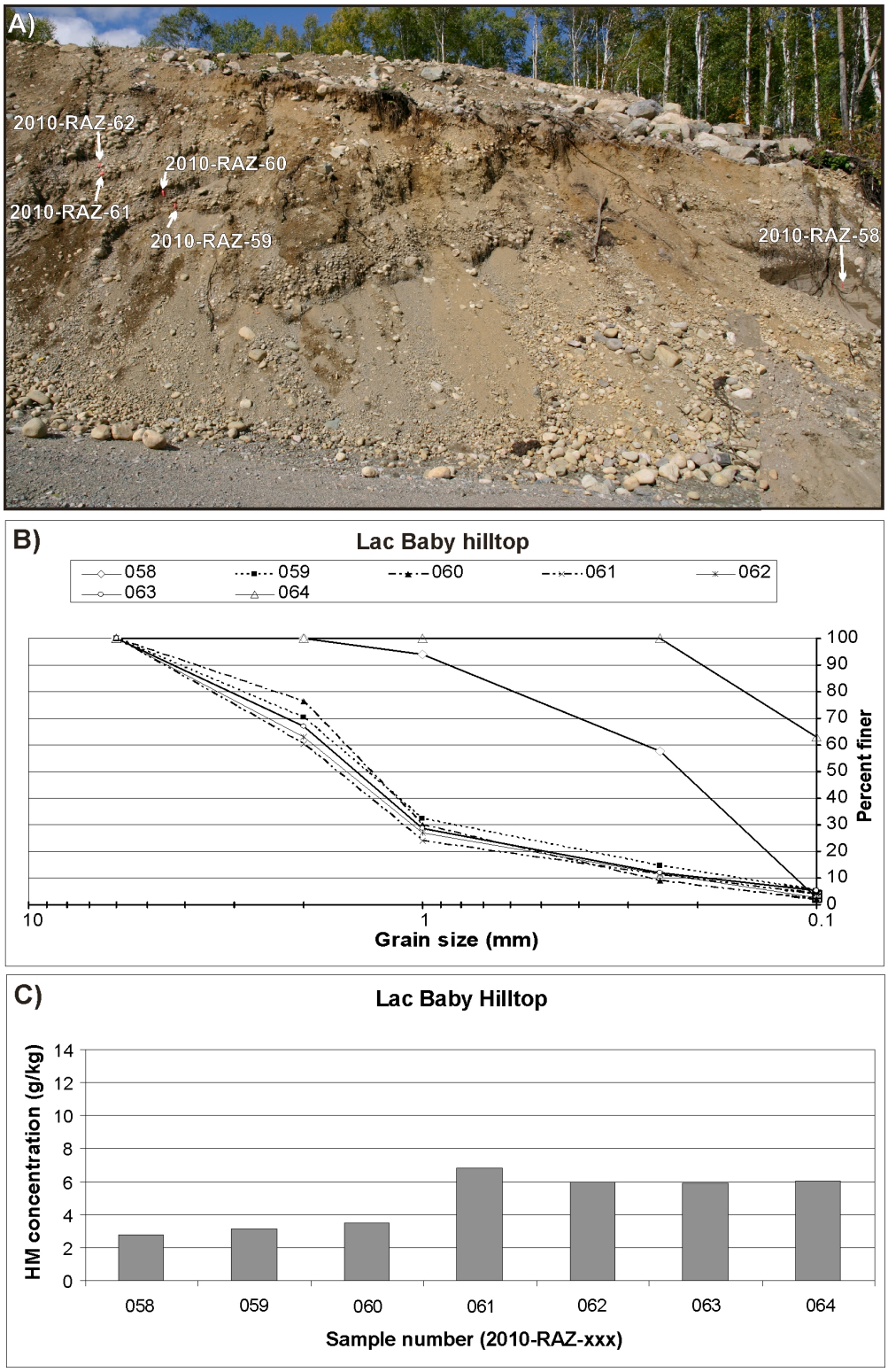


Figure 12:A) Overview of the Lac Baby hilltop exposure and sampling sites (Note: two sampling sites are not shown but were located within 1 m of the left edge of the photo). B) Grain size curves from sampled facies. C) Heavy Mineral concentrations of sampled facies.

5.2.3. Lac Baby Esker Camping: sedimentology

A partial, flow-normal, cross-section of an esker ridge is exposed in the Lac Baby pit (Fig. 13). The exposure can be subdivided into three main elements. The southeast flank consists of gently down-flow-dipping beds of planar stratified coarse sand interbedded with pebble to cobble gravel. The southwest flank consists of down-flow dipping cross-sets of medium to coarse sand truncated by a concave surface rising in elevation toward the ridge crests. Continuation of this surface defines the esker ridge form. The bulk of the ridge form consists mainly of planar and cross-stratified gravel with occasional planar bedded sand.

Eight facies were identified and sampled (Table 3). Overall, facies span a textural range between medium sand and boulder gravel (Table 3). Samples from the coarsest facies consisted mainly of the matrix material, which was typically composed of materials smaller than pebbles (Fig. 14).

5.2.4. Lac Baby Camping Esker heavy mineral counts

Heavy mineral concentrations within sedimentary facies are highly variable, ranging from < 2 to 15 g/kg (Fig. 15). A first order trend indicates that HM concentrate preferentially within sand-rich facies (Fig. 15, Table 3) and that HM concentrations generally decrease with increasing grain size. For example, coarse and medium sand facies have HM concentrations that are ~75-300 % greater than all other facies (Compare Figs. 15 A, C with Figs. 15 B, D-H). As well, most other facies have HM grain concentrations at or below 4 g/km. There are, however, some notable exceptions that require further examination. In particular, the boulder gravel facies has HM concentrations between 4-6 g/kg, and these concentrations are approximately median to the range noted in the suite of samples. In contrast, the dipping planar-bedded sand facies (Table 3, Fig. 15 H) has the lowest HM concentrations despite a texture approaching that of the HM-rich facies (Fig. 14).

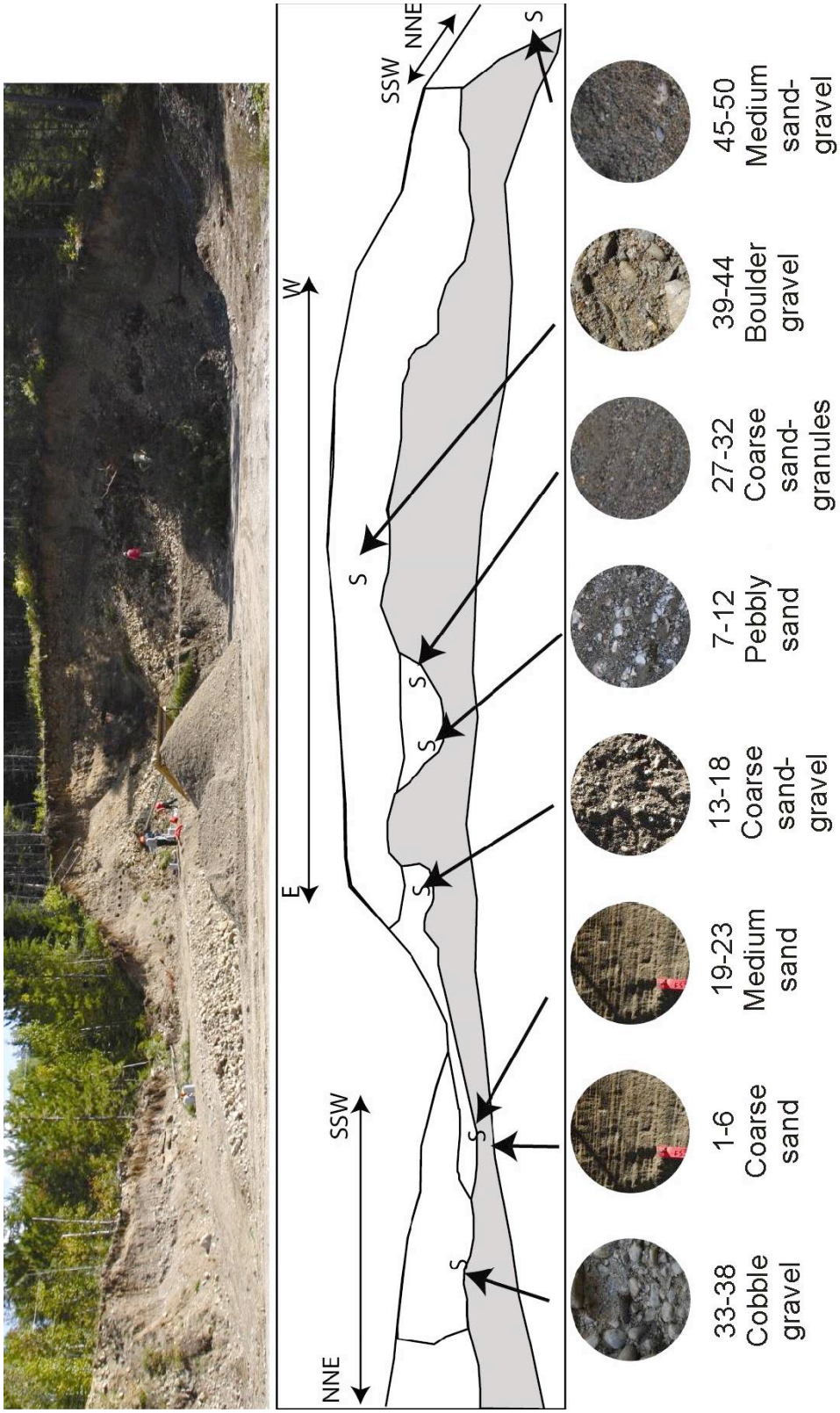
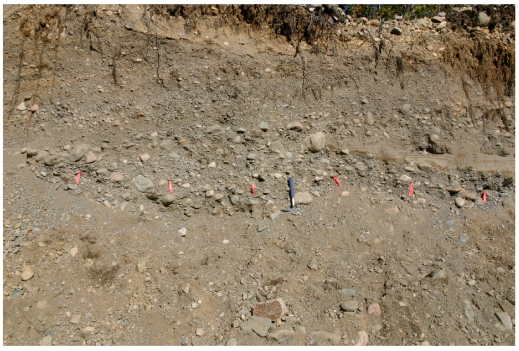


Figure 13: Exposure panorama and sketch locating sampling locations from the eight facies identified at the Lac Baby esker site. Grey area labelled S = slumped material.

Table 3: Summary characteristics of eight sedimentary facies identified in the Lac Baby esker pit. Rank refers to the relative abundance of HM/KIM in a facies when compared among all facies

Facies Name (sample #)	Description	Rank HM	Rank KIM	Representative Photo
Coarse sand (1-6)	Planar-bedded, well-sorted coarse sand with medium sand bed tops. Sub-horizontal beds thickening downflow from 0.5-2cm to 4-6 cm.	1	1	
Pebbly sand (7-12)	Dipping, planar-bedded pebbly sand. Pebble-rich bed bases fining upward to coarse sand. Occasional clast clusters.	7	6	
Coarse sand and gravel (13-18)	Subhorizontal, weakly bedded coarse sand and gravel. Normally graded beds consisting of clast-supported, matrix-poor bases and	6	3	
Medium sand (19-24)	Planar-bedded, well-sorted medium sand. Sub-horizontal beds thickening down flow from 0.5-2cm to 4-6 cm.	2	2	

Table 3: continued

Facies Name (sample #)	Description	Rank HM	Rank KIM	Representative Photo
Coarse sand and granules (27-32)	Dipping, planar-bedded coarse sand and granules interbedded with planar-bedded medium sand. Individual subangular to angular pebbles occur along some beds.	4	5	
Cobble gravel (33-38)	Faintly dipping, poorly sorted cobble and pebble gravel in a coarse sand to granule matrix. Clasts are typically sub-angular to sub-rounded. Clast clusters commonly occur. Faint normal grading may be present in some beds.	5	4	
Boulder gravel (39-44)	Heterogeneous boulder gravel in a coarse sand and granule matrix. Clasts commonly sub-angular to sub-rounded. Faint stratification sometimes visible. Locally clast supported but more commonly matrix supported.	7	3	
Medium planar bedded sand (45-50)	Steeply-dipping planar-bedded medium sand. Occurs as part of rhythmic graded gravel-sand couplets. Occasional lone pebbles within beds.	8	8	

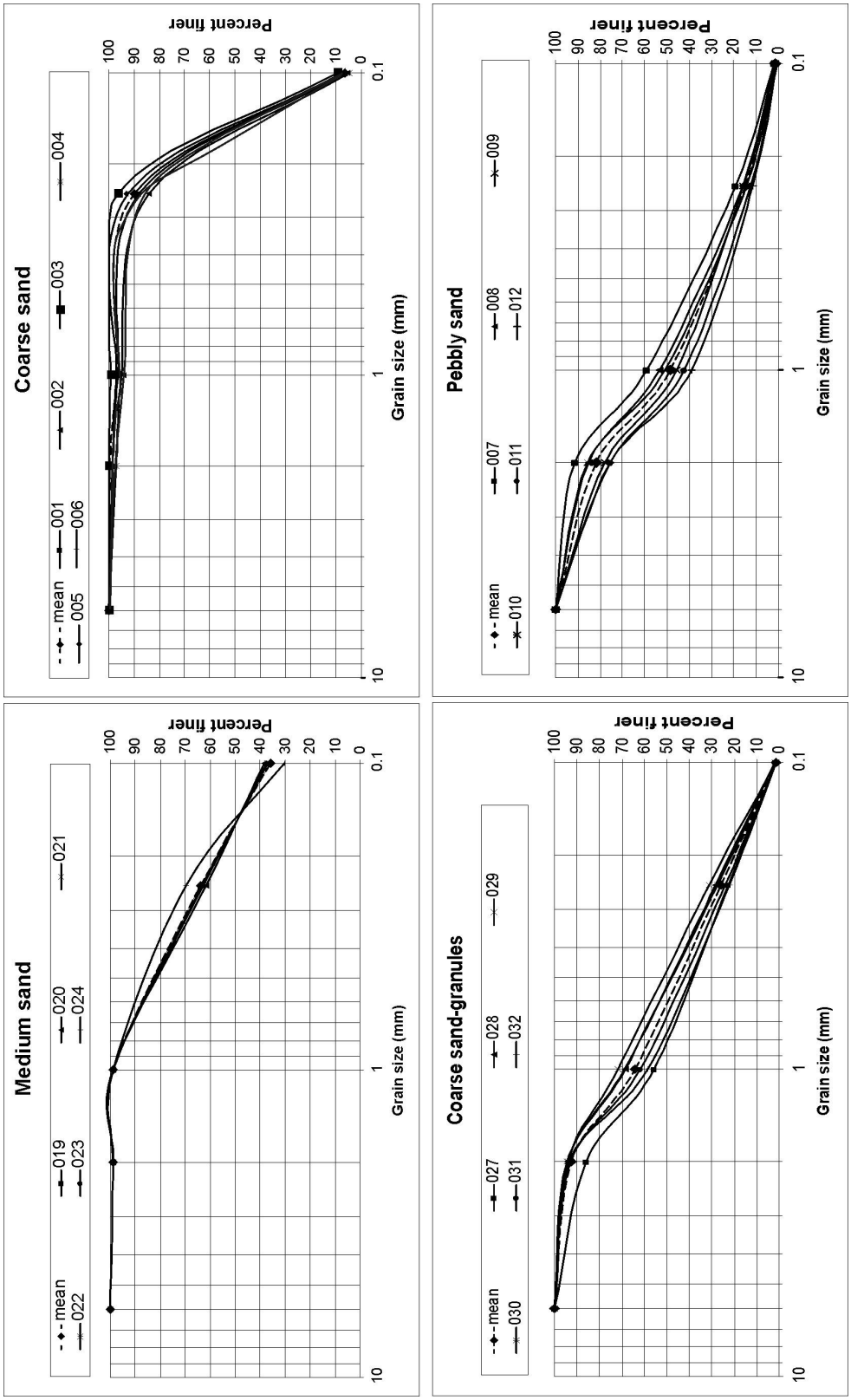


Figure 14: Grain size curves from the eight facies sampled at the Lac Baby pit.

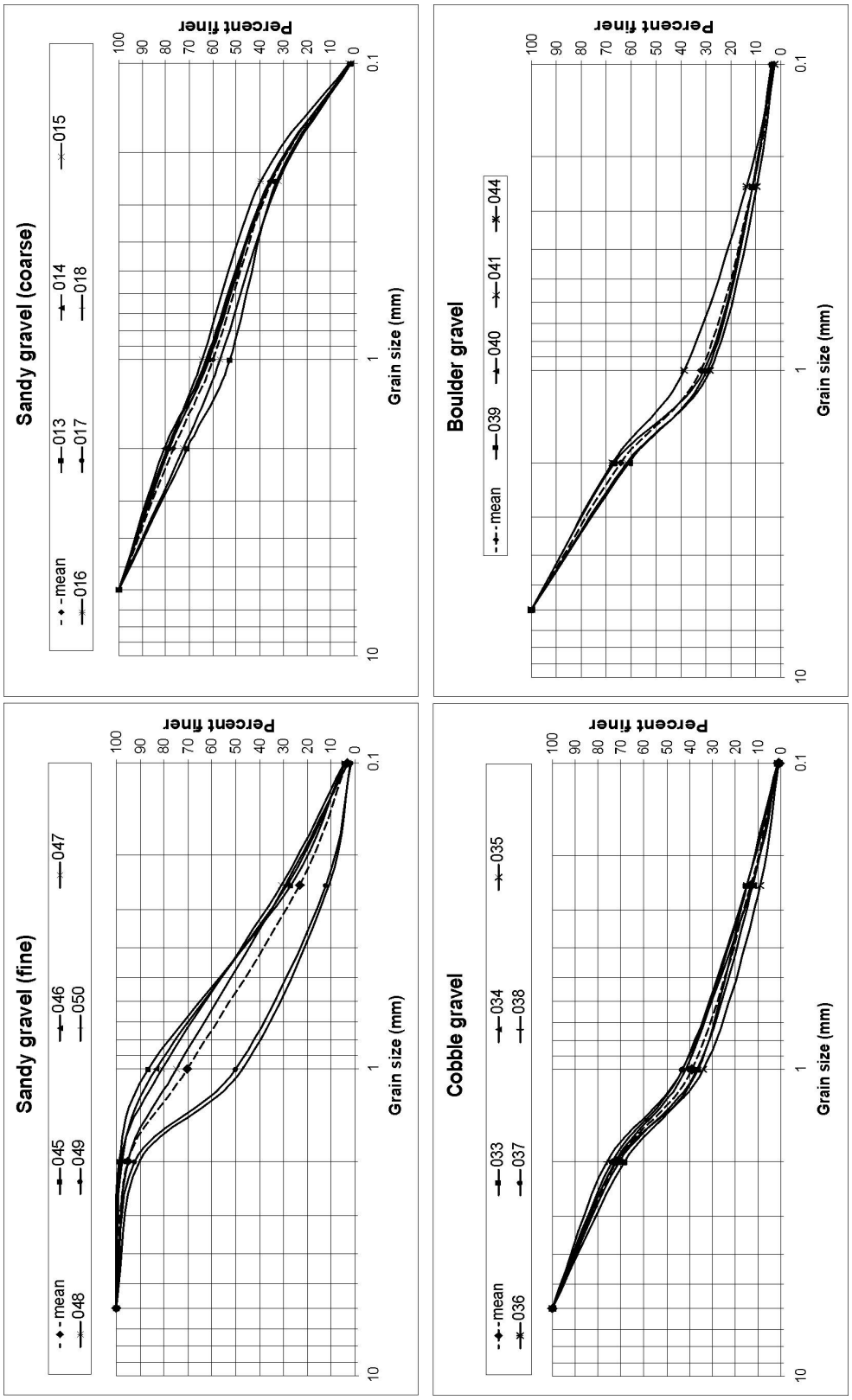


Figure 14: continued

The variability among facies could result from intrinsic variability of HM concentrations in individual facies. However, this possibility can be largely discounted due to the fact that there is generally low intra-facies variability in HM grain concentrations (Fig. 15). This indicates that inter-facies comparisons are valid and, more importantly, that differences in grain concentrations are unlikely to result from variability in the availability of HM, or the sampling scheme. Instead, these results suggest a process control on HM concentrations associated with depositional conditions of individual facies.

5.2.5. Lac Baby Camping Esker KIM and abundance

All sampled facies at Lac Baby contained KIM grains. Olivine and Mg-ilmenite dominate the suite of KIMs present, followed by both types of garnet (Fig. 16). These results are consistent with the dominant mineralogy of kimberlite cobbles found in the Lac Baby pit and in the vicinity of the Lac Baby esker (Section 5.2; Figs. 10, 11).

Despite the presence of KIM grains in all facies, grain abundance varies up to 20-fold between facies. This variability in KIM abundance among facies resembles the pattern observed in the HM distributions. In particular, the inverse relationship between KIM abundance and facies coarseness is more pronounced than in the HM data (compare 'ranks' in Table 3). For example, the highest KIM abundance occurs in one of the finer-grained and best sorted facies (Figs. 17 A, C), which has the #1 rank for HM and KIM. However, the boulder gravel facies (Fig. 17 F, G) has high HM, but low KIM. The planar-bedded medium sand facies, despite its finer grain size (Fig. 17 H) has low HM and KIM concentrations.

As was the case for the HM data, intra-facies variability is low. Most samples fall within one standard deviation of the mean KIM count for each facies. Some rare exceptions occur however: sample 001 and 019 (Figs. 16 A, D) are slightly below one standard deviation. It is also notable that within most facies (boulder gravel, and coarse sand and gravel being the exceptions), the relative differences between samples are similar in both the HM and KIM datasets: a sample with high HM concentrations also has high KIM

counts (and vice versa). These results further suggest that inter-sample comparisons are feasible and that KIM dispersal mainly (though not exclusively) reflects process controls rather than supply limits.

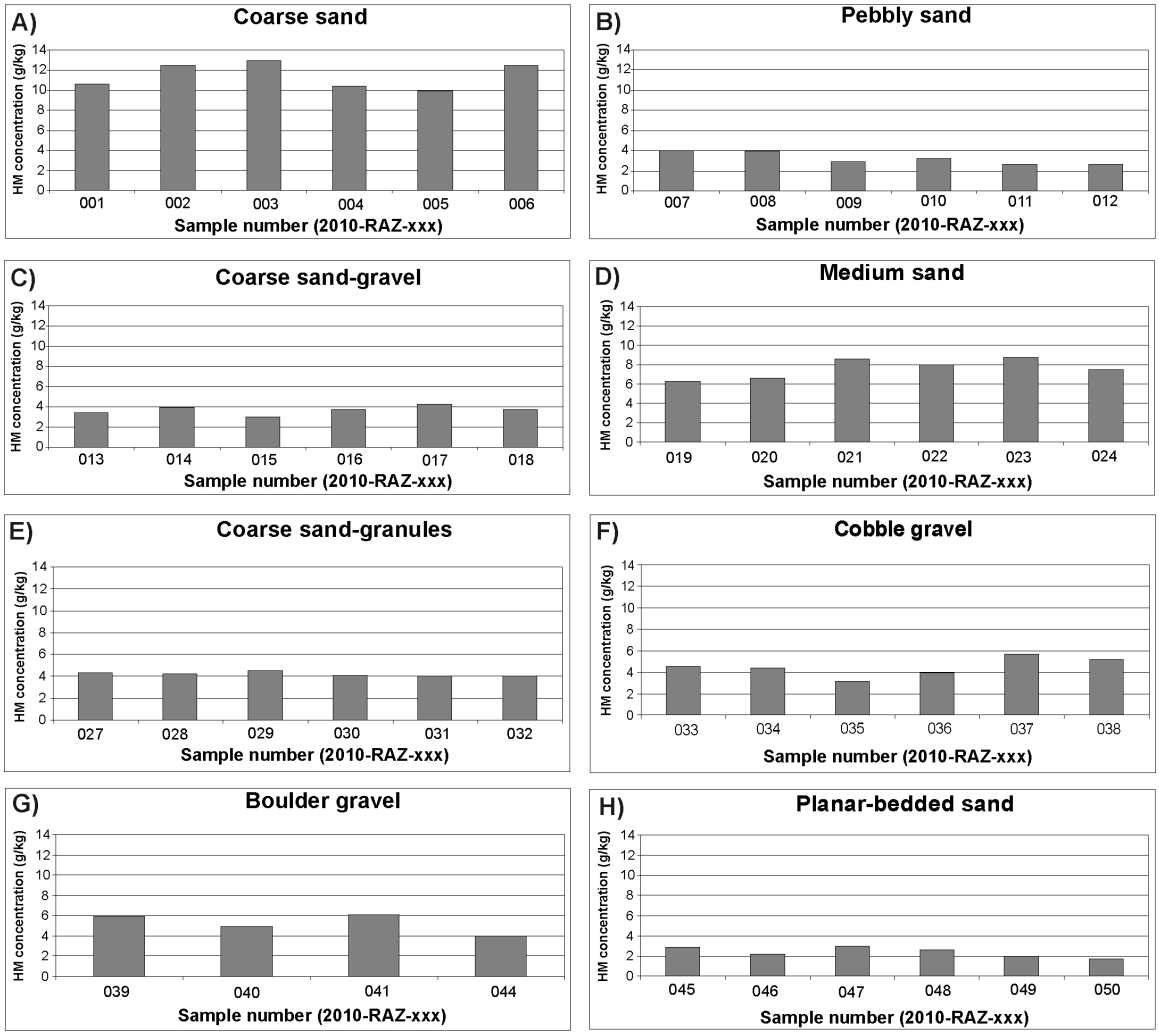


Figure 15: Heavy mineral concentrations in eight facies sampled at the Lac Baby camping site.

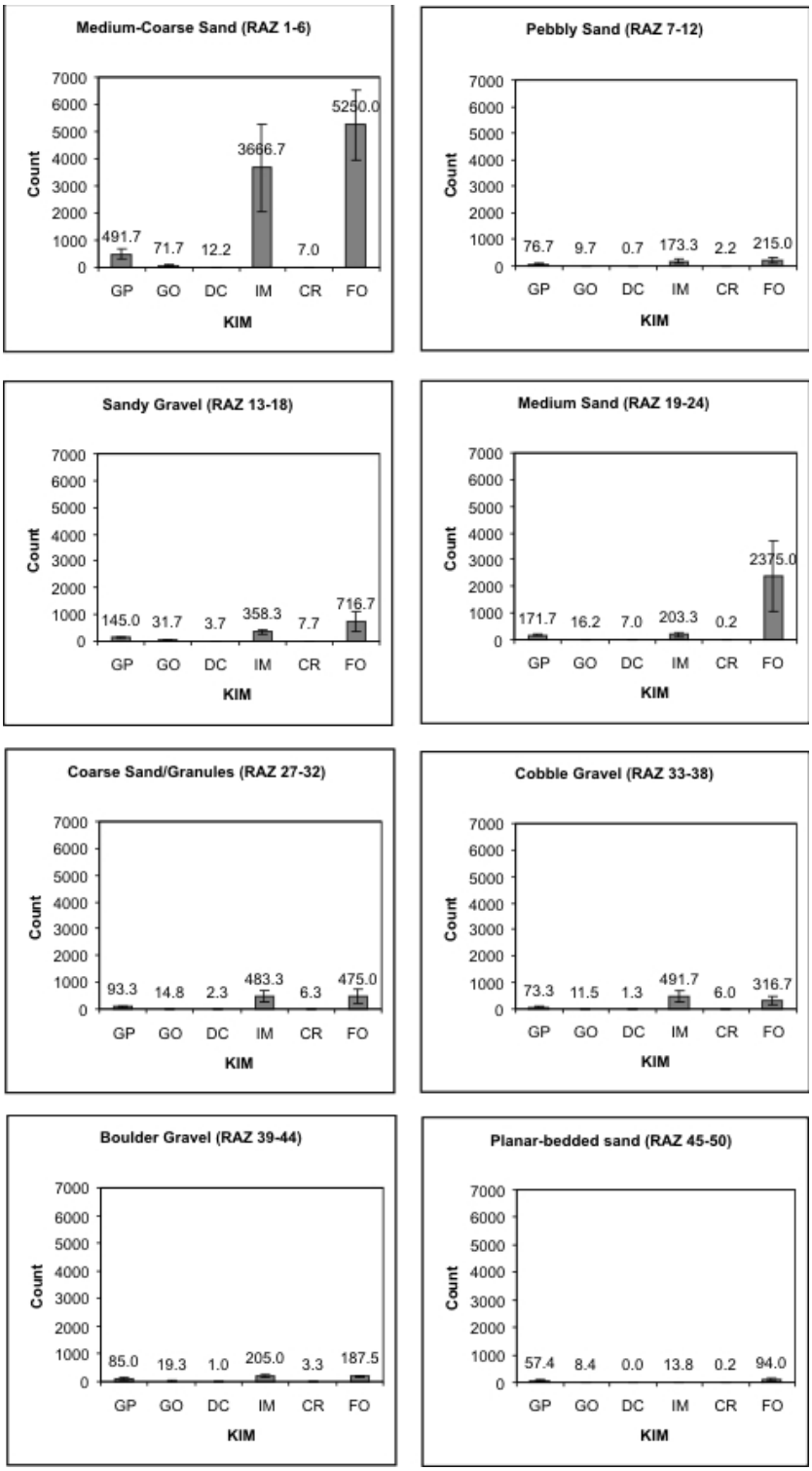


Figure 16: Breakdown of mean KIM mineralogy within facies at Lac Baby camping site. Error bars (one standard deviation) illustrate the range of each KIM within samples.

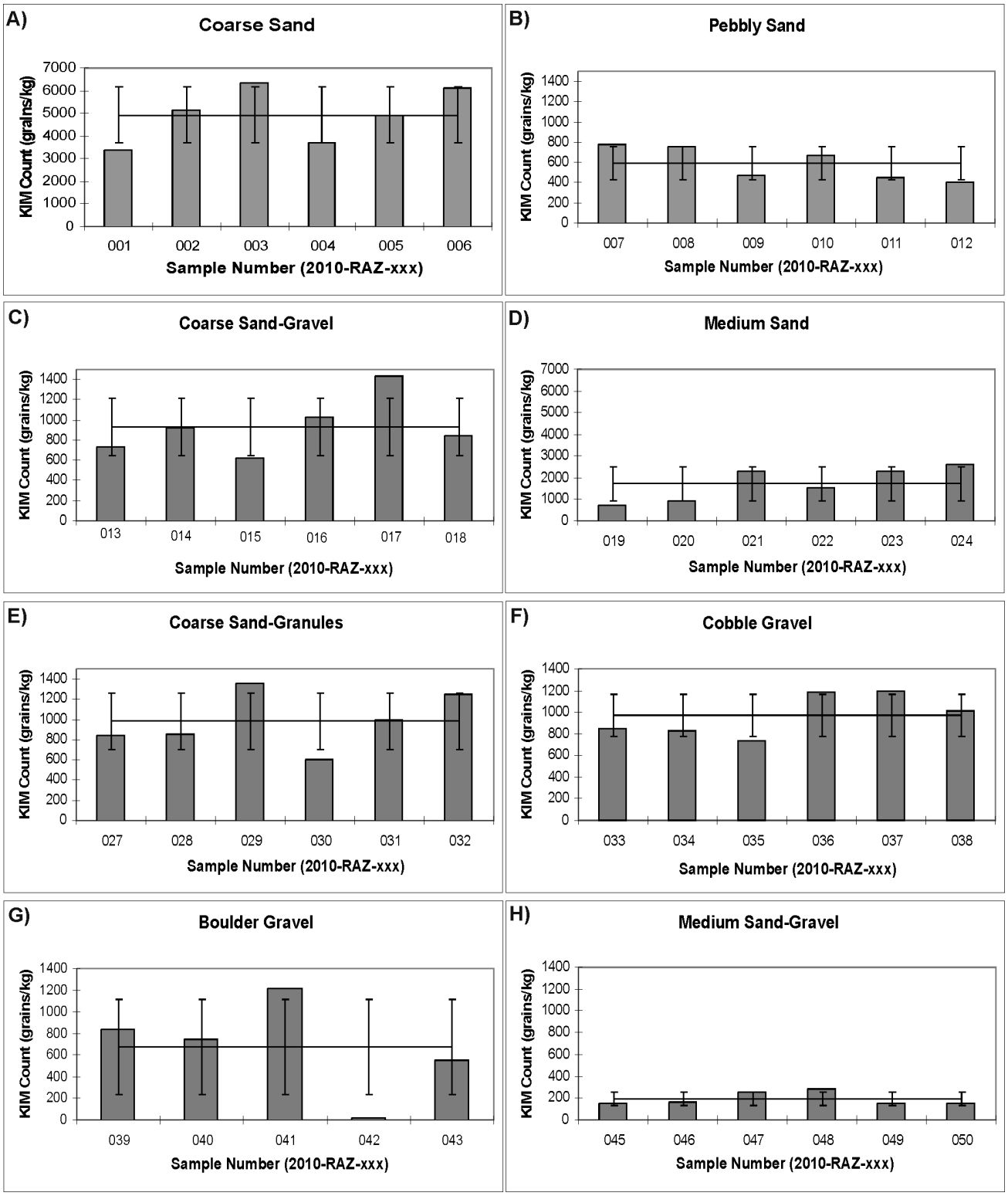


Figure 17: Kimberlite indicator mineral concentrations in eight facies sampled at the Lac Baby camping site. Mean KIM counts (line) and one standard deviation (error bars) are shown for visual assessment of intra-facies variability. Note: y-axis scaling differences for graphs A and D.

5.3. Site C Lac de Quinze Esker

Located just south of the dam from Rapides-des-Quinze the two sites are approximately 1 km apart and were inactive pits with extensive slumping. Three 15 kg samples were collected from sand, pebbly sand, and gravel. Heavy mineral recover for the three samples normalized to 1 kg range from 20.9 to 30.0 g. KIM recovery ranged from 1 to 5 grains with one chromite grain and the remainder olivine grains. The pebbly sand had the highest mass of heavy minerals followed by the gravel sample. These data suggest kimberlite SC-118 is not providing abundant KIM into the glacial or glaciofluvial system.

5.4. Sites E and F Lac de Quinze Esker

Sites E and F are both road side sites with limited stratigraphic, architectural and landform information. Surface sediment along the roadside was dominated by sand. Sample 54 at site E yielded 107 g of <2 mm HM whereas sample 55 (site F) yielded 27 g. Only one potential KIM mineral was identified from sample 54. Sample 56, a 1 kg sample (from site F), yielded 10.4 g of < 2 mm HM fraction (normalized 1 kg) and no KIMs.

6. Discussion

Case studies have documented preferential concentration of heavy minerals in gravely facies of modern streams (e.g., Afanasev et al., 1984; Muggeridge, 1995) and this relationship is also applicable to ancient streams (Carling and Breakspear, 2006). As a result, gravely stream facies are targeted during stream sampling campaigns. In contrast, sandy facies are commonly avoided (e.g., Gregory and White, 1989). Based on these approaches, HM and KIM sampling of eskers has also focused preferentially on gravely rather than on sandy facies (Atkinson, 1989; Craigie, 1993; Parent et al., 2004). However, esker sampling in the Lac de Gras area sought out gravelly sand facies (Fipke, pers. comm to Sharpe and Cummings, March 2010)

6.1. General trends

Results from detailed facies-scale sampling of esker segments and other glacifluvial deposits within the Lac Baby segment of the Laverlochère glacifluvial complex clearly show that certain sandy facies preferentially concentrate HM and/or KIM. The results also show, however, that not all sandy facies concentrate HM/KIM equally. For example, HM/KIM are most abundant within well-sorted sandy facies recording bedload transport and grain-by-grain deposition. In contrast, poorly sorted facies recording rapid deposition of potentially dense sediment flows do not concentrate HM/KIM to the same degree, presumably as a result of limited bedload transport and longitudinal sorting.

6.2. Complex trends in dispersal and concentration

Results also indicate that gravely facies should not be completely abandoned as sampling media. Cobbly and bouldery facies concentrate HM grains to varying degrees. Detailed process understanding of sedimentary facies and sediment entrainment within eskers are required to maximize HM/KIM retrieval in gravely esker facies. For example, the boulder bedform at the MRP exhibits HM grain counts approaching the highest concentrations recorded at Lac Baby where gravely facies tend to have much lower HM/KIM concentrations. At MRP, the matrix filling interstices between clasts is well sorted and, as discussed in section 5.1.2, may result from space-filling after deposition of the coarser framework gravel. Alternatively, both sand and gravel may be penecontemporaneous. In either case, the sandy matrix has likely undergone prolonged transport and longitudinal sorting. Its deposition may result from flow separation in the lee of the bedform brinkpoint. Thus, although gravel dominates these facies, it is the matrix characteristics that determine the degree of HM/KIM concentration.

Furthermore, results of HM and KIM concentration in gravely facies at the Lac Baby pit seem to contradict some of the statements above. For example, gravely facies have some of the highest HM concentrations. Yet, the KIM abundance for the same facies is among the lowest. These HM-KIM discrepancies may reflect differences in the stratigraphic position of facies within the esker and local variability in the supply of KIM. That a

significant mineralogical variation exists within the kimberlite clasts studied here (and in previous studies) strongly suggests there are multiple kimberlite sources providing KIM.

For example, HM are available from the ongoing breakdown of most material in contact with sediment moving within the esker, and with surrounding till sources. HM can potentially originate far from the depositional site. In this case, HM are unlikely to be supply limited and HM grains can be repeatedly remobilized from upflow esker segments. In contrast, availability of KIM may be more limited due to the punctual nature of kimberlite pipes: KIM can only be entrained locally if the esker directly erodes a kimberlite source or incorporates till that previously incorporated material from a nearby kimberlite source. At Lac Baby, the highest KIM and HM counts occur in facies that are near the base of the esker exposure, potentially recording sediment deposition at a time when KIM-rich material had been entrained (from the till or directly from a kimberlite source). Following initial entrainment of the KIM, the source may have been either depleted or esker sediments shielded the source from further erosion. In contrast, gravely facies occur in the upper half of the exposure. Despite poorer matrix sorting in the gravely facies, it is clear that some degree of HM concentration has taken place. Therefore, the low KIM counts might reflect the low availability of KIM due to shielding/depletion, while HM remain available for concentration due to their regional abundance.

These findings appear to contradict existing sampling protocols, based on fluvial settings, emphasizing sampling of gravely facies (Afanasev et al., 1984; Muggeridge, 1995). They can be rationalized, however, once sorting processes and rapid deposition are considered. In fluvial settings, it is generally recognized that HM grains become trapped within gravel interstices overtime. In this situation, gravel depositional processes have little to do with the occurrence of HM: grains undergo sorting prior to gravel infiltration and gravel facies act as hosts for HM. In contrast, some sampled gravely facies within the Lac Baby esker record rapid en-masse deposition of sediments with limited sorting, resulting in low HM/KIM concentrations. Other gravely facies have higher HM/KIM concentrations due to varying degrees of grain sorting.

Overall, results from Lac Baby indicate that HM/KIM concentration is strongly controlled by depositional processes and, in a secondary fashion by indicator grain availability. These controls emphasize the importance of facies interpretations for sampling strategies, and the interpretation of HM/KIM data. In the absence of detailed facies information, well-sorted sandy facies such as planar-bedded sand offer the highest potential for detecting HM/KIM in eskers.

7. Conclusions

Findings reported herein represent preliminary steps into understanding HM/KIM grain concentration within eskers. These results highlight the following:

i) Well sorted sandy facies, particularly planar-bedded sand, offer the greatest potential for detecting HM/KIM in eskers.

ii) Gravely facies tend to have lower HM/KIM abundance than most sandy facies. However, gravely facies with well-sorted interstitial sand have high HM/KIM

iii) Within gravely facies, matrix characteristics (especially sorting) is the key indicator of the potential for HM/KIM abundance as the degree of sorting of medium to coarse sand grains may be a better indicator of the presence of HM/KIM in a deposit.

iv) Although general patterns may be discerned, it is also apparent that local factors affect HM/KIM abundance. In particular, the availability of KIM may have an impact on their presence within facies that are able to concentrate these indicators (as seen by elevated HM but an absence of KIM within a facies). Hence sampling of similar sedimentary facies in different stratigraphic positions within the esker may yield different results.

This paper documents some of the first process-based inferences of the mechanisms of HM/KIM grain concentration within glacifluvial sediments. From a conceptual standpoint, these results highlight fundamental process differences in HM/KIM partitioning between fluvial and glaciofluvial environments. These fundamental process differences need to be better recognized and integrated within sampling protocols. The process differences and variations in HM/KIM provenance, sourcing, and esker architecture and stratigraphy, need to be more clearly identified in order to effectively guide sampling strategies and interpretations of results.

8. References

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