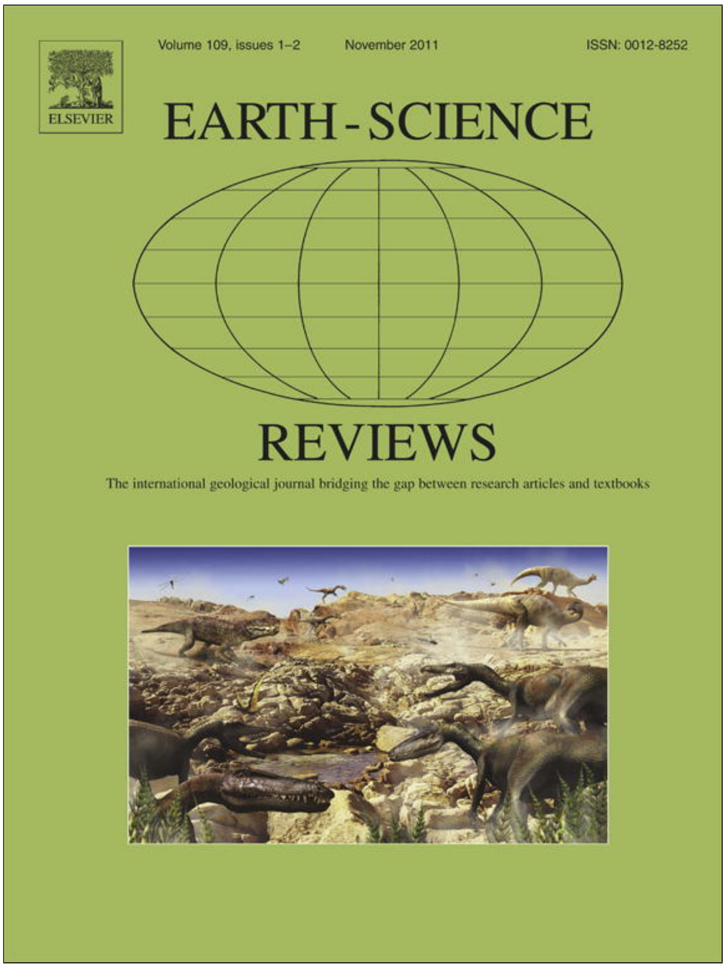
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Eskers as mineral exploration tools

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ABSTRACT

Eskers are commonly sampled for indicator minerals during drift prospecting campaigns on the Precambrian Shield. However, a literature review reveals that indicator mineral dispersal in esker sedimentary systems is poorly understood. As a result, exploration companies lacking their own proprietary knowledge are left with little basis for understanding how to collect esker samples or how to interpret esker data. Based on the literature review, and drawing insights from a broader body of literature on modern glaciers, laboratory experiments, and gravel-bed streams, a preliminary conceptual framework for esker sedimentary systems is established to address these issues. A research strategy is then outlined, one whose objective is to fill knowledge gaps and, in doing so, improve the effectiveness of mineral exploration in glaciated terrain.

Contents

1. Introduction

Eskers are common in glaciated terrain (Fig. 1; Levasseur, 1995; Brennand, 2000). They are, along with stream sediments and till, one of three principal media sampled during drift prospecting to identify indicator mineral dispersal trains downflow of mineral deposits (Fig. 2). Esker sampling is a proven method: it has led to the discovery of several kimberlites (Lee, 1968), including the Lac de Gras kimberlite field, home to Canada's first diamond mine (Krajick, 2001; Kjarsgaard and Levinson, 2002). Although commonly associated with diamond exploration, esker sampling can be used to explore for any mineral deposit type that yields a characteristic suite of indicator minerals (e.g., Ni–Cu–PGE deposits; Averill, 2009). Given this, one might expect that indicator mineral dispersal in esker sedimentary systems is a well researched and well understood phenomenon. However, based on the paucity of published literature on the subject, we suggest this is not the case. Exploration companies lacking 'in-house' knowledge are faced with two major, unanswered questions.

Question 1 — esker sampling methods
How should eskers be sampled for indicator minerals?

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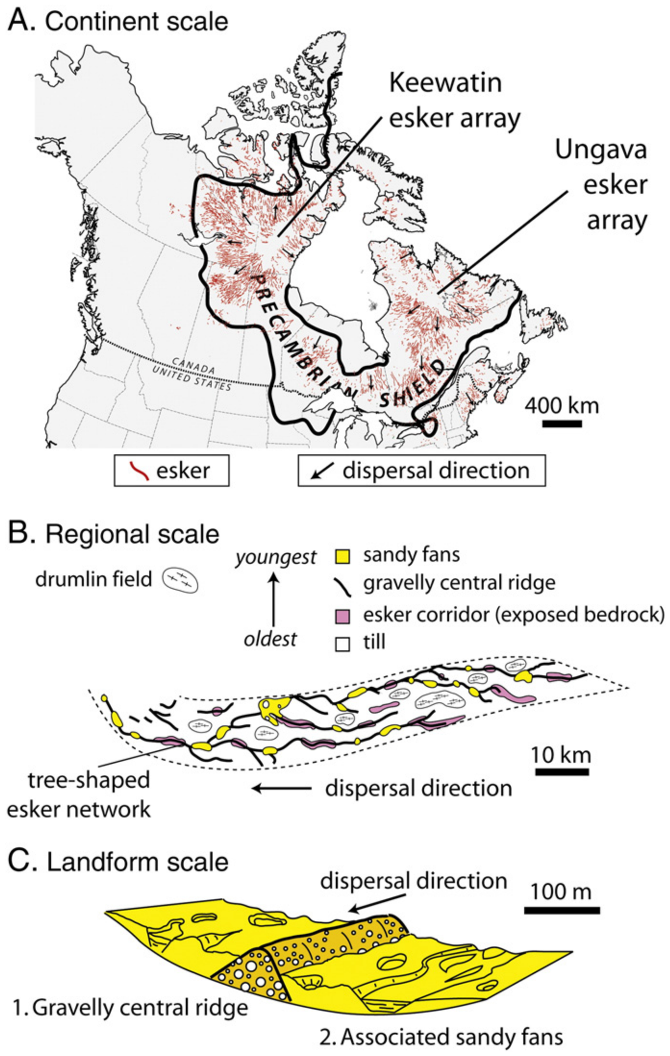

Fig. 1. Eskers viewed at various scales. Modified from Prest et al. (1968), Aylsworth and Shilts (1989), and Bolduc (1992). Esker corridors can in some areas be more continuous than illustrated.

Question 2 — esker data interpretation

How should esker data be interpreted? Specifically, if an indicator mineral is found in an esker, how far down-esker did it travel? Did it travel farther than a pebble from the same source? What about a boulder?

The objectives of this paper are to (1) review the salient features of eskers and their dispersal trains; (2) review ideas on how eskers and their dispersal trains form, from bedform to basin, drawing insight from a broader body of literature on modern glaciers, lab experiments, and gravel-bed streams; (3) discuss the implications of (1) and (2) with respect to the two applied questions at hand, namely how to sample an esker and how to interpret esker data; and (4) recommend future research.

2. Eskers: a primer

Eskers are shoestring-shaped ridges of glaciofluvial sand and gravel (Cummings et al., 2010). They are present throughout glaciated parts of North America, but are best developed and best exposed on the Precambrian Shield (Fig. 1). In this paper, we focus specifically on eskers on the Shield because it is here where they are most commonly sampled during mineral exploration.

Like spokes on a wheel, most Shield eskers radiate out from two areas where ice masses were centered during the last deglaciation (Fig. 1A), one in Keewatin and one in Ungava (Shilts et al., 1987). Additional esker ridges are present in the outer portions of the arrays that counterbalance radial divergence and maintain a quasi-regular spacing of 8 to 15 km (Aylsworth and Shilts, 1989; Bolduc, 1992). When traced outward (downflow) from the array centers, eskers tend to join together, forming tree-shaped networks that look like tributary stream networks (Fig. 1B), albeit conspicuously elongate ones (Bolduc, 1992). Terminal fans are generally absent or poorly developed at the end of the networks (Shilts et al., 1987). Closer inspection reveals that individual limbs of the networks consist of two geomorphic elements, a narrow coarse-grained ridge-shaped element, commonly gravelly, superimposed or flanked by broad finer-grained fan-shaped elements, commonly sandy (Fig. 1C). Gravelly ridge elements are on average 10 to 100 m wide and 3 to 25 m high and consist of varying proportions of medium to coarse sand and well rounded gravel. Locally, gravelly ridges are overlain by sparse boulders, as is commonly the adjacent landscape. Ridge flanks tend to be near the angle of repose, and their tops are sharp- to round-crested or flat (Bolduc, 1992; Dredge et al., 1999). Sandy fan elements are of similar height or less than the gravelly

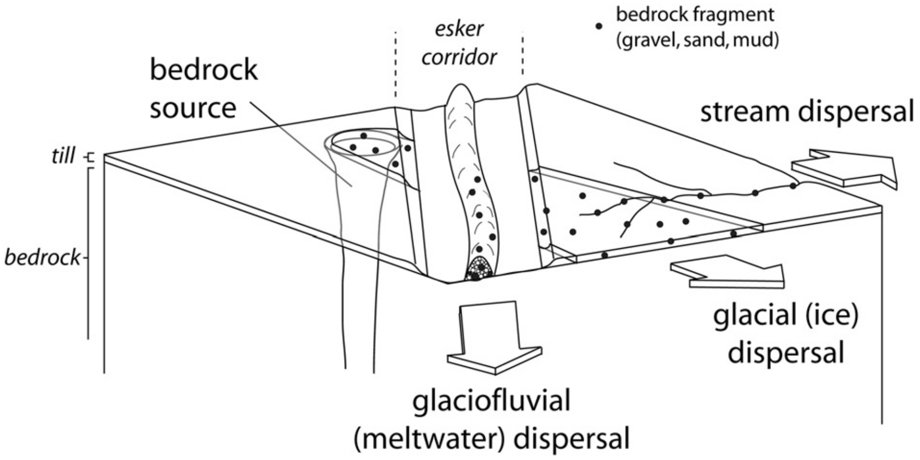

Fig. 2. The three principal mechanisms by which bedrock fragments are dispersed in glaciated terrain, and the three principle media — till, eskers, and stream sediments — that are sampled for indicator minerals during exploration in such settings. Aeolian dispersal may also be important, especially for mud and finer sand (Pye, 1987), but the dispersal trains are likely too aerially extensive and diffuse to be of practical use. Coastal processes likely concentrated indicator minerals as opposed to dispersing them significantly because late-glacial water bodies were ephemeral.

ridges but an order of magnitude wider (Cummings et al., 2011b). Their surfaces are boulder-free, flat topped to irregular, and can be ornamented by circular (ice-block) depressions and, less commonly, braid-bar-like features (Bolduc, 1992; Dredge et al., 1999). Gravelly ridges and sandy fans are typically mapped as eskers sensu stricto and esker-associated proglacial outwash, respectively (e.g., Aylsworth and Shilts, 1989; Bolduc, 1992).

Few subsurface (stratigraphic) data exist on the Shield to rigorously constrain these geomorphic observations in the vertical (time) dimension. Several inferences can be made, however, using indirect data and reasoning. The Quaternary stratigraphic succession on the Shield is generally simple: it consists of diamicton (till), glaciofluvial sand and gravel (e.g., eskers), and, locally, glaciolacustrine or glaciomarine mud (Prest et al., 1968; Fulton, 1995). Shield eskers commonly reside in discontinuous, till-free, channel-form zones of exposed bedrock, here termed *esker corridors*, each several hundred meters to several kilometers wide (Fig. 1B; Craig, 1964; Rampton, 2000; Utting et al., 2009). This suggests eskers generally rest erosively on their substrates (for an alternate view, see Lundqvist, 1979). Moving stratigraphically upward, gravelly ridge elements are commonly depicted as underlying sandy fan elements (e.g., Fig. 1C), a relationship supported by the rare high-quality subsurface datasets in Shield areas (e.g., Sharpe et al., 1992).

3. Esker depositional models

Researchers generally agree on a basic depositional scenario for eskers during the last deglaciation (Fig. 3; Cummings et al., 2010). It is the details of this scenario, not the scenario itself, that pose most controversy. Below, we outline this basic scenario. For alternative models, see Levasseur (1995) and Huddart and Bennett (1997).

Most glacial meltwater is produced at the glacier surface, and primarily at lower altitudes where the air temperature is warmer, during positive-degree days (Box et al., 2006). Geothermal heating and shear at the base of the glacier also produce meltwater, and do so perennially, but at rates that are typically orders of magnitude less, at least outside zones of abnormally high geothermal heat flux (Fahnestock et al., 2001). Surface meltwater flows under gravity down crevasses and moulins to the base of the glacier (Zwally et al., 2002), then under pressure to the ice front through tunnels melted up into the ice, termed R-channels (after Röthlisberger, 1972). Meltwater discharge from R-channels is highly seasonal and spiky (Østrem, 1975) and can be punctuated by jökulhlaups from supra- or subglacial lake drainage events (e.g., Fowler and Ng, 1996). Clastic particles are entrained from the underlying sediment and/or bedrock (Alley et al., 1997), and from debris-rich basal ice (Shreve, 1985a), which continuously flows into R-channels under the weight of the overlying ice (Röthlisberger, 1972). Distributed, pressurized meltwater at the base of the glacier, which occurs in linked cavities and thin films (Fountain and Walder, 1998), likewise flows into R-channels, because the R-channels tend to be at a lower pressure (Röthlisberger, 1972; Shreve, 1972; Boulton et al., 2007). Finer sediment fractions in the R-channel are bypassed to the ice front, whereas coarser fractions deposit subglacially (Cummings et al., 2011b). Sediment may deposit in subglacial cavities adjacent to the R-channel (Gorrell and Shaw, 1991), but, given the paucity of sediment in esker corridors (e.g., Craig, 1964), areas lateral to R-channels are net sediment sources, not net sediment sinks. The end result is a narrow coarse-grained ridge, commonly gravelly (R-channel deposit — the esker sensu stricto), that correlates downflow to a broad, finer-grained proglacial fan, commonly sandy and locally deformed due to melt of buried ice (Shilts et al., 1987), which takes on the form of a subaerial outwash fan, delta, or subaqueous outwash fan depending on the presence and depth of proglacial water.

Within this basic scenario, the most contentious issue is R-channel length (Brennand, 2000). Two end-member models exist, referred to here as the *short-conduit model* (Fig. 3A) and the *long-conduit model* (Fig. 3B).

In the short-conduit depositional model (Fig. 3A), the ice sheet is envisioned to remain active as its margin retreats, which generates a steep ice profile and a narrow ablation zone. Abundant melting is restricted to the fringe of the ice sheet, R-channels are short, and short channel–fan segments are deposited in them. As the ice retreats, the short channel–fan segments shingle time-transgressively onto each other, eventually depositing a long esker ridge. Tree-shaped esker

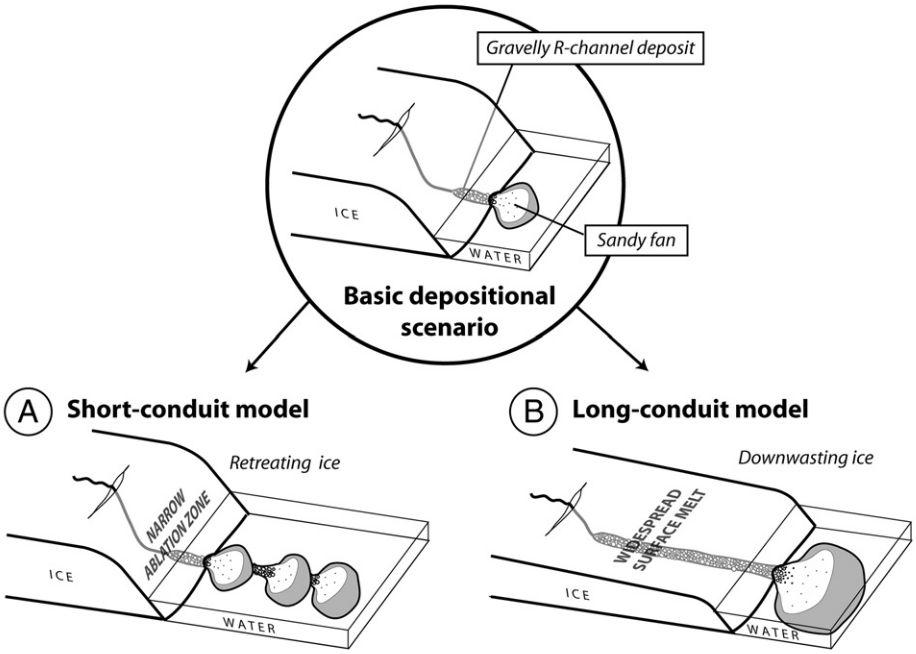

Fig. 3. The basic depositional scenario in which most eskers are envisioned to form, and two end-members of this basic scenario, here referred to as the short- and long-conduit models. The proglacial area is depicted as subaeuqueous, but it could equally be subaerial. Irrespective, a fan-shaped proglacial sediment body should form. (A) The short-conduit model. In this model, the subglacial conduits (R-channels) remain short and the ice retreats, causing channel–fan segments to shingle onto each other, eventually generating an esker. (B) The long-conduit model. In this model, the ablation zone is envisioned as being large and R-channels consequently long. A single long channel–fan segment is deposited.

networks, which imply optimized area-to-point fluid drainage (Bejan, 2000), are arguably difficult to explain under this model; they may form because a tree-shaped template was provided by a subglacial stream network maintained by basal melt (Ashley et al., 1991; Boulton, 2009), because a tree-shaped template was provided by a surface stream network (Shilts, 1984), or because moulins and surface streams migrated during esker deposition (Hooke and Fastook, 2007). St. Onge (1984) suggests that eskers near Redrock Lake, N.W.T., consist of segments that are 1–2 km long, whereas Hooke and Fastook (2007) argue the Katahdin esker, Maine, consists of segments that are ~5 km long. In addition to these authors, versions of this model have been invoked by De Geer (1912), Banerjee and MacDonald (1975), Shilts (1984), Hebrand and Amark (1989), and Boulton (2009).

In the long-conduit depositional model (Fig. 3B), the basic scenario remains the same, but the ice is envisioned to thin or downwaste in place, generating a low ice-surface profile and widespread surface melting. This permits R-channels to lengthen accordingly. In each R-channel, a single long channel–fan segment forms “synchronously” that may take on a tree-like shape. Brennand and Shaw (1996) argue that the Harricana esker, Quebec, consists of a single ~300 km long tree-shaped segment, and Shreve (1985a,b) argues that the Katahdin esker, Maine, consists of a single ~150 km long tree-shaped segment. Ice-front retreat may occur subsequent to esker deposition, causing sandy proglacial fans to deposit over or beside the gravelly ridge (Brennand and Shaw, 1996), but the length and shape of the esker, as envisioned in this model, fundamentally reflects the length and shape of the original, long, tree-shaped R-channel. In addition to the aforementioned authors, versions of the long-conduit model have been invoked by Hummel (1874), Sollas (1896), Flint (1930), and Brennand (1994).

4. Esker dispersal trains

Esker dispersal trains have been investigated by a number of researchers at various levels of detail (Hellaakoski, 1931; Trefethen and Trefethen, 1944; Virkkala, 1958; Lee, 1965, 1968; Gillberg, 1968; Van Beever, 1971; Shilts, 1973; Buck, 1983; Brown, 1988; Pertunnen, 1989; Lillieskold, 1990; Bolduc, 1992; Brennand, 1994; Ellemers, 1994; Johnson, 1994; Golubev, 1995; Levasseur and Prichonnet, 1995; Henderson, 2000; Parent et al., 2004; Tremblay et al., 2009). In well-constrained esker studies — studies in which multiple samples were collected from eskers and till downflow of a known bedrock source — gravel dispersal trains measured head to tail are about the same length as gravel dispersal trains in the underlying till, but are shifted down-flow relative to the till by several kilometers to at most 25 km (Fig. 4). Coarse-sand dispersal trains in the eskers are similar in length to the gravel dispersal trains (Fig. 4). Eskers are commonly enriched in heavy minerals relative to till (Wolfe et al., 1975; Averill, 2001). Aeolian deflation or wave reworking of the esker surface may cause further enrichment of heavy minerals following esker deposition (Craigie, 1993). Gravelly esker facies can contain more, less, or similar amounts of heavy minerals than sandy esker facies (Pertunnen, 1989). Heavy mineral assemblages are commonly reported to be texturally and mineralogically immature, meaning that grains tend to be relatively angular and that easily weathered mineral species (e.g., olivine), or easily weathered components of individual grains (e.g., kelyphite rims on garnets), are not necessarily under-represented (Wolfe et al., 1975; Dredge et al., 1997; Averill, 2001). Gravel clasts, in contrast to sand grains, tend to be well rounded; even friable lithologies, such as shale (e.g., Johnston, 1994), tend to become rounded in esker sedimentary systems.

Given the short- versus long-conduit debate (Fig. 3), one might surmise that the dispersal data in Fig. 4 have an obvious explanation: eskers must form according to the short-conduit model, namely in segments as the ice front retreats; the segments must be short, between 1 and 25 km long; and this must limit esker dispersal to distances of 1 to 25 km past the edge of the till dispersal train. Such a conclusion is preliminary for two reasons. First, the esker dispersal-train dataset is small, and therefore of questionable statistical significance, especially for sand-sized indicator minerals (e.g., heavy minerals). Second, as outlined below, processes in long conduits could potentially produce similar results.

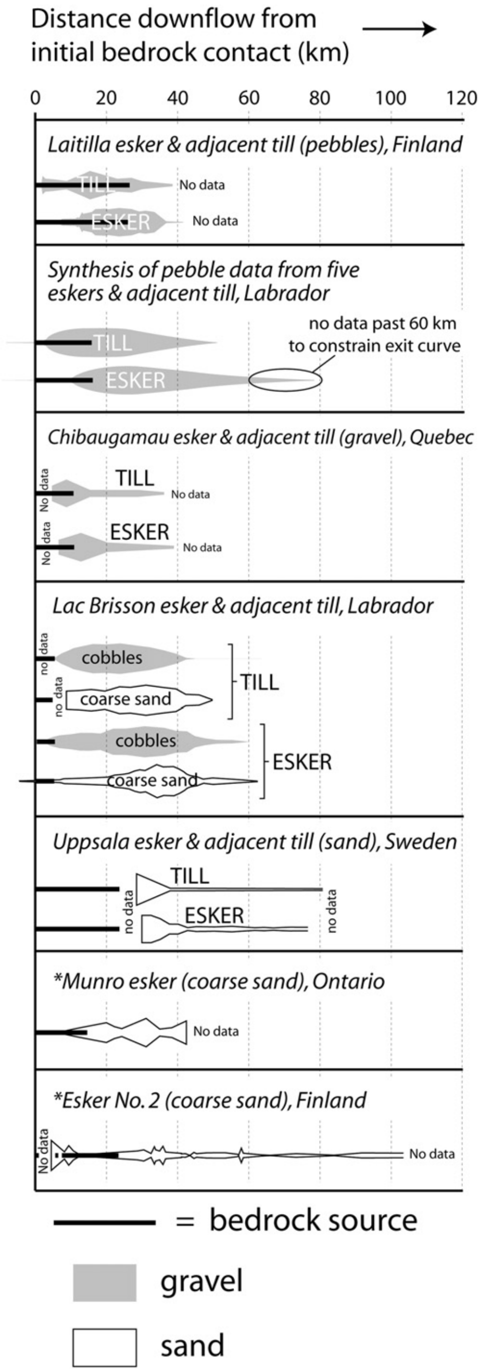

Fig. 4. Summary of dispersal data from esker downflow of known bedrock sources. In order to illustrate the relative contribution of glacial (till) versus glaciofluvial (esker) transport to total dispersal, studies where both esker and till data were collected are highlighted. Laitilla esker data from Hellaakoski (1931); Munro esker data from Lee (1965); Uppsala esker data from Gillberg (1968); Finnish esker No. 2 data from Pertunnen (1989); Labrador and Lac Brisson esker data from Bolduc (1992); and Chibaugamau esker data from Levasseur and Prichonnet (1995).

4.1. Variables affecting dispersal trains

Clastic dispersal trains in sedimentary media — whether in eskers, till, stream deposits, aeolian deposits, or otherwise — can be viewed as the product of five variables: (1) source characteristics (S), (2) dispersal regime (D), (3) weathering regime (W), (4) base-level (B) changes, and (5) residency time (T) of clastic particles in the sedimentary system (Fig. 6). In other words,

$$\text{Clastic dispersal train} = \mathrm{f}\{S, D, W, B, T\}.$$

Different dispersal trains reflect different combinations of these controlling variables. In some cases, a particular variable dominates. Gold dispersal trains in till are commonly short (<5 km), dilute, and composed of flatish, silt-sized grains, because gold-grain sources (S), such as quartz veins, are commonly small and the gold in them is scarce, flatish, and silt-sized (Averill, 1990). By contrast, aeolian dispersal trains emanating from major deserts can be global in scale (Pye, 1987), not because S is global in scale, but because D is. Heavy mineral assemblages in fluvial dispersal trains in classic diamondiferous regions (Africa, Borneo, Brazil, Australia) tend to be texturally and mineralogically mature, meaning that grains tend to be well rounded and easily weathered minerals under-represented (e.g., Mosig, 1980). This is because the long T (e.g., 90 Ma in southwestern Africa; Sutherland, 1982) compounds the effects of D and what is already an intense and chemically dominated W (Marshall and Baxter-Brown, 1995), resulting in shorter dispersal distances for labile particles and longer dispersal distances for resistant ones (Jones and Humphrey, 1997). As an extreme example, diamonds, which lose little if any mass during transport (Afanasev et al., 2008), can be dispersed thousands of kilometers from source (Sutherland, 1982), and in some cases are the only indicator minerals left (Marshall, 1991). An intense D can have similar effects as an intense W, in that it enhances downflow partitioning of different lithologies (Kodama, 1994). Change in B, which in a stratigraphic sense (Sloss, 1962) equates to shoreline translation for most non-glacial sedimentary systems (Posamentier and Allen, 1999) and ice-front translation for most glacial sedimentary systems (Alley et al., 2003; Cummings et al., 2011b), functions to shift depositional environments across the landscape, superimposing, or in the case of till, possibly mixing (Fink and Stea, 1995), dispersal trains of different age and provenance, and causing widespread patterns of erosion or deposition. Huge, dilute, fan-shaped till dispersal trains composed exclusively of weathered, rounded clasts, such as the >1000 km long Omar dispersal train (Prest et al., 2000), which are co-mingled with smaller, local dispersal trains, could be interpreted as recording multiple changes in B associated with multiple glaciations. Alternatively, dynamics internal to D (e.g., migrating ice divides) may produce dispersal responses that, in some cases, may be difficult to differentiate from those generated by changes in B.

Key controlling variables for esker dispersal trains can be estimated based on previous work. The primary source (S) of most esker dispersal trains on the Shield is a pre-existing, poorly sorted till dispersal train (Bolduc, 1992), with secondary contributions typically coming from bedrock (Alley et al., 1997) and/or basal ice (Shreve, 1985a). The dispersal regime (D) is both glacially influenced and fluvial (i.e., it is glaciofluvial). Sediment is transported in near-freezing water (e.g., Hong et al., 1984; Ettema and Daly, 2004) up or downslope through pressurized R-channels (Röthlisberger, 1972; Shreve, 1972), primarily during rapid, high-magnitude flood events (Gorrell and Shaw, 1991; Brennand, 1994; Cummings et al., 2011b). Water discharge increases down R-channel (Shreve, 1972), as does sediment transport capacity in some cases (Alley et al., 1997). The bed material in the R-channel is gravelly and the total sediment load is heterogeneous (mud>or=sand>gravel; Cummings et al., 2007). The key unknown with respect to D is the length of the R-channels (Fig. 3). The weathering regime (W) is weak compared to that of the classic diamondiferous regions discussed above, both subglacially (Anderson, 2007) and proglacially (Peltier, 1950). It has little effect on silicate indicator minerals (Averill, 2001), though labile grains (e.g., sulfide grains, carbonate grains) are commonly weathered out of soil profiles (Shilts, 1973). In terms of B, the ice front is generally thought to have retreated, either during (Hooke and Fastook, 2007) or following (Shreve, 1985a,b; Brennand and Shaw, 1996) esker deposition, causing distal facies (sandy fans) to deposit over top of or adjacent to proximal facies (gravelly ridges). The residency time (T) for clastic particles in esker sedimentary systems is geologically instantaneous: it ranges from as little as several days, as observed for modern jökulhlaup eskers (e.g., Burke et al., 2008), to perhaps as much as tens or hundreds of years, when radiocarbon-constrained ice retreat rates (Dyke and Prest, 1987) and time-frames needed for gravel rounding (Kuenan, 1956) are taken into account.

Because of the weak W and short R, the dispersal regime (D) is suspected to take on paramount importance in controlling the nature and attenuating the length of esker dispersal trains downflow of S. Three phenomena — *selective sorting*, *abrasion* (i.e., comminution), and *dilution* — are of particular importance. As a lead up to a discussion of how these phenomena operate in esker sedimentary systems, it is instructive to first examine how they operate in gravel-bed streams, a similar but better understood type of gravel-bed fluvial sedimentary system.

4.2. Dispersal trains in gravel-bed streams

Attenuation of dispersal trains in gravel-bed streams downflow of S commonly reflects some combination of selective sorting, abrasion, and dilution (Fig. 5). Flowing water, unlike flowing ice, is not competent enough to transport all grain sizes at the same rate. As such, selective sorting of the dispersal train material occurs (Parker, 2008). Sediment is mobilized primarily during floods. Gravel and heavier, coarser sand grains tend to roll or slide along the bed as bedload or bounce along as intermittent suspended load in the lower, slower moving part of the flow, whereas finer, lighter sand and mud tend to travel in the upper, faster moving part of the flow as suspended load.[1] The finer, lighter particles therefore travel farther during each flood than larger, denser grains (e.g., Frostick et al., 2006). Mud and the finest sand fractions travel in suspension and, if they are not trapped in floodplains (Goodbred and Kuehl, 1999), commonly bypass the system entirely (Wilcock, 2004). For example, much of the mud at the mouth of the Amazon River is derived thousands of kilometers up-river from the Andes Mountains (McDaniel et al., 1997). Abrasion is also significant in gravel-bed streams, its rate proportional to grain size: gravel clasts abrade (lose mass) orders of magnitude faster than sand grains — experiments suggest that angular sand grains may require hundreds to thousands of kilometers of transport before they become rounded (Kuenan, 1956, 1959). Gravel abrasion does not necessarily require entrainment; it may occur in part by in-place jostling (Schumm and Stevens, 1973). In conjunction, abrasion and selective sorting cause down-stream fining of the bed material (Frings, 2008; Parker, 2008), with breaks in slope commonly characterized by abrupt gravel–sand transitions (Yatsu, 1955). In general, the larger the clast, the closer the source: boulders tend to fine downflow over several kilometers, cobbles and pebbles over tens of kilometers, and sand over hundreds to thousands of kilometers (Fig. 6). In many streams, dilution of dispersal trains by influx of coarser sediment occurs primarily at tributary junctions; this can generate smaller, nested downflow fining cycles, termed *sedimentary links* (Rice and Church, 1998), which add noise to the main downstream fining trend (Knighton, 1980). Dilution with coarser material can also occur if the stream is incising into a coarse-grained substrate, as is common for streams

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[1] Wilcock (2004) suggests that, as a general rule of thumb, grains with a similar density as quartz (~2.65 g/cm^3) that are coarser than 8 mm (boulders, cobbles, and larger pebbles) always travel as bedload in gravel-bed streams, grains finer than 1/8 mm (very fine sand and mud) always travel as suspended load, and grains in between 8 and 1/8 mm travel either as bedload or suspended load, depending on the strength of the flow.

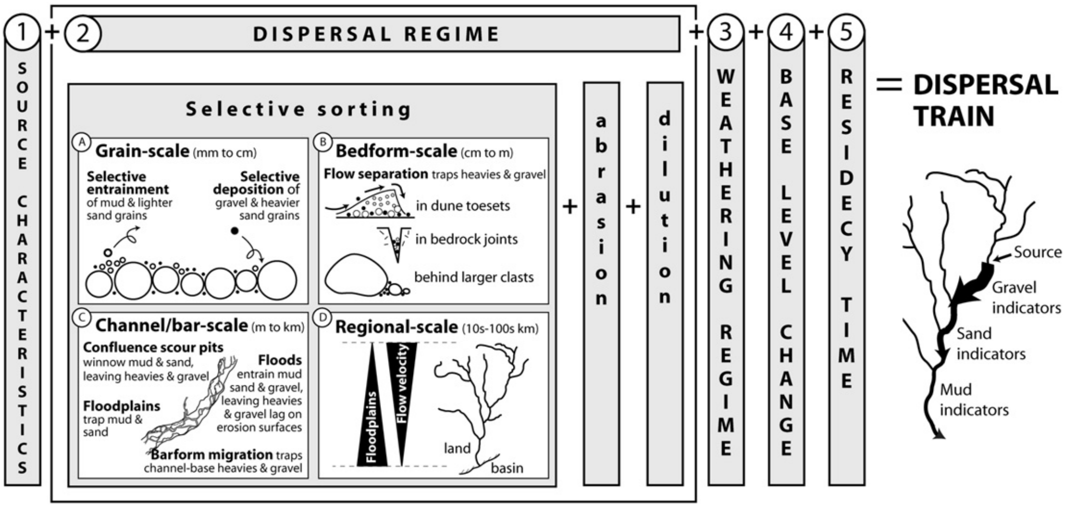

Fig. 5. Conceptual framework for generation of clastic dispersal trains in fluvial systems. This diagram is shown here because every aspect of it, from the minutia of the grain-scale sorting processes to the nature of the resultant regional dispersal train, constitutes a testable hypothesis for how esker dispersal trains are generated. The effects of selective sorting are cumulative so that regional scale sorting equals the sum of sorting at all scales, from A through to D. As with esker systems, the sediment source is assumed to be poorly sorted. Based in part on ideas from Gregory and White (1989), Jones and Humphrey (1997), Wilcock (2004), Carling and Breakspear (2006), Parker (2008), and references therein.

in till-covered Shield areas undergoing post-glacial isostatic rebound (e.g., Davey and Lapointe, 2007). Because of the combination of selective sorting, abrasion, and dilution, dispersal trains in gravel-bed streams tend to fine downflow and can span the entire length of the system, which for large rivers can be hundreds to thousands of kilometers in extent (Fig. 5).

4.3. Implications for glaciofluvial systems

Theoretically, selective sorting and abrasion should operate similarly in R-channels as they do in gravel-bed streams; fluid–bed interactions and sediment transport mechanisms are similar in open channels (streams) and pipes (esker sedimentary systems), as are the bedforms and sedimentary structures produced (McDonald and Vincent, 1972; Southard and Boguchwal, 1990). It is the glacial influence on the fluvial system that differentiates esker sedimentary systems from gravel-bed streams. In particular, the mechanisms and rates by which dispersal trains become diluted may be different. Dilution of esker dispersal trains, like those of streams, can occur by tributary sediment input (Lillieskold, 1990; Bolduc, 1992) and/or vertical down-cutting into the substrate (Alley et al., 1997). However, a third dilution mechanism — lateral influx of poorly sorted till and/or debris-rich basal ice along the length of the R-channel — may deliver significant amounts of sediment to esker sedimentary systems (Trefethen and Trefethen, 1944; Röthlisberger, 1972; Shreve, 1972). Inward-trending striae near some eskers (e.g., Veillette, 1986) attest to this process. Shreve (1985a) considers it to be *the* major mechanism by which sediment is delivered to R-channels. Levasseur and Prichonnet (1995) suggest dilution from debris flowing into the R-channel was more important than other processes in generating the downflow attenuation of a dispersal train in the Chibaugamau esker, Quebec. Meltwater could equally deliver adjacent sediment to R-channels, possibly at the tail end of broader jökulhlaup-like floods beneath the glacier (e.g., Paola, 1983; Brennand and Shaw, 1996; Fowler and Ng, 1996; Burke et al., 2008). In sum, because of dilution, in addition to selective sorting and abrasion, deposition of eskers in short segments as outlined in the short-conduit model (Fig. 3A) may not necessarily be a prerequisite for the development of short esker dispersal trains downflow of the till source (Fig. 4). Rather, similar dispersal trains could potentially be produced due to intense dilution in a long conduit (Fig. 3B).

5. Discussion

Provided this context, we now return to our two main questions: how should eskers be sampled, and how should data be interpreted?

5.1. Question 1. Esker sampling methods

The goal of drift prospecting is simple: first, locate a dispersal train; second, trace the dispersal train back to the bedrock source. Eskers can be used during both stages, but they are typically used during the former.

5.1.1. Regional-scale sampling (10s to 100 s of km)

Eskers, like regional stream networks, are commonly sampled during the initial, reconnaissance stages of an exploration campaign (Atkinson, 1989; Craigie, 1993; Krajick, 2001; Kjarsgaard and Levinson, 2002). A reasonable question might therefore be the following: Should long eskers be targeted first, just as regional stream networks are targeted first, the idea being that they are more likely to contain the longest dispersal trains? If the data are representative, there is no reason to suspect this to be the case, at least for coarse sand and gravel fractions. Previous work suggests that long eskers commonly contain dispersal trains that are only a fraction of total esker length (Fig. 4), and there is no obvious correlation between esker length and dispersal train length. Rather, the length of the underlying till dispersal train across which the esker passes may be the primary control on the length of dispersal trains in the coarse sand and gravel fractions. Whether this applies to finer sand and mud fractions is unknown; they are more likely to travel as suspended load, and will therefore be more likely to travel farther down the R-channel or beyond (Cummings et al., 2007). If the esker in question formed under the long-conduit model (Fig. 3B), it could potentially contain both local and regional provenance signals, depending on what grain size is analyzed. Eskers formed under the short conduit model, by contrast, should contain limited dispersal distances for all grain sizes — gravel, sand, and mud. Gillberg (1968) claims that several eskers in Sweden contain such dispersal trains.

How closely should samples be spaced along an esker? This is perhaps the main "regional-scale" question faced prior to the start of a drift prospecting campaign, irrespective of the media sampled. The spacing will need to be adjusted for the geographic region and mineral deposit type in question. For example, a closer spacing may

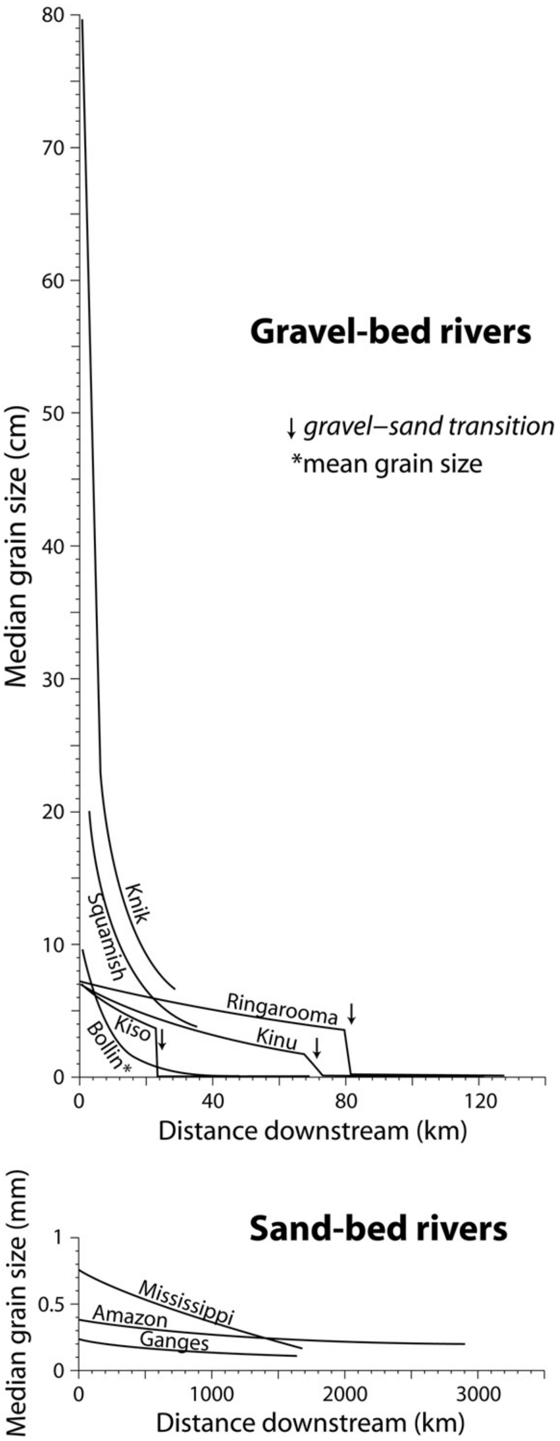

Fig. 6. Downstream fining of bed material in modern rivers. Note that in general the larger the clast size, the more rapid the downstream fining. Similar relationships are suspected to apply for esker dispersal trains downflow of the till source. Data from Yatsu (1955), Bradley et al. (1972), Knighton (1980, 1999), Nordin et al. (1980), Brierly and Hickin (1985), Kodama (1994), and Frings (2008).

be required during gold exploration than kimberlite exploration, because visible gold-grain dispersal trains in till (Averill, 1990) are generally shorter and more dilute than kimberlite dispersal trains (Armstrong and Kjarsgaard, 2003). In areas of reconnaissance exploration where no a priori knowledge exists, samples should be spaced along the esker as closely as possible, given budgetary constraints. Sampling tributary confluences to reduce the number of samples per 'catchment', a common practice for streams, may be effective on eskers, given that co-mingled provenance signals have been observed at esker tributary confluences (Lillieskold, 1990; Bolduc, 1992). Samples should be collected at least several hundred meters downflow of the confluence to ensure proper co-mingling of sediment signals from the two tributary branches (cf. Best and Brayshaw, 1985).

5.1.2. Landform-scale sampling (100 s of m to several km)

In the past, esker indicator-mineral sampling campaigns have typically targeted gravelly ridge elements — the eskers sensu stricto — as opposed to the associated sandy fan elements (e.g., Parent et al., 2004). This method is prudent for two reasons. First, heavy minerals are known to concentrate in gravelly facies of some gravel-bed streams, and especially bouldery and tightly packed gravelly facies, whereas they can be scarce to absent in sandy stream facies (Fig. 7). This has led, in part, to the saying that "the more difficult the sample is to collect, the better is its quality" (Gregory and White, 1989). Second, gravelly ridge elements represent a more proximal part of the esker sedimentary system than sandy fans (Banerjee and MacDonald, 1975); their matrices, if anything, might therefore be expected to record a more proximal provenance signal.

Although prudent, this method of sampling eskers is not proven. It is unclear whether gravelly facies in eskers do, as a general rule, contain more heavy minerals than sandy facies (see data in Pertunnen, 1989). It is also questionable whether samples from gravelly ridges and sandy fans provide significantly different provenance signals. Gillberg (1968) reports similar transport distances for carbonate sand grains in gravelly ridges and sandy fans of several Swedish eskers. It is possible that it does not matter what parts of the esker complexes are sampled — gravelly ridges or sandy fans. The idea that sandy fans provide comparable data (e.g., Gillberg, 1968) to that from gravel ridges constitutes a testable hypothesis.

5.1.3. Facies-scale sampling (cm to m)

"Bedform" or "facies" scale sampling takes into account selective sorting at a "bedform" or "bed" scale; it is the smallest scale of interest when planning esker-sampling targets, and accounts for variation within, or on the surface of, gravelly ridges and sandy fans. During reconnaissance sampling, it is desirable to target facies that are prone to containing indicator minerals because even one or two indicator minerals can lead to a mine discovery (Muggeridge, 1995). What facies contain the most heavy minerals in eskers, if any? No published data exist to constrain this. Potential insights can be gained, however, from the gravel-bed stream literature (e.g., Best and Brayshaw, 1985; Atkinson, 1989; Gregory and White, 1989; Carling and Breakspear, 2006). Two general themes emerge. First, heavy minerals tend to concentrate in zones of flow separation, such in the lee of bedforms and barforms, behind larger boulders, and in bedrock crags. Second, heavy minerals tend to concentrate as lag on erosion surfaces, such as at the winnowed heads of mid-channel bars, on the tops of dunes, in tributary confluence scour pits, in channel thalwegs, and on flood-generated erosion surfaces. These two general themes — that heavy minerals concentrate in zones of flow separation (e.g., in cross-bed toesets; in sediment behind boulders) and as lag on erosion surfaces — constitute another testable hypothesis for eskers. In addition to these potential sampling targets, pebbly aeolian deflation lags, which commonly cover the surface of eskers on the Shield, and wave-reworked beach ridges, which can be present locally, may prove to be locations where heavy minerals become concentrated after deposition of the esker. These deposits are commonly targeted during esker sampling campaigns, in addition to locations where streams have cut through eskers (Craigie, 1993). Irrespective of what type of material is sampled, it is wise to describe it on-site and photograph the sample pit. This will help vet lab results following the field campaign.

Sediment in esker corridors, where present, represents an additional, untested "facies-scale" sampling target (Fig. 1B). Till patches in esker corridors (e.g., Rampton, 2000), because of their thinness, may be derived from more proximal bedrock sources than the top of the thick till outside

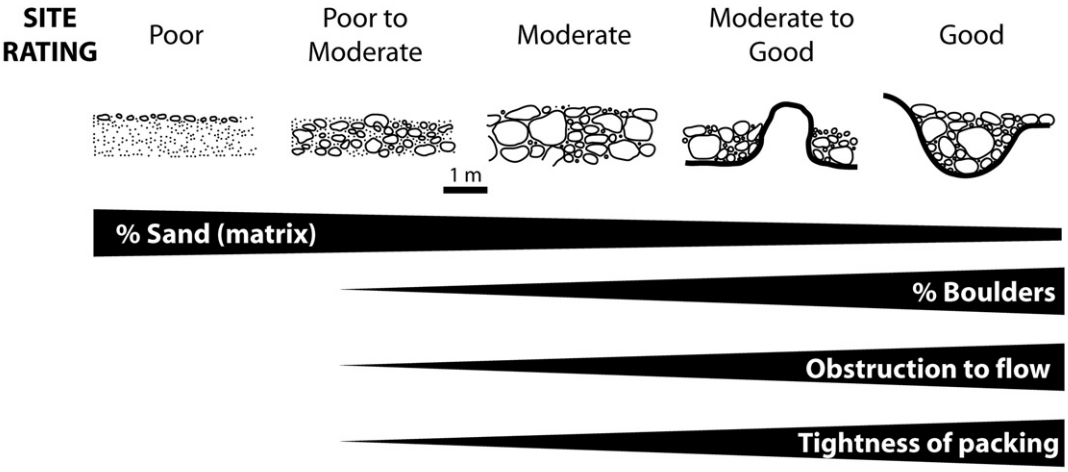

Fig. 7. Concentration of kimberlite indicator minerals in different fluvial facies down-stream from the Devil's Elbow kimberlite, Australia (modified from Muggeridge, 1995). Note that gravelly and sandy facies are rich and poor in indicator minerals, respectively. This is apparently a common observation in Australia, and has led, in part, to the saying that, in general, "…the more difficult the sample is to collect, the better is its quality" (Gregory and White, 1989). Gold in Klondike placers exhibits similar relationships: heavy minerals are commonly abundant in bouldery gravel facies and scarce to absent in sandy facies (Lebarge et al., 2002). Whether such a relationship applies to eskers represents a hypothesis waiting to be tested.

the corridors, the typical till-sampling medium. Lag in bedrock joints and crevasses, a favored sampling target in classic diamondiferous regions (Gregory and White, 1989), may be present in the corridors, as may larger glaciofluvial bed forms (St. Onge, 1984; Brennand and Sharpe, 1993; Rampton, 2000; Utting et al., 2009), both of which may be indicator concentration sites (Rampton and Sharpe, 2009).

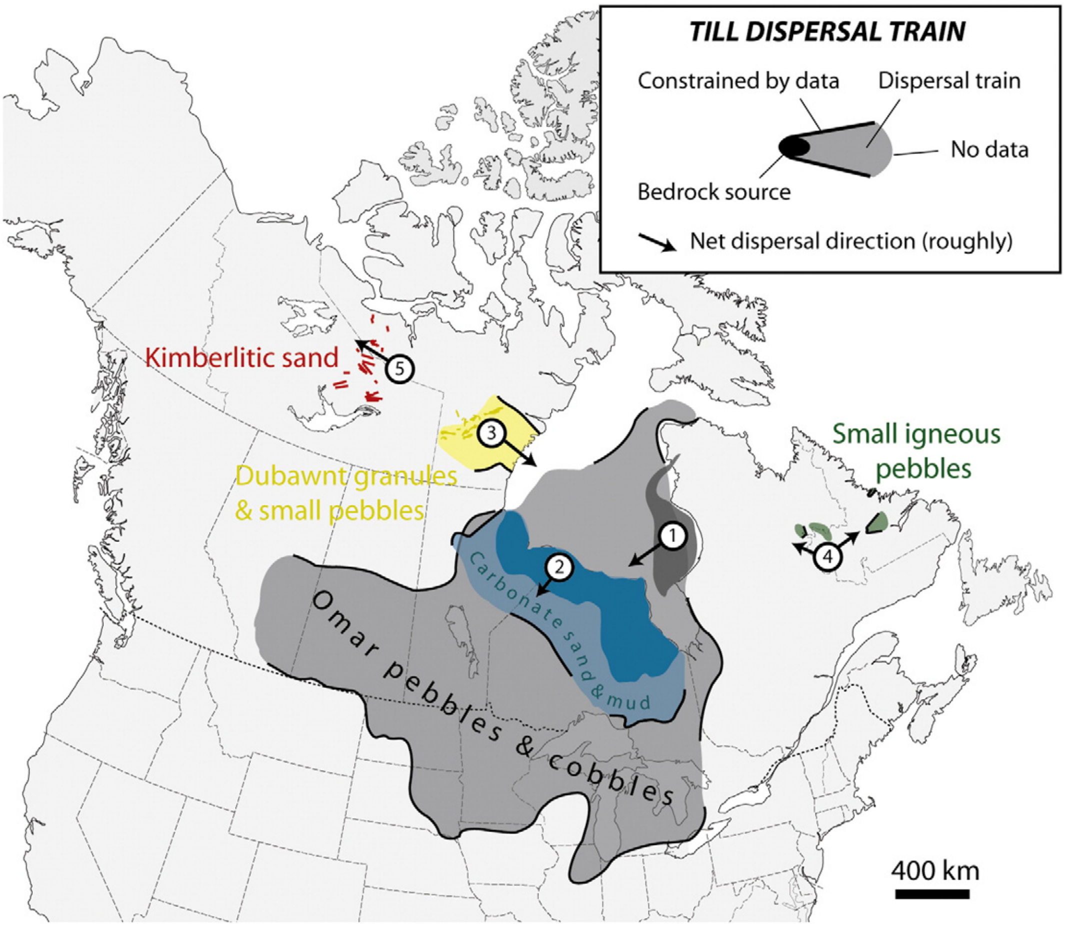

Fig. 8. Selected till dispersal trains in North America. These and other, commonly smaller till dispersal trains (e.g., Averill, 1990; not shown) are the primary source for sediment in esker dispersal trains. Their size therefore exerts a first-order control on the size of esker dispersal trains (e.g., Fig. 4). Darker shades demarcate bedrock source areas for lighter colored till dispersal trains. (1) Omar dispersal train (Prest et al., 2000); (2) Hudson Bay carbonate dispersal train (Karrow and Geddes, 1987; Dredge, 1988); (3) Dubawnt dispersal train east of Keewatin ice divide (Shilts et al., 1979); (4) Pebble dispersal trains near Ungava ice divide (Klassen and Thompson, 1989); (5) kimberlite indicator-mineral dispersal trains west of Keewatin ice divide (Armstrong and Kjarsgaard, 2003).

5.2. Question 2. Esker data interpretation

When an indicator mineral is found in an esker, only one question matters: where is the bedrock source? Several points can help guide interpretation, as outlined below.

1. The longer the till dispersal train, the longer the esker dispersal train
   The till dispersal train across which the esker passes, in most cases, is probably the primary source of esker sediment. As such, the use of eskers as mineral exploration tools is a two-stage process: trace the esker dispersal train back to the till dispersal train, then trace the till dispersal train back to the bedrock source (Hellaakoski, 1931; Shilts, 1973). Data in Fig. 4 provide a preliminary guideline for the first step of this process: coarse sand and gravel dispersal trains in eskers studied to date do not extend far — typically only a few to a maximum of 25 km — beyond the edge of the till dispersal train from which they were sourced. As such, in areas where eskers trend parallel to drumlins, striae, and till dispersal trains (most areas), the longer the till dispersal train, the longer the esker dispersal train. In areas where eskers cross till dispersal trains obliquely (e.g., Shilts, 1976), the length of the intersected portion of the till dispersal train will act as a first-order control on esker dispersal train length.
   A simple discussion of the second part of this exploration process — how to trace till dispersal trains back to their bedrock sources — is rendered problematic by the fact that a process model that adequately explains both the origin of till *and* the dispersal trains it contains does not exist. This represents the major unresolved problem in applied glacial geology today. See Drake (1983), Miller (1984), Dilabio and Coker (1989); Kujansuu and Saarnisto (1990), and McClenaghan et al. (2001) for insights.
2. Anomalous samples may be significant, but should be treated with caution
   Although the processes by which till dispersal trains form are not well understood, what is known is that their size varies tremendously, from less than a kilometer (Averill, 1990) to over a thousand kilometers (Prest et al., 2000) (Fig. 8). Short- and long dispersal-trains are commonly co-mingled within the same till unit (Finck and Stea, 1995). Short, concentrated till dispersal trains have the potential to yield recognizable esker dispersal trains. Clusters or trends in indicator-mineral data in esker samples (i.e., evidence for discrete dispersal trains) are therefore good signs. By contrast, isolated indicator clasts or isolated "hot" samples in eskers should be treated with caution in absence of detailed follow-up sampling because they may be sourced from large, diffuse dispersal trains (e.g., Prest et al., 2000). The level of skepticism should increase in proportion to the durability of the clast (e.g., diamonds will survive long distance transport) and in inverse proportion to clast size (see point 3 below).
   In Fig. 4, the esker dispersal trains do not appear more spiky than the till dispersal trains. However, concentration of heavy minerals at a "bedform" or "facies" scale is suspected to occur in esker sedimentary systems because it occurs in gravel-bed streams. As such, there is almost certainly some noise in the data. The key is to filter the noise and resolve the signal (the dispersal train). Again, data clusters or trends are good signs; isolated "hot" samples should be treated with caution.
3. The larger the clast, the closer the till source
   Fluvial dispersal trains fine downflow (Fig. 6); the same is suspected to apply to esker dispersal trains beyond the limit of the till dispersal train.[2] Within the till dispersal train, poorly sorted debris, including gravel, may have been introduced along the length of the R-channel (Shreve, 1985a; Fowler and Ng, 1996), which would counteract downflow fining.
4. The more angular the gravel clast, the closer the till source
   Gravel is typically more angular in till than in eskers; gravel abrasion therefore occurs in esker sedimentary systems. As such, angular or striated gravel clasts in eskers may not have not traveled far from their till source. It is unclear if this relationship applies for sand-sized indicator minerals, which tend to be angular in eskers (Wolfe et al., 1975; Averill, 2001), possibly because sand experiences little abrasion over the time scales involved in esker deposition (e.g., Kuenen, 1959).

6. A look forward

If a theme has emerged from this review, it is that little published work exists to help understand how to sample eskers for indicator minerals during exploration (Question 1) or how to interpret results (Question 2). Several lines of research have the potential to fill these knowledge gaps, as outlined below.

Regionally, the opportunity exists to move past the *qualitative* (air-photo-based) depiction of eskers as lines on maps (e.g., Fig. 1A) to a *quantitative* understanding of esker geomorphology through the analysis of modern landscape-imagery (e.g., satellite images, digital elevation models; see Broscoe et al., 2011). The resultant regional data — such as the height, width, shape, continuity, and volume of eskers and associated esker corridors — will provide new insight into how eskers form (Fig. 3). This will lay a more rigorous, empirical foundation for understanding, and possibly predicting, indicator mineral dispersal in esker systems at the local scale.

Within this remotely-sensed regional framework, "landform-scale" field work is required. Eskers that cross known bedrock sources should be targeted. Analysis of indicator minerals in the suspended load fraction (fine sand, coarse silt) in addition to the more commonly analyzed bedload fraction (pebbles, coarse sand) may help determine if the esker formed in segments or not. The adjacent till should be analyzed to ascertain the relative contribution of glaciofluvial (esker) versus glacial (till) transport to total dispersal. The sedimentology and sedimentary architecture of eskers need to be considered. For example, different geomorphic elements (gravelly ridges, sandy fans) at different stratigraphic levels should be sampled, as should sediment from esker corridors, to determine if differences in indicator mineral provenance, concentration, and/or textural and mineralogical maturity exist. A combination of methods, including numerical calculations using existing glaciological theory, data syntheses (e.g., inward-trending striae near eskers), and scrutiny of depositional and erosional features in esker corridors, may help constrain the size of esker sediment-source areas and the mechanisms (ice-mediated and/or meltwater-mediated) by which sediment is transferred from source area to esker.

At the smallest scale (individual clasts), abrasion experiments (e.g., Cummings et al., 2011a) can help quantify the break down and wear of different bedrock lithologies during transport in esker systems and the characteristic size fractions and textural maturities (roundness, shape) of the indicator mineral assemblages that are produced.

By fostering insight into how esker sedimentary systems work, such research initiatives will, in concert, help improve the chances of success when using eskers as mineral exploration tools.

7. Conclusions

1. Esker dispersal trains on the Shield are sourced primarily from underlying till dispersal trains, with possible secondary contributions from bedrock and/or debris-rich basal ice. The use of eskers as mineral exploration tools is therefore a two-stage process: trace

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[2] Eskers themselves do not exhibit net downflow fining, presumably because of influx of coarse sediment (i.e., dilution of dispersal train) along the length of the R-channel and/or deposition in segments, as per the short-conduit model.

the esker dispersal train back to the till dispersal train, then trace the till dispersal train back to the bedrock source.

2. Measured from head to tail, gravel dispersal trains in eskers studied to date are similar in length to the till dispersal train from which they were sourced, but they are shifted 1–25 km downflow.
3. Sand dispersal trains (e.g., heavy minerals) in eskers have less commonly been studied than gravel dispersal trains in eskers. Previous studies have investigated coarse sand. If the data are representative, coarse sand dispersal trains in eskers, like gravel dispersal trains in eskers, are similar in length to the till dispersal trains from which they were sourced, but are shifted by 1–25 km downflow. Whether this is representative of eskers in general is unknown due to the paucity of published data.
4. Sand-sized indicator minerals (heavy minerals) are commonly enriched in eskers relative to till, in some cases by several times per unit volume. Sampling sandy fans may yield similar data as sampling gravelly ridges, and at the same time be less time consuming and thus more cost effective.
5. Due to lack of data, however, it is unclear whether heavy minerals preferentially concentrate in gravelly ridges or sandy fans of esker complexes (or neither), and whether certain sedimentary facies in these geomorphic elements are more likely than others to contain high concentrations of heavy minerals.

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