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Eskers as Mineral Exploration Tools: An Annotated Bibliography

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

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FOREWORD

Eskers are common in Canada, especially on the Precambrian Shield (Fig. 1). 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. Esker sampling is a proven exploration method: it has led to the location of several kimberlite pipes (Lee, 1968), including the Lac de Gras kimberlite field, home to Canada's first diamond mine (Krajick, 2003).

The bibliography compiles key papers on how sediment is eroded, transported, partitioned, modified, and deposited in *esker sedimentary systems*[1], and the nature of the clastic dispersal trains that result. It was assembled during the writing of a short, accompanying review paper on esker dispersal trains (Cummings et al., 2010). All references on esker dispersal trains we could find are included herein. To provide context and ideas, we also include some key papers from related disciplines (e.g., dispersal in gravel-bed streams).

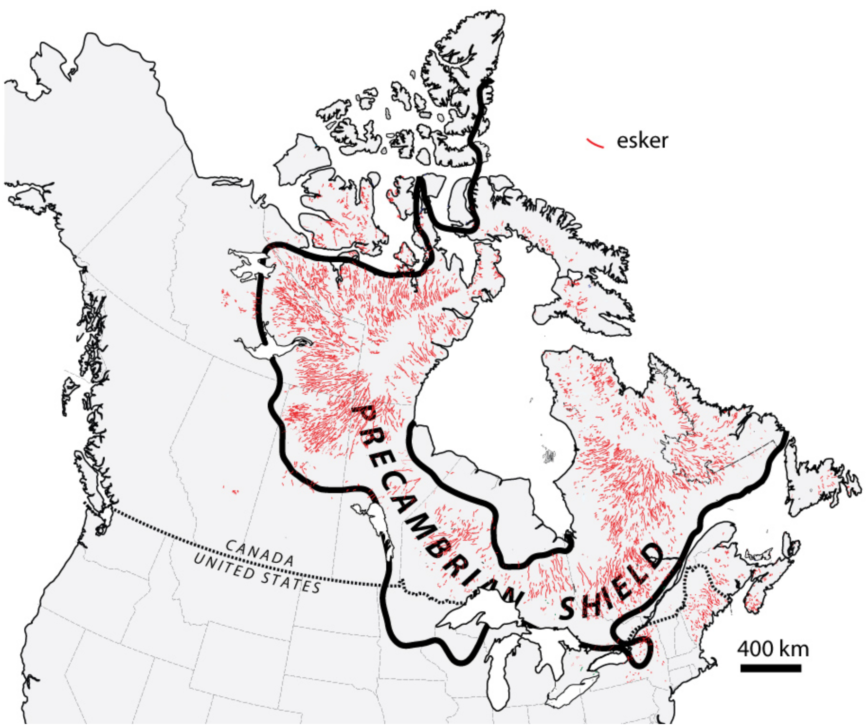

Figure 1. Eskers in North America. Numerous eskers are also present over Paleozoic and Mesozoic sedimentary bedrock in parts of Canada off the Precambrian Shield, but these eskers are either buried (e.g., Hudson Bay Lowlands, Champlain Sea basin) or are too small to plot at this scale (e.g., Prairies, Southern Ontario).

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[1] For clarity, an *esker sedimentary system*, as defined here, is an open thermodynamic flow system within which an esker is envisioned to form. It includes (1) the external ("allocyclic") forcings (insolation, geothermal heat flux, gravity) that set up the energy gradient that drives mass and energy through the system; (2) internal ("autocyclic") feedbacks between different components of the system (air, water, ice, entrained sediment, and substrate); (3) the geometry and evolution of the meltwater flow system that results; and, ultimately, (4) the shape, size, and internal heterogeneity of the esker sediment body and the dispersal trains within.

BIBLIOGRAPHY

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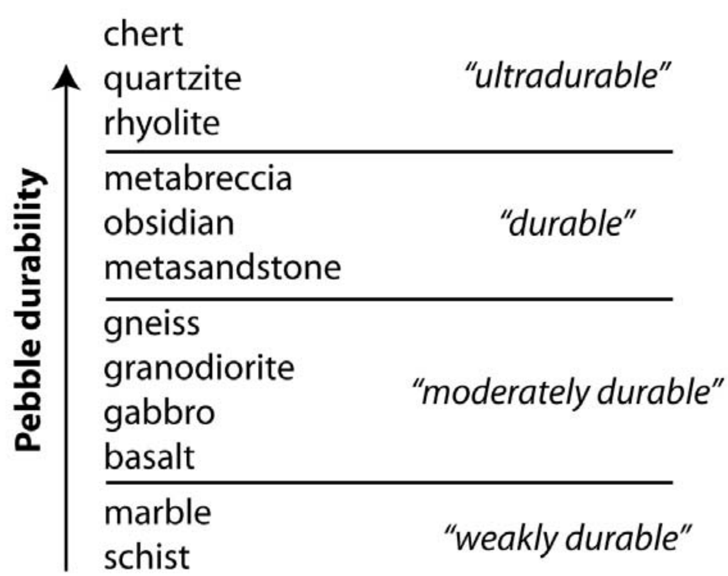
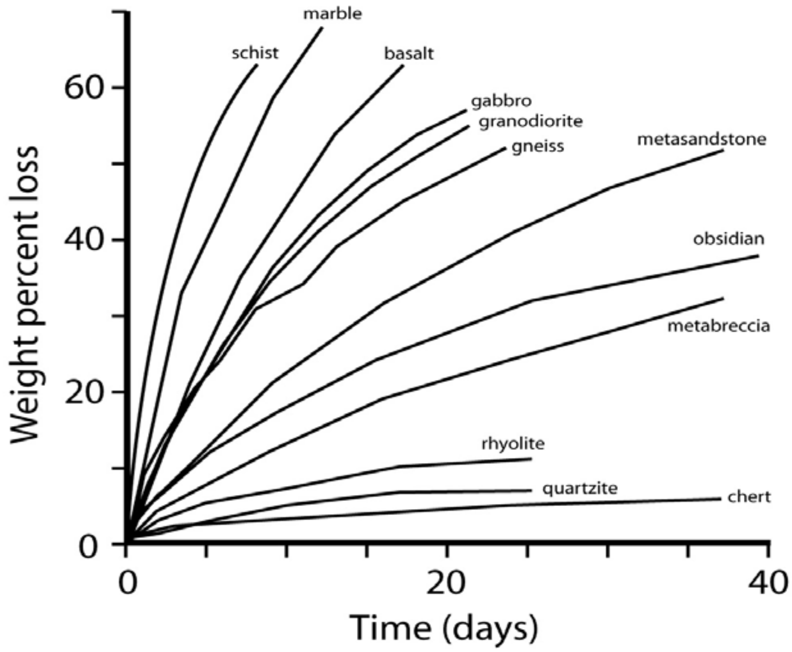
Abbott, P.L. and Peterson, G.L. 1978. Effects of abrasion durability on conglomerate clast populations: Examples from Cretaceous and Eocene conglomerates of the San Diego area, California. Journal of Sedimentary Petrology, v. 48(1), p. 31–42.

***Synopsis**. In their tumbling mill experiments on pebbles, Abbott & Peterson (1978) found that the durability of marble & schist < basalt, granodiorite, gneiss & gabbro < obsidian, metasandstone & metabreccia < silicic rhyolite, quartzite & chert. The figures below pertain to experiments using monolithic populations.*

***Exploration significance**. Gravel clasts in eskers are commonly similar in lithology to those in the subjacent till. However, they are much more rounded; even friable lithologies like shale become rounded in esker sedimentary systems. Presumably, however, lithologies become rounded and lose mass at different rates, and they may also break down into different grain populations. Understanding how quickly gravel becomes worn and how it breaks down into indicator grains is therefore important in interpreting provenance signals from eskers. This paper presents the results of tumbling mill experiments for several common bedrock lithology types. Rocks such as chert and quartzite proved to be highly resistant, whereas others such as schist and marble lost mass rapidly over the course of the experiments. The latter might therefore be expected to be under-represented in eskers.*



Classification of the lithologies according to their resistance to wear in the tumbling mill



Percent mass loss with time during the tumbling-mill experiment

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Afanasev, V.P., Varlamov, V.A. and Garanin, V.K. 1984. The abrasion of minerals in kimberlites in relation to the conditions and distance of their transportation. Russian Geology and Geophysics, v. 49, p. 91–97.

***Synopsis**. A study of coarse olivine sand grains (0.5–1 mm) in a bedrock river downflow of a known kimberlite. Concludes, among other things, that olive grains tend to concentrate in gravel-rich facies.*

***Exploration Significance**. If the same rules apply to eskers, heavy minerals may be more highly concentrated in gravelly as opposed to sandy facies.*

Key quotes

- *"The Muna [river]…is characterized by an alternation of rapids over bars and smooth reaches, the total extent of the latter being several times greater. The flow is more rapid over the bars, and it is here that the coarse clastic alluvial and minerals of the heavy fraction are concentrated; in the intervening reaches the current is slow and the alluvium consists predominantly of fine-grained sand, often enriched in clayey material."*

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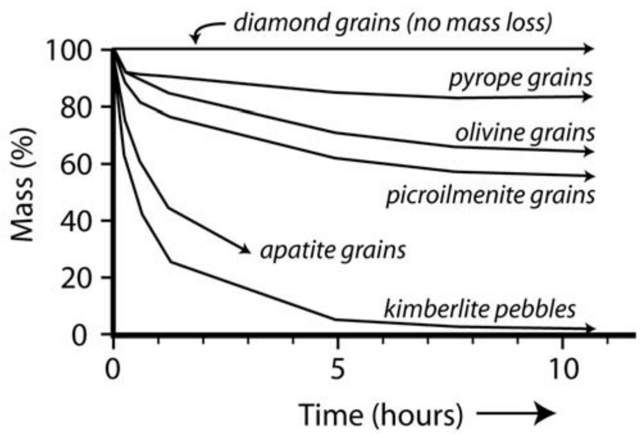
Afanasev, V.P., Nikolenko, E.I., Tychkov, N.S., Titov, A.T., Tolstov, A.V., Kornilova, V.P. and Sobolev, N.V. 2008. Mechanical abrasion of kimberlite indicator minerals: experimental investigations. Russian Geology and Geophysics, v. 49, p. 91–97.

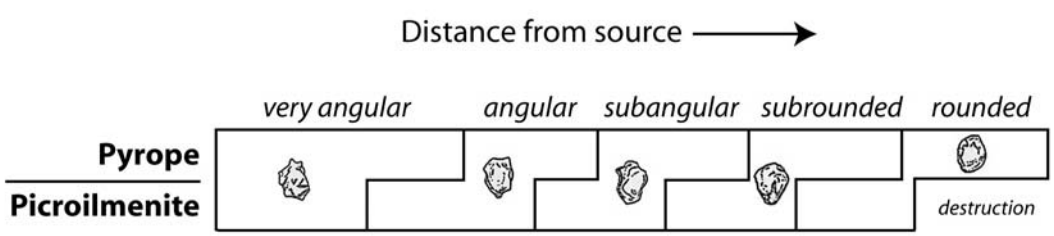
***Synopsis**. A study of wear experienced by very coarse sand sized kimberlite indicator minerals (1–2 mm diameter) subjected to ultrasonic vibrations in a metal tube. All grains put into vibrator at the same time. Total run time = 635 minutes. Concludes that, in terms of kimberlite indicator-mineral resistance, diamond > pyrope > olivine > picroilmenite > apatite (see figure). The diamonds did not lose any mass. Picroilmenite became rounded faster* *than pyrope (see figure). Kimberlite pebbles (5–8 mm diameter) experienced the most mass loss.*

***Exploration Significance**: Kimberlite pebbles will likely break down and become worn more rapidly than sand-sized kimberlite indicator minerals in esker sedimentary systems. Different kimberlite indicator minerals may also display different levels of wear for the same transport distance. However, if the experiments of Kuenen (1959) apply, sand grains may experience little wear in esker sedimentary systems. This may be supported by the observations of Wolfe et al (1973), Dredge et al. (1997), and Averill (2001), who all observe few signs of physical wear on indicator minerals in eskers.*

As an additional point, the experiments by Afasanev et al. (2008) show nicely that diamonds are ultra-resistant to wear. Because of the complex dispersal history in Canada in which bedrock clasts have been displaced, in some cases, over one thousand kilometres (Prest, 2000), isolated diamond finds in drift should be treated with a healthy degree of scepticism.



Plot of indicator-grain mass loss during experiment



Plot of relative rounding for pyrope versus picroilmenite during experiment

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Alley, R.B., Lawson, D.E., Larson, G.J., Evenson, E.B., and Baker, G.S. 2003. Stabilizing feedbacks in glacier-bed erosion. Nature, v. 424, p. 758–760.

***Synopsis**. Based on glaciological theory plus observations from Matanuska Glacier, Alaska, the authors propose that "…beds of terminal regions of highly erosive glaciers [become stabilized] at a slope just sufficient to cause supercooling of subglacial waters". The authors call this the "graded glacier" hypothesis, and draw analogy to the "graded stream" hypothesis.*

***Exploration Significance**: This paper highlights the potentially broader role of meltwater as a sediment dispersal agent beneath glaciers.*

Key quotes

- *Specifically, the argument the authors make is that (1) "…rapid glacial geomorphic activity appears to be restricted to glaciers with abundant surface meltwater flowing along their beds…", (2) "…sediment discharge from such highly erosive glaciers is dominated by material carried in subglacial streams, (3) "…rapid subglacial erosion produces overdeepenings, with the glacier bed rising in the direction of ice flow…", and that (4) if the bed becomes too steep (or glacier slope too gentle) supercooling will occur, leading to a decrease in sediment transport capacity in subglacial streams that will "…eliminate local erosion, trap sediment transported from upglacier, and so prevent further local deepening of the glacier bed and steepening of the slope on the downglacier side of the overdeepening"*

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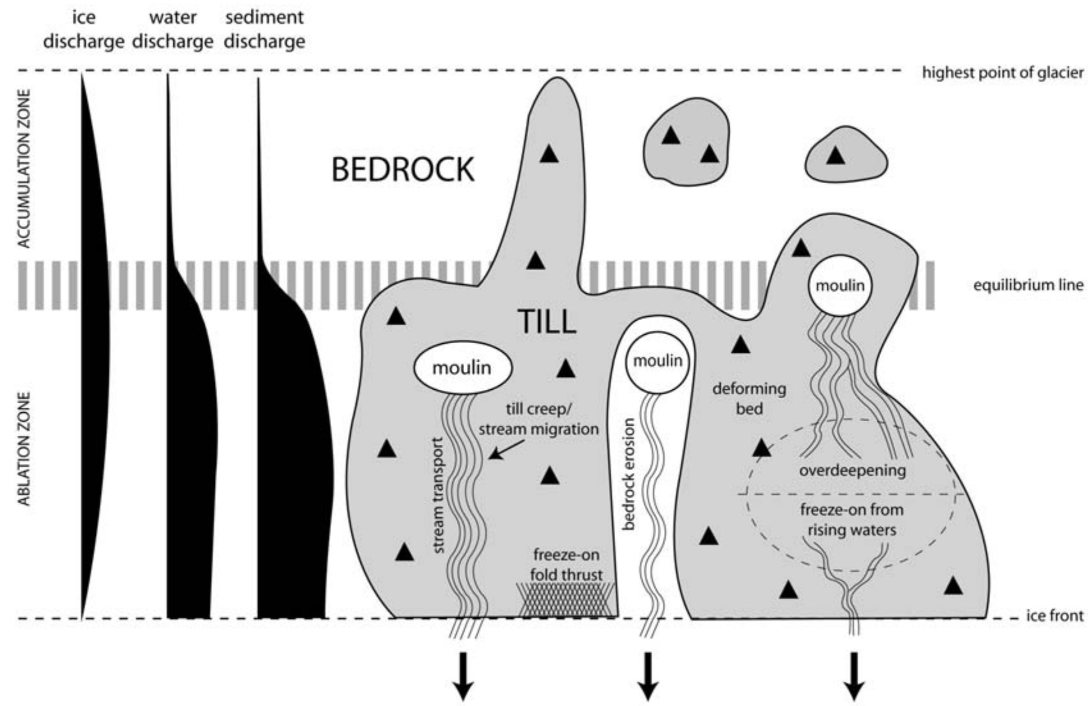
Alley, R.B., Cuffey, K.M., Evenson, E.B., Strasser, J.C., Lawson, D.E., and Larson, G.J. 1997. How glaciers entrain and transport basal sediment: Physical constraints. Quaternary Science Reviews, v. 16, p. 1017–1038.

***Synopsis**. This paper presents several ideas of how debris is entrained by meltwater beneath glaciers. It is rich on ideas, but devoid of hard field data to support them. A significant contribution nonetheless.*

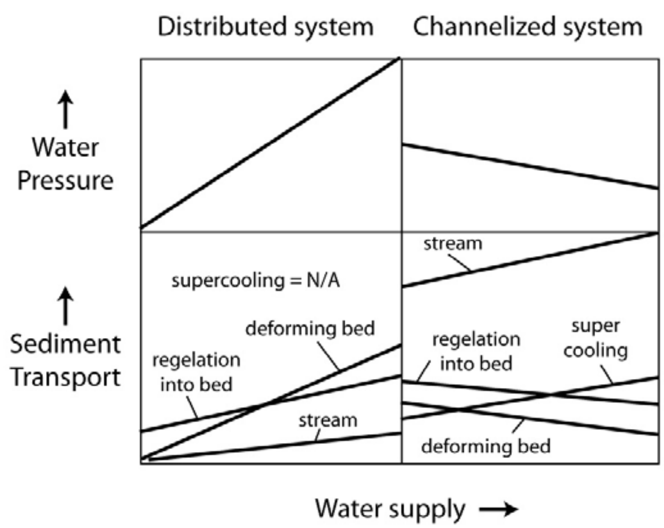
***Exploration significance.** Provides a conceptual framework for understanding sediment dispersal in esker sedimentary systems.*

Key quotes

- *"In comparison to nonglacial streams, glacial streams are bedload-dominated…"*
- *"…enough is known empirically to predict that subglacial streams fed by surface melt should have exceptionally high sediment-transport capacity, due to high water discharges forced by steep head gradients, and due to temporal concentration of this discharge."*
- *"…in both fluvial and glacial cases a large fraction of the precipitation that falls upstream…is transported by a stream channel or channels, so the [water discharges] are roughly equivalent for similar climates and drainage-basin areas"*
- *"…in the fluvial system, the slope decreases exponentially from the drainage divide to the lowlands, whereas in the glacial system the slope increases approximately quadratically in the same direction. Typical lowland river slopes are 0.0001…whereas typical ice marginal slopes are 0.01 or higher. In this case, bedload transport capacity is approximately four orders of magnitude higher for the glacier meltwater streams. The concurrence of high slope and high discharge in the glacial case, which is rarely found in fluvial systems, makes the glacial meltwater streams particularly effective transporting agents."*
- *"Similar reasoning may be applied to downstream variations in transport capacity. The slopes of subaerial streams flowing on unconsolidated sediment evolve through time so that the sediment transport capacity of the stream just balances the sediment supplied to the channel (the 'graded' condition…). The stream acts as a conveyor but does little local erosion. In contrast, the hydraulic gradients driving subglacial streams are controlled primarily by the ice–air surface slope and only secondarily by basal conditions…In many cases the hydraulic gradient along a subglacial stream is modelled to steepen toward the ice front…and the transport capacity should strongly increase downstream. A net downstream increase in transport capacity means the channel has the ability to erode and further accumulate load…Concentrated stream erosion is one of several possible mechanisms that can produce overdeepenings…"*
- *"If the banks [of the channel] are not erodible (for instance, in a Röthlisberger channel if the temporal changes are rapid, then both [channel width and height] are effectively constant; increased discharge is achieved by increased head-gradient linked to filling of moulins toward the ice surface) then the dependence of bedload capacity on water flux will be even stronger, up to [sediment discharge $\propto$ water discharge$^{9/2}$], an extreme non-linearity."*
- *"In many instances, the glaciofluvial system removes all available sediment and flows on bedrock, or beneath portions of a glacier with till in other regions…Subglacial streams on bedrock almost always will have unsatisfied transport capacity…In comparison, much subaerial runoff is generated in contact with sediment so that most of its transport capacity is satisfied at all times. We infer, then, that glacial streams typically will generate much larger unsatisfied transport capacity than subaerial streams, leading to production of water-erosion features on bedrock to a degree that appears unusually or even spectacular in comparison to non-glacial environments. We expect such erosion features to develop especially during glacial retreat across scoured landscapes, where the rapid runoff from glacial melting can attached the bedrock exposed by the glacial scouring."*
- *"Where a glacier brings sediment and streams together, one should expect most of the sediment to be removed"*
- *"Most glacially transported sediment is likely to pass through subglacial and proglacial streams, and eventually to be lost from the glacial system entirely. Where subglacial streams are active, they typically will dominate other sediment transport mechanisms."*



Conceptual model of sediment transport beneath a glacier. The authors assume almost all geomorphic work (sediment erosion and transport) occurs in the ablation zone. We have added the equilibrium line by assuming its position corresponds to the location of maximum ice discharge and the transition from very low subglacial water and sediment flux (accumulation zone) to high subglacial water and sediment flux (ablation zone). We have also adjusted the water and sediment discharge scales according to statements made in the original figure caption (i.e., the logarithmic statement—see Alley et al., 1997).



Theoretical sediment transport mechanisms where distributed versus channelized meltwater systems exist at the base of the glacier (from Alley et al, 1997).

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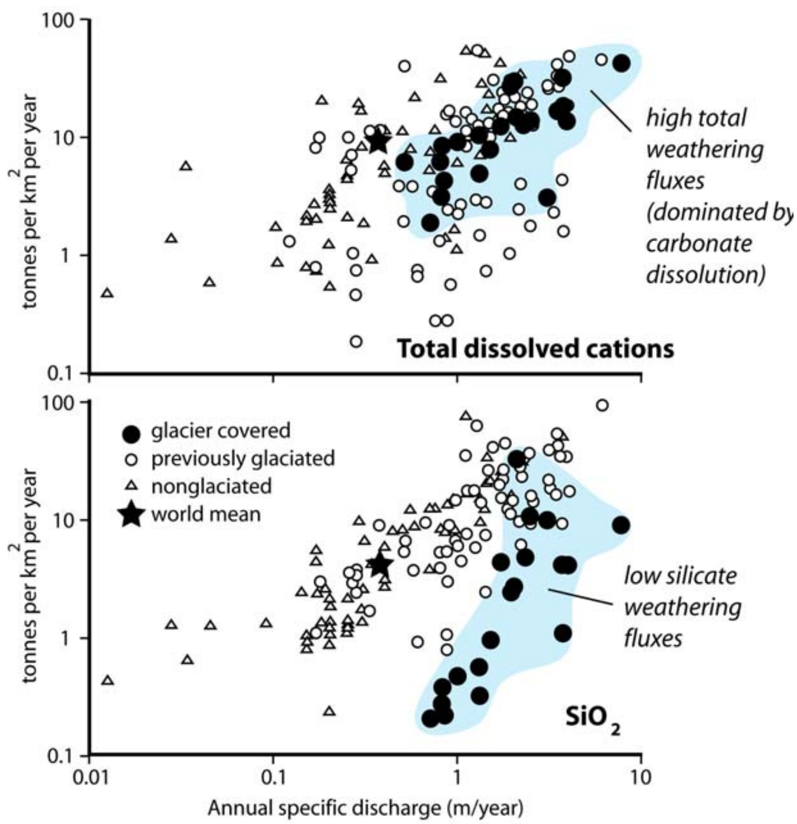
Anderson, S.P. 2007. Biogeochemistry of glacial landscape systems. Annual Review of Earth and Planetary Sciences, v. 35, p. 375–399.

***Synopsis**. A review of the weathering flux in glaciated versus non-glacial catchments.*

***Exploration significance**. Silicate weathering fluxes may be depressed beneath glaciers relative to proglacial and non-glacial areas. (Total weathering fluxes, by contrast, appear to be greater, and tend to be dominated by carbonate ions, even where carbonate bedrock does not underlie the glacier.) Depressed subglacial silicate weathering rates may be one of the factors that contributed to the fresh, unweathered appearance of kimberlite indicator minerals in glacial deposits reported by Dredge et al. (1997) and Averill (2001).*



Weathering fluxes in glacial versus non-glacial streams.

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Atkinson, W.J. 1989. Diamond exploration philosophy, practice, and promises: a review *in* O'Reilly, S.Y. (ed.), Kimberlites and Related Rocks: Their Mantle/Crustal Setting, Diamonds and Diamond Exploration. Proceedings of the 4th International Kimberlite Conference, Perth, Australia. GSA Special Publication Number 14, p. 1075–1107.

***Synopsis**. Short overview of kimberlite exploration techniques in non-glaciated terrain.*

***Exploration significance**: The author suggests that stream sampling guidelines are followed when sampling eskers for indicator minerals. For example, it is suggested that* *gravelly facies in eskers are commonly targeted (see below). This is one of the few published sources that formally states this.*

Key quotes

- *"In Yakutia, USSR, the cold climate inhibits chemical weathering and olivine grains 1.0 to 0.5 mm travel up to 100 km from kimberlites without significant wear…In Africa and Australia, in warmer climates with marked seasonal rainfall, indicator minerals have been found to travel from 20 km or more for 0.4 mm size grains, to only 1 or 2 km for 1.0 mm size grains dependant on stream gradient and stream flux"*
- *"As the indicators are heavy they concentrated en route in natural trap sites, e.g. above rock bars, in crevices in bedrock, in gravel point bars often on the inside of meanders."*
- *"In exploration small samples of this gravel, typically 8–40 kg in size, are collected at reconnaissance intervals of 3 to 15 km along the streams, a typical coverage of say, 1 sample per 50 sq km…Where kimberlite indicators are found then follow up gravel sampling is undertaken at closer intervals until the source area is defined. This technique has been responsible for the discovery of the economic Mir and Udachnya kimberlite pipes in USSR, and the Ellendale and Argyle lamproite pipes in Western Australia. In North America, gravels from eskers have been sampled in similar manner."*

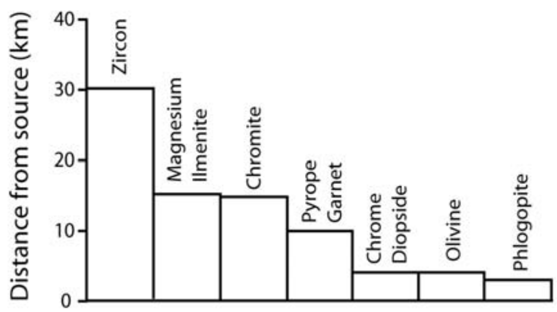

Figure showing detrital trains of indicator minerals in streams "under Australian conditions"

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Averill, S.A. 2001. The application of heavy indicator mineralogy in mineral exploration with emphasis on base metal indicators in glaciated metamorphic and plutonic terrains *in* McClenaghan, M.B., Bobrowsky, P.T., Hall, G.E. and Cook, S.J. (eds.), Drift Exploration in Glaciated Terrain. Geological Society of London, Special Publication 185, p. 69–81.

***Synopsis**. Review of the use of heavy minerals in drift prospecting. Suggests that kimberlite indicator minerals in eskers and till tend to display little wear, irrespective of proximity to source; that gold-grain dispersal trains in till tend to be short (< 1 km); that most gold (>90%) in glacial deposits is silt sized; and that esker are depleted in gold relative to till.*

***Exploration significance**: A key finding expressed here is that grain morphology (e.g., rounding)) may not be an effective proxy for kimberlite indicator mineral transport distance in glaciated settings. Most gold in glacial deposits is pristine to slightly modified.*

Key quotes

- *"Eighty to 90% of gold grains in till are silt sized, mirroring the grain size of the parent bedrock mineralization."*
- *"Most gold grain dispersal trains [in till] related to significant mineralization are < 1 km long…their gold grains are primarily of the pristine and modified classes. The anomaly strength midway along the train is typically 2 to 4 grains/kg but in a few trains, especially in the La Ronge Belt…it reaches ten grains per kilogram."*
- *"Esker sediments are depleted in gold grains relative to tills. This depletion occurs in part because esker sediments consist mainly of sorted medium to coarse sand grains whereas gold grains by nature are mostly silt sized. Although heavy, these small gold grains tend to be flushed from coarse esker sands and gravels into distal outwash silty sands due to the effective reduction in specific gravity that occurs with decreasing grain size (Stokes' law). Also the rapid rate of deposition of esker sediments does not permit the few available coarse gold grains to be concentrated into placer beds. Reported occurrences of placer gold such as in the Munro Esker in the Matheson district of the Abitibi Greenstone Belt…are generally hosted by glaciolacustrine beach deposits developed on eskers rather than in true esker sediments."*
- *"All KIM [kimberlite indicator mineral] species are chemically stable in immature glacial drift; Cr-diopside and garnet are not selectively destroyed as in mature nonglacial terrains (Mosig 1980). However certain KIMs,*

especially garnets, tend to occur as highly fractured grains in kimberlite as a consequence of hydration either during volcanism or bypreglacial weathering, and their subsequent grain size and relative abundance in glacial drift are controlled in part by this preparatory fracturing (Averill & McClenaghan 1994; McClenaghan & Kjarsgaard 2001). Fracture prone Cr-pyrope macrocrysts, for example, tend to break into large numbers of medium sand sized (0.25-0.5mm) grains whereas fracture resistant Mg-ilmenite generally remains at coarse sand size (0.5-1.0mm) and therefore tends to be less abundant."

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Averill, S.A. and McClenaghan, M.B. 1994. Distribution and character of kimberlite indicator minerals in glacial sediments, C14 and Diamond Lake kimberlite pipes, Kirkland Lake, Ontario. Geological Survey of Canada, Open File 2819, 48 p.

***Synopsis**. Study of indicator minerals in glacial deposits downflow of a kimberlite. Concludes, among other things, that the size and shape of indicator minerals does not change significantly downflow in the dispersal train.*

***Exploration significance**: Grain morphology (e.g., rounding)) may not be an effective proxy for kimberlite indicator mineral transport distance in glaciated settings. Rather, kimberlite indicator minerals in eskers and till may tend to display little wear, irrespective of proximity to source. (<u>D. Cummings note</u>: Similar opinions were communicated orally to us by Chuck Fipke and Chad Ulansky during a visit to the CF Minerals lab, Kelowna, in April 2010, and by Stu Averill during a visit to the Overburden Drilling Management lab, Ottawa, in February 2010.)*

Key quotes

- *"An important finding bearing on the global search for kimberlite is that the size and character of indicator mineral grains change very little during glacial and glaciofluvial transport…good preservation of indicator minerals…may be due…to the fact that mineral transport was rapid…Only picroilmenite, which occurred as larger, whole xenocrysts in the weathered kimberlite, appears to have been subject to fragmentation during transport…Leucoxene coatings were removed from the ilmenite xenocrysts by a few hundred meters of glaciofluvial transport but resorption textures are well preserved."*

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Aylsworth, J.M. and Shilts, W.W. 1989. Glacial features around the Keewatin ice divide: Districts of Mackenzie and Keewatin. Geological Survey of Canada, Paper 88–24, 21 p.

***Synopsis**. A regional air-photo–based geomorphological study of eskers in Keewatin. Documents landform relationships (e.g., eskers and esker corridors) that lend insight into potential sediment source areas for esker systems. Concludes that Keewatin eskers can be traced up to 700 km in length, breaks included, with unbroken segments up to 75 km. Esker segments are commonly connected by areas of outwash or belts of bedrock stripped free of till. Ice is thought to have been stagnant locally during deposition. Eskers are thought to be subglacial. Major retreat moraines are interpreted to be coalesced glaciofluvial fans and deltas. Authors note that, while eskers die out downflow approaching the edge of the Shield, they become well developed again on Paleozoic sediments.*

The accompanying map is the best source of information on the macroscopic geomorphology of eskers in North America—it is more detailed than the Prest and Fulton maps of Canada and at the same time covers a huge area. This study contains little explicit groundtruthing (though some groundtruthing was performed) and no dispersal data.

***Exploration significance**: Eskers on the Shield documented herein are 10s to 100s of kilometres long. Long eskers are either believed to have been deposited beneath the glacier in one long segment (e.g., Flint, 1930) or in shorter segments as the ice-front retreats (e.g., St. Onge, 1984). Though not stated in the Aylsworth and Shilts paper, Shilts (1984) suggests that he favours the latter interpretation, though he also believes ice stagnation was integral.*

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Bejan, A. 2000. Shape and Structure, from Engineering to Nature. Cambridge University Press, 324 p.

Synopsis*. An interesting perspective of how complexity (and specifically tree-shaped complexity) is generated in Nature. Adrian Bejan is a specialist in non-equilibrium thermodynamics. He found that tree-shaped flow structures are the best way to evacuate heat from small electronic devices, then extended this idea to explain the geometry of flow structures in Nature. His basic hypothesis is that complexity (order) in Nature is the product of thermodynamically open systems, and forms to optimize flow through the system, an idea that may have been drawn from the work of Ilya Prigogine. Theory contained within the book could potentially be used to understand phenomena such as, for example, the length and spacing of subglacial streams associated with esker deposition.*

Exploration significance*: Given the tree-like shape of eskers, subglacial streams involved in esker deposition are also suspected to have been at least somewhat tree-shaped. Whether subglacial stream length = esker length, however, is debatable: some authors support this view (Brennand, 1994), whereas others suggest the subglacial streams were much shorter and that eskers formed in segments as the ice front retreated (e.g., Hooke and Fastook, 2007).*

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Bejan, A. and Lorente, S. 2007. Constructal tree-shaped flow structures. Applied Thermal Engineering, v. 27, p. 755–761.

Synopsis*. An interesting perspective of how tree-shaped structures are generated in Nature.*

Exploration significance*: Given the tree-like shape of eskers, subglacial streams involved in esker deposition are also suspected to have been at least somewhat tree-shaped. Whether stream length = esker length, however, is debatable; the possibility exists that they were considerably shorter.*

Key quotes

- *"For a finite-sized open system to persist in time (to survive) it must evolve in such a way that it provides easier and easier access to the currents that flow through it."*
- *"…the tree-shaped flow path can be deduced by minimizing the resistance to flow between a point and a finite-size volume. The same principle generates other engineering shapes such as the round duct, the aerodynamic and hydrodynamic shapes of airborne and seaborne bodies, and the characteristic internal spacings of spaces bathed by streams."*
- *"Architectures are destined to remain imperfect because of finite-size constraints. Flows must always overcome resistances. The challenge then is to do the best possible under the specified constraints. This is accomplished by spreading the imperfections (the resistances) through the system in ways that are beneficial in the global sense.* Optimal distribution of imperfection *is the generation of physical structure—the actual being of the flow system."*

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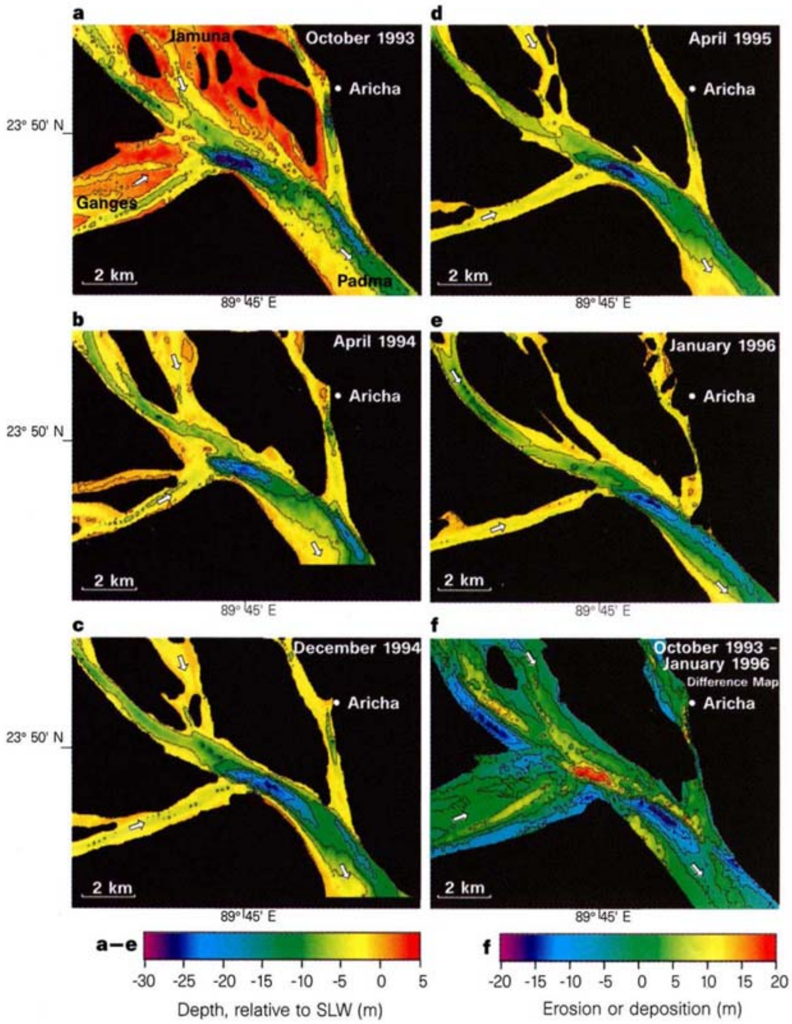
Best, J.L. and Ashworth, P.J. 1997. Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. Nature, v. 387, p. 275–277.

Synopsis*. Study of a tributary confluence scour in a large braided river. Concludes that confluences can be several times deeper than the rest of the river, and can scour below base level.*

Exploration Significance*: Tributary confluences are commonly sampled in both streams and eskers, the idea being (1) that the sample may potentially be enriched in indicator* *minerals, as commonly observed in fluvial systems (Slingerland and Smith, 1984), and (2) that one sample will capture dispersal trains from both tributaries. Intermingling of dispersal trains emanating from esker tributaries has been observed at esker tributary confluences (Lillieskold, 1990; Bolduc, 1992), suggesting the subglacial streams in which they formed were tree-shaped and coeval. However, confluences in streams are zones of net degradation, whereas confluences in esker sedimentary systems are zones of net aggradation. Whether similar concentration effects occur at confluences in esker sedimentary systems is therefore questionable.*



Scour at channel confluence, Jamuna River, Bangladesh. These scour zones are commonly places where indicator minerals concentrate (see Best and Brayshaw, 1985). Though similar scour may affect R-channels, tributary junctions of eskers in East Arm were not observed to be consistently thicker.

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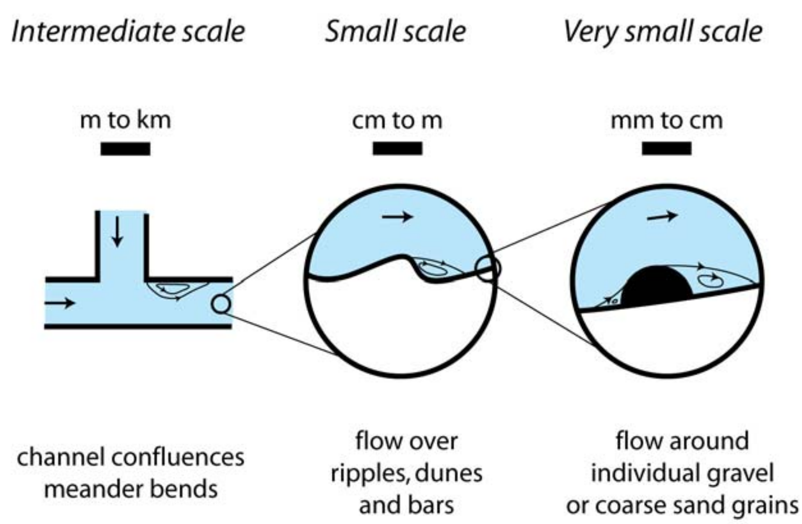
Best, J.L. and Brayshaw, A.C. 1985. Flow separation—a physical process for the concentration of heavy minerals within alluvial channels. Journal of the Geological Society of London, v. 142, p. 747–755.

***Synopsis**. Experimental study of magnetite dispersal and partitioning (1) across small bed obstacles, and (2) at tributary confluences. Concludes that heavy minerals have the potential* *to concentrate wherever flow separation occurs. The paper contains nice figures (see below).*

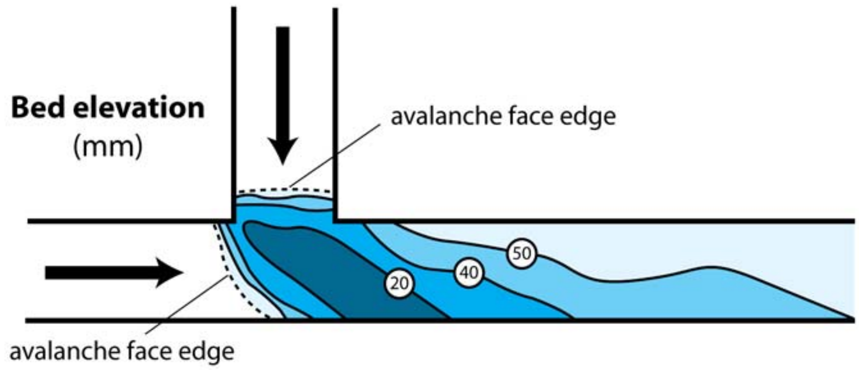
***Exploration significance**: One key finding is that mixing of dispersal signals at tributary junctions does not occur directly at the tributary junction. Rather, it occurs some distance downflow of the junction (equal to several channel widths in the experiments). As such, when sampling an esker tributary junction, it might therefore be prudent to sample downflow of junction by a certain distance, maybe around half a kilometer or so, not directly at the junction, in order to insure that sediment from each esker tributary is being sampled. The stream sampling team at GSC-Ottawa commonly employs this tactic when sampling streams (Steve Day, personal communication, 2010).*

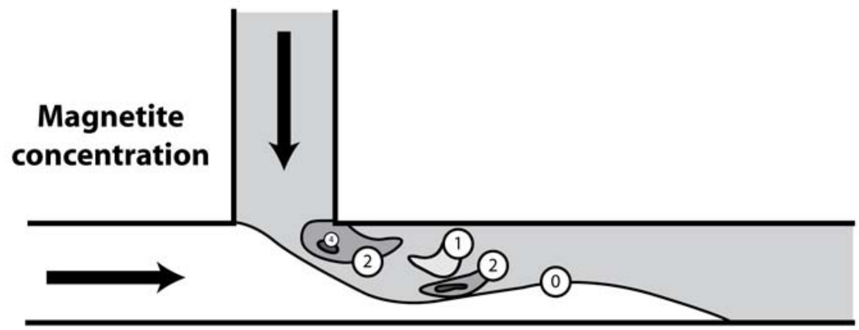
Key quotes

- *"…placers have been recorded from a wide range of locations and at vastly differing geomorphological scales. Large, fluvial placers occur at points of abrupt valley widening (Kuzvart and Bohmer 1978). At a mesoscale, familiar sites are the heads of mid-channel bars (Toh 1978; Smith & Minter 1980), the convex bends of meanders (Kuzvart & Bohmer 1978), positions downstream from channel junctions (Mosley & Schumm 1977) and at the bedrock contact (Gunn 1968; Tuck 1968; Adams et al. 1978). Placers have also been recorded from numerous sites on a microscale: common locations for heavy mineral concentration are the scoured bases of trough cross-sets (Toh 1978), dune crests (Brady & Jobson 1973), bedding planes (Cheel 1985) and in association with plane parallel lamination (Slingerland 1977)."*



Flow separation at various scales in fluvial systems. Each of these has the potential to concentrate heavy minerals. Similar processes are suspected to operate in esker systems.





Experiment showing concentration of magnetite grains in confluence scour.

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Bolduc, A.M. 1992. The formation of eskers based on their morphology, stratigraphy, and lithologic composition, Labrador, Canada. Unpublished PhD thesis, Lehigh University, 190 p.

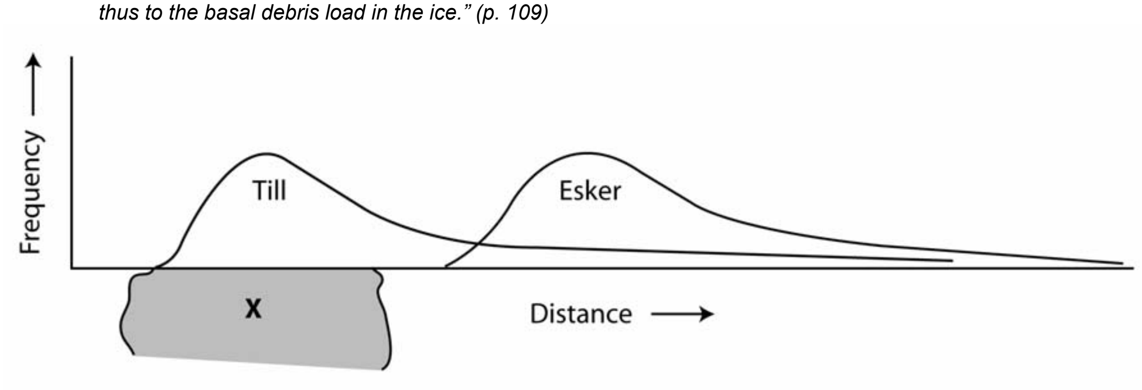
***Synopsis**. Along with Levasseur (1995) and Gillberg (1968), this is a must-have—a great place to start. It is the most comprehensive study of eskerine gravel dispersal to date, and, with the exception of Levasseur and Prichonnet (1995), is the only comprehensive study of an esker dispersal train on the Canadian Shield. (The study is "comprehensive" in that till is investigated in parallel to the eskers, so deconvolution of glacial (till) and eskerine dispersal is clear.) Coarse sand dispersal is also investigated in one esker. Concludes that gravel and medium–coarse sand dispersal trains in eskers are of similar length to the underying till dispersal train, from which they tend to be primarily sourced, but are shifted downflow by several kilometres to at most 25 kilometers. Despite extensive dataset, Bolduc does not come down with a hard conclusion of how eskers are generated.*

***Exploration significance**: Are gravel and medium–coarse sand dispersal trains in eskers typically short, like the ones studied by Bolduc?*

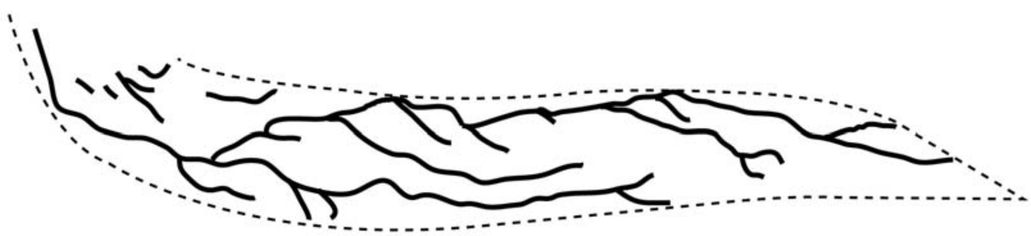
Key quotes

- *"There appears to be a fundamental difference between fluvial and fluvioglacial systems, which is that fluvioglacial drainage basins retain their elongate shape regardless of esker size…The regular spacing between eskers (12–15 km) also reflects the amount of meltwater to drain, and is therefore a characteristics of the subglacial drainage of an ice sheet. The length-area ratio and the regular spacing between eskers indicate that*

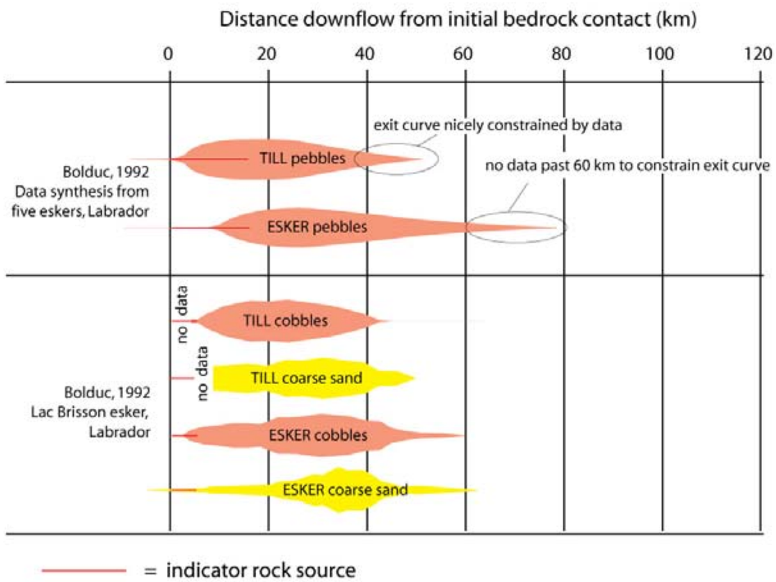
- *"Sample density varies along an esker and between eskers…Smoothing over a fixed distance (e.g., 5 km) regardless of sample density…would not have been appropriate. Smoothing over 5 km would have meant using one sample along some portions of an esker, and up to 10 samples along other segments. In order to treat all eskers similarly, a moving average of 5 samples appeared the best treatment, and the following discussion refers to the smoothed curves."*
- *"Relative proportions of clast abundances within eskers are a direct reflection of their proportions within till. Thus, esker composition relates to glacial erosion of bedrock, rather than fluvioglacial erosion of bedrock, and thus to the basal debris load in the ice." (p. 109)*



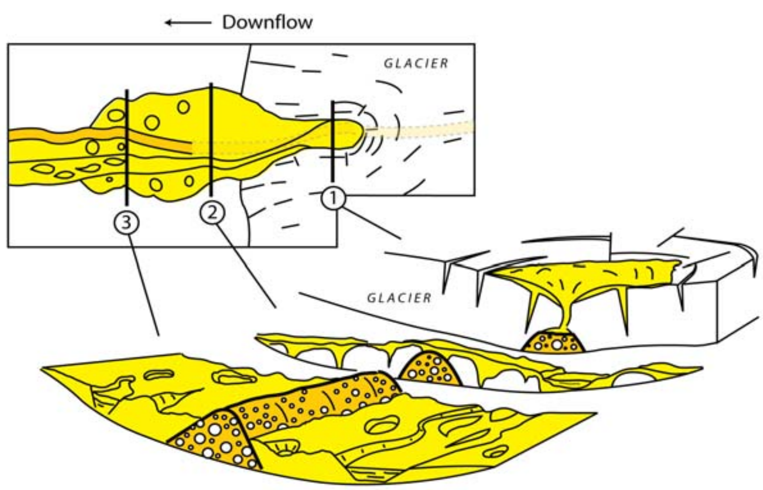
Theoretical dispersal curves for gravel-sized clasts downflow of bedrock source in till and esker



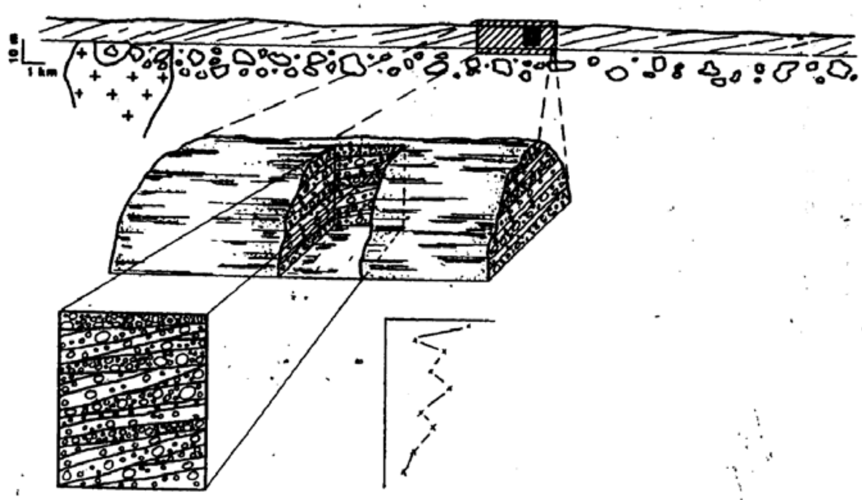
Planform shape of the Lac Brisson esker, Labrador (no scale provided in Bolduc, 1992). Note how "catchment" is elongate, as is common for Shield eskers, but uncommon for fluvial systems.



Dispersal data from several eskers and adjacent till in Labrador



Conceptual depositional model for eskers in Labrador



Conceptual "shingled" facies architecture invoked to explain short indicator dispersal typical (?) of Shield eskers. [Note that this is contradicted by Bolduc's statement that subglacial conduits were the same length and shape as the resultant tree-shaped eskers. See p. 58 in Bolduc, 1992.] Paleoflow is to the right. Note that upward, down-esker indicator trajectory is similar, both in terms of scale and geometry, to till-dispersal models (e.g., Puranen, 1990; MacClenaghan and Kjarsgaard, 2007).

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Boulton, G.S. 2006. Glaciers and their coupling with hydraulic and sedimentary processes *in* Knight, P.G. (ed.), Glacier Science and Environmental Change, Blackwell Publishing, p. 3–22.

***Synopsis**. Discusses the basal boundary of glaciers, and the origin of till and subglacial landforms. Includes a nice summary table that lists the debris concentrations in basal ice from modern glaciers (see below). Note that, in general, very little debris exists.*

***Exploration significance**. Did similar debris concentrations exist at the base of the Laurentide Ice Sheet? If so, could basal ice have been the primary sediment source for eskers? Or is till eroded from esker corridors a more likely sediment source?*

Basal ice is commonly touted as a key source of debris for eskers: it should flow into subglacial conduits like toothpaste (Rothlisberger, 1971), and, in doing so, feed debris to the esker sedimentary system. Paucity of sediment in basal ice of modern glaciers brings into question how much sediment existed in the basal ice of the Laurentide Ice Sheet and, by extension, how important it was as a debris source for eskers (especially compared to the subjacent till). (This debate would only have exploration significance if the provenance of debris in the basal part of the Laurentide Ice Sheet differed substantially and consistently from that of the subjacent till. There is currently no strong evidence for or against this.)

Glacier	Debris volume concentration (%)	Debris zone thickness (m)	Potential melt-out till thickness (m)
East Antarctica margin	0–12	15	0–1.8
Antarctic Byrd core	7	4.8	0.34
Camp Century, Greenland	0.1	15.7	0.016
Nordenskioldbreen, Spitsbergen	40	0.4	0.16
Barnes ice cap, Baffin Island	6–10	8	0.048–0.08
Breidamerkurjokull, Iceland	50	0.15–0.3	0.075–0.15
Breidamerkurjokull, Iceland	8–10	0.05–0.3	0.004–0.02
Matanuska, Alaska, dispersed facies	0.04–8.4	0.2–8	>0.0008
Matanuska, Alaska, stratified facies	0.02–74	3–15	>0.006
Glacier d'Argentiere, France	43	0.02–0.04	0.009–0.017
Myrdalsjokull, Iceland	15–31	2–5	0.3–1.55
Bondhusbreen, Norway	0.39	5	1.95
Watts, Baffin Island	14–57	0.8–2.9	>0.4

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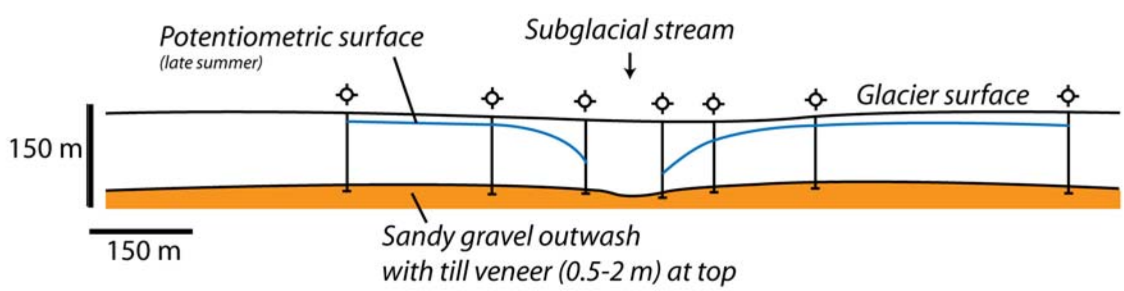
Boulton, G.S., Lunn, R., Vidstrand, P., and Zatsepin, S. 2007a. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part 1–glaciological observations. Quaternary Science Reviews, v. 26, p. 1067–1090.

***Synopsis**. Nice example from a modern glacier of inflow of distributed subglacial water (higher pressure) into an R-channel (lower pressure). Argues that R-channels in this setting are recharged by groundwater flow. In this setting, the glacier is underlain by 15 m of gravel outwash with only a skiff (0.5–2 m) of till on top. Thirty metres upflow from ice margin, the R-channel is 3 m wide and 1 m high*

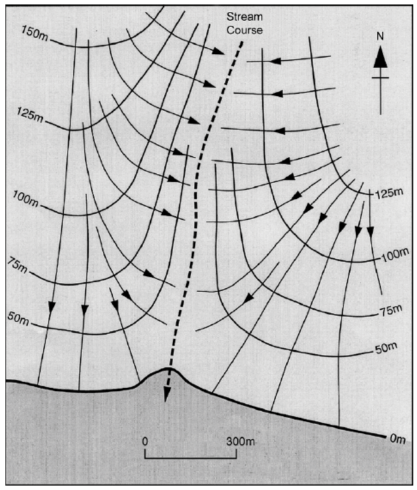
***Exploration significance**. Raises the questions of (1) how important subglacial water inflow (and particularly groundwater inflow) into R-channels was beneath the Laurentide Ice Sheet, (2) whether this water could have transported sediment into the R-channel, and (3) how basal melting may have factored into the observed regular spacing and tree-like shape of eskers on the Precambrian Shield.*

Key quotes

- *"Boreholes drilled through an Icelandic glacier into an underlying till…reveal a subglacial groundwater catchment that is drained by a subglacial stream along its axis. The stream tunnel is characterized by low water pressures, and acts as a drain for the groundwater catchment, so that groundwater flow is predominantly transverse to ice flow, towards the channel."*
- *"A high regional geothermal flux, up to five times the normal continental rate, enhances the rate of basal melting, such that even in winter, when there is little or no supraglacial water available to penetrate to the bed, significant subglacial water discharges can be maintained."*
- *"Evience from borehole heads and dye tracing suggests that Darcian groundwater flow is the predominant means by which tunnels scavenge meltwater from the glacier sole"*



Potentiometric surface during the melt season for wells screened beneath a glacier in subglacial sandy gravel outwash. Note how potentiometric surface slopes toward inferred position of subglacial stream. Groundwater flow is toward stream, oblique or transverse to ice surface slope.



Conceptual model of groundwater flow in the vicinity of subglacial stream

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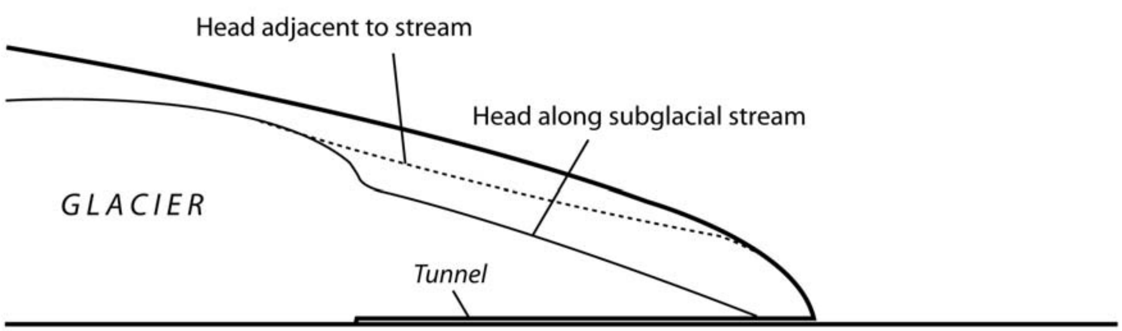
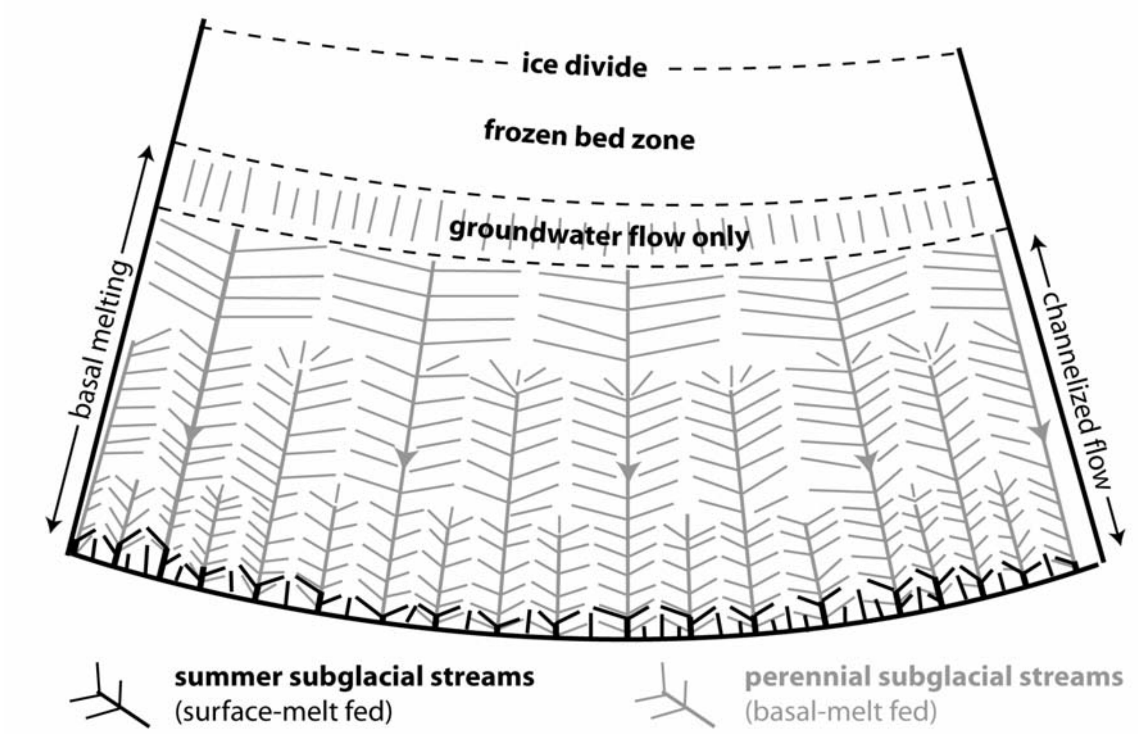
Boulton, G.S., Lunn, R., Vidstrand, P., and Zatsepin, S. 2007b. Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part II—theory and simulation of a modern system. Quaternary Science Reviews, v. 26, p. 1091–1105.

Synopsis*. Numerical modelling of subglacial drainge. Guided by a field case study from Iceland (Boulton et al., 2007a).*

Exploration significance. *Theoretical studies like this one give insight into how sediment may be transferred into esker sedimentary systems (subglacial streams). Along with glacier ice (Rothlisberger, 1972), distributed meltwater beneath glaciers should flow into subglacial streams, if subglacial streams exist. Results from this study suggest the angle of meltwater inflow may be oblique close to the ice margin and at right angles farther beneath the ice. The potential for erosion during such meltwater inflow would be highest close to the conduit, where the potentiometric gradient is steepest.*



Theoretical piezometric surfaces in channelized vs distributed (off-channel) flow systems. Note that slope of hydraulic gradient does not change, which may suggest sediment transport capacity, unlike rivers, is constant downflow (see also Alley et al., 1997).



Conceptual model of meltwater drainage beneath an ice sheet. In this model, most geomorphic work is performed by the summer streams, whose effects are suggested to be limited to very near the ice margin.

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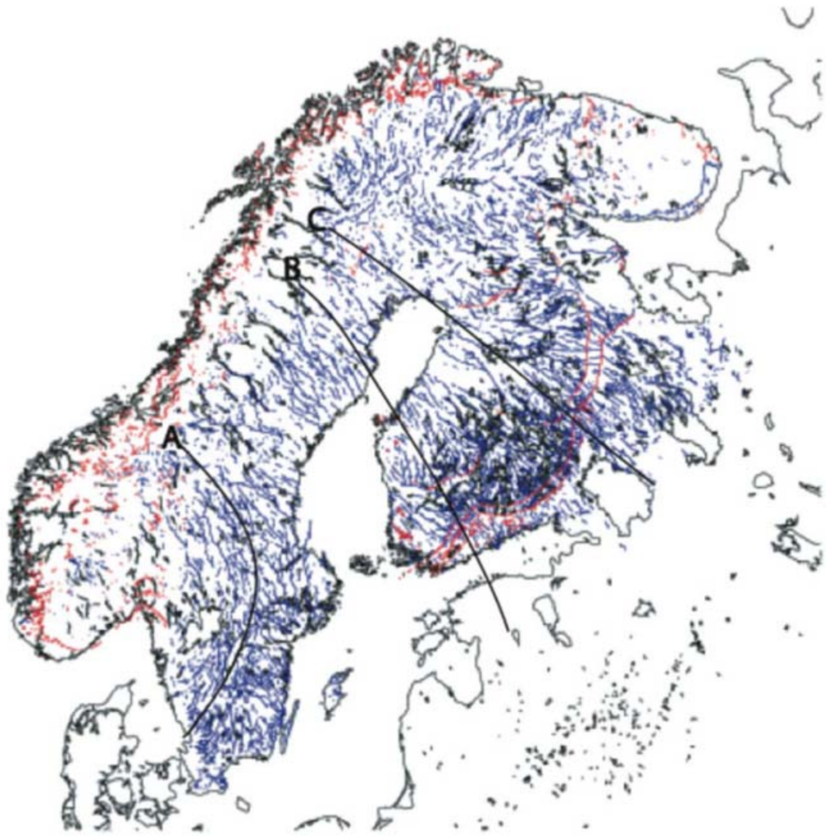
Boulton, G.S. 2009. Drainage beneath ice sheets: Groundwater–channel coupling, and the origin of esker systems from former ice sheets. Quaternary Science Reviews, v. 28(7–8), p. 621–638.

***Synopsis**. Extension of ideas developed from a modern glacier (Boulton et al., 2007a) and numerical modelling (Boulton et al., 2007b) to the deposition of eskers by Late Pleistocene ice sheets. Concludes that eskers formed in short segments as the ice front retreated.*

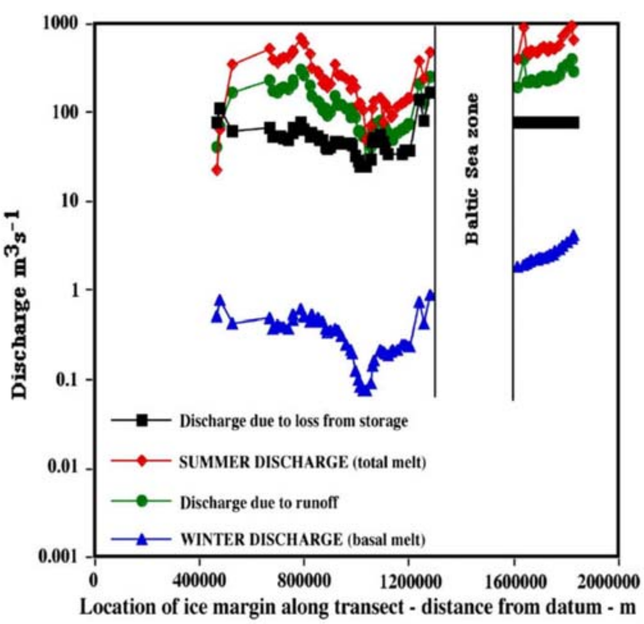
***Exploration significance**. If eskers formed in short segments, as suggested, dispersal trains in eskers should be no longer than the length of the segments.*

Key quotes

- *"…in the absence of a significant gravitational component produced by a sloping bed, water velocities in a water-filled tunnel will like within the relatively narrow range of about 2–6 m/s for a wide range of discharges."*
- *"In north Germany, the frequency of tunnel valleys appears to be very similar to that of eskers on the Fennoscandian Shield to the north. In what follows, we shall assume that both eskers and tunnel valleys reflect a similar phenomenon, the existence of major channels at the ice–bed interface (and will argue this in detail in a further article), with the former occurring on a hard bed and the latter on a soft bed."*
- *"The frequency of tunnels is the minimum required to draw down groundwater pressures so that these are less than the ice pressure at the groundwater divide between adjacent catchment areas."*
- *"The geometry of the esker-forming channel system, and the spacing between channels/eskers, is largely determined by base flow (mostly basal melting) during the long winter period and by the transmissivity of the bed."*
- *"The major, perennial streams which tend to created long, continuous esker systems, flow both in winter, when they are largely fed by basal meltwater, and in summer, when, in addition, they also drain considerable discharges of surface water that penetrate through the glacier. Whereas the geometry of the system is determined by winter conditions, sedimentation along and beyond tunnels, which creates eskers and associated proglacial fans, is largely determined by the much larger summer discharges."*



Eskers (blue) and end moraines (red) in Scandinavia



Theoretical discharge components of R-channels during retreat of Fennoscandinavian Ice Sheet

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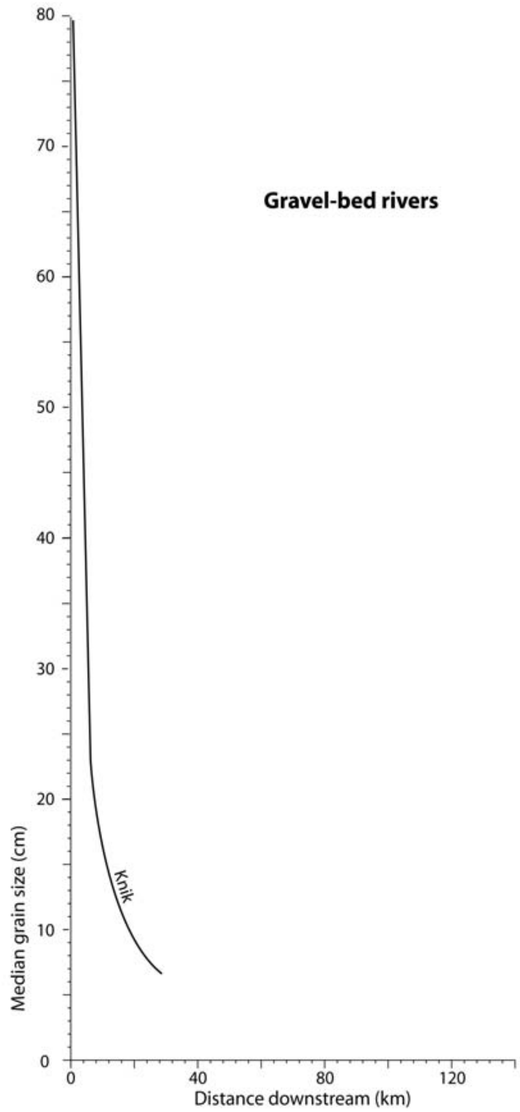
Bradley, W.C., Fahnestock, R.K., and Rowekamp, E.T. 1972. Coarse sediment transport by flood flows on Knik River, Alaska. Geological Society of America Bulletin, v. 83, p. 1261–1284.

***Synopsis**. Study of downstream fining in the Knik River, a proglacial outwash plain. Finds rapid decrease in grain size. Based on abrasion experiments, authors conclude this is due to selective sorting, not abrasion. The bed material studied here is coarser than in most other downstream-fining studies. Likely as a consequence of this, the downstream-fining curve is extremely steep: the boulders deposit VERY close to source.*

***Exploration significance**: Dispersal trains in eskers are suspected to fine downflow (even though esker sediments as a whole do not.). As in fluvial systems, this is likely cause by a combination of abrasion, which does affect gravel in eskers, causing it to become rounded and selective sorting, which also must occur given the lack of mud and finer sand in eskers compared to its abundance in till, the source of most esker sediment.*

Key quotes

- *"Knik River…is a glacial river with a valley train which was, until recently, swept each summer by a brief large flood resulting from the sudden drainage of an ice-dammed lake (Lake George)."*
- *"During its first 16 mi of travel, where alluvial contamination from side streams is unimportant, the coarse fraction of the valley train changes systematically in size and shape. Grain size decreases by 94 percent, although this figure pertains to two populations: oversized particles and coarse particles which are readily moved by Knik flood flows. If the latter population alone is considered, reduction is 87 percent."*
- *"Sixteen miles of travel [and abrasion] in a Kuenen-type abrasion tank reduced the size of Knick River gravel by only 8 percent and failed to change its shape. We conclude that downvalley changes in size and shape of coarse gravel are caused chiefly by sorting processes, aided by frost action which splits foliated particles into platy fragments."*



Downstream fining, Knik River (proglacial outwash), Alaska (noise filtered out). Note that these clasts are larger than most other gravel-bed studies reviewed in this bibliography, and that the corresponding downstream-fining curve is extremely steep.

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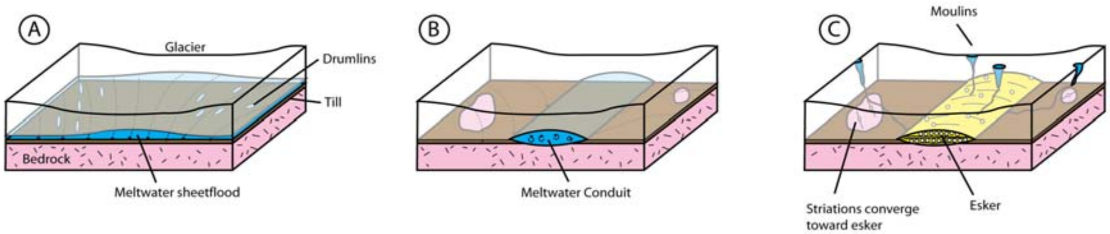
Brennand, T.A. and Shaw, J. 1996. The Harricana glaciofluvial complex, Abitibi region, Quebec: its genesis and implications for meltwater regime and ice-sheet dynamics. Sedimentary Geology, v. 102, p. 221–262.

***Synopsis**. Detailed sedimentological investigation of the Harricana esker, Quebec. Concludes that esker formed in one single, long (hundreds of km) subglacial conduit beneath the Laurentide Ice Sheet.*

***Exploration significance**. If eskers commonly form as envisioned by Brennand and Shaw—namely in one single long subglacial conduit—esker dispersal trains have the potential to be as long as the esker itself, especially for finer fractions (wash load).*

Key quotes (some paraphrased)

- *"[Downflow widening of landform]…together with unidirectional paleoflows…and the relatively continuous upslope path of the southward-widening complex, favour synchronous formulation of the Harricana complex in a continuous closed condtuit, beneath an ice sheet which thinned southward. Subaqueous fans and grounding-line deposits with fine gravel and sandy in-phase wave structures in the south, may have been deposited in subglacial cavities adjacent to the complex, or later deposited in reentrants in calving ice fronts.".*
- *Gravel-clast roundness decreases downflow over 250 km length of esker*



"Post-sheetflood" depositional model for Harricana esker, northern Ontario

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Brennand, T.A. 1994. Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implications for esker genesis and meltwater regime. Sedimentary Geology, v. 91, p. 9–55.

Synopsis. *Detailed sedimentological study of several eskers in south-central Ontario. Concludes that the eskers formed in long, continuous conduits under extremely high meltwater discharge regimes (similar to that of the Amazon River, the largest river on Earth).*

Exploration significance. *If eskers commonly form as envisioned by Brennand—namely in one single long subglacial conduit—esker dispersal trains have the potential to be as long as the esker itself, especially for finer fractions (wash load).*

Key quotes (some paraphrased)

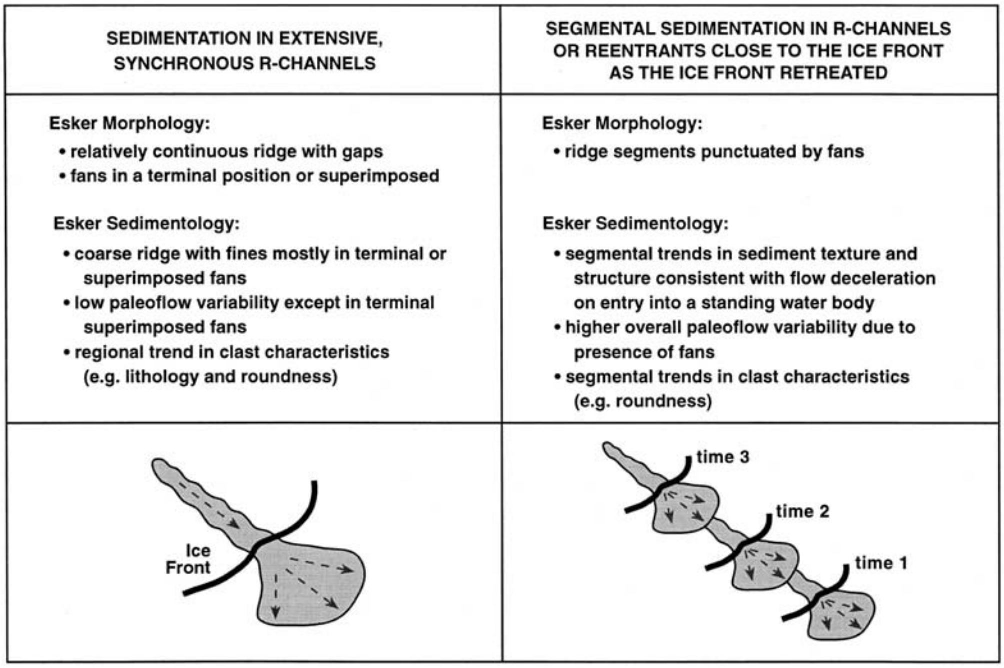
- *"Eskers of south-central Ontario were deposited in closed, subglacial conduits which were continuous…This interpretation is supported by: the intimate association of eskers with an anastomosing network of tunnel channels; relatively continuous esker ridges; minimal post-formational disturbance of esker sediments; intercalation of till and stratified sand and gravel; diapiric folding at an esker core; low variability in paleocurrent direction; and upslope flow paths."*
- *"Esker ridge morphology is attributed to synchronous erosion, transportation and deposition along the main conduits, such that ridge discontinuities are primarily explained as zones of non-deposition during esker formation."*
- *"The location of macroforms within conduits was primarily controlled by conduit geometry and sediment availability, and later by feedback between macroform and conduit geometries."*
- *Associated hummocky terrain is interpreted to have been deposited in subglacial cavities adjacent to the main conduit.*
- *Clast roundness and clast sphericity data show no clear downflow trends*

========

Brennand, T.A. 2000. Deglacial meltwater drainage and glaciodynamics: inferences from Laurentide eskers, Canada. Geomorphology, v. 32, p. 263–293.

Synopsis. *Comprehensive, provocative review of eskers and esker sedimentary systems.*

Exploration significance. *This paper provides a conceptual framework for understanding sediment dispersal in eskers. If eskers form in short segments as the ice retreats, they will contain short dispersal trains. If they form as one long segment in one long subglacial stream, they may contain long dispersal trains (especially for finer grain sizes).*



Theoretical differences between eskers deposited synchronously vs time transgressively

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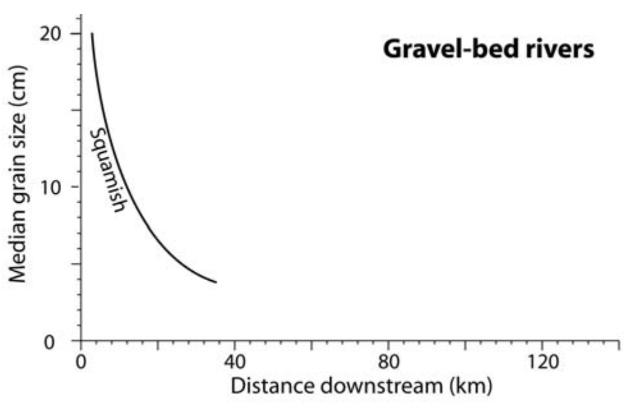
Brierly, G.J. and Hickin, E.J. 1985. The downstream gradation of particle sizes in the Squamish River, British Columbia. Earth Surface Processes and Landforms, v. 10, p. 597–606.

Synopsis. *Study of bed material in the Squamish River. Documents pronounced downstream fining of medium grain size over several 10s of kilometres.*

Exploration significance: *Dispersal trains in eskers are suspected to fine downflow, possibly somewhat like the sediments in the Squamish River. If this is true, a general rule might be "the larger the clast, the closer to source" (which for eskers is typically an underlying till dispersal train).*



Downstream fining, Squamish River, British Columbia (noise filtered out).

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Brown, T.R. 1986. Eskers and Heavy Mineral Prospecting, Northeastern Minnesota. Unpublished MSc thesis, University of Minnesota, 103 p.

***Synopsis**. Investigation of heavy minerals in several eskers in Minnesota. Heavy minerals were collected from eskers, but not from adjacent till. This precludes deconvolution of eskerine and glacial (till) dispersal.*

***Exploration significance**: Gravel in Minnesota eskers has a similar lithological make up as gravel in subjacent till (a common observation in glaciated terrain).*

Key quotes

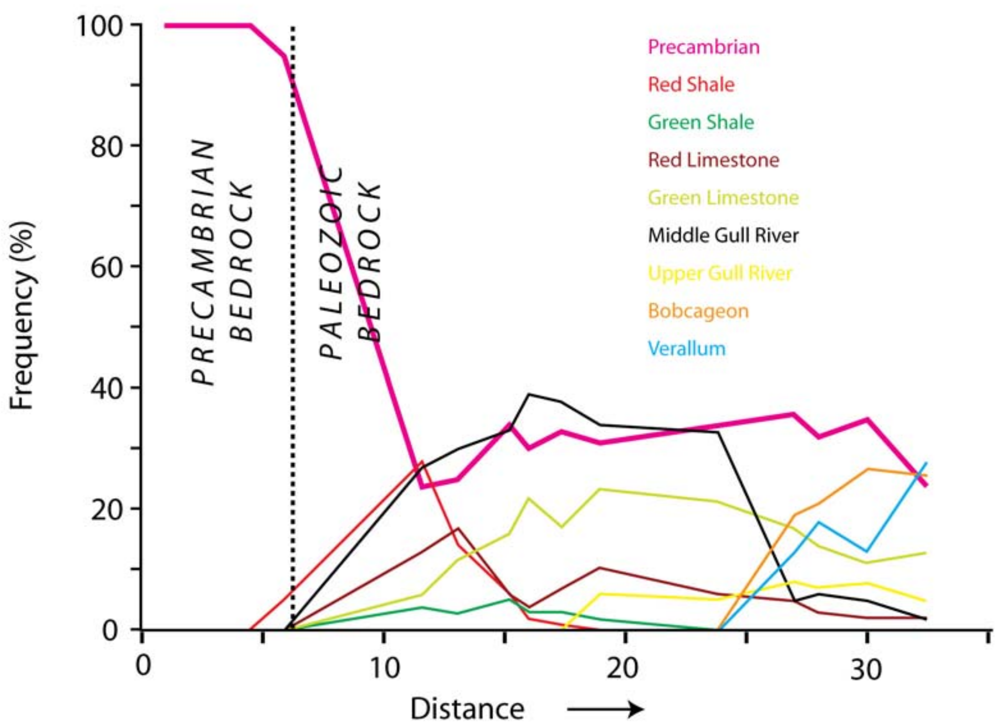
- *"One consistent fact shown by the stone counts is that the percentage of a given lithology in the esker, usually in the boulder fraction and often in the pebble fraction, has a similar percentage in the [neighbouring] till. This…indicates the material in the esker was derived from either the englacial load, or by meltwater erosion of the underlying till."*

========

Buck, S. 1983. Transport distances of bedrock particles in the Tweed esker. Unpublished MSc thesis, Brock University, 83 p.

***Synopsis**. Study of pebble indicators down flow of several different bedrock sources. Till dispersal not studied in parallel (i.e., cannot deconvolve eskerine from till dispersal). Concludes that cobbles and pebbles show very similar dispersal curves. K distances range from 5 to 11 km. First appearance downflow from presumed bedrock source varies from -0.85 km to 4.8 km.*

***Exploration significance**. Material can be incorporated quickly into eskers downflow of bedrock contacts.*



Dispersal curves for various cobble lithologies in Tweed esker, Ontario

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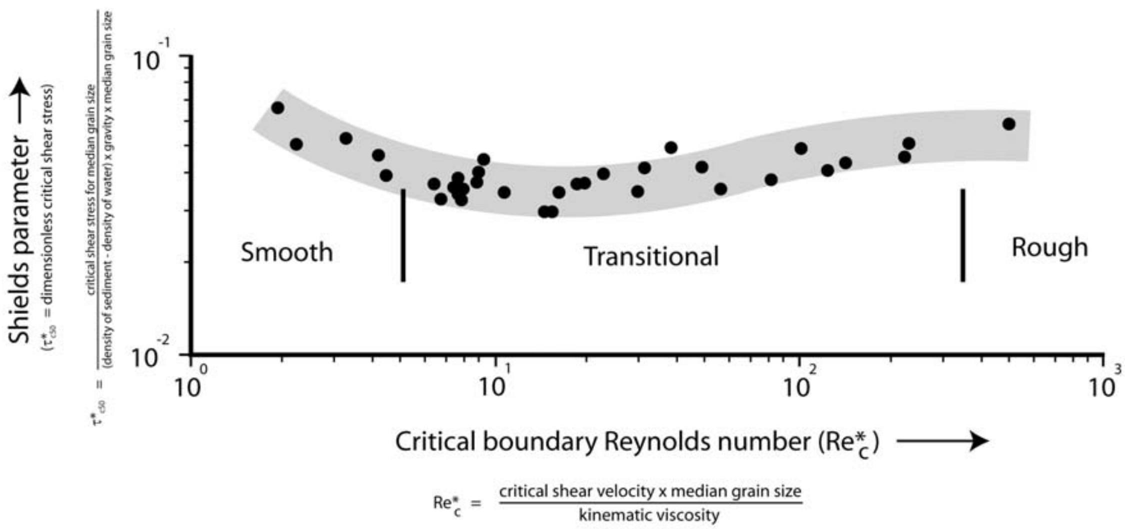
Buffington, J.M. and Montgomery, D.R. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research, v. 33(8), p. 1993–2029.

***Synopsis**. Review of experiments investigating the threshold of sediment motion. Concludes that, while Shields curve still stands as best way to estimate initiation of motion, the data contain significant scatter, primarily because of different agreements over definition of "initiation of motion".*

***Exploration significance**: Sand is easier to entrain than mud or gravel. Entrainment from well-sorted sediment beds will therefore be selective: sand will mobilize first, mud and gravel later, at higher velocities.*



Shields curve (1936) showing initiation of motion (from Buffington and Montgomery, 1997)

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Burton, J.P. and Fralick, P. 2003. Depositional placer accumulations in coarse-grained alluvial braided systems. Economic Geology, v. 98, p. 985–1001.

***Synopsis**. Flume study to determine what factors cause heavy minerals to concentrate in gravel-rich facies. The tendency for HMs to concentrate in gravel increased with (1) increasing mineral density, (2) decreasing flood frequency, (3) decreasing concentration of granules to small pebbles, (4) a rapid drop in regional bed (energy) slope (i.e., in zones of energy loss and net deposition), (5) increased flow velocity (velocities sufficient to suspend quartz but not other heavy minerals).*

***Exploration significance**: Sandy-sized heavy minerals in fluvial systems tend to concentrate in gravelly facies. Is the same true for eskers?*

Key quotes

- *"Data from these studies indicate that a number of conditions are necessary, or at least desirable, for heavy minerals to accumulate in coarse-grained alluvium. These are (1) a low proportion of granule to very small pebble-sized lithic fragments; (2) a very heavy mineral population whose hydraulic behavior more closely resembles that of the pebble population than that of the quartz sand; (3) flow velocities capable of creating a suspension cloud from the coarse-grained quartz sand population; (4) a change in the regional slope (inflection point) creating a gradient-parallel zone of energy loss; (5) infrequent major flood events; and possibly (6) preconcentration, i.e., an enriched, erosional lag upslope from the ultimate area of depositional placer*

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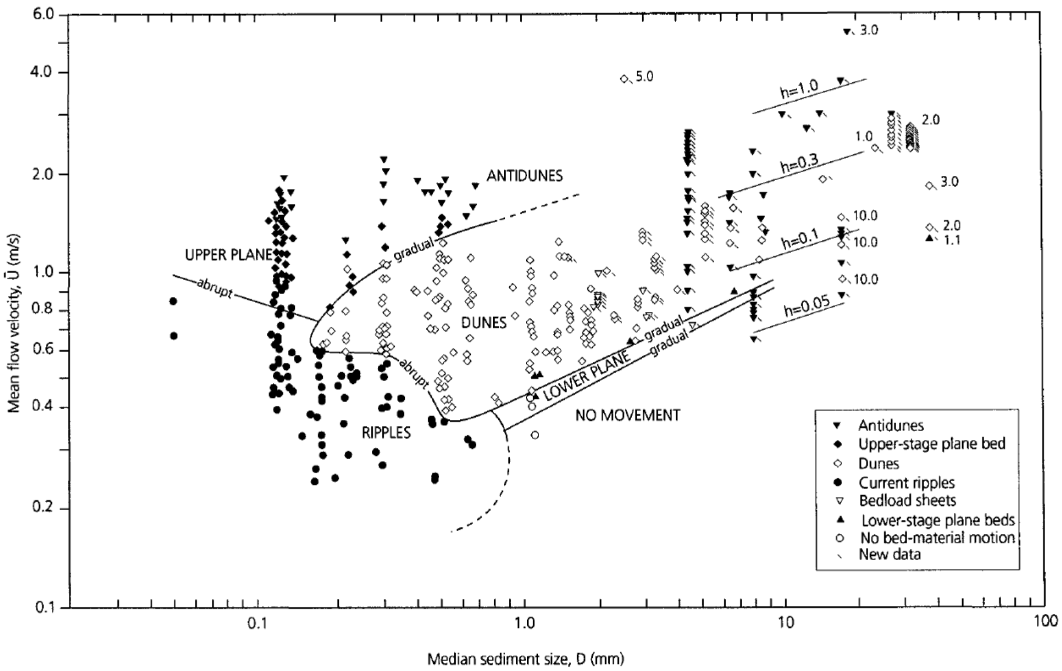
Carling, P. 1999. Subaqueous gravel dunes. Journal of Sedimentary Research, v. 69(3), p. 534–545.

***Synopsis**. Literature review of bedforms generated in gravel. Concludes that while dunes are not as common in gravel-bedded rivers as they are in sand-bed rivers, they do occur, even at very coarse (pebble, cobble, possibly boulder) grain sizes. The author extends the bedform phase diagram of Southard and Boguchwal (1990) into coarser grain sizes (see figure below).*

***Exploration significance**: Dunes, where present in esker dispersal systems, should cause flow separation and heavy mineral entrapment, just like they do in fluvial systems, either permanently (in zones of net deposition) or temporarily (in zones of net erosion). In other words, dunes function to hinder down-stream dispersal of indicator minerals. (ASIDE: Although gravel dunes are not common in gravel-bed rivers, they can form during high magnitude events. Most stratification in gravelly eskers tends to be crude and horizontal. Dune-scale cross-beds are observed locally, however, suggesting that dunes may rarely form and be preserved in esker systems.)*



Phase diagram for unidirectional bedforms in sand and gravel

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Carling, P.A. and Breakspear, R.M.D. 2006. Placer formation in gravel-bedded rivers: A review. Ore Geology Reviews, v. 28, p. 377–401.

***Synopsis**. Review of small-scale heavy mineral trap sites in gravel bed rivers. A general conclusion is that heavy minerals concentrate in gravel-rich strata.*

***Exploration significance**: If esker systems are comparable to the fluvial systems described herein, heavy minerals will tend to concentrate where flow separation occurs, and will be more abundant in gravelly than sandy facies.*

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Carling, P.A., Orr, H., and Kelsey, A. 2006. The dispersion of magnetite bedload tracer across a gravel point-bar and the development of heavy-mineral placers. Ore Geology Reviews, v. 28, p. 402–416.

***Synopsis**. Study of magnetite sand dispersal across a fluvial point bar composed of sandy fine gravel. Concludes that coarser-grained bar head is enriched in magnetite relative to finer-grained bar tail.*

***Exploration significance**: If esker systems are comparable to the fluvial system described herein, heavy minerals may tend to concentrate in gravelly facies.*

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Carlson, A.E., Jenson, J.W., Clark, P.U. 2007. Modeling the subglacial hydrology of the James Lobe of the Laurentide Ice Sheet. Quaternary Science Reviews, v. 26, p. 1384–1397.

***Synopsis.** Numerical modelling of water flow beneath a glacier that overlies a low-permeability (mudy-rich till) substrate.*

***Exploration significance**: Glaciofluvial dispersal beneath glaciers may not be strictly limited to esker systems (i.e., R-channels).*

Key quotes

- *"…the [numerical model] simulations indicate that the regional aquifer system could not have drained even the minimum amount of basal meltwater that might have been produced at the glacier bed. Therefore, excess drainage must have occurred by some sort of channelized drainage network at the ice–till interface…Results suggest that for conduits assumed to be on the order of a tenth of a meter deep and up to a meter wide, inter-conduit spacing must on the order of tens–hundreds of meters apart to maintain basal water pressures below the ice overburden pressure while evacuating the hypothesized minimum meltwater flux."*

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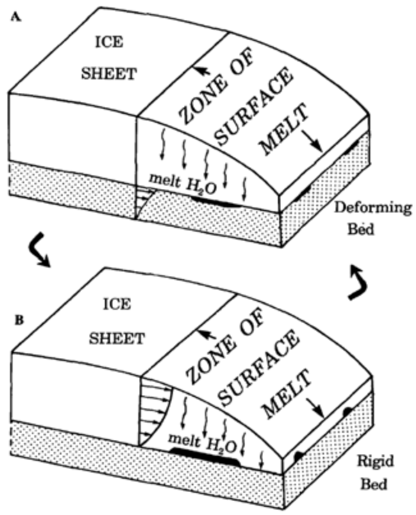
Clark, P.U. and Walder, J.S. 1994. Subglacial drainage, eskers, and deforming beds beneath the Laurentide and Eurasian ice sheets. Geological Society of America Bulletin, v. 106, p. 304–314.

***Synopsis**. Based on theoretical considerations, the authors argue that R-channels should form beneath glaciers where till is coarse-grained, rigid, and highly permeable (e.g., Shield) and N-channels should form where till is muddy, deformable, and impermeable (e.g., Prairies).*

***Exploration significance**: Predicts markedly different subglacial meltwater dispersal regimes in areas of muddy till (e.g., Prairies) and sandy till (Shield). Specifically, the slow-moving (0.1–0.3 m/s), pressurized ($P_{water} = P_{ice}$) subglacial meltwater in broad shallow N-channel ("canals") predicted in areas of muddy till would not be able to mobilize gravel, but could potentially winnow sand and mud. Field evidence for such "canals" has yet to be observed.*

Key quotes

- *"Eskers are a few tens to hundreds of meters in width and height. Such dimensions are much greater than what is physically reasonable for an R channel—even channels associated with gigantic Icelandic outburst floods have diameters of no more than about 10 m (Nye, 1976). Thus eskers cannot form wholly within any single conduit, but must be built up over time as sediment melts out of channel walls and is deposited and reworked on the channel floor…:" <u>Note (Don Cummings):</u> R-channels (and esker-like ridges of sand and gravel) with heights of up to 30 m form during jokulhlaups in Iceland (Andrew Russell, personal communication, 2009)*
- *"…an important distinction between R channels and canals is that the water velocity should be considerably higher in the former than the latter, on the order of 1–3 m/s for R channels, but only about 0.1–0.3 m/s for canals (estimated from the results of Walder and Fowler [in press]). This difference is due to the considerably greater cross-sectional area (for a given discharge) for a canal network than for channels."*
- *"The width of this zone of surface melting (ablation zone) [of the Laurentide Ice Sheet], but it was likely on the order of hundred of kilometres…and would not have included ice divides at maximum extent."*



Conceptual model of subglacial meltwater flow (A) on a deforming bed, where N-channels are hypothesized to form (e.g., sandy till on Shield), and (B) on a rigid bed, where R-channels are hypothesized to form (e.g., mud-rich till in Prairies).

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Clarke, G.K.C. 2005. Subglacial processes. Annual Review of Earth and Planetary Sciences, v. 33, p. 247–276.

Synopsis*. From a theoretical standpoint, this paper reviews the interactions between ice, meltwater, sediment, and bedrock that are thought to occur beneath glaciers.*

Exploration significance: *This paper provides a conceptual framework for understanding sediment sourcing and dispersal in esker sedimentary systems.*

Key quotes

- *"The main consequences of water-coupled subglacial sediment transport processes are to erode soft sedimentary beds and alter their mechanical and hydraulic properties by the selective removal of fine-grained sediment. Without fines-removal the comminution process tends to be self-limiting and the regelation infiltration process is suppressed."*
- *"Conceivably, glaciers organize the properties of their substrates to minimize the amount of geomorphic work that they must perform."*
- *The question of subglacial landform genesis has "…captured the interest of mathematically inclined glaciologists who see soft-bedded streamlined bedforms such as drumlins, lineations, and transverse ribbed moraines as expressions of fluid dynamical instabilities in the deforming substrate…"*

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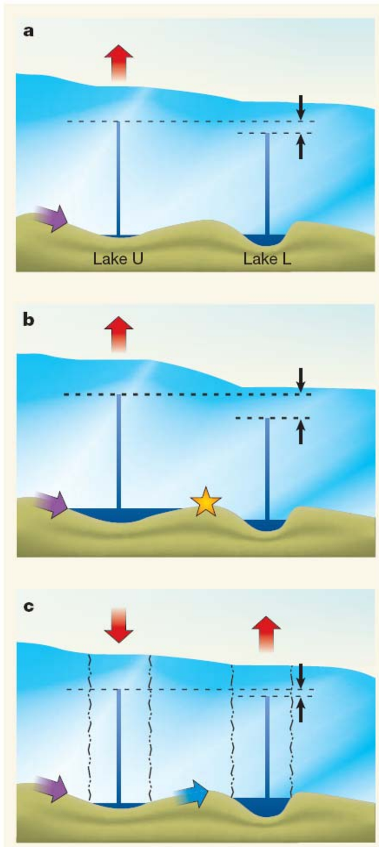
Clarke, G.K.C. 2007. Ice-sheet plumbing in Antarctica. Nature, v. 440, p. 1000–1001.

***Exploration significance**. Subglacial lakes exist; they may drain from one to another; and this may disperse sediment beneath glaciers.*



"Piston" model for drainage between Antarctic subglacial lakes

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Costa, J.E. 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Geological Survey of America Bulletin, v. 94, p. 986–1004.

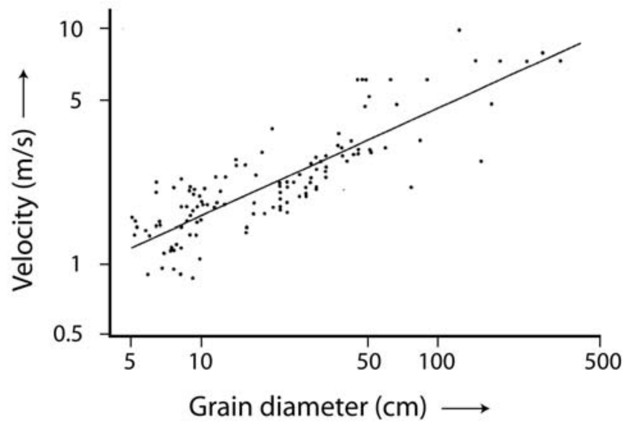
***Synopsis**. Reviews proxy data used to reconstruct, in semi-quantitative fashion, the paleohydraulics of flash floods. Concludes that clast size (flow competence) increases with flow velocity (see figure below).*

***Exploration significance**: Since large clasts (cobbles, small boulders) are common in eskers, flows that deposited eskers were likely fast—they may have commonly travelled at several meters per second (cf. Brennand, 1994; Boulton et al., 2009). This may have implications for how indicator minerals were transported and concentrated (e.g., Burton and Fralick, 2003; Frostick et al., 2006).*

Key quotes

- *"Krumbein and Lieblein (1956)…showed with extreme value theory that most of the anomalously large particles in gravel deposits are normal members of the stream particle population"*

- *"For particles coarser than 30 mm, Fahnestock (1963) concluded that the size of particles in motion varied with the 2.6 power of average velocity"*



Correlation of flow velocity and grain size based on gravel flume experiments and measurements from natural settings

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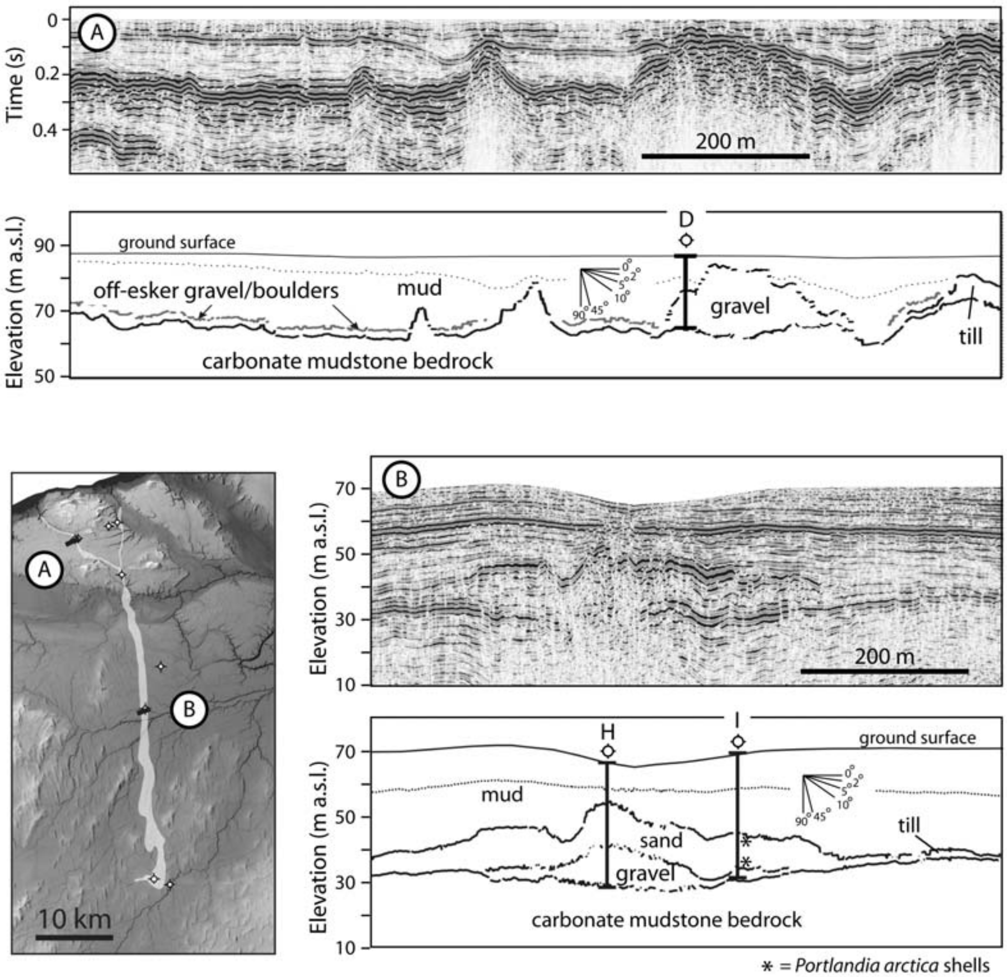
Cummings, D.I., Pugin, A., Pullan, S., Gorrell, G., Ponomarenko, D., Logan, C., Hunter, J., Russell, H.A.J. and Sharpe, D.R. (accepted) Geology of a muddy glaciated basin fill, with a focus on esker sedimentation. Geological Society of America Bulletin

***Synopsis**. Integrated seismic–outcrop–core–air photo study of a mud-buried esker in the Champlain Sea basin near Ottawa. Concludes that the esker was sourced from till; that fine sand and mud bypassed the subglacial stream and deposited proglacially as subaqueous outwash whereas most gravel and coarser sand remained in R-channel; and that the ice margin retreated during deposition, causing subaqueous outwash to blanket the gravelly subglacial stream deposit.*

***Exploration significance**. Finer sediment (almost all mud and very fine sand) in esker sedimentary systems may tend to bypass subglacial streams to ice front. Sandy proglacial fans, if anything, will therefore record more distal provenance signals than gravelly esker ridges.*



Seismic transects across two parts of the Vars–Winchester esker, Champlain Sea basin, Ottawa. (A) Gravelly central ridge only (R-channel deposit). (B) Gravelly central ridge (R-channel deposit) gradationally overlain by sandy carapace (subaqueous outwash fan complex). The interpretation is that the ice margin retreated during deposition, which, according to Walter's Law, superimposed distal over proximal deposits. Note that till is absent beneath the gravelly central ridge in both cases.

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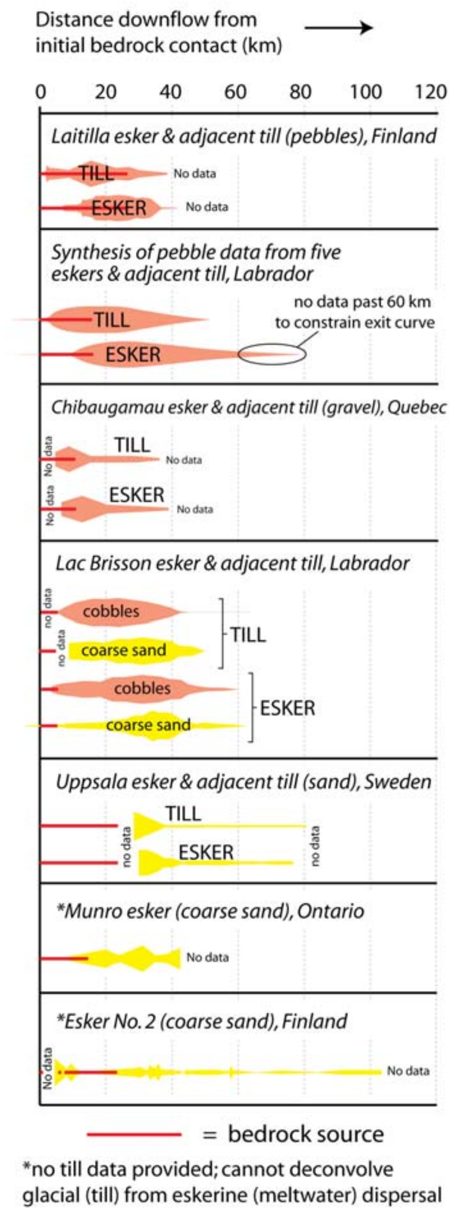
Cummings, D.I., Russell, H.A.J., Sharpe, D.R., and Kjarsgaard, B.A. 2010 (in review). Eskers as diamond exploration tools: A review and look forward. Geological Survey of Canada, Current Research paper

***Synopsis**. Synthesis of public-domain esker-dispersal data. Concludes that gravel and medium–coarse sand dispersal trains in eskers studied to date are typically of similar length to those in the underlying till from which they were primarily sourced, but are shifted down-flow relative to the till dispersal trains by several kilometres to at most 25 kilometres.*

***Exploration significance**: Long (10s to 100s of km), tree-shaped eskers, which are commonly targeted during regional exploration, may in fact contain short dispersal trains (gravel & coarse sand)—possibly similar in length to those in the regional till. This idea remains untested throughout most of Canada.*



Summary of dispersal data from eskers 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. Data from Hellaakoski (1931), Gillberg (1968), Pertunnen (1989), Bolduc (1992), Levasseur and Prichonnet (1995), and McClenaghan and Kjarsgaard (2001). Yellow is sand, pink is gravel, red is bedrock source.

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Dalrymple, R.W. and Rhodes, R.N. 1995. Estuarine dunes and bars *in* Perillo, G. (ed.), Geomorphology and Sedimentology of Estuaries. Developments in Sedimentology, v. 53, p. 359–422.

> ***Synopsis***. *In-depth review of bedforms and barforms generated in unidirectional flows. Specific to tide-dominated environments, but many insights are applicable to fluvial and glaciofluvial environments as well.*

***Exploration significance**: If bedforms and barforms exist in esker sedimentary systems, which they almost definitely do—at least locally if not ubiquitously—based on stratification in eskers (Brennand, 1994), they would function to trap indicator minerals and thus stop their downstream dispersal, either temporarily (in zones of net erosion) or permanently (in zones of net deposition). Gravelly bedform and barform deposits in eskers may therefore be indicator-mineral concentration sites.*

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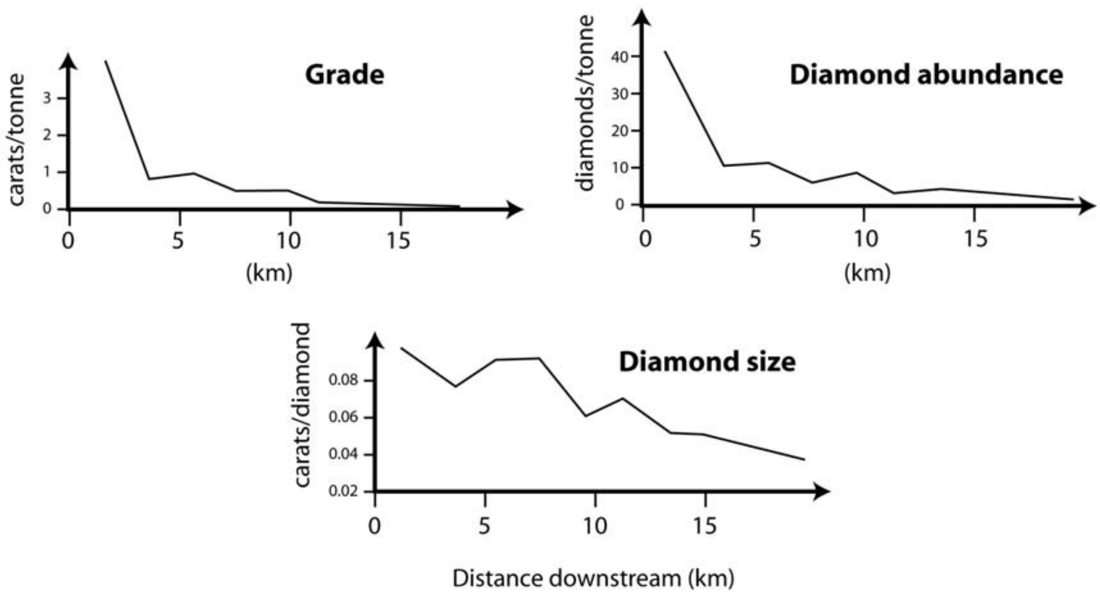
Deakin, A.S., Boxer, G.L., Meakins, A.E., Haebig, A.E., and Lew, J.H. 1989. Geology of the Argyle alluvial diamond deposits *in* O'Reilly, S.Y. (ed.), Kimberlites and Related Rocks: Their Mantle/Crustal Setting, Diamonds and Diamond Exploration. Proceedings of the 4th International Kimberlite Conference, Perth, Australia. GSA Special Publication Number 14, p. 1108–1116.

***Synopsis:** Review of alluvial diamonds in a stream downflow of a lamproite diatreme. The normal suite of kimberlitic indicator minerals is absent, which reflects the mineralogy of the primary source. Diamonds are the best "indicator mineral". The diamonds decrease in grade, size, and abundance downstream over about 15 km. The highest grades are situated where steep gradients give way to broad plains.*

***Exploration significance**. Might zones of rapid flow expansion in esker sedimentary systems (e.g., proglacial fans) be indicator-mineral concentration sites, as they appear to be in this fluvial system? This is somewhat counterintuitive to the idea that indicator minerals tend to concentrate in gravelly facies (e.g., Parent et al., 2004), but may have some support: Perttunnen (1989) documents high indicator-mineral counts in stratified end moraines at the termination of several Finnish eskers.*

Key quotes

- *"The normal suite of kimberlitic indicator minerals is absent from the Argyle alluvials, reflecting the mineralogy of the primary lamproite source, where chrome diopside and pyrope garnet are rare and picroilmenite is absent…At Argyle, the most abundant and readily identifiable indicator mineral proved to be diamond itself."*
- *"The highest grades…are situated…where the steep gradients…give way to broad plains"*
- *"Samples were processed…with top and bottom screen sizes of 12 mm and 0.8 mm respectively"*
- *"Diamond entrapment [in the proximal part of the gravel-bed stream]…is aided by the coarse nature of the gravels…"*
- *At almost all locations, diamond size, abundance, and grade tend to increase with depth within the gravel deposit.*
- *"The alluvial diamonds are of better quality compared to the lamproite diamonds owing to elimination of the more brittle, fractured, poor quality stones during fluvial transportation"*



Decrease in grade, diamond abundance, and diamond size in the Argyle alluvial diamond deposit, western Australia, downflow from the AK1 lamproite diatreme along a gravel-bed stream (Smoke Creek)

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Dredge, L.A., Ward, B.C., and Kerr, D.E. 1997. Morphology and kelyphite preservation on glacially transported pyrope grains *in* LeCheminant, A.N. et al (eds), Searching for Diamonds in Canada. Geological Survey of Canada, Open File 3228, p. 197–203.

Synopsis*: Study of grain shape and surface texture of pyrope garnets in eskers and till. Results suggest that grains in both esker and till experienced little wear during ~ 20–30 km of transport.*

Exploration significance*. Grain shape (e.g., rounding) and surface texture may not be an effective proxy for indicator-mineral transport distance in glaciated settings. This study provides data to back up the common contention (e.g., Averill, 2001) that indicator minerals in glaciated settings (eskers, till) are commonly texturally immature, irrespective of transport distance.*

Key quotes

- *"In the 0.25 to 0.5 mm size fraction, there is little change in garnet shape and surface texture with glacial transport. Kelyphite surfaces are rounded, even near pipes; garnet grains are angular near pipes, and remain angular as distance of transport increases, but far-travelled glacial grains have more conchoidal surfaces than grains near pipes. Not all kelyphite is removed during glacial transport, although the surface area and thickness of the kelyphitic layer decreases as distance of transport increases. The presence of kelyphite does not imply proximity to a kimberlite source."*

Material	Estimated distance from pipe from pipe (km)	Number of pyrope grains	Number of pyrope grains with kelyphite	Percent pyrope grains with kelyphite	Percent surface covered with kelyphite	Maximum kelyphite thickness (μm)
Till	< 1	> 675	52	~ 8	50	24–40
Esker	20	267	27	10	50	10–35
Till	25	70	3	4	< 25	2
Till	30	60	14	23	25	15

Characteristics of glacially transported pyrope grains, Lac de Gras region

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Ellemers, P.C.C. 1994. A comparison of the esker and till geochemistry of the Winter Lake region, N.W.T., to the bedrock geochemistry of the Point Lake greenstone belt. Unpublished BSc thesis, University of Regina, 82 p.

***Synopsis**: "Whole rock" geochemistry study of till and eskers. Results suggest that the esker dispersal trains are short, generally < 20 km long downflow of the bedrock source (the same length as the till dispersal trains they overlie), and that they are not shifted downflow of the underlying till dispersal trains.*

***Exploration significance**. Are short dispersal trains typical of eskers?*

Key quotes (paraphrased)

- *For the elements analyzed, "…esker concentrations were on average 5 times higher than the till concentrations…" (p.12)*
- *Observed dispersal trains in both till and eskers downflow of Greenstone belt outcrop.*
- *Esker & till dispersal trains are similar: there is no obvious down-ice displacement of esker dispersal train relative to the till dispersal train*
- *Greenstone belt elements typically appeared in esker and till directly over bedrock. Peak concentrations ("K") were reached within kilometres of the bedrock source. Exit points tend to occur < 20 km downflow of bedrock source for both esker and till.*

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Ettema, R. and Daly, S.F. 2004. Sediment transport under ice. United States Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Report TR-04-20, 63 p.

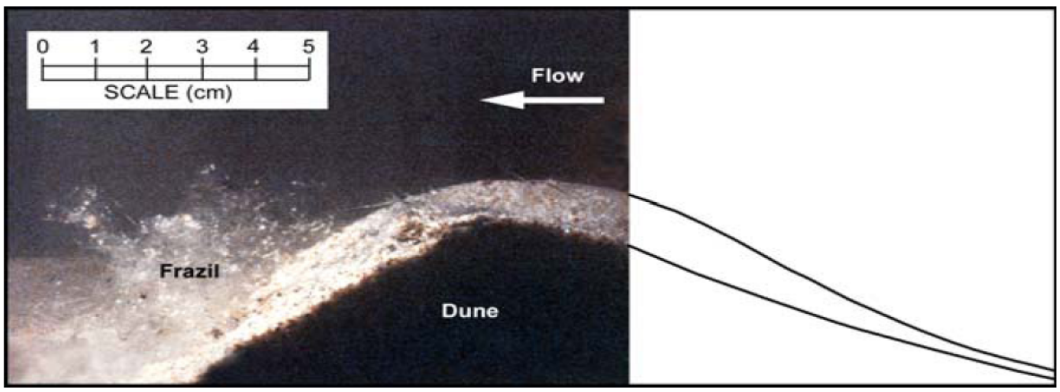
***Synopsis:** Review of sediment transport beneath ice-covered subaerial rivers. The review reveals several phenomena that could impact sediment dispersal in 0^{o}C water: frazil ice flocs form that can scavenge suspended sediment; anchor ice may blanket parts of the bed, reducing entrainment; whereas the increased viscosity of water may enhance entrainment*

***Exploration significance**. The fact that the water in subglacial streams is near 0^{o}C and commonly pressurized brings with it a special set of circumstances that may lead to differences in selective sorting (entrainment, deposition) and abrasion with respect to fluvial systems. It is unclear exactly how this would impact dispersal in esker sedimentary systems.*

Key quotes

- *"Large-scale turbulence in comparatively shallow, swift-flowing rivers and streams can mix suspended ice crystals and flocs of active frazil across the full depth of flow. While the flow is supercooled, the frazil may adhere to bed sediment or individual boulders and accumulate as a porous and spongy mass…it is possible that [this] may diminish bed-sediment entrainment…"*

- *"Under conditions of sufficiently frigid weather and substantial flow turbulence, extensive areas of a river's bed can become blanketed by anchor ice."*
- *"[Lab studies]…show how frazil flocs become sediment laden and lose their buoyancy as they tumble along the flume's sand bed, and eventually become included within an ice–sand clump of anchor ice. As the negatively buoyant flocs of frazil and sediment accumulate in the trough of a dune or a ripple, they become infiltrated by sand, buried, and compressed. The resulting clumps of bonded ice and sediment may then enlarge as additional frazil flocs fuse to them, or as the clumps further grow amidst supercooled water."*
- *"Martin (1981) mentions an instance where anchor ice entrained and moved boulders up to 30 kg in weight"*
- *"Frazil and suspended sediment may interact directly in the water column, causing suspended sediment to be included in ice slush. The details of the interactions, and the likelihood of their occurrence, are not well understood. Barnes (1928) and Altberg (1936) mention an intriguing observation that frazil-ice formation appears to remove suspended sediment from a flow; after a frazil-ice event, water seems clearer."*
- *"Ice is attended by cold water, usually at or slightly above 0ºC."*
- *"The studies confirm that sediment transport rate increases with decreasing water temperature…The flume data report by Hong et al. (1984), for instance, show that the mean concentration of bed-sediment transport increased by factors up to seven and ten for a water temperature drop from 30 to 0ºC. The increase, obtained with [grain size] = 0.11 mm, is attributable to increased concentration of sediment transport in a bed layer…and increased uniformity of concentration distribution over the flow depth. The latter effect is largely attributable to the reduced fall velocity of suspended particles."*



Frazil ice accumulating in the lee of a dune. The dune will migrate and bury the frazil, eventually forming an ice-bonded clump of sand. This process might operate in R-channels, but it is unclear how it might affect downstream dispersal of heavy minerals.

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Evenson, E.B. and Clinch, J.M. 1987. Debris transport mechanisms at active alpine glacier margins: Alaskan case studies *in* Kujansuu, R. and Saarnisto, M. (eds.), INQUA Till Symposium, Finland, 1985. Geological Survey of Finland, Special Paper 3, p. 111–136.

***Synopsis**. Study of the provenance of sediment in subaerial outwash plains emanating from the termini of active alpine glaciers in Alaska. Results suggest fluvial "inwash" of material from surrounding highlands delivers > 90% of the debris to the outwash plain.*

***Exploration significance**. Water, as opposed to glacier ice, can be the dominant sediment-dispersal agent in some (most?) glaciated alpine catchments. Till in these settings may be largely recycled fluvial material.*

Key quotes

- *"Detailed morphosequence mapping and provenance investigations at active glacier margins in Alaska clearly demonstrate that the bulk (90% +) of glacial debris is delivered to lobate ice margins by lateral, englacial and subglacial fluvial systems. Supraglacial transport (medial moraine debris) delivers a much smaller fraction (<10%) while englacial (regelation bands, injection features etc) and subglacial transport deliver no significant amount of material."*
- *"…fluvial transport always dominates over glacial transport and the vast majority of the debris found in outwash, push moraines and till is inwash-sourced [i.e. derived from inwash of fluvial debris from the highlands surrounding the glacial termini]."*

- *“Our results show that fluvial activity and not glacial transport is the dominant debris transport mechanism in the [Alaskan glaciers] investigated. Large quantities of fluvially rounded, sorted material are transported from sources located throughout the glacierized basin to the ice margin, where they are deposited as outwash or recycled to form till and push moraines.”*
- *“…the similarity in clast composition of the basal tills and the fluvial transported debris suggests that a large fraction of basal debris load, including tills, is recycled fluvial material.”*

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Ferguson, R.I. 2003. Emergence of abrupt gravel to sand transitions along rivers through sorting processes. Geology, v. 31(2), p. 159–162.

Synopsis. *Numerical modelling study that suggests selective deposition, not abrasion, is the dominant mechanism that causes rapid gravel–sand transitions in rivers*

Exploration significance. *Eskers are coarse-grained, like the bed material in gravel-bed streams. However, unlike many gravel-bed rivers, they lack abrupt gravel–sand transitions moving downflow. Rather, eskers tend to have a similar, gravel-rich composition over their entire length, which in some cases is hundreds of kilometers. Esker and stream sedimentary systems work differently. A different conceptual model is required for eskers in order to optimize sampling for indicator minerals and accurately interpret results.*

Key quotes

- *“Geomorphologists seeking to explain this discontinuity in bed caliber have generally invoked the disintegration of pebbles of certain lithologies into sandsized crystals during weathering or transport. However, abrupt transitions are not restricted to particular lithologies, and can occur over distances too short for significant abrasion: 30 km along major rivers (e., 0.1 km in small rivers, and 1 m in laboratory experiments. In such cases an alternative explanation is that bedload transport and deposition act in a more highly size selective way than usual.”*
- *“Gravel to sand transitions are most common where relatively steep mountain rivers emerge onto valleys or plains with much lower slope, and the reduction in fluid shear stress (t) forces the river to deposit most of its bedload.”*

========

Ferguson, R.I. and Ashworth, P. 1991. Slope-induced changes in channel character along a gravel-bed stream: The Allt Dubhaig, Scotland.

Synopsis. *Study of a rapid gravel–sand transition in a small Scottish river across which channel changes from braided to meandering. Concludes that these changes are due to profile concavity inherited from previous glaciation.*

Exploration significance. *Eskers are coarse-grained, like the bed material in gravel-bed streams, but they do not exhibit net downstream fining, even in some cases over 100s of kilometers. Why do they not fine downflow? Why do they lack similar rapid gravel–sand transitions? Is the energy level and coarse-debris influx constant along a single, long subglacial conduit (e.g., Shreve, 1985a,b), or do eskers form time-transgressively in segments as the ice front retreats (e.g., St. Onge, 1984)? Do dispersal trains for particular lithologies fine downflow?*

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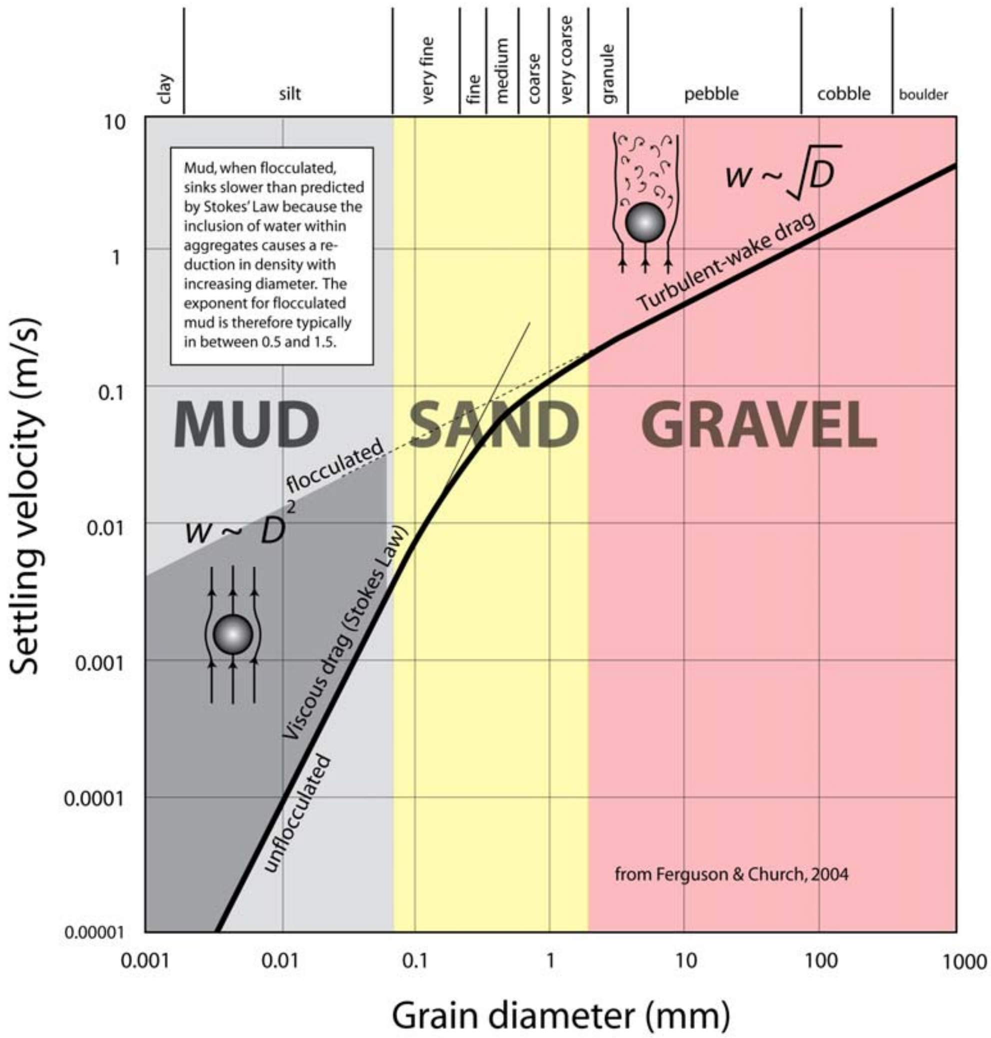
Ferguson, R.I. and Church, M. 2004. A simple universal law for settling velocity. Journal of Sedimentary Research, v. 74(6), p. 933–937.

Synopsis. *Previous experimental data show that fine particles (diameter (D) < 0.1 mm) settle through water at velocities that are proportional to D^2 (fall is resisted by viscous drag of laminar flow around grains), whereas coarser particles (D > 1 mm) settle at velocities that are* *proportional to √D (fall is resisted primarily by turbulence generated in wake of particle). This paper proposes equations that purportedly fit the experimental data better.*

***Exploration significance**. Since the settling velocity versus grain size curve has a significant "dog leg" at around medium sand (see figure below), finer and coarser indicator minerals in eskers (and streams) are that much more likely to settle at different speeds and, by extension, record more distal and proximal provenance signals, respectively. (Very fine sand and mud commonly travel as wash load, whereas*



Summary diagram showing the settling velocity versus grain size. Modified from Ferguson and Church (2004).

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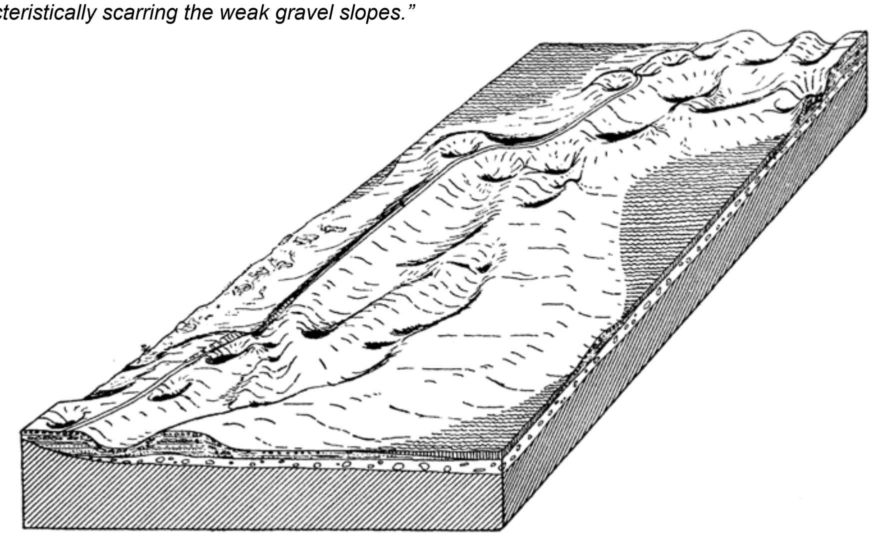
Flint, R.F. 1930. The origin of the Irish "eskers". Geographical Review, v. 20(4), p. 615–630.

***Synopsis**. An influential study that describes Irish eskers as consisting of masses of sediment (commonly horizontally stratified) that vary in shape from broad, flat-topped and pitted to narrow ridges. Concludes that the esker material was deposited primarily in ponded water at various levels; that the ponded water must have been contained by walls of ice; and that the ice sheet in Ireland must therefore have been stagnant and must have downwasted in place during esker deposition.*

***Exploration significance**. Eskers on the Canadian Shield are similar to the eskers in Ireland described by Flint (1930): in places, they are broad, flat-topped and pitted, whereas in others they are narrow and ridge-like. As such, elements of the "stagnant ice" depositional model proposed by Flint should be considered when developing a conceptual framework to interpret indicator mineral data from Shield eskers.*

Key quotes

- *"As the situation stands at present…in America the term esker is restricted to sinuous ridges of gravel and sand believed to have been deposited by glacial streams; in Ireland it refers to all mound- or ridge-like accumulations of stratified material; in Scandinavia it is not used at all, being replaced, in the American sense, by as; and in Great Britain it is being superseded by ose."*
- *"Three general types, classified according to surface form, may be recognized: elongate ridges, isolated mounds and hummocks, and board flat-topped masses"*
- *"…the stratification near the edges of the [esker] forms is rudely parallel to the steep side slopes. This curious behavior of the layers of sediment was caused in part by slump after deposition in more nearly horizontal positions by in larger part by undisturbed initial deposition at angles oblique to the bedding planes in the center of the mass"*
- *"[Sollas] maintained that the branching pattern made by the groups of [esker] chains of deposits was except for its discontinuity, essentially a stream pattern. Although much of Sollas' theory appears, in light of later knowledge, to be entirely sound, it fails to consider the broad mesa-like masses which are fully as numerous and widespread as the narrow ridges. Many of these are far too wide to have been developed in tunnels, and their shapes do not remotely resemble the shapes of former streams.*
- *"The requisite conditions [to generate the Irish eskers] are fulfilled by a great mass of* stagnant *ice standing over the whole of the central lowland, its entire expanse seamed with crevasses and tunnels, the formed filled with water, and some of the latter furnishing conduits through which flowing water connected the crevasses. The ice must have been stagnant, since the slightest movement of the mass would have disturbed or destroyed the delicate system of detrital deposits accumulating within and beneath it. The ice must have melted away in place, because any withdrawal of an ice front would have discharged streams of meltwater, trimming and characteristically scarring the weak gravel slopes."*



Cartoon of Irish eskers showing facies architecture and stratigraphic position of the eskers. Bedrock is grey, till is white with clasts, mud and organic deposits are grey. Note that the term "esker" is applied to the entire ridge, irrespective of inferred origin. This is the traditional (pre-1900s) definition, and is still widely used today in Ireland. In many ways, it is more flexible than the North American tendency to think of eskers uniquely as the casts of ice-contact streams.

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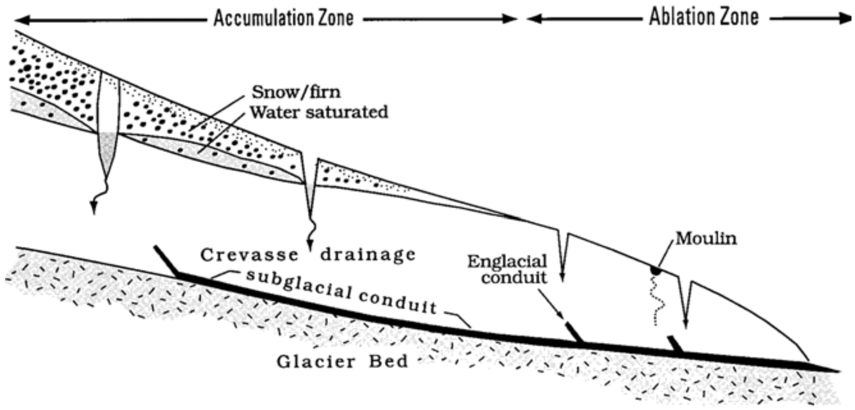
Fountain , A.G. and Walder, J.S. 1998. Water flow through temperate glaciers. Reviews of Geophysics, v. 36(3), p. 299–328.

***Synopsis**. Presents a conceptual model of water flow through temperate glaciers..*

Exploration significance*. Gives an idea of how meltwater disperses sediment beneath glaciers.*



Conceptual water flow through a temperate glacier.

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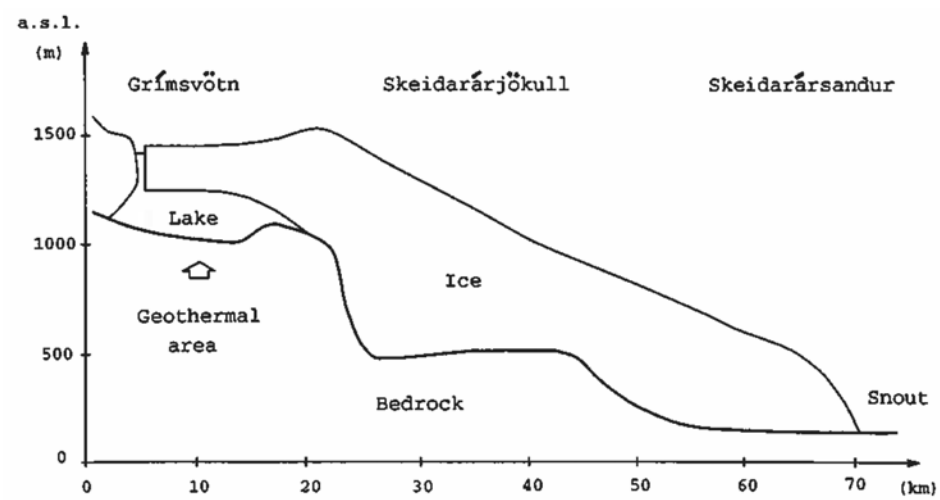
Fowler, A.C. and Ng, F.S.L. 1996. The role of sediment transport in the mechanics of jokulhlaups. Annals of Glaciology, v. 22, p. 255–259.

Synopsis. *Suggests that R-channels can increase in size by an order of magnitude during jökulhlaups, scavenging sediment in the process.*

Exploration significance*. Could jokulhlaups be one way that sediment passes from esker corridors into R-channels?*



Conceptual dip cross-section of Vatnajökull and the subglacial lake Grimsvötn along the jokulhlaup drainage route.

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Frings, R.M. 2008. Downstream fining in large sand-bed rivers. Earth-Science Reviews, v. 87, p. 39–60.

Synopsis. *Comprehensive review of downstream fining in both sand- and gravel-bedded rivers—a good place to start on this topic. Concludes that sand-bed rivers do fine downflow, but that the fining occurs over greater distances and is more subtle than in gravel-bed rivers.*

Exploration significance. *Dispersal trains in eskers that are composed of sand-sized indicator minerals from a given source should fine downflow over greater distances than gravel dispersal trains from the same source.*

Key quotes

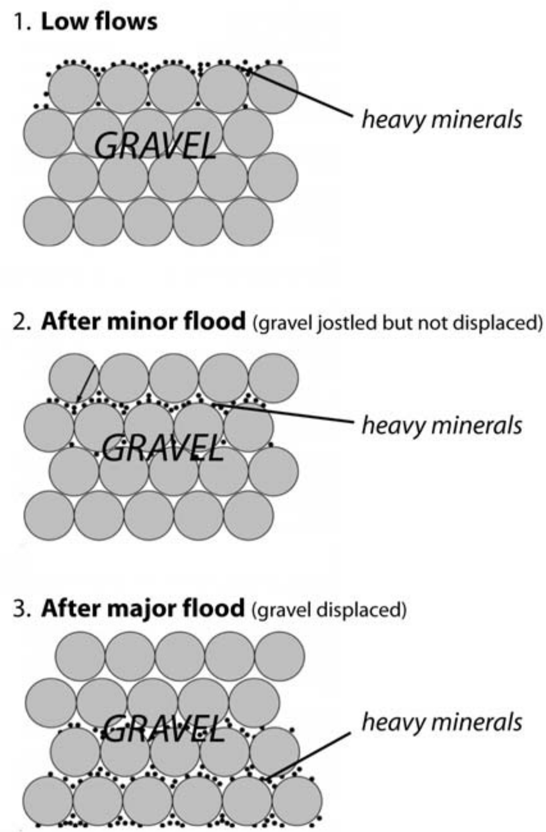
- *"…downstream fining processes are divided into three categories: abrasion, selective transport, and sediment addition–extraction."*
- *"…many sand-bed rivers (though not all) are in state of fully mobilised transport...Selective transport in these rivers is probably mainly the result o the presence of suspended load transport in combination with the effects of dune and perhaps bend sorting"*
- *"Overbank sedimentation…may significantly decrease the downstream fining rate in large sand-bed rivers, because especially fine grains are removed from the bed."*
- *"Meander migration may cause a net loss of coarse grains from the channel in aggrading circumstances, increasing the downstream fining rate."*
- *"The dominant control on abrasion rate is lithology…After lithology, grain size has the strongest influence on abrasion rates. Abrasion rates commonly increase with grain size, firstly because larger grains have a higher kinetic energy…and secondly because larger grains have smaller saltation lengths and hit the river bed more frequently than finer grains"*
- *"Lewin and Brewer (2002), indeed found only a weak dependency of abrasion rates on flow velocity. Kuenene's (1956) experiments also show that abrasion rates do not necessarily increase when grain velocity increases."*
- *"The abrasion rate is commonly observed to be more rapid for angular grains than for wel-rounded grains…The main reason is that sharp-angled pieces are very prone to chipping, which is one of the most effective abrasion mechanisms."*
- *"The abrasion rate of coarse grains has been observed to diminish slightly when finer grains are added…probably due to damping of the impacts."*
- *"…abrasion rate is greatest if the sediment grains are non-durable, large, angular and weathered"*

========

Frostick, L.E., Murphy, B. and Middleton, R. 2006. Unravelling flood history using matrices in fluvial gravel deposits *in* Sediment Dynamics and the Hydromorphology of Fluvial Systems. IAHS Publication 306, p. 425–433.

Synopsis. *These flume experiments suggest that the infiltration of sands into gravels is largely controlled by flood magnitude and frequency. During large flood events the surface framework particles are entrained, the bed dilates and material falls through the pore spaces and accumulates at the base of the bed. Without bed dilation, sand infiltration is minor to negligible.*

Exploration significance. *Do floods promote heavy mineral concentration in gravel, as these experiments suggest (cf. Burton and Fralick, 2003)? This is significant because some authors argue that eskers are deposited primarily during high-magnitude floods (e.g., Brennand, 1994; Cummings et al., accepted).*



Flume experiment results showing degree of infiltration of sand into a gravel bed after flows of different magnitude.

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Geike, J. 1894. The Great Ice Age and its Relation to the Antiquity of Man (3rd edition). Edward Stanford, London, 850 p.

***Synopsis**. A good, insightful summary of the state of knowledge of eskers 125 years ago. The observations are still relevant today. Geike argues that supraglacial streams might be more likely to deposit sheets of debris, not discrete esker-like ridges (see below).*

***Exploration significance**. Despite being over 100 years old, the observations herein are high quality and contribute to the conceptual debate over how eskers form. Specifically, Geike argues that a supraglacial origin for eskers is improbable. In doing so, he seems to be implying that eskers are more likely deposited, at least in part, in subglacial streams, and that they were sourced from debris at the base of the glacier.*

Key quotes

- *"[The eskers in Scotland] usually rise more or less abruptly above the general level of the ground to heights of 20 or 30 or even of 50 or 60 ft, with a breadth at the base of 100 to 400 or 500 ft. The sides of the more sharply-crested ridges often slope at angles of 30˚ or 35˚, while the broader topped banks are not so steep…They either rest on boulder clay or solid rock and it is particularly worthy of note that the gravel and sand of which they are composed are strictly confined to the ridges and mounts; that is to say, these deposits do not spread out laterally upon the adjacent low ground…The steeper ridges are composed chiefly of gravel, generally coarse, and showing little or no trace of bedding. Indeed, in many places they consist of tumultuous heaps of coarse gravel, shingle, and water-worn boulders; or, as the case may be, of an agglomeration of large blocks and angular and subangular debris mixed with earthy grit and sand…Similar ridges (known as åsar, pronounced osar), are grandly developed in Sweden, and I shall, therefore, adopt the Swedish name for ours."*

- *"It is now believed that these remarkable åsar are of fluvio-glacial origin—formed by torrents and streams flowing either upon or underneath the mer de glace. Their subglacial origin was advocated a number of years ago by Mr. D. Hummel of the Geological Survey of Sweden, but more recently Dr. Holst has formulated the view that the åsar have been accumulated in the beds of supra-glacial rivers. This theory, which some glacialists think explains the phenomema more satisfactorily than Hummel's, is nevertheless not without its difficulties. It is quite possible, indeed, that both infra- and supra-glacial torrents and streams existed during the melting of the mer de glace, just as we know is the case in Greenland. Among the phenomena which Hummel specifies as peculiarly suggestive of the origin of the åsar, are the frequent passage of the gravel into true morainic matter (a passage which may be traced not only along the sides of an ås, but also in the direction of its trend); the appearance of large and small angular fragments of rock in the heart of well water-worm gravel; the less rounded aspect of the stones in the upper part of an ås; the existence of water-worm materials underneath true bottom-moraine; the confused and dislocated or jumbled aspect of the bedding sometimes seen in the interior of an ås; the general agreement that obtains between the trend of the rock striations and the direction followed by the åsar; and finally, the entire absence of fossil organic remains...So far as the Scottish åsar are concerned, Hummel's theory seems to explain the phenomena more satisfactorily than [the supraglacial model].*
- *"[Dr. Holst] thinks…that the ås-rivers flowed upon and not underneath the mer de glace. During the melting of the ice-sheet numerous rivers, it is conceived, would flow over its surface, following of course the general direction of the ice itself. These rivers would be small or large, according as the water-divides were near each other or widely separated. Such conditions would necessarily obtain in the highest degree in regions where the mer de glace flowed across broad lowland tracts towards its termination. Over such regions there would be a general absence of crevasses, and the superficial waters would thus have free course.*
- *"[A difficulty with the supra-glacial model] presents itself. As the materials continued to be dissolved out of the ice and to find their way down the slopes of the ice valleys into the rivers, the bottoms of those valleys and the beds of the streams themselves would come to be protected from ablation. The ice of the water divides and upper slopes of the valleys would by and by melt away more rapidly than those portions of the mer de glace which were deeply buried under rock debris. Thus in time the configuration of the surface would be so altered that the rivers would be compelled to desert their gravel beds, which by and by would themselves be converted into water divides, while the sites of the former divides would be occupied by newer watercourses. In short, the tendency of the superficial water flow would be rather to distribute morainic material in irregular sheets over the surface of the ice, than to arrange it in determinate linear course."*

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Gillberg, G. 1968. Lithological distribution and homogeneity of glaciofluvial material. Geologiska Föreningens i Stockholm Förhandlingar, v. 90, p. 189–204.

***Synopsis**. An extensive study of gravel, sand, and mud dispersal (carbonate particles) in several eskers and the adjacent till in Sweden downflow of known bedrock sources. Along with Bolduc (1992) and Levasseur (1995), this is a must-have. Unfortunately somewhat lacking in detail—many interesting statements are made, but the data are not described sufficiently (especially till data). Concludes that gravel, sand, and mud in the eskers studied is "…mostly of extremely local origin".*

***Exploration significance**. Is most gravel, sand, and mud in Canadian eskers "…of extremely local origin", as Gillberg argues for these Swedish eskers? Are these data representative of most eskers?*

Key quotes

- *"Glaciofluvial material from eskers and outwash deltas in different areas has been lithologically analysed…it is mostly of extremely local origin…it shows great accordance with the till in the nearest proximal vicinity."*
- *"…a clear tendency is evident—lithologically the glaciofluvial material varies much more than the till...Both the fine material (<0.2 mm in size) and, in some areas, the sand (2–0.2 mm in size) [in the glaciofluvial samples] are more homogeneous than the gravel but never to the same degree as in the till."*

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Gregory, G.P. and White, D.R. 1989. Collection and treatment of diamond exploration samples *in* O'Reilly, S.Y. (ed.), Kimberlites and Related Rocks: Their Mantle/ Crustal Setting, Diamonds and Diamond Exploration. Proceedings of the 4th International Kimberlite Conference, Perth, Australia. GSA Special Publication Number 14, p. 1123–1134.

***Synopsis**. Overview of stream sampling (and other) diamond-exploration techniques in non-glaciated terrain.*

***Exploration significance**. Many of these insights could potentially be extended to esker sampling—but they require testing first to see if they work.*

Key quotes

- *"For reconnaissance pathfinder sampling the optimum sample density of 6 kg of < 2.5 mm diameter screened sediment per km^2 of drainage catchment is adhered to. In the field this means collecting samples with a minimum weight of 25 kg, and usually samples range from 25 kg to 200 kg to cover catchment areas of 4 to 20 km^2, respectively. It is critical that samples be collected from good trap sites. The best sites are vertical crevices or joints trending near normal to the active drainage. Other sites, such as depressions in the river channel, basal gravel accumulations, boulder bars, the lee of rock bars and the underside of tree roots, vary from good to moderate in the order listed. Pot-holes are not good sites as pathfinder minerals may be destroyed by attrition. Samples collected from sand choked streams, so common in Australia, are usually worthless. Pathfinder minerals are rarely trapped or concentrated in this environment and a negative result can assume unwarranted significance when plotted on a map."*
- *"It is vital that all material filling crevices is collected as this is where pathfinders are usually trapped. Generally the more difficult the sample is to collect, the better is its quality."*

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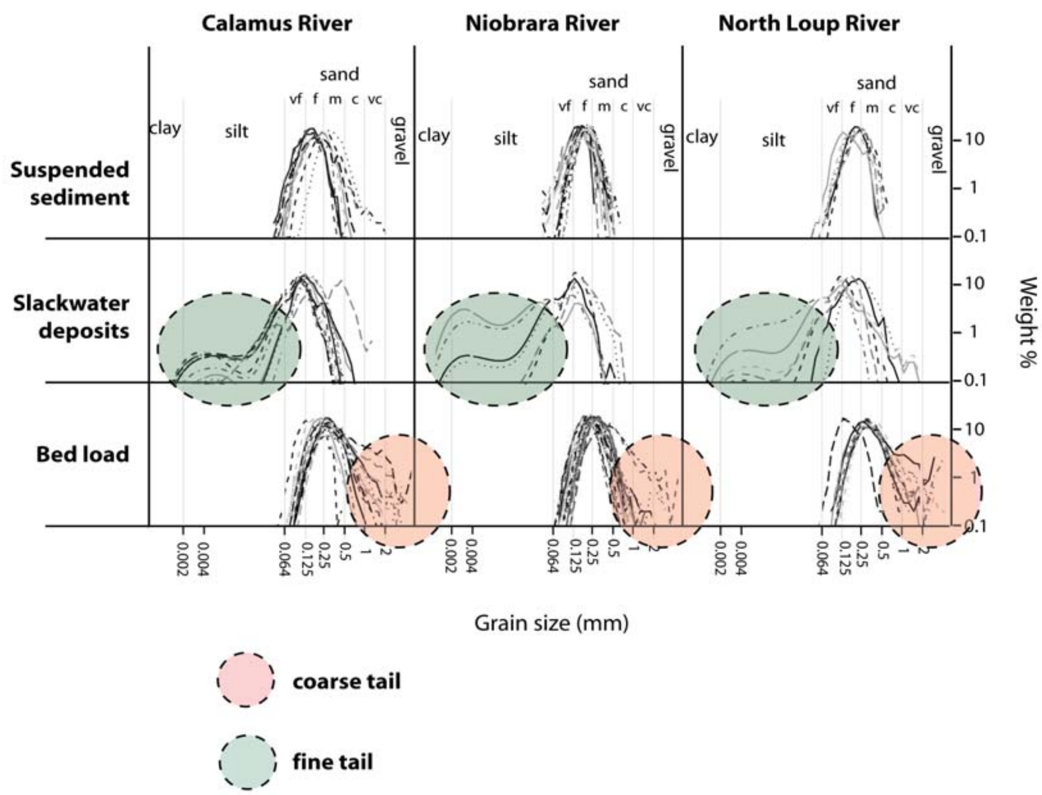
Hajek, E.A., Huzurbazar, S.V., Mohrig, D., Lynds, R.M. and Heller, P. 2010. Statistical characterization of grain-size distributions in sandy fluvial systems. Journal of Sedimentary Research, v. 80, p. 184–192.w

***Synopsis**. Study of grain size distributions of bedload, suspended load, and slackwater deposits in three sand-bed rivers. Shows that bedload tends to have a coarse tail, suspended load is slightly finer and better sorted, and slackwater deposits are slightly finer still, with a fine tail.*

***Exploration significance**. In subglacial streams with similar hydraulic regimes as the sand-bed rivers described herein, silt and clay would travel in suspension, very fine to medium sand would travel as both suspended load and bedload, and gravel and very coarse sand would travel as bedload. Because suspended sediment travels faster downflow than bedload, indicators in these different grain size populations would travel different distances down flow during a given event—those in the finer fractions would generate longer dispersal trains.*

Key quotes

- *"It is important to note that all three [sand-bed] rivers show significant overlap between bed-material-load and suspended-load samples. Despite having slightly different modes and asymmetry…, in general, the majority of grain sizes moving along the bed are also carried in suspension."*



Grain size of bedload, suspended load, and slackwater deposits in three sand-bed rivers

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Hammer, P.T.C., Clowes, R., and Ramachandran, K. 2004. Seismic reflection imaging of thin, kimberlitic dykes and sills: exploration and deposit characterization of the Snap Lake dyke, Canada. Lithos, v. 76, p. 359–367.

***Synopsis**. Seismic images of Snap Lake kimberlite. Concludes that kimberlite has lower density (average 2.44 ± 0.04 g/cm^3) than host rock (average 2.95 ± 0.03 and 2.66 ± 0.03 g/cm^3).*

***Exploration significance**. Kimberlite with similarly low density will be slightly easier to entrain in subglacial streams than higher density clasts from the host rock. Over time, and barring abrasion or a counteracting selective deposition process, this could lead to selective sorting and enhanced downflow dispersal of kimberlite clasts.*

Key quotes

- *"Clearly, the kimberlite samples exhibit significantly lower P-velocities (average 4.3 ± 0.1 km/s at 50 MPa) than those measured in the host rock (average 5.6 ± 0.2 km/s at 50 MPa). Similarly, densities measured at laboratory pressure and temperature indicate that the Snap Lake kimberlite densities (average 2.44 ± 0.04 g/cm^3) are consistently lower than those of the host rocks (average 2.95 ± 0.03 and 2.66 ± 0.03 g/cm^3)."*

========

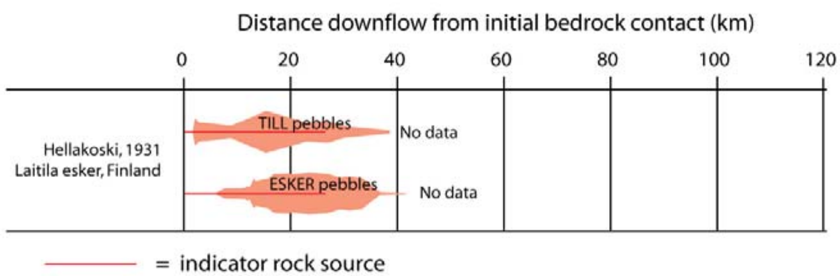
Hellaakoski, A. 1931. On the transportation of materials in the esker of Laitila. Fennia, v. 52, p. 282–311.

***Synopsis**. This was the first comprehensive (i.e., integrated till–esker) study of an esker dispersal train. The author only investigated gravel. He concludes that the gravel dispersal train in the esker is approximately the same length as the dispersal train in the underlying till,* *that it was sourced from the underlying till, and that it is shifted downflow relative to the till dispersal train by several kilometres.*

Exploration significance. *Are most gravel dispersal trains in eskers short (similar in length to the underlying till dispersal train) and shifted downflow only by a small amount relative to the till dispersal train?*

Key quotes

- *"The bed rock is very often exposed in the close vicinity of the esker chain."*
- *The height of the esker "…very seldom exceeds 20 m."*
- *"The esker…runs throughout its course indisputably in the direction of the striae…"*
- *"Plateaus are absent, as is generally the case with subaquatic oses"*
- *"The author has sometimes counted the stones in two divisions (100 and 100, for instance), and has thereby found out that the esker yields such regular percentages for the rocks that 100 stones give much the same result as do 200"*
- *"…the underlying bed rock may sometimes mark the overlying morainic drift [i.e., till] very strikingly. Even at a distance of 1.5 km from the proximal contact it is represented in the percentage figures, and its percentages increases rapidly, as if scattered by exploded bombs, being soon some 50%"*



Dispersal data in Laitila esker and adjacent till, Finland

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Hong, R.J., Karim, F., and Kennedy, J.F. 1984. Low-temperature effects on flow in sand-bed streams. Journal of Hydraulic Engineering, v. 110(2), p. 109–125.

Synopsis*. In their flume experiments, these authors observe a seven- to ten-fold increase in rate of very fine sand transport (d = 0.11 mm) with a temperature drop from 30 to 0ºC.*

Exploration significance*. All things equal, floods of equal magnitude in subglacial streams should be more prone to dispersing sediment than in non-glacial streams because of the colder water (ice is usually attended by water at around 0ºC). This is significant, because most sediment in eskers appears to have been deposited during high-magnitude, flood-like flows (e.g., Brennand, 1994; Cummings et al., accepted). This tendency for enhanced entrainment at low temperatures may be counteracted by other phenomena particular to near-freezing water, such as the development of anchor ice on the bed and/or frazil ice flocs in the flow, which could scavenge suspended sediment as they settle (see Ettema and Daly, 2004).*

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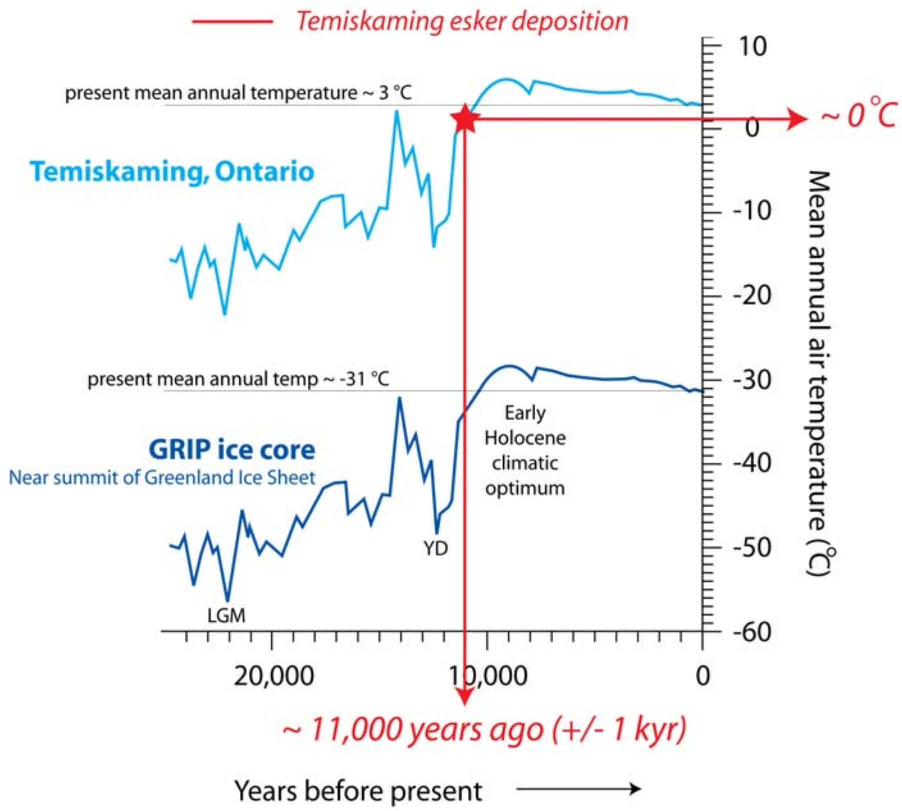
Hooke, R. LeB. and Fastook, J. 2007. Thermal conditions at the bed of the Laurentide ice sheet in Maine during deglaciation: Implications for esker formation. Journal of Glaciology, v. 53(1), p. 646–658.

Synopsis*. Numerical ice sheet modelling exercise. The paper clearly outlines how the modelling was performed, and clearly links input variables to the model outputs and the conclusions made (which is in stark contrast to, for example, Boulton's numerical modelling* *papers pertaining to eskers). Concludes that eskers in Maine most likely formed in short (< 5 km) segments as the ice front retreated. This is a good paper to read to understand how numerical ice-sheet models are used in glacial geology.*

***Exploration significance**. Eskers deposited under the model envisioned by Hooke and Fastook (2007) would have short dispersal trains—possibly 5 km or less downflow from their ultimate source (likely the underlying till)—for all grain sizes.*



Temperature proxy data (GRIP ice core data, Greenland) used to drive the numerical model of Hooke and Fastook (2007). Instead of showing the offset for Maine, which these authors used, an offset for Temiskaming, Ontario is shown because it is more relevant from a Canadian mineral-exploration perspective. (Temiskaming it is the first place in Canada where an esker was used to locate a kimberlite pipe (Lee, 1968) and some eskers in the area contain indicator minerals that cannot be traced back to known kimberlites.) Note that the best developed eskers in North America and Fennoscandinavia—those that form huge radial arrays around former spreading centres on the Precambrian shields—were deposited during the early Holocene, a time when air temperatures may have been warmer than today.

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Hooke, R. LeB., Wold, B., and Ove Hagen, J. 1985. Subglacial hydrology and sediment transport at Bondhusbreen, southwest Norway. Geological Society of America Bulletin, v. 96, p. 388–397.

***Synopsis**. A rare, direct study of a meltwater system at the base of a modern glacier. Access to the glacier base was obtained through tunnels excavated through bedrock beneath the glacier for a hydroelectric project. The authors conclude that suspended sediment and water pressure is highest in spring, and that both decrease during the melt season as the* *conduit system grows in response to the heightened discharge. Large boulders (1 m diameter) caught in subglacial sedimentation chambers, but similar boulders are very rare in the proglacial zone—suggests there is a downstream fining due to either abrasion and/or selective sorting.*

***Exploration significance**. Dispersal in subglacial streams in likely sporadic and seasonal, which may have implications for how indicator minerals are transported and concentrated in eskers (e.g., Burton and Fralick, 2003; Frostick et al., 2006). Large boulders may more commonly deposit in subglacial streams than proglacial fans.*

Key quotes

- *"Early in the melt season, suspended sediment discharges in the subglacial water channels are large..."*
- *"The number of boulders (>200 mm) transported by the [subglacial] streams and caught in the [subglacial] sedimentation chamber ranges from 200 to 500/yr; usually 10 to 20 of these are 1 cubic meter or larger. In contrast, in front of the glacier, rocks larger than 200 mm are rare"*
- *"…the debris concentration [in basal ice] is relatively low and decreases rapidly with height above the bed; the mean concentration is ~ 15 km/cubic meter in the lowermost 2 m of ice, but near the subglacial water courses, it is approximately an order of magnitude less…Much of the debris is silt-sized and is evenly distributed in the ice, giving it a greyish colour. Coarser material sometimes occurs in debris-bearing layers…Rocks larger than 150 mm are usually found at the bed or in the lower meter of ice. Appreciable thicknesses of bottom moraine beneath the basal ice are not common…Where [present], it is generally less than a meter thick and is concentrated in depressions and lee-side areas….The contact between this bottom moraine and the basal ice is usually sharp…"*
- *"The mean debris concentration in the basal ice is ~ 15 km/m^3, and the basal ice flux is 2,400 m^3/yr (2 m thick x 400 m wide x 30 m/yr). The debris flux past the [subglacial] intakes in the ice is thus only ~ 360 mt/yr. In contrast, the diverted water transports ~ 8,000 mt/yr…"*
- *Winter stream discharges "…range from 0.05 to 0.2 m^3/s…Possible sources for this water include melting of ice due to geothermal and frictional heating, release of water from storage in cavities within or under the glacier, ground water, and drainage from Lake Holmavatn"*
- *"The large, suspended sediment flux accompanying the first really high discharge of the melt season is interpreted as being, for the most part, a result of flushing of fine particles produced by abrasion since the last period of high water pressure, possibly as long ago as the previous spring…Large discharges later in the summer have appreciably lower sediment concentrations. This is presumably because the channel system is now well developed, and so water pressures are lower and separation less extensive. Alternatively, there may be less material available in such a short time after initial flushing…"*

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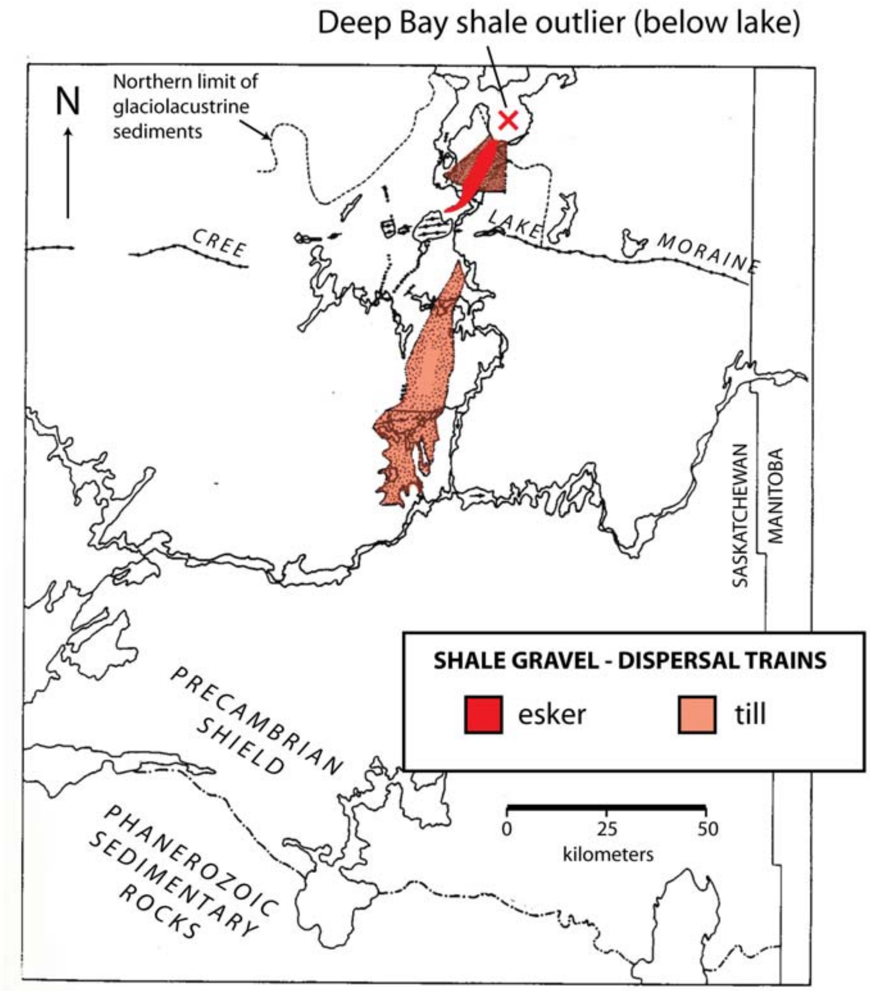
Johnson, W.G.Q. 1994. Glacial indicator fans or trains from the Mesozoic shale outlier, Deep Bay, Reindeer Lake, Saskatchewan. Saskatchewan Research Council, Publication No. R-1210-8-E-94, 73 p.

***Synopsis.** Documents a shale gravel-clast dispersal train in an esker in Saskatchewan. Concentrates mainly on the till dispersal train south of the Cree Lake Moraine. Only briefly discusses the esker dispersal train (several paragraphs only, plus the figure below).*

***Exploration significance**. This was the only moderately well-constrained study (i.e., known source; till investigated in parallel) of an esker dispersal train we could find for the Precambrian Shield west of Hudson's Bay.*



Gravel dispersal trains in till and an overlying esker system downflow of the Deep Bay Mesozoic shale outlier, northern Saskatchewan. The dispersal train to the south of the moraine is interpreted to be older that those north of the Cree Lake Moraine, which are interpreted to have been deposited during a readvance of the ice front to the moraine position (till dispersal train) followed by net ablation and ice-front retreat (esker system dispersal train).

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Jones, L.S. and Humphrey, N.H. 1997. Weathering-controlled abrasion in a coarse-grained, meandering reach of the Rio Grande: Implications for the rock record. GSA Bulletin, v. 109(9), p. 1080–1088.

***Synopsis**. Tumbling mill abrasion experiment performed on gravel (> 4 mm) coupled with field work from the Rio Grande River. Concludes that (1) the high initial downstream-fining trend observed in field is due to rapid abrasion of weathered crust following entrainment, and (2) that intermittent chemical weathering in hot humid settings during long-term transport can enhance downstream fining, making the fining trend more pronounced than that predicted by abrasion experiments.*

***Exploration significance**. The environmental setting of the Rio Grande described herein contrasts with the cold and commonly dry setting in northern Canada where the best developed eskers are located. This cold, dry setting, in addition to the low chemical* *weathering rates for silicate minerals beneath glaciers (Anderson, 2007) and the short time-span involved in esker deposition, may lead to less pronounced changes in the composition and physical properties of indicator-mineral dispersal trains in eskers (e.g., Averill, 2001) compared to their fluvial counterparts in hotter and wetter settings (e.g., Mosig, 1980).*

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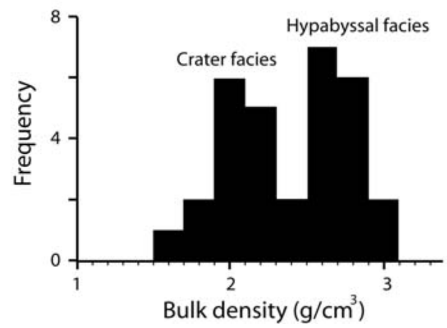
Katsube, T.J. and Kjarsgaard, B. 1996. Physical characteristics of Canadian kimberlites *in* LeCheminant, A.N., Richardson, D.G., DiLabio, R.N.W., and Richardson, K.A. (eds.), Geological Survey of Canada, Open File 3228, p. 241–242.

Synopsis. *Study of the physical properties of kimberlite hand samples. Concludes that crater and hypabyssal kimberlite facies tend to be less and more dense, respectively, than granite.*

Exploration significance. *Given their different densities, crater and hypabyssal kimberlite clasts will experience selective entrainment in esker sedimentary systems: all other things being equal, the former will be slightly easier to entrain than the latter.*

Key quotes

- *"…physical properties are closely related to the kimberlite facies classification: hypabyssal (HB) and crater (CR)…HB-kimberlites are characterized by higher bulk density…and low effective porosity values…CR-kimberlites are characterized by low [bulk density]…and high [effective porosity] values."*



Density of kimberlite. Note that crater & hyperbyssal facies are less & more dense than granite, respectively. Accordingly, the two lithologies may be transported differently down-esker.

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Kjarsgaard, B.A., and Levinson, A.A. 2002. Diamonds in Canada. Gems and Gemology, v. 38, p. 208–238

Synopsis. *This paper contains accounts of eskers that have been used to explore for, and in some cases find, kimberlites.*

Exploration significance. *Esker sampling has worked in the past to find kimberlites in Canada, including the Lac de Gras kimberlite field, home to Canada's first diamond mine. (Although commonly associated with diamond exploration, esker sampling can be used to locate any mineral deposit type that yields heavy minerals.)*

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Kjarsgaard, I.M., McClenaghan, M.B., Kjarsgaard, B.A. and Heaman, L.M. 2004. Indicator mineralogy of kimberlite boulders from eskers in the Kirkland Lake and Lake Timiskaming areas, Ontario, Canada. Lithos, v. 77, p. 7-5–731.

Synopsis. *Reports the occurrence of kimberlite boulders in eskers and documents their chemical make-up.*

Exploration significance. *Kimberlite boulders can survive glaciofluvial transport; they do not necessarily immediately break down into smaller, sand- and mud-sized indicator particles upon entrainment (although some specific kimberlite facies likely do).*

========

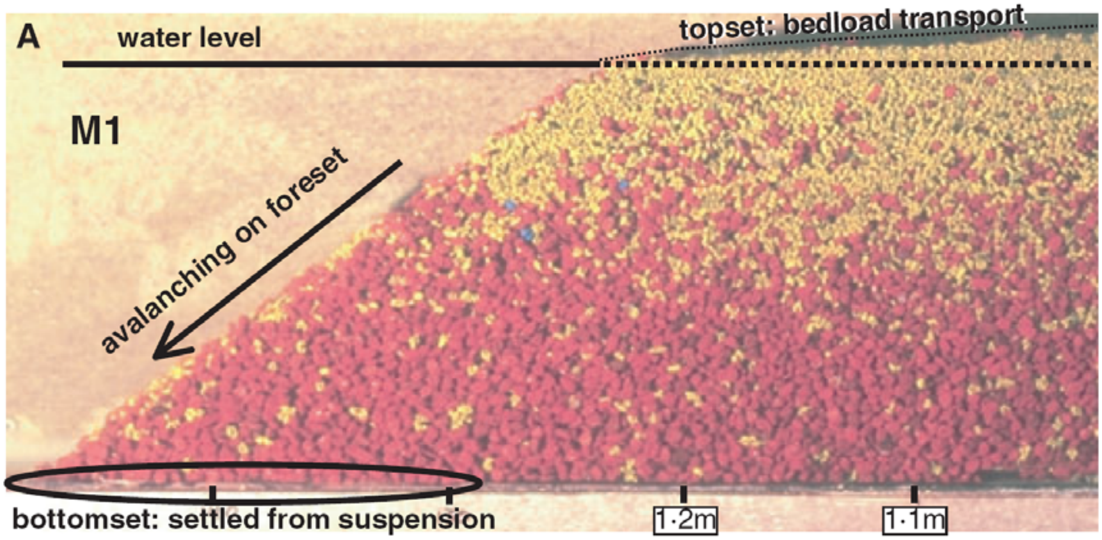
Kleinhans, M.G. 2005. Grain-size sorting in grainflows at the lee side of deltas. Sedimentology, v. 52, p. 291–311.

Synopsis. *Experimental investigation of sorting on the angle-of-repose lee-face of a delta/dune/barform. Only quartz-density sediment used. Concludes that cross-strata produced by downstream migration of such forms fines upward.*

Exploration significance. *If heavy minerals concentrate with coarser sediment in cross-strata (e.g., Slingerland and Smith, 1986), they will tend to occur near the base of the cross-sets.*

Key quotes

- *"Sediment deposition and sorting on the lee slope of the [Gilbert-type] delta is the result of (i) grains falling from suspension… (ii) kinematic sieving… (iii) grainflows, in which protruding large grains are dragged downslope by subsequent grainflows. The result is a fining upward vertical sorting in the delta."*
- *"Kinematic sieving is only effective if the grain-size differences are large enough, e.g. more than about two in a bimodal mixture…"*



Grain-size sorting on an experimental "delta" slipface

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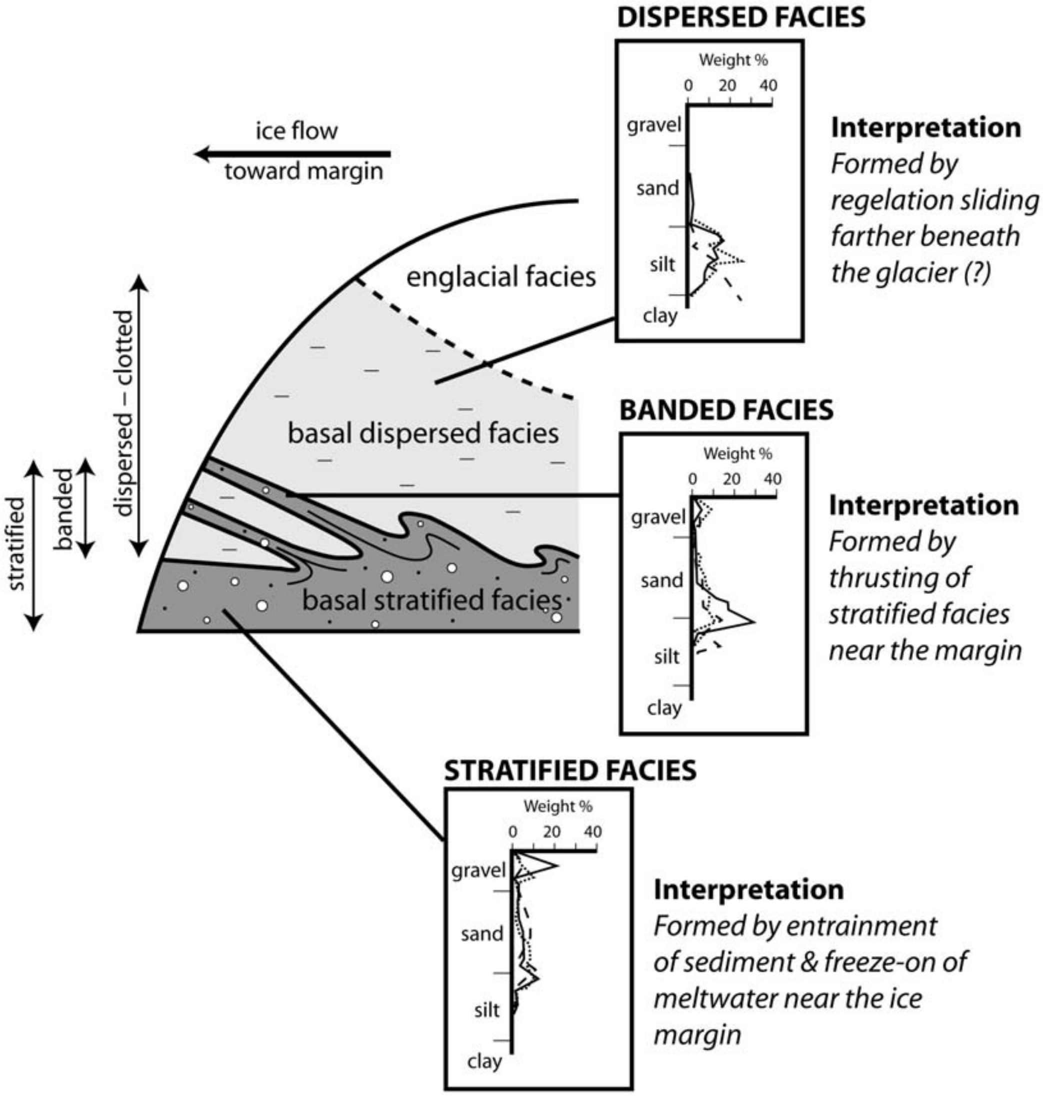
Knight, P.G. 1994. Two-facies interpretation of the basal layer of the Greenland ice sheet contributes to a unified model of basal ice formation. Geology, v. 22, p. 971–974.

Synopsis. *This study of basal ice of the Greenland ice sheet, and comparison with a well studied Alaskan example (Matanuska Glacier concludes that two main types of basal ice exist: (1) a facies rich in gravel, sand and silt ("stratified" facies), which is interpreted to form by entrainment and freeze-one near the ice margin, and (2) an overlying facies ("dispersed" facies) rich in silt, which is interpreted to form farther up-glacier, possibly by regelation sliding.*

***Exploration significance**. The interpretations presented herein, if correct, suggest that most geomorphic work (i.e., most erosion and transport) by ice sheets is performed near the ice margin.*



Sediment distribution in basal ice, based on observations from Greenland

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Knight, P.G. 1997. The basal ice layer of glaciers and ice sheets. Quaternary Science Reviews, v. 16, p. 975–993.

***Synopsis**. Review of basal ice: physical characteristics, origins, and debris entrainment mechanisms. Expands on the ideas in Knight (1994).*

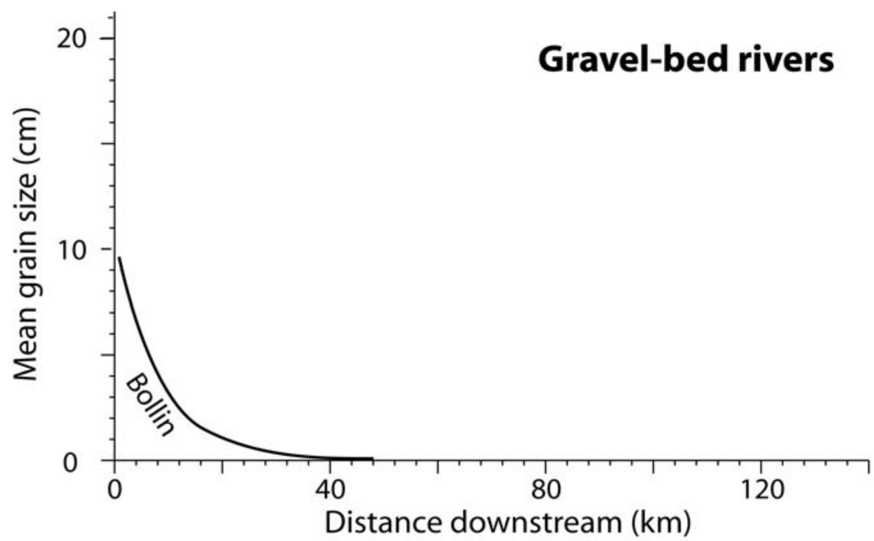
***Exploration significance**. The interpretations presented herein, if correct, suggest that most geomorphic work (i.e., most erosion and transport) by ice sheets is performed near the ice margin.*

========

Knighton, A.D. 1980. Longitudinal changes in size and sorting of stream-bed material in four English rivers. Geological Society of America Bulletin, v. 91, p. 55–62.

***Synopsis**. Study of downstream fining in four small gravel-bed rivers. Concludes that mean grain size decreases exponentially downstream, but that there is considerable scatter due to tributary inputs.*

***Exploration significance**: Dispersal trains in eskers are suspected to fine downflow, possibly somewhat like the sediment in the rivers studied by Knighton (1980). If this is true, a general rule might be "the larger the clast, the closer to source" (which for eskers is typically an underlying till dispersal train).*



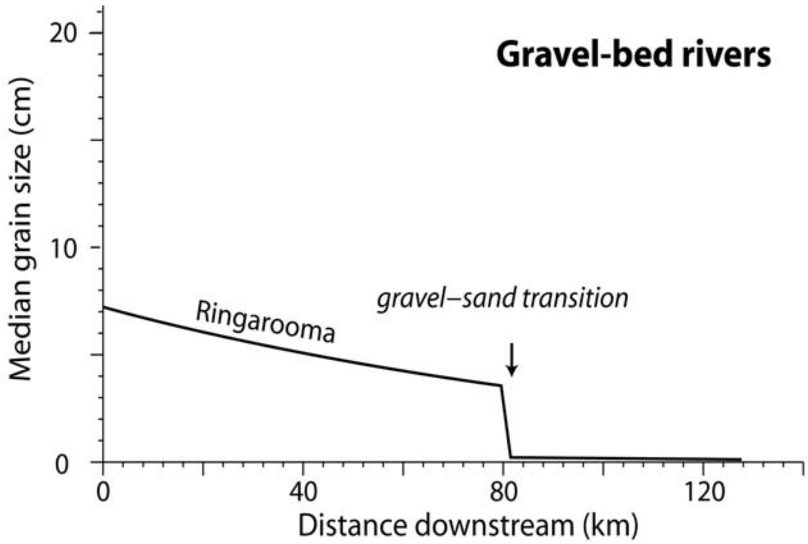
Downstream fining, Bollin River, England (noise filtered out).

========

Knighton, A.D. 1999. The gravel–sand transition in a disturbed catchment. Geomorphology, v. 27, p. 325–341.

***Synopsis**. Study of a gravel-bed river in Tasmania into which a large quantity of poorly sorted mining tailings have been dumped over the past 125 years. The river fines downflow, and experiences an abrupt jump from gravel to sand bed (in less than 500 m).*

***Exploration significance**: Dispersal trains in eskers are suspected to fine downflow, possibly somewhat like the sediments in the Rangarooma River. If this is true, a general rule might be "the larger the clast, the closer to source" (which for eskers is typically an underlying till dispersal train).*



Downstream fining, Ringarooma River, Tasmania (noise filtered out).

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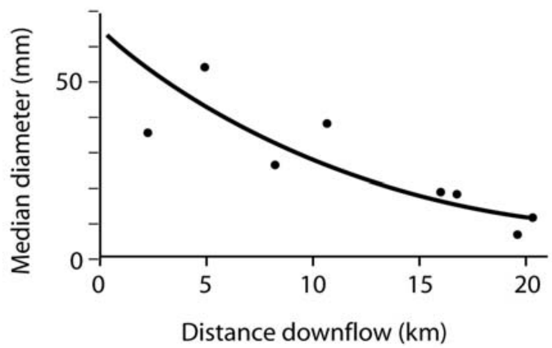
Kodama, Y. 1994a. Downstream changes in the lithology and grain size of fluvial gravels, the Watarase River, Japan: Evidence of the role of abrasion in downstream fining. Journal of Sedimentary Research, v. A64, p. 68–75.

Synopsis. *Study of downstream fining in the Watarase River (see also Yatsu, 1955). Concludes that size distribution of the gravel is strongly related to lithology.*

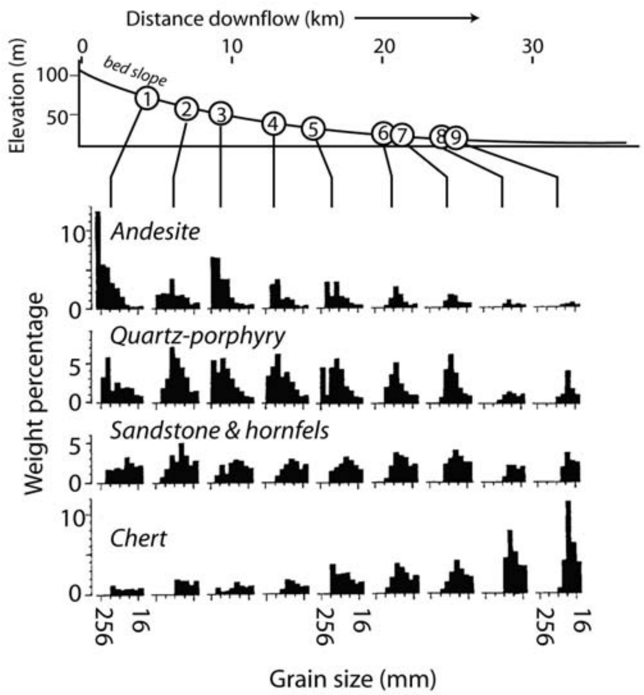
Exploration significance*: Dispersal trains in eskers are suspected to fine downflow, possibly somewhat like the sediments in the Watarase River. If this is true, a general rule might be "the larger the clast, the closer to source" (which for eskers is typically an underlying till dispersal train).*

Key quotes

- *"Some studies have related abrasion and differential transport to degradation or aggradation of the river…The general result is that abrasion dominates in a degrading river and sorting dominates in an aggrading river."*
- *"…previous experimental studies on gravel abrasion showed much lower diminution rates than those of gravel in natural streams (e.g., Kuenen, 1956)"*
- *"Some large boulders on Japanese alluvial fans are strongly asymmetrical…On the upstream side, where other grains collide, surface textures are usually round, and there are many tiny grooves or notches along bedding planes or joints. On the downstream side, which is scooped out as with a spoon, surface textures are smooth. Small particles in eddies generated in the lee of the boulders may polish the surface during floods."*
- *"A larger gravel particle can become smaller in situ by collisions from other large particles or by polishing by small particles"*



Downflow fining trend, Watarase River, Japan. This river was also studied by Yatsu (1955).



Downflow changes in gravel lithology, Watarase River, Japan

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Kodama, Y. 1994b. Experimental study of abrasion and its role in producing downstream fining in gravel-bed rivers. Journal of Sedimentary Research, v. A64(1), p. 76–84.

Synopsis. *Tumbling mill experiment designed to replicate high-velocity gravel transport in high-gradient alluvial fans. Results suggest that, under high-velocity conditions, gravel abrasion rates are one to two orders of magnitude greater than those obtained from previous (lower-velocity) experiments. Author suggests that abrasion may therefore be dominant process behind downstream fining in high-gradient settings.*

Exploration significance*. Gravel clasts in eskers are commonly similar in lithology to those in the subjacent till. However, they are much more rounded; even friable lithologies like shale become rounded in esker sedimentary systems. Presumably, however, lithologies become rounded and lose mass at different rates, and they may also break down into different grain* *populations. Understanding how quickly gravel becomes worn and how it breaks down into indicator grains is therefore important in interpreting provenance signals from eskers. If the opinions expressed by Kodama are correct, abrasion may be a more significant cause for downstream fining than typically believed (most recent studies suggest the primary cause for downstream fining in gravel-bed streams is selective sorting).*

========

Krajick, K. 2001. Barren Lands: An Epic Search for Diamonds in the North American Arctic. W.H. Freeman, 442 p.

***Synopsis**. Biographical account of Chuck Fipke's quest to find diamonds in Canada, culminating in his discovery of the Lac de Gras kimberlite field, N.W.T.*

***Exploration significance**. An esker sample led to the discovery of Canada's first diamond mine. Chuck Fipke, like DeBeers before him and many afterwards, specifically targeted eskers in his search for diamonds across the Canadian Shield.*

Key quotes

- *"[The Russian scientists] calculated how far indicators could travel—garnets 125 miles from known pipes, ilmenites further. In the cold, dry Arctic, even chrome diopsides sometimes made it thirty miles." (p. 138). NOTE: Krajick is likely referring to glacial (till) dispersal here, not eskerine dispersal.*
- *"[The Russian scientists] quantified a key concept: The bigger the grain, the closer you are." (p. 139)*

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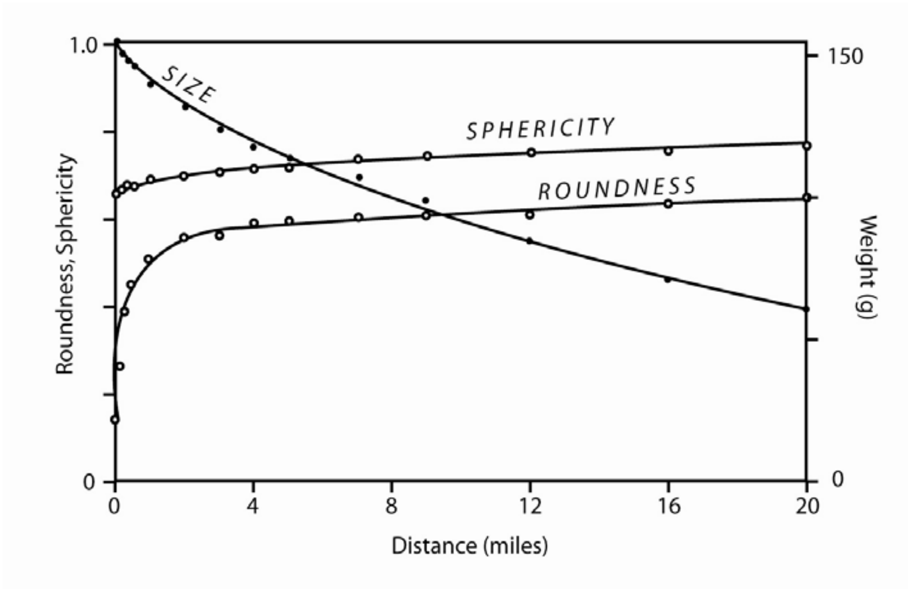
Krumbein, W.C. 1941. Measurement and geological significance of shape and roundness of sedimentary particles. Journal of Sedimentary Petrology, v. 11, p. 64–72.

***Synopsis**. Abrasion experiment that examines changes in clast shape during transport.*

***Exploration significance**. Gravel clasts in eskers are commonly similar in lithology to those in the subjacent till. However, they are much more rounded; even friable lithologies like shale become rounded in esker sedimentary systems. Presumably, however, lithologies become rounded and lose mass at different rates, and they may also break down into different grain populations. Understanding how quickly gravel becomes worn and how it breaks down into indicator grains is therefore important in interpreting provenance signals from eskers. Because abrasion of gravel occurs in esker sedimentary systems (gravel clasts are almost invariably rounded), gravel dispersal trains may fine downflow.*



Tumbling mill experiment results for limestone pebbles

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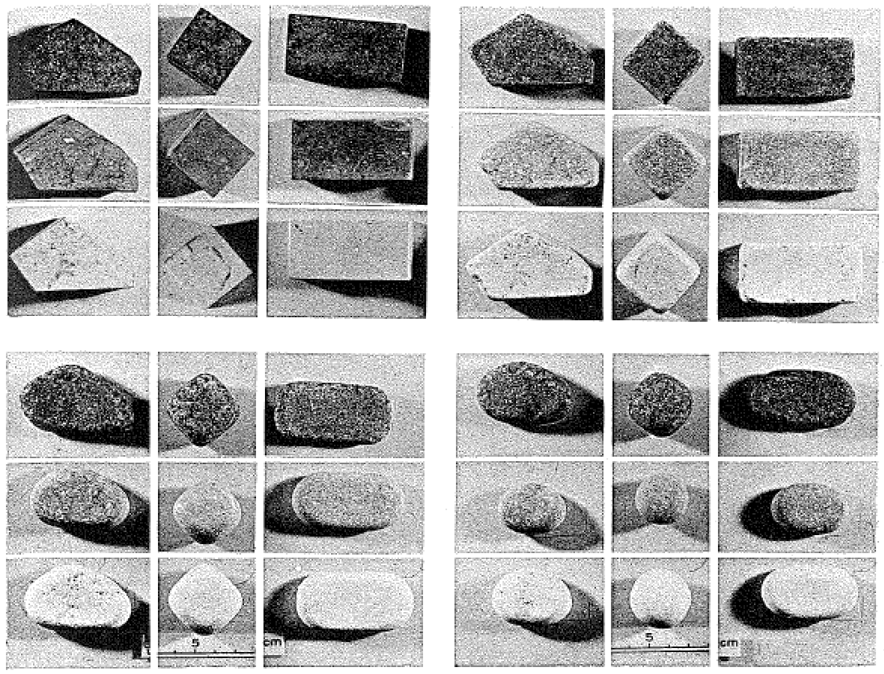
Kuenan, Ph.H. 1956. Experimental abrasion of pebbles. 2. Rolling by current. Journal of Geology, v. 64, p. 336–368.

***Synopsis**. Abrasion experiment that examines changes in pebble shape, size, and roundness during transport.*

***Exploration significance**. Gravel clasts in eskers are commonly similar in lithology to those in the subjacent till. However, they are much more rounded; even friable lithologies like shale become rounded in esker sedimentary systems. Presumably, however, lithologies become rounded and lose mass at different rates, and they may also break down into different grain populations. Understanding how quickly gravel becomes worn and how it breaks down into indicator grains is therefore important in interpreting provenance signals from eskers. Because abrasion of gravel occurs in esker sedimentary systems (gravel clasts are almost invariably rounded), gravel dispersal trains may fine downflow.*



Abrasion of pebbles after 0, 6, 52 and 142 km of fluvial transport in a circular flume

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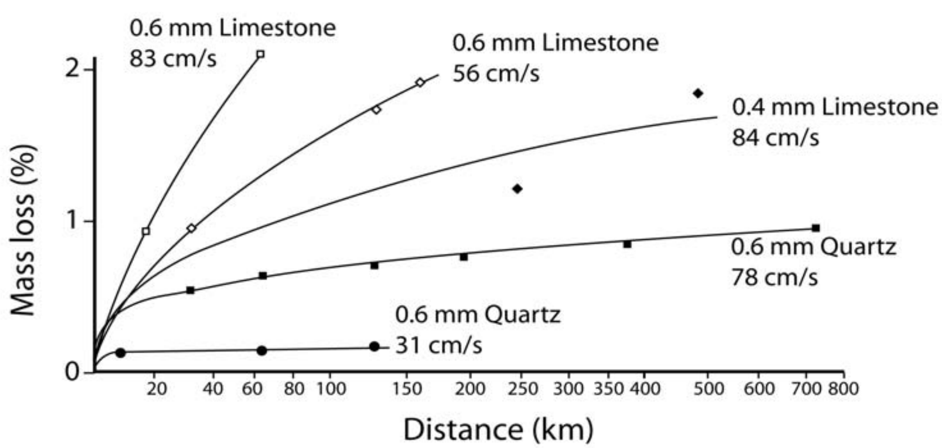
Kuenen, Ph.H. 1959. Experimental abrasion. 3. Fluviatile action on sand. American Journal of Earth Science, v. 257, p. 172–190.

***Synopsis**. Sand-grain abrasion experiment using using a circular flume. Most grains studied experienced less than 2% mass loss over hundreds of kilometres of transport. Concludes that mechanical abrasion of sand is likely negligible in most rivers.*

***Exploration significance**. Do sand grains also experience negligible wear in esker sedimentary systems? Several studies support this idea (Dredge et al., 1997; Averill, 2001). Sand-grain wear may therefore be a poor proxy for transport distance in eskers, just as it appears to be for till (McClenaghan and Kjarsgaard, 2001; Averill, 2001).*



Sand-grain mass loss with distance traveled in circular flume

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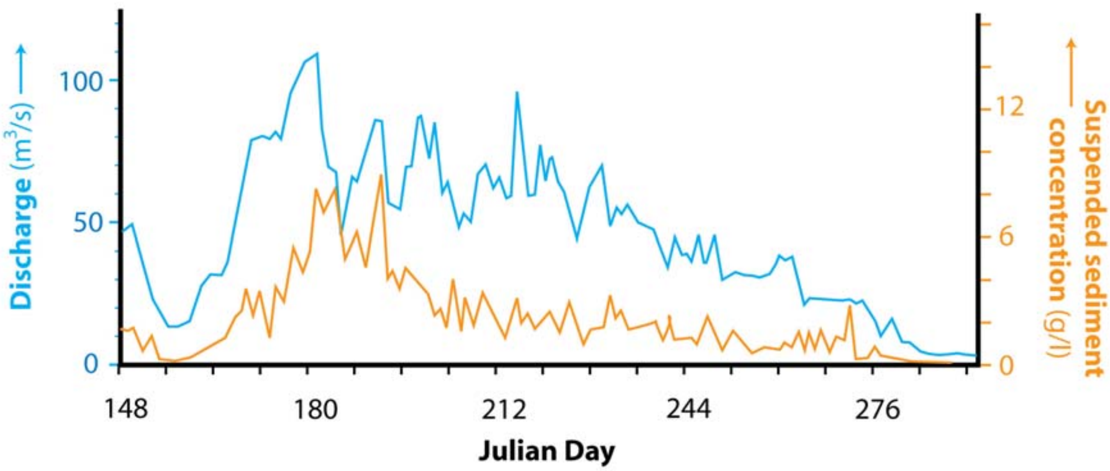
Kumar, K., Miral, M.S., Joshi, V., and Panda, Y.S. 2002. Discharge and suspended sediment in the meltwater of Gangotri Glacier, Garhwal Himalaya, India. Journal des Sciences Hydrologiques, v. 47(4), p. 611–619.

***Synopsis**. Study of water and sediment discharge in a glaciated catchment. Concludes that sediment flux is greatest early in the melt season (see also Hooke et al., 1985).*

***Exploration significance**. Sediment dispersal in esker sedimentary systems likely occurs over multiple, high-magnitude flood events over multiple melt seasons. This may impact how gravel clasts and heavy minerals are dispersed, abraded, and concentrated (see Burton and Fralick, 2004; Frostick et al., 2006).*



Meltwater discharge vs suspended sediment concentration during the melt season of 1999 measured in a stream fed by Gangotri Glacier, Himalaya, India

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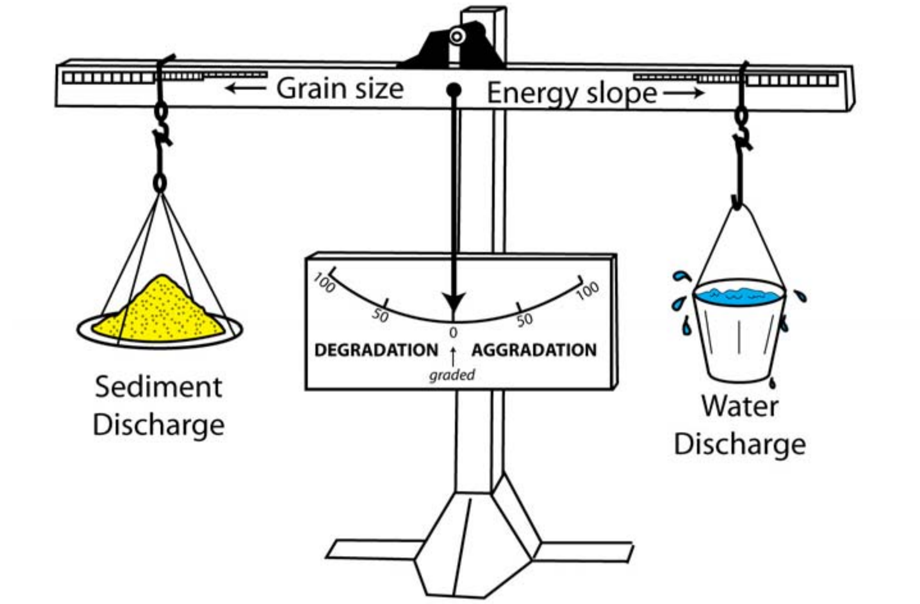
Lane**,** E.W. 1955**.** Design of stable channels**.** Transactions of the American Society of Civil Engineers (ASCE), v. 120, p. 1234–1260.

***Synopsis**. Seminal paper on the theory of the graded river. Concludes that a river will reach grade (i.e., no net aggradation or degradation) if all the sediment that enters a reach is transported out of the reach. This is thought to reflect a balance between water discharge and slope on one hand, and grain size and sediment discharge on the other. Alter any one variable, and the others will change accordingly.*

***Exploration significance**. Because there is commonly little sediment beneath eskers (eskers on the Shield commonly sit erosively on bedrock in esker corridors—see St. Onge, 1984), subglacial streams may commonly be sediment starved. For esker sedimentary systems, Lane's sediment balance, as depicted below, may more commonly lean to the right-hand side than not. Some authors suggest that, for this reason, subglacial streams may commonly have unfulfilled transport capacity, and may therefore have more energy to erode their substrates than proglacial or non-glacial alluvial streams do (e.g., Alley et al., 1997, 2003).*



Lane's sediment balance.

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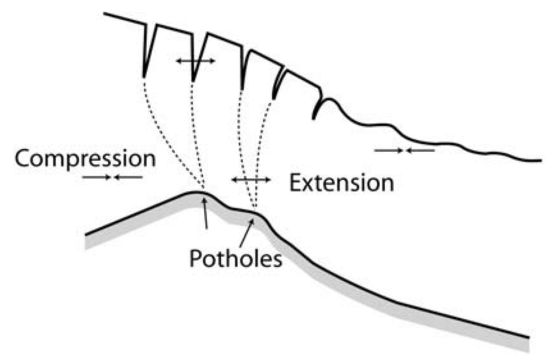
Lawson, D.E. 1993. Glaciohydrologic and glaciohydraulic effects on runoff and sediment yield in glacierized basins. US Army Corps of Engineers, Cold Regions Research and Engineering Laborary (CRREL), Monography 93-2, 108 p.

***Synopsis**. The most comprehensive study of a modern glaciofluvial sedimentary system.*

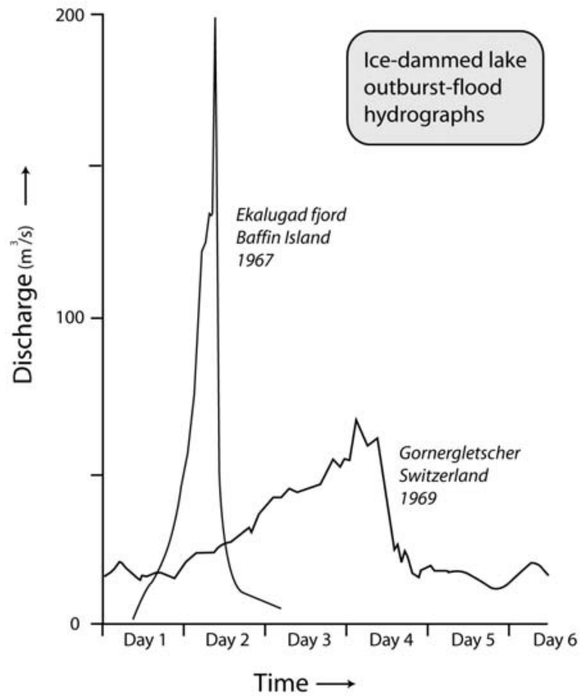
***Exploration significance**. Provides insight into some of the processes and depositional environments involved in the generation of esker dispersal trains.*

Key quotes

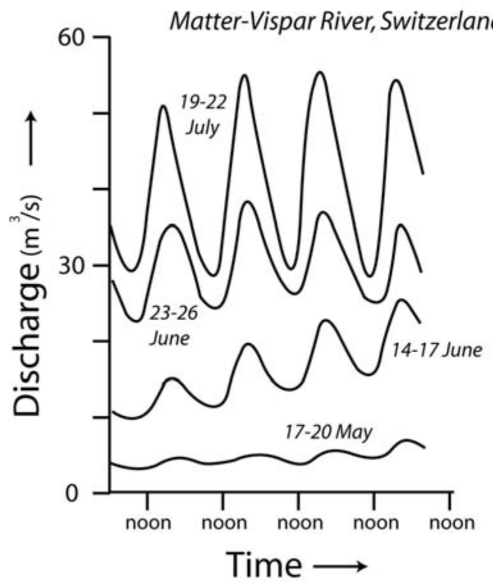
- *"Outburst floods can far exceed "normal" floods; on the Knik River in Alaska…the measured peak outburst flood from a glacier-dammed lake was 22.3 (m^3/s)/km^2, whereas the 100-year flood is calculated at 3.9 (m^3/s)/km^2…"*
- *"Temperate glaciers…lying on bedrock are commonly characterized by a thin (less than 1 m) debris-laden basal layer in which primarily rock fragments have been incorporated. These fragments are reasonably well-dispersed in small concentrations throughout the regelation ice, typically at volumes less than 5%...This material is thought to be incorporated primarily by regelation in response to pressure-melting around bedrock roughness features or obstructions to sliding…"*
- *"Much thicker (several to 10 m or more) and more heavily debris-laden basal zones characterize glaciers where thermal conditions at the ice/bed interface permit the freezing of melwater and the creation of new ice at the glacier sole…During freeze-one, sediments or rock particles at or below the ice/bed interface can be included within the new ice. The resultant debris-rich basal zone is typically stratified, with layers or lenses of high and low sediment concentration…As a sediment source, limited measurements from glaciers and ice sheets suggest that this horizon commonly transports the majority of the glacier's sediment load…Sediment volumes range from several percent to over 90% in individual strata, with a mean exceeding approximately 25% by volume…"*
- *"Bogen (1989)…suggested that the abrasive capacity of sediment-laden meltwaters (s) might be represented as $s = Q_s rqd$, where Q_s = annual suspended sediment load; r = grain shape, values ranging from 1 to 5 for well-rounded to angular particles; q = proportion of quartz particles to all other mineral particles in the 0.063–0.125 mm size range; d = proportion of sand-size particles (0.063–0.5 mm diameter) to total sediment weight"*



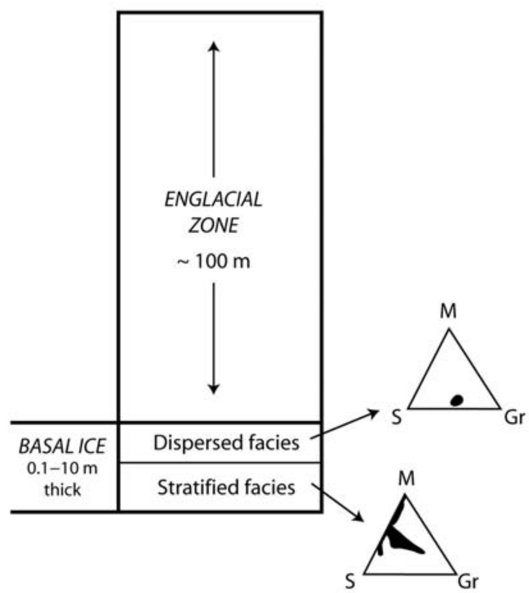
"Moulin" model of pothole formation in bedrock uplands



Hydrographys of relatively small jokulhlaups from modern alpine glacial settings



Diurnal discharge variations over time in proglacial stream



Sediment in basal ice, Matanuska Glacier, Alaska. Average sediment concentration in basal ice is 25% (varies from 0 to 90%).

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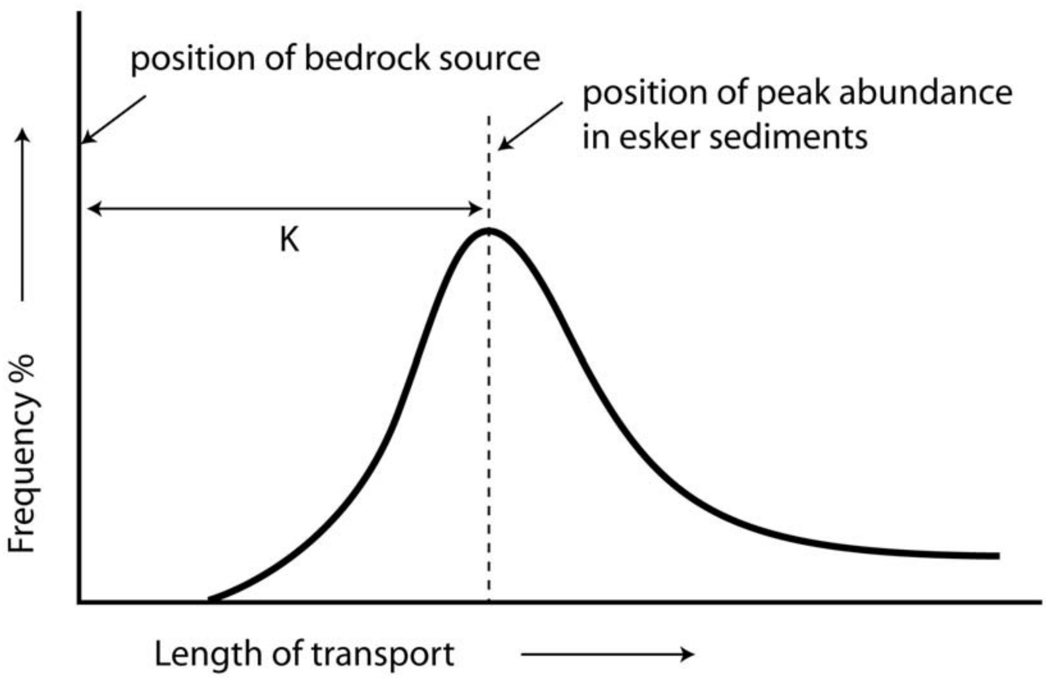
Lee, H.A. 1965. Investigations of eskers for mineral exploration / Buried valleys near Kirkland Lake, Ontario. Geological Survey of Canada, Paper 65-14, 24 p.

***Synopsis**. Study of pyrope, dunite granules, and gold grains in the Munro esker. Of the data collected, only the pyrope grains form part of a clear dispersal train with a distinct head.*

***Exploration significance**. Esker sampling is a proven exploration method: the pyrope grains in the Munro esker were later used to find a kimberlite pipe (see Lee, 1968).*

Key quotes

- *"The results of the data on hand appear geologically reasonable and encouraging but further field work is needed to surmount some of the problems of sampling."*
- *"In terms of mineral exploration all eskers are similar and represent uniform meltwater conditions and thus generalizations regarding one esker can be applied to others"*
- *"A gravelly sand is preferable [for sampling' and was available by taking samples positioned at the crest of the…ridges."*
- *"Short transport is expected in an esker because esker streams are thought to be short lived and overloaded with sediment."*



Hypothetic frequency distribution illustrating concept of transport distance "K"

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Lee, H.A. 1968. An Ontario kimberlite occurrence discovered by application of the glaciofocus method to a study of the Munro esker. Geological Survey of Canada, Paper 68-7, 3 p.

Synopsis*. Used the dispersal train described in Lee (1965) to locate a kimberlite pipe.*

Exploration significance*. Esker sampling is a proven exploration method: indicator minerals within eskers can be traced back to sources in the bedrock.*

========

Levasseur, D. 1995. Les eskers: Essai de synthese bibliographique. Geographie physique et Quaternaire, v. 49(3), p. 459–479.

Synopsis*. This is the most comprehensive review of the esker literature, including much of the early (pre-1900) work. Along with Bolduc (1992), this is a good place to start. Lots of data are presented, but little critique of the data is made.*

Exploration significance. *A good reference for all things esker. Provides context for understanding esker dispersal trains.*

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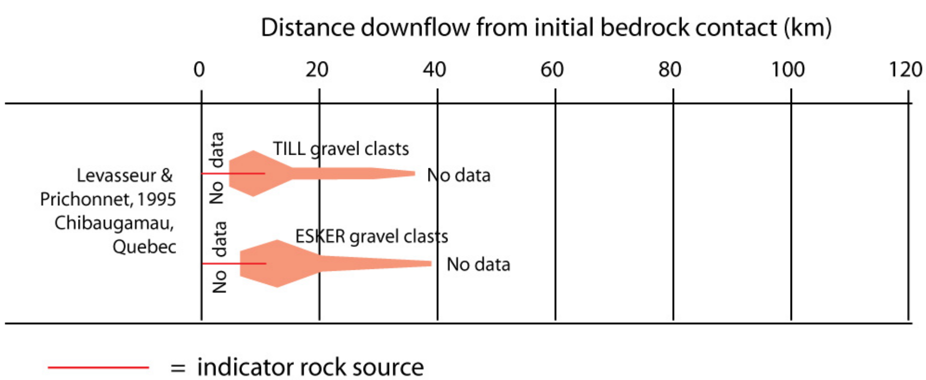
Levasseur, D. and Prichonnet, G. 1995. La dispersion clastique des debris rocheux dans les esker et le till adjacent de la region de Chapais–Chibougamau (Quebec) au Wisconsinien superieur. Geographie physique et Quaternaire, v. 32, p. 590–602.

Synopsis. *A good data-driven study of gravel dispersal in an esker near Chibougamau, Quebec. Concludes that the gravel dispersal train is of similar length to that in the underlying till, but is downshifted by several kilometers. Also concludes that dilution by sediment input downflow of the bedrock source, and not abrasion or selective deposition, caused the down-esker decrease in indicator concentration. They have some nice data to support this. Dispersal curves are similar irrespective of the size of gravel (granules, small pebbles, large pebbles or cobbles).*

Exploration significance. *Are most gravel dispersal trains in eskers similar in length to those studied by Levasseur and Prichonnet—similar in length the underlying gravel dispersal train in till and shifted downflow only by a small amount?*

Key quotes

- *"Le tunnel dans lequel a été mis en place l'esker du lac Waconichi devait mesurer plus de 25 km pour que l'on puisse expliquer la présence de débris rocheux de la Formation de Chibougamau à plus de 25 km en aval de la source la plus proche (cet a dire dans le till)."*
- *"La majorité des eskers de Chapais–Chibougamau sont de tres grande dimension : ils peuvent atteindre facilement plus de 40 m de hauteur et 1 a 3 km to largeur…Par ailleur, la couverture régionale de till est relativement mince"*
- *"Ces résultats nous permettent donc d'avancer que la désagrégation est assez limitée lors du transport glaciare ou fluvioglaciaire. La diminution de la fréquence d'un marquer pétrographique donne, pour une certaine taille, est sourtout contrôlée par le taux d'incorporation des débris non marquers et par la sédimentation progressive des fragments rocheux provenant de l'affleurement indicateur."*



Dispersal data from the Chibougamau esker, Quebec

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Lewin, J. and Brewer, P.A. 2002. Laboratory simulation of clast abrasion. Earth Surface Processes and Landforms, v. 27, p. 145–164.

***Synopsis**. Review of experimental and field studies on clast abrasion. Concludes that abrasion rates observed during experiments are too low because the apparatuses used to not replicate field conditions (especially clast breakage, crushing or sandblasting).*

***Exploration significance**. Lab experiments like this one can help determine whether, for example, a particular ore body is more or less resistant than the surrounding country rock (and thus help interpret gravel indicator assemblages), but only in a relative sense, because abrasion rates in tumbling mills and circular flumes tends to be lower than abrasion rates in Nature.*

Key quotes

- *"Abrasion is a composite process, and the effects achieved appear to be dominated by percussion in the tank [circular flume] and grinding in the [tumbling] barrel. Breakage, crushing and sandblasting are not modeled effectively [in experimental abrasion studies], nor are effects achieved on clasts when they form part of the bed."*

Lillieskold, M. 1990. Lithology and transport distance of glaciofluvial material *in* Kujansuu, R. and Saarnisto, M. (eds.), Glacial Indicator Tracing. A.A. Balkema, Rotterdam, p. 151–164.

***Synopsis**. Review of esker dispersal trains in Finland and elsewhere. Concludes that "…Particles within esker systems transported as bedload in glacial meltwater streams have been crushed and abraded rapidly, and in consequence the true amount of long-distance material remains low." Problem: No till data were collected in parallel to the eskers described herein (two classic studies—Hellakosk (1931) and Virkkala (1958)—excepted). (Till data were in fact collected adjacent to one esker, the Indal valley esker, but the way these data are plotted make it difficult to understand sample locations and, by extension, the results.) Given the lack of till data, it is impossible to deconvolve glacial (till) from glaciofluvial (esker) transport in the case studies summarized, which makes it impossible to evaluate conclusions.*

***Exploration significance**. Are gravel dispersal trains in eskers typically short, like most described herein?*

========

Marshall, T.R. 1991. The diamondiferous gravels of the southwestern Transvaal, South Africa *in* Meyer, H.O.A. and Leonardos, O.H. (eds.), Diamonds: Characterization, Genesis, and Exploration. Proceedings of the 5th International Kimberlite Conference, Araxá, Brazil, p. 187–201.

***Synopsis**. Review of alluvial diamonds in South African gravel deposits.*

***Exploration significance**. This study demonstrates that care must be taken when transposing ideas regarding dispersal from the classic (equatorial) diamond regions to northern settings, and to eskers in particular. In the classic equatorial settings, transport time spans are typically orders of magnitude larger than for eskers, and chemical weathering is more intense, which can lead to very different dispersal distances and different indicator mineral assemblages being preserved. Marshall presents an extreme case here—only diamond is left!*

Key quotes

- *"Modern proponents of the distant kimberlite source for diamonds in the southwestern Transvaal gravels have used the lack of indicator minerals as their main argument…The present study has indicated that garnets and ilmenites do, in fact, exist…but the quantities…are extremely limited. One suggestion explaining (at least*

- *"In the alluvial deposits…the diamond acts as a heavy mineral and is, therefore, concentrated by sedimentary processes."*
- *"It is to be concluded that all [gravel] clasts have been derived from local source areas, including the well-rounded Transvaal and Waterberg quartzites which have been eroded from nearby outcrops of Dwyka tillites."*

========

Marshall, T.R. and Baxter-Brown, R. 1995. Basic principles of alluvial diamond exploration. Journal of Geochemical Exploration, v. 53, p. 277–292.

Synopsis. *Review of exploration methods for alluvial diamonds.*

Exploration significance. *Care must be taken when transposing insights from the classic (equatorial) diamond regions to northern settings where eskers are located. In the classic settings, transport time spans are typically order of magnitude larger, and chemical weathering is more intense, which can lead to very different indicator mineral assemblages being preserved.*

Key quotes

- *"Sampling of drainages for indicator minerals has limited application in alluvial [diamond] exploration"*
- *"…the most economically significant deposit type is the marine, followed by the fluvial"*
- *"Fluvial deposits can be separated into two broad categories, namely plateau gravel deposits and coastal plain gravels"*
- *"Most of the well-known fluvial diamond fields of India, South Africa and parts of South America are the fossil terrace remnants of tropical rivers that were far more active and impressive in scale than their descendants in more arid and temperate eras."*
- *"Diamonds do not reduce in size by abrasion. However, very large and irregularly shaped diamond crystals are rapidly broken up by impact into minute cleavage fragments and dispersed in the alluvial system. This is why alluvial diamond deposits, both fluvial and marine, and generally characterized by better quality diamonds than their primary sources"*

========

McCandless, T.E. 1990. Kimberlite xenocryst wear in high-energy fluvial systems: experimental studies. Journal of Geochemical Exploration, v. 37, p. 323–331.

Synopsis. *Tumbling mill experiment on kimberlite indicator minerals. The kimberlite xenocrysts studied experienced abrasion during these tumbling mill experiments, suggesting that the morphology of indicator minerals becomes modified as they are transported in water.*

Exploration significance. *It is possible these findings are not directly transposable to glaciated settings (i.e., Canada): as pointed out by Wolfe et al. (1975), Dredge et al. (1997) and Averill (2001), most sand-sized particles in glacial deposits tend to exhibit little wear, irrespective of transport distance (see also Kuenen, 1959).*

Key quotes

- *"The kelyphite is usually removed in the early stages of weathering and abrasion to expose a distinctive sub-kelyphitic surface…resembling the skin of an orange"*
- *"In the coarse-gravel charge, evidence of wear appeared rapidly, with pitting integrated enough to be readily visible on cleavage, curvelinear and conchoidal surfaces. Scattered pits developed on the high points of the orange peel surfaces. Abrasion surfaces were strongly developed along the edges of intersecting surfaces. Abrasion surfaces on the clinopyroxenes could be seen without the aid of the microscope. Major breakage along cleavages greatly reduces the size of some of the clinopyroxene grains."*
- *"Mineral wear in the sandy charge is less advanced than in the coarse-gravel change. Slight frosting appeared on the garnets, and narrow abrasion surfaces began to develop along sharp edges. The orange-peel texture on both garnets and clinopyroxenes was unaffected. Clinopyroxenes evidenced minor wear along cleavages, as chips 0.5 mm or less in size."*

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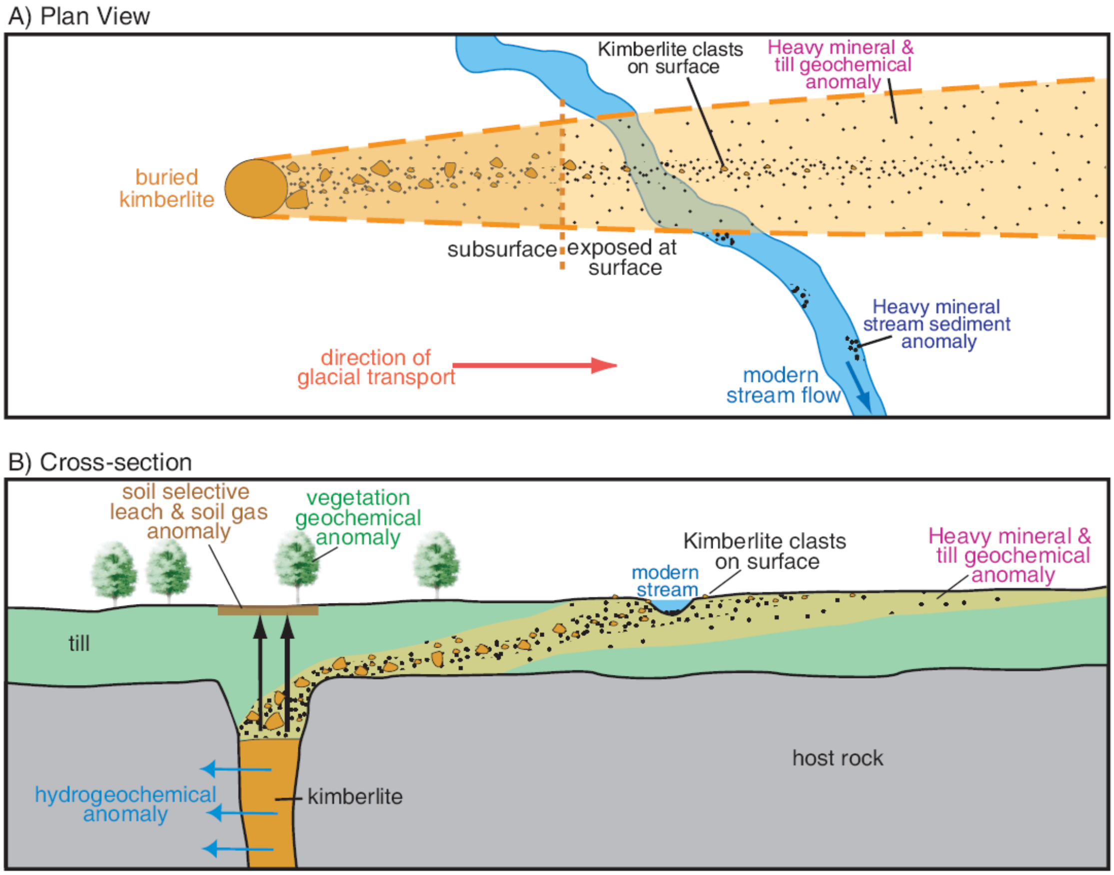
McClenaghan, M.B. and Kjarsgaard, B.A. 2001. Indicator mineral and geochemical methods for diamond exploration in glaciated terrain in Canada *in* McClenaghan, M.B. et al (eds), Drift Exploration in Glaciated Terrain. Geological Society, London, Special Publication, 185, p. 83–123.

***Synopsis**. An overview of kimberlite indicator minerals and their use in diamond exploration in glaciated terrain.*

***Exploration significance**. A good source of information on kimberlite indicator minerals in general and, specifically, kimberlite indicator minerals in till.*

Key quotes

- *"The finer (0.25–5 mm) fraction of heavy mineral concentrates prepared from till samples is best suited for indicator mineral surveys"*
- *Kimberlite indicator minerals are "…far more abundant in kimberlite than diamonds; visually and chemically distinct; sand-sized (0.25 to 2 mm); and, sufficiently dense to be concentrated by gravity methods"*
- *"Kimberlite indicator minerals include: xenocrysts derived from disaggregated peridotite and eclogite mantle xenoliths (olivine, enstatite, Cr-diopside, Cr-pyrope, Cr-spinel, pyrope–almandine garnet, omphacitic pyroxene, and diamond); the associated megacryst suite of minerals (low-Cr Ti-pyrope, Mg-ilmenite, Cr-diopsite, phlogopite, zircon and olivine); and kimberlite-derived olivine, spinel and ilmenite."*
- *"…diamond indicator minerals include: subcalcic Cr-pyrope, commonly referred to as G10 pyrope…Cr-pyrope, commonly referred to as G9 pyrope…high Cr–Mg chromite…and high Na–Ti pyrope almandine garnet"*
- *"Preservation of kimberlite fragments in till and esker sediments is variable. Fresh, dense, hypabyssal facies kimberlite boulders and cobbles often survive to the present day. In contrast, highly porous and fragmental crater and diatreme facies are highly susceptible to rapid breakdown in the postglacial (<9000 years) surface weathering environment."*
- *"The principle criterion for sampling glaciofluvial sediments, in most cases, is the presence of medium to very coarse sand and gravel to collect sediment suitable for the recovery of indicator minerals."*
- *Till samples are typically 10 to 20 kg. A 1 kg (0.5 l) sample of till can also be collected for geochemical analysis of the matrix.*
- *"If present, fluvial glaciofluvial or beach sediments are sampled initially instead of till…because they can represent the bedrock composition of a large area and sample collection is simple…Systematic follow-up study is then completed using regional indicator mineral sampling of till"*
- *"Cr-pyrope in kimberlite is commonly 0.1 to 1 cm in diameter…and is highly susceptible to fracturing during decompression and cooling…As a glacier entrains and transports kimberlite, Cr-pyrope preferentially breaks along the pre-existing fractures into angular grains that are dominantly sand-sized (< 2 mm) particles. These grains appear to remain at this size regardless of glacial transport distance…Olivine is the most abundant indicator mineral grain in the 0.25 to 0.5 mm fraction of kimberlite and till. Mg-ilmenite tends to occur among coarser sand-sized fractions in till. Cr-diopside and Cr-spinel tend to occur in the smaller size fraction (0.5 mm) in kimberlite and glacial sediments"*
- *"Indicator mineral abundance in till is not affected by degradation or physical breakdown of grains during glacial transport. All kimberlite indicator minerals survive long distance glacial transport. The relative abundance of indicator minerals in individual kimberlites varies significantly…and it is these variations in the kimberlite mineralogy that control the relative amounts of indicator minerals in glacial sediments down-ice…Decreases in concentrations down-ice are the result of dilution, not degradation."*



Hypothetical till dispersal train

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McDonald, B.C. and Vincent, J.S. 1972. Fluvial sedimentary structures formed experimentally in a pipe, and their implications for interpretation of subglacial sedimentary environments. Geological Survey of Canada, Paper 72-27, 29 p.

Synopsis. *Closed-conduit flume bedform experiment. The experiment reproduced the same bedforms as in open-channel flow (i.e., stream flow), with one major exception: antidunes do not form following plane bed because of lack of a free surface for the bed to couple with. Instead, with increasing shear, dunes are washed out, plane bedforms, and the shear layer continues to increase in thickness as flow velocity increases.*

Exploration significance. *The flow structure and bedforms generated in pipes (e.g., subglacial streams) and flumes (e.g., streams) are similar. Indicator mineral concentration processes at the "bedform" scale are therefore suspected to be similar in stream and esker sedimentary systems.*

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McDaniel, D.K., McLenann, S.M., and Hanson, G.N. 1997. Provenance of Amazon Far muds: Constraints from Nd and Pb isotopes *in* Flood, R.D., Piper, D.J.W., Klaus, A., and Peterson, L.C. (eds.), Proceedings of the Ocean Drilling Program, Scientific Results, v. 155, p, 169–176.

***Synopsis**. Concludes that most mud in Amazon Fan is derived from the Andes Mountains, which is thousands of kilometers up-river.*

***Exploration significance**. Mud tends to travel as wash load in fluvial systems. As such, unless floodplains are extensive, most tends to be bypassed to the basin (lake or sea). Presumably, mud should behave in a similar way in esker sedimentary systems: most should bypass the ice-contact channel to the ice front. If this assumption is correct, mud dispersal trains associated with eskers should be as long as the subglacial streams within which the eskers formed. Very fine sand, which also commonly travels as wash load in rivers (Wilcock, 2004), may be dispersed in a similar fashion.*

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Middleton, G.V., and Southard, J.B. 1984. Mechanics of Sediment Movement. SEPM Short Course Number 3.

***Synopsis**. Overview of the mechanics of how sediment is eroded, transported and deposited on the earth's surface.*

***Exploration significance**. This book remains <u>the</u> basic reference on the mechanics of sediment erosion, transportation and deposition. If you need details on any of these subjects, this is the place to start.*

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Morris, P.H. and Williams, D.J. 1999. A worldwide correlation for exponential bed particle size variation in subaerial aqueous flows. Earth Surface Processes and Landforms, v. 24, p. 835–847.

***Synopsis**. Comparison of bed material from numerous natural gravel- and sand-bed streams and small-scale experimental flows. Concludes that streams tend to fine exponentially downflow, independent of the size of the bed material or the length of the stream. Suggests that abrasion in gravel- and sand-bed streams may be inefficient at stream lengths below 10–100 km, and about 500 km, respectively.*

***Exploration significance**. Eskers are commonly tree-shaped, like streams. However, unlike streams, eskers lack net downstream fining trends. Rather, some seem to consist of multiple shorter segments, each of which fines downstream (e.g., St. Onge, 1984). What does this say about how eskers form? The answer must account for these apparently paradoxical observations.*

Key quotes

- *"The particle size of the bed sediments in or on many natural streams…varies exponentially with distance along the stream…"*
- *"A comparison of exponential laboratory abrasion and field diminution coefficients suggests that abrasion is unlikely to be significant in gravel and sand bed streams shorter than about 10 to 100 km, and about 500 km, respectively."*

========

Morris, P.H. and Williams, D.J. 1999. Worldwide correlations for subaerial aqueous flows with exponential longitudinal profiles. Earth Surface Processes and Landforms, v. 24, p. 867–879.

Synopsis*. Review of relationship between longitudinal profile of streams and grain size of the stream bed. Concludes that most rivers that decrease in slope downflow also fine downflow.*

Exploration significance*. The energy slope in subglacial streams may increase downstream (e.g., Alley et al., 1997), not decreases as it does in most fluvial systems, although discharge should increase downstream in both cases. Might this have something to do with the lack of downflow fining in eskers? Or is deposition of eskers in segments (e.g., St. Onge, 1984) the root of the cause? This is significant: both models have different implications for sediment dispersal in esker sedimentary systems.*

Key quotes

- *"There is a very strong worldwide correlation between the exponential bed concavity coefficient,* e, *for a wide range of subaerial mobile bed aqueous flows and the stream length…that is complementary to the corresponding correlation for the exponential particle size diminution coefficient, α (Morris and Williams, 1999). A similar, very strong correlation between* e *and α has also been shown to exist. All three correlations extend over virtually the whole range of L, stream bed sediment particle sizes, and some other hydraulic parameters and conditions found on Earth. The two new correlations tend to confirm the earlier suggestion (Morris and Williams, 1999) that there are underlying mechanisms (Pizzuto, 1992; Sinha and Parker, 1996; Morris and Williams, 1997b) common to all kinds of mobile bed subaerial aqueous flows with exponential profiles and particle size diminution."*

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Mosig, R.W. 1980. Morphology of indicator minerals as a guide to proximity of source *in* Glover, J.E. and Groves, D.I. (eds), Kimberlites and Diamonds, p. 81–88.

Synopsis*. Study of indicator-mineral morphology in Australian streams downflow of known kimberlites. Conclusions summarized in table below.*

Exploration significance*. If the results presented here are representative, kimberlite indicator minerals may experience considerable abrasion in streams in the classic equaorial diamondiferous settings. However, these insights do not appear transposable to glaciated settings, where kimberlite indicator minerals tend to show little wear, irrespective of transport distance (e.g., Averill, 2001).*

Key quotes

- *"Judged by their resistance to abrasion and decomposition when they are subjected to stream transportation, the main kimberlitic indicator minerals are distributed in the following order: chrome diopside, pyrope, picroilmenite. Chrome diopside has the lowest resistance, being worn down and decomposed [to a size less than 0.4 mm] over the initial few kilometres from the source"*
- *"A comprehensive grain-by-grain examination of the heavy mineral content is generally carried out on the minus 14 plus 40 B.S. mesh range (~ 1.2 to 0.4 mm). This size range is considered to be the most suitable in which to search for indicator minerals, and for morphological determinations."*

	Distance from source	
	< 4 km	> 4 km
Phlogopite	Grains become bleached with increasing travel	Absent
Chrome diopside	Grains lose green colour intensity with increasing travel. Grains rapidly become finer with travel and decompose.	Generally absent
Composite grains	Grains usually found only close by kimberlite	Absent
Picroilmenite	Grains lose leucoxene rims with travel	Grains become worn
Pyrope	Kelyphite removed with increasing travel	Frosted surface to grains
Zircon	Often frosted and weakly pitted	Worn, rounded edges
Olivine	Grains rapidly decomposed to nontronite clay. Rarely found unaltered.	Absent

Observed sand-sized indicator properties in Australia as a function of distance from source

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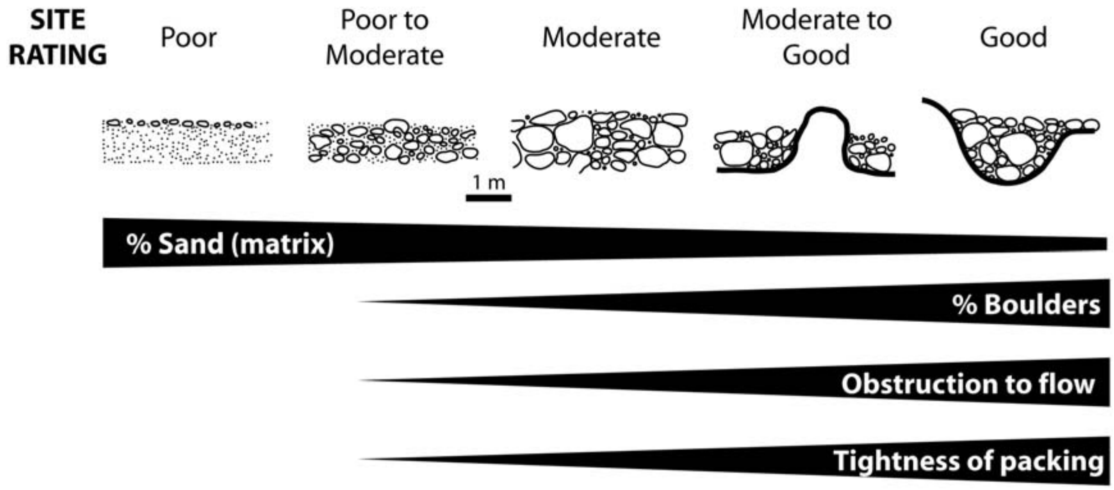
Muggeridge, M.T. 1989. The efficiency of fluvial trap sites in concentrating kimberlitic indicator minerals: an experimental sampling survey *in* O'Reilly, S.Y. (ed.), Kimberlites and Related Rocks: Their Mantle/Crustal Setting, Diamonds and Diamond Exploration. Proceedings of the 4th International Kimberlite Conference, Perth, Australia. GSA Special Publication Number 14, p. 1154–1168.

Synopsis*. Sampling study in Smoke Creek 15 km downflow of Devil's Elbow kimberlite in the Kimberley Region of Western Australia. Samples collected from a variety of trap sites, each no more than 200 m apart. Concludes that indicator minerals are preferentially concentrated in gravelly fluvial facies.*

Exploration significance*. Do indicator minerals in eskers tend to concentrate in gravelly facies, as they seem to do in this fluvial system?*

Key quotes

- *"For a river bed site to have good potential for concentrating kimberlitic minerals the* in situ *gravel should be clast supported, poorly sorted and tightly packed."*
- *"The results indicate the deepest part of the main, active flow channel is an important horizon for concentration of kimberlitic minerals whilst flood level areas seem least favourable."*



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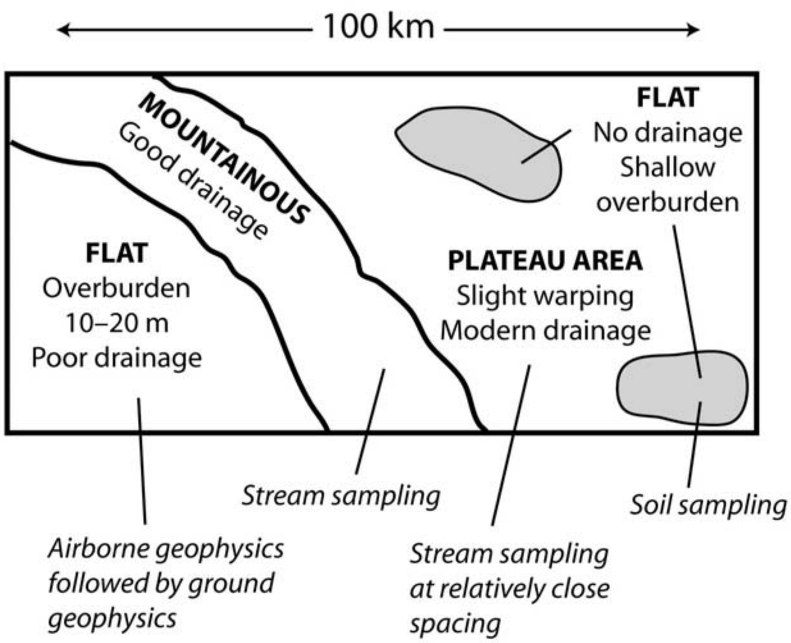
Muggeridge, M.T. 1995. Pathfinder sampling techniques for location primary sources of diamond: Recovery of indicator minerals, diamonds, and geochemical signatures. Journal of Geochemical Exploration, v. 53, p. 183–204.

Synopsis. *Review of stream sampling techniques used during diamond exploration. Concludes that gravel should be targeted, not sand.*

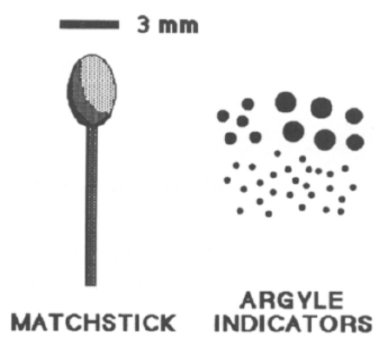
Exploration significance. *Similar techniques are generally used when sampling eskers.*

Key quotes

- *"Prior to 1970 De Beers' regional exploration programmes in southern Africa covered huge tracts of country…on a grid basis by loam and stream sampling"*
- *"Detectable geochemical halos around kimberlitic intrusions are very small in extent due to the extremely limited influence of material derived from these diminutive sources on their host environments. Detectable limits of mineralogical halos around kimberlitic bodies are generally considerably broader, governed by the fact that indicator mineral grains can be individually recognisable and significant.""*
- *Kimberlitic fragments "…seldom exceed 2 mm in diameter, and, in many environments, the are predominantly less than 0.5 mm"*
- *"Diamonds themselves, being the hardest known natural substance, survive erosion and transportation well, and can be misleading if found alone (without indicators)…as they can travel great distances from their source."*
- *"The search must be aimed at recovering the smallest clue—a single indicator grain!"*
- *"In low relief areas with poor drainage, sampling rivers alone is insufficient to test for the presence of diamonds, and other methods must additionally be employed…"*
- *"Point bars…are not recommended for indicator mineral exploration…"*



Examples of terrain types and exploration strategies in non-glaciated settings



Size and number of indicator grains that lead to the discovery of the Argyle mine, Australia

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Newitt, D.M., Richardson, J.F., Abbott, M., and Turtle, R.B. 1955. Hydraulic conveying of solids in horizontal pipes. Transactions of the Institution of Chemical Engineers, v. 33, p. 93–110

***Synopsis**. Theoretical equations are derived to express the head loss along a pipe in terms of the mean velocity of flow, concentration size and density of the solids, and the pipe diameter for the various types of flow encountered in hydraulic conveying. Experiments with a variety of materials in a 1 in. pipe are described, and the data obtained are correlated by the theoretical equations. These equations are compared with existing empirical correlations.*

***Exploration Significance**. Provides an improved context for understanding the transport of sediment within an R-channel.*

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Nixon, P.H. 1980. Regional diamond exploration—theory and practice *in* Glover, J.E. and Groves, D.I. (eds), Kimberlites and Diamonds, p. 64–75.

Synopsis. *Review of diamond exploration strategies in non-glaciated terrain.*

Exploration significance. *One interesting suggestion that Nixon makes is that there are typically more kimberlite indicator minerals in the > 0.5 mm fraction than in the "finer fraction". Is this true for glaciated settings? (D. Cummings note: This is contrary to some information we have received from industry explorationists, who suggest that there tend to be more indicator minerals in finer sand fractions. Ward et al. (1997) also report this.)*

Key quotes & observations

- *"The ratio of positive indicator minerals found in the two size fractions [>0.5 mm and a "fine fraction"] was 5 in the coarse fraction, and 1 in the fine fraction. Considering the longer time necessary to examine the fine fractions, it is debatable whether these are worth collecting"*
- *Indicator minerals persist several miles downstream, even below a small dyke, with the ilmenite/garnet ratio usually increasing.*

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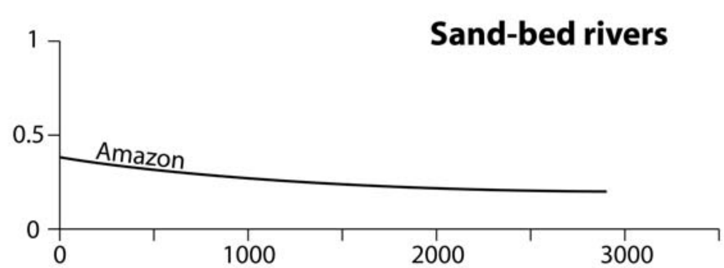
Nordin, C.F. Jr, Meade, R.H., Curtis, W.F., Boslo, N.J. and Landim, P.M.B. 1980. Size distribution of Amazon River bed sediment. Nature, v. 286, p. 52–53.

Synopsis. *Study of bed material from the Amazon River. Concludes that there is a remarkably constant grain size over much of the river's 3000 km course—the bed material consists predominantly of fine sand from start to finish.*

Exploration significance. *Addresses the perplexing question of whether eskers necessarily fine downstream with a fluvial example that does not.*

A key idea

- *Cross-channel variation in particle size at cross-sections was at least as great as downstream encountered along the entire 3,300-km reach.*



Average grain-size of bed material, Amazon River (noise filtered out). The data show a very subtle downstream fining trend over 3000 km, but only if effects of local hydraulic sorting (e.g., sorting on the outsides of bends) are weeded out. If all samples are included, data shows basically no downstream fining trend. This is at odds with other major sand-bed rivers, such as the Ganges and Mississippi, which display subtle but recognizable downstream fining trends.

========

Paola, C., 1983. Origin of the middle Mause Esker, Perthshire, MSc. Thesis, University of Reading, 107 p.

***Synopsis**. Laboratory simulation using a half-round pipe mounted in a flume indicates that such a ridge is not stable if the pipe edges are closed but is stable if the edges are open, permitting flow out the side of the pipe. Experimentation with a tunnel at the base of a plaster block suggests that flow over the edges of a subglacial tunnel may initiate development of meanders.*

***Exploration Significance**. Provides experimental evidence to support the potential of subglacial flow expansion lateral to semicircular R-channel conduits. The implication is that some flanking esker ridge deposits may be deposited subglacially, not necessarily proglacially.*

Key quotes (paraphrased)

- *The esker contains no faults and must have been deposited as a free-standing ridge*
- *Many features of the Middle Mause esker are understandable in terms of a model in periodic outflow results from hydrostatic lifting of the ice.*

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Parent, M., Beaumier, M., Girard, R., Paradis, S. J. 2004. Diamond exploration in the Archean craton of northern Quebec Kimberlite indicator minerals in eskers of the Saindon-Cambrien corridor. Géologie Québec, MB 2004-02, 16 p.

***Synopsis**. A regional diamond-exploration study using eskers. Outliers of the Sakami Formation exposed near the former ice divide in Labrador contain very distinctive red sandstones and orange quartzites, such that their distribution in glacial and fluvioglacial sediments in the area provides a unique opportunity to identify and characterize drift dispersal patterns. Two-hundred and twelve samples were collected during the survey, which was conducted in the Saindon–Cambrien corridor. Most of the samples (204) were collected in cobbly and pebbly esker facies in order to take advantage of "the hydraulic sorting effects in fluvioglacial tunnels". Indicator minerals recognized are distributed along two nearly perpendicular corridors that intersect in the eastern part of the study area*

***Exploration Significance**. One of only a few (the only?) published reports of a regional esker-based sampling program.*

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Parker, G. 2008. Transport of gravel in sediment mixtures *in* Garcia, M.H. (ed.), Sedimentation Engineering: Processes, Measurements, Models, and Practice. American Society of Civil Engineers, New York, p. 165–251.

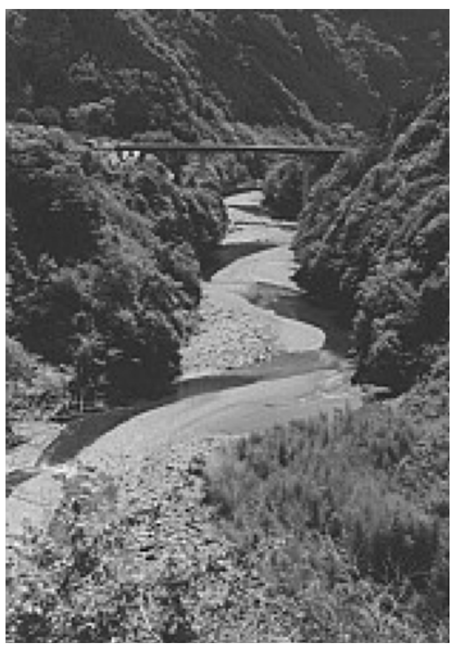
***Synopsis**. A comprehensive review of sediment transport in gravel-bed streams.*

***Exploration significance**. Most ideas in this chapter represent testable hypotheses of how sediment is dispersed in esker sedimentary systems.*

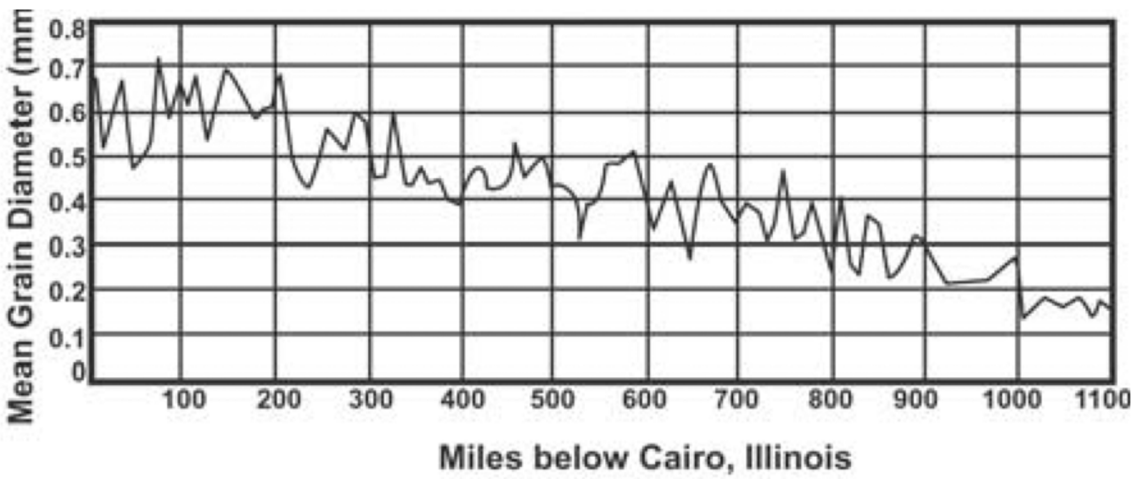
Key quotes

- *"Sorting appears at the largest scale in terms of the tendency for characteristic grain sizes to become finer over 10's to 100's of km"*
- *"Most sediment sorting in rivers is accomplished by the differential transport of different sizes. In the case of heavy minerals (placers) however, increased specific gravity replaces the role of increased size." p. 6*
- *"In addition to selective transport, however, rivers have the opportunity to create finer grains from coarser grains. This is sometimes accomplished by shattering of grains, but is more commonly associated with a*

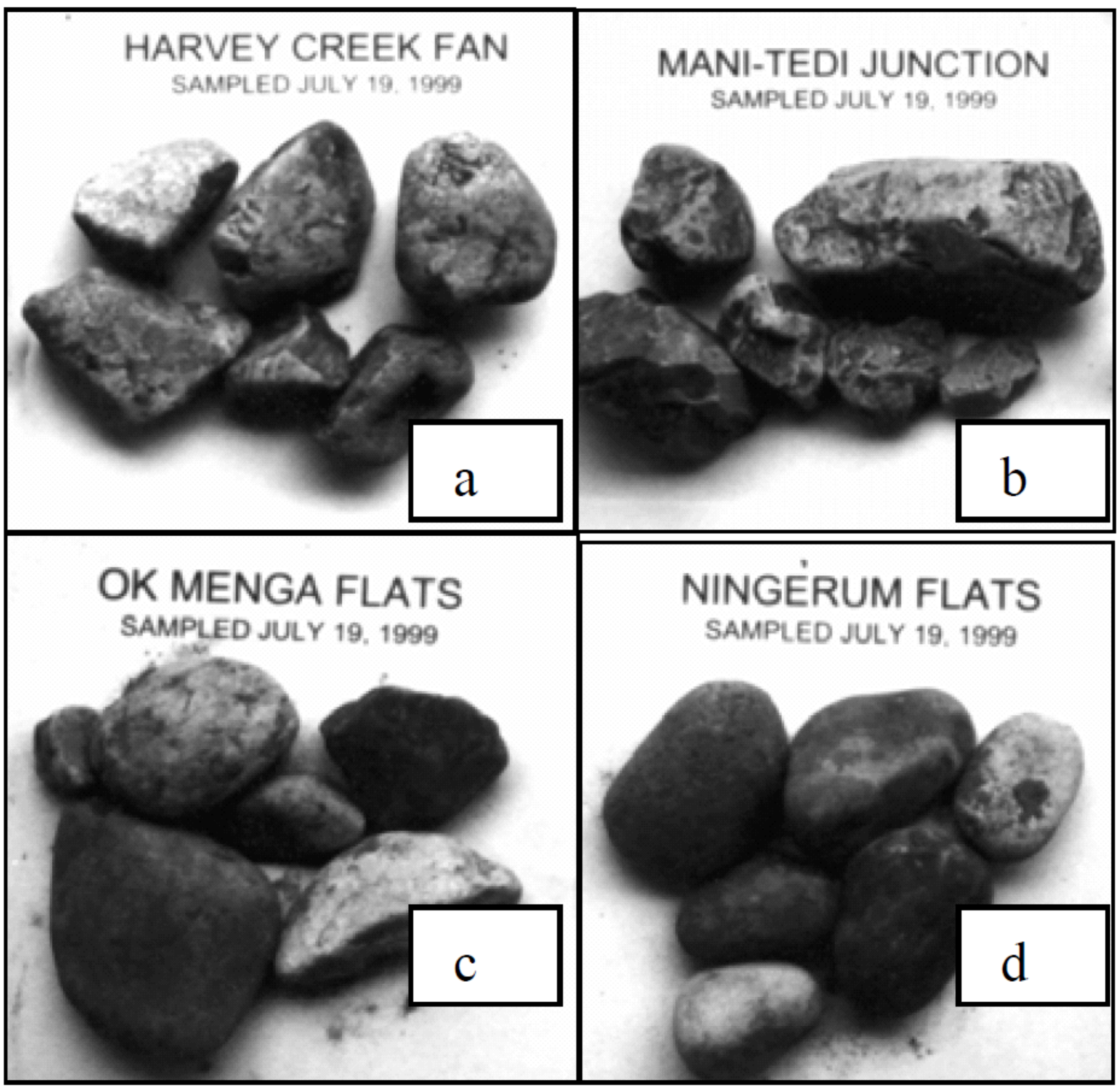
- *"The installation of a dam on a river typically blocks the downstream delivery of all but the finest sediment, creating a pattern of bed aggradation upstream. The dam raises base level, i.e. the downstream water surface elevation to which the river upstream must adjust, forcing upstream-migrating deposition. This deposition is most intense near the delta at the upstream end of the reservoir. As a result, the effect is to intensify the upward concavity of the long profile of the bed upstream of the dam. The more sharply declining bed slope intensifies selective transport of fine material, setting up strong local downstream fining." p. 7*
- *"…bank-full flows in gravel-bed rivers often correspond to conditions that are not greatly higher than that needed to mobilize gravel." p. 9*
- *"Gravel-bed rivers undergoing downstream fining often but not always end in a rather abrupt transition to a sand-bed reach over a few km."*
- *"Rivers that are constrained from meandering or braiding by artificial, inerodible banks often develop a pattern of alternate bars instead." p. 106*
- *In comparison to gravel-bed streams, "…sand bed streams tend to a) be suspension-dominated and b) contain sediment that is much more uniform than gravel-bed streams...Sorting of suspended sediment arises from a rather different mechanism than that applying to bed-load. In turbulent suspensions of sediment, the finer particles tend to ride higher in the water column. This biases them toward a zone of higher velocity, and amplifies their downstream transport rate at the expense of the coarser grains. For the same reason finer particles are more likely to be carried overbank and deposited on the floodplain." p. 108–109*
- *"As noted above, sand and silt often move through a gravel-bed river as throughput load during floods, with little interplay with the beds beyond partial filling of the interstices of newly-deposited gravels. When the concentrations of these "fines" are too high, or when the flow velocities are too low to prevent excess accumulation of within the gravel framework, the gravels can become polluted with fines. This fines pollution degrades the gravel bed as both spawning grounds and habitat for anadromous fish. The discharge of relatively sediment-free flushing flows, often from an upstream reservoir, can at least partially remove the fines and renew the gravel." p. 121*
- *"Hassan et al. (1992), for example, found that the [average distance moved by tracers] tends to decrease only weakly with increasing grain size D_i for the finer sizes in a mix, but declines notably with increasing grain size for the sufficiently coarse grains." p. 122*



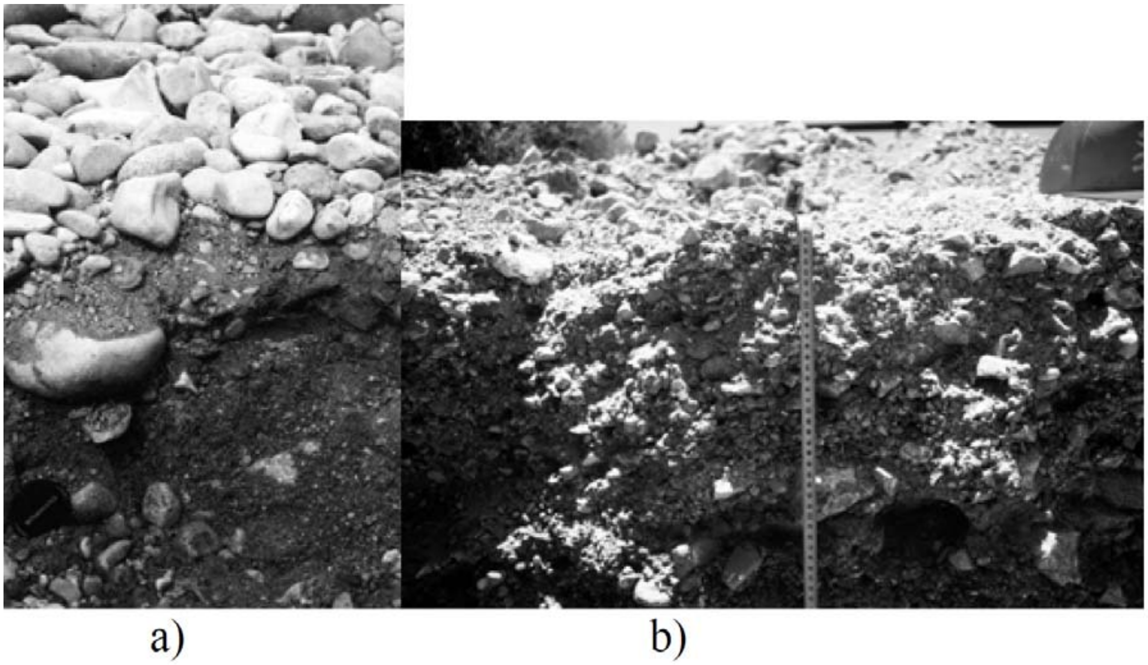
An example of intermediate-scale sediment sorting in a stream—a downstream view of the Ooi River, Japan, showing gravel and sand sorting on the bars. Barforms in rivers commonly have coarse heads and finer tails. This can lead to preferential indicator mineral concentration.



Downstream fining in a suspension-dominated, sand-bed river (Mississippi River)



Pebbles in the Ok Tedi River, Papua New Guinea, collected downstream of the Ok Tedi mine. (A) 1 km downstream, (B), 8 km downstream, (C) 27 km downstream, (D) 90 km downstream. The effects of abrasion here are obvious—note that grains become progressively rounder in a downstream direction.



Contrasts in surface armouring between (a) a perennial stream with low sediment supply (River Wharf, UK), and (b) an ephemeral stream with a high sediment supply (Nahal Yatir, Isreal). Which of these end-member examples do esker systems most closely resemble? From Powell (1998), as reference in Parker (2008).

Selective sorting of pebbles on sandy dunes. Heavy minerals show similar tendencies—they commonly preferentially accumulate in dune toesets.

========

Pertunnen, M. 1989. Transportation of garnets in glaciofluvial deposits in southeastern Finland *in* Dilabio, R.N.W. and Coker, W.B. (eds.), Drift Prospecting, Geological Survey of Canada, Paper 89-20, p. 13–20.

***Synopsis**. Study of heavy minerals in several Finnish eskers. Samples were collected from the cores of the eskers, avoiding slopes where shore accumulations commonly occur. Samples were collected from the upper or basal portion of the gravel pits above ground-water level. The material collected varies in grain size. The "coarse material" discussed in this paper consists predominantly of cobbles, pebbles and gravel, but the "fine material" contains a certain amount of gravel and/or sand. The highest garnet values were found within 8 km of the source area. The garnets can be traced over a distance of 100 km.*

***Exploration Significance**. Garnets in the esker dispersal trains that were studied drop to background abundances at distances of ~ 40 km from source. Low abundance may also occur close to garnet source; consequently, individual garnet abundances are ambiguous.*

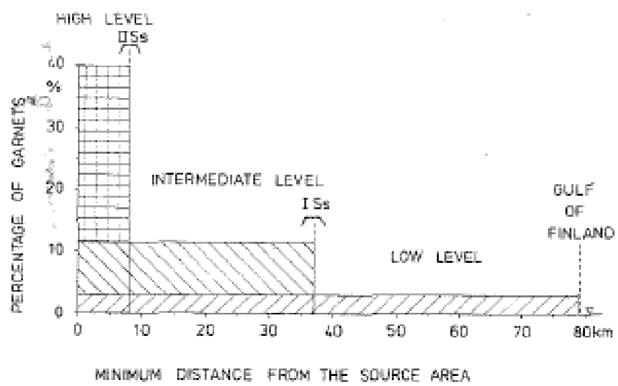
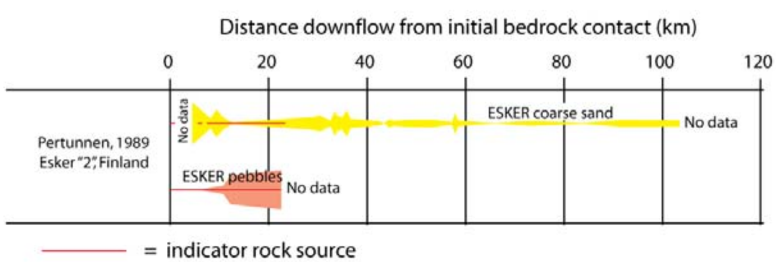


Figure 11. Simplified model of the transport and deposition of garnets from the source area, based on the diagram in Fig. 10.

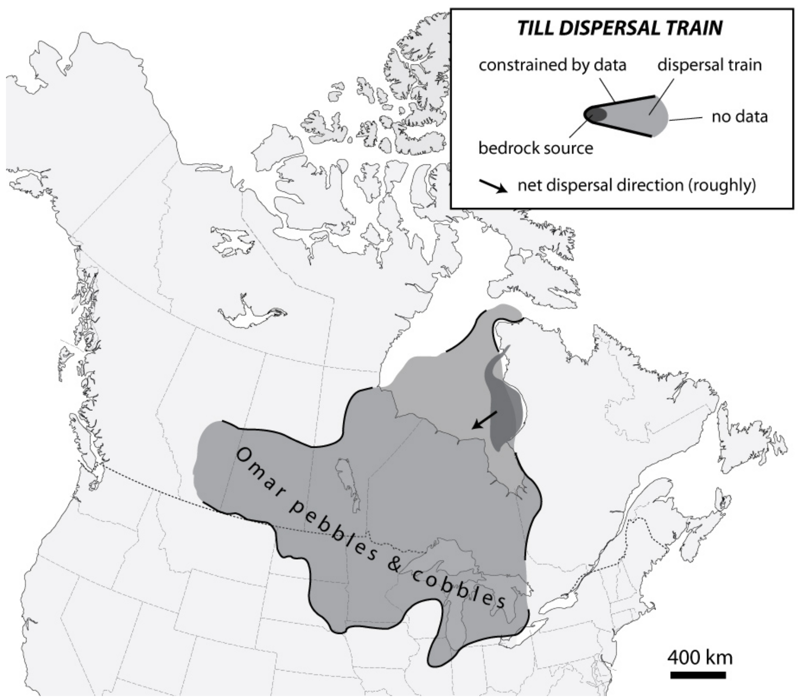


Dispersal data from "esker 2", Finland. Although this might appear to indicate long-distance eskerine dispersal, in fact no data are provided to deconvolve eskerine from glacial (till) dispersal (the long esker dispersal train might simply be sourced from a long till dispersal train).

Prest, V.K., Donaldson, J.A. and Mooers, H.D. 2000. The omar story: the role of omars in assessing glacial history of west-central North America. Geographie physique et Quaternaire, v. 54(3), p. 257–270.

***Synopsis**. Study of distinctive erratic rock fragments from the Omarolluk Formation of the Belcher Islands of eastern Hudson Bay. Concludes they have been dispersed hundreds of kilometres northwestward, westward and southward for hundreds of kilometres across Hudson Bay, western Canada, Northern Ontario, and several adjoining northern States.*

***Exploration significance**. Till dispersal trains can be huge and dilute. Esker dispersal trains sourced from till dispersal trains can therefore be correspondingly huge and dilute. These huge dispersal trains (till or esker) may be unrecognizable based on data obtained from a small property. Isolated gravel or sand indicator grains (e.g., isolated diamonds) in the data must be treated with scepticism: they may have been displaced hundreds of kilometres from their bedrock source.*



The Omar glacial dispersal train and its bedrock source.

========

Punkari, M. 1997. Subglacial processes of the Scandinavian Ice Sheet in Fennoscandia inferred from flow-parallel features and lithostratigraphy. Sedimentary Geology, v. 111, p. 263–283.

***Synopsis**. A lithostratigraphic study of esker in Fennoscandinavia. Concludes that "Esker pattern suggests that upglacier parts of eskers were deposited far (> 100 km) from ice margins following collapses of most tunnel systems. Such esker cores are in places covered by subglacial till. Probably even extensive glaciofluvial beds were deposited subglacially during deglaciation.".*

***Exploration Significance**. Provides a regional interpretation of the deglaciation of Fennoscandinavia. In particular, Punkari argues that the esker-depositing subglacial streams* *were long (>100 km), which would have obvious implications for sediment dispersal (long subglacial streams means long dispersal is possible). Is a similar esker depositional model applicable to the deglaciation of parts of North America?*

Key quotes

- *"Excess water may have formed a linked cavity system, later channelized to a tunnel network…Meltwater was probably collected by sheet flow at the interface and by groundwater flow into a drainage network, including N-channels feeding central R-channels…R-channels may have been able to reach the ice margin, where most glaciofluvial deposition occurred."*

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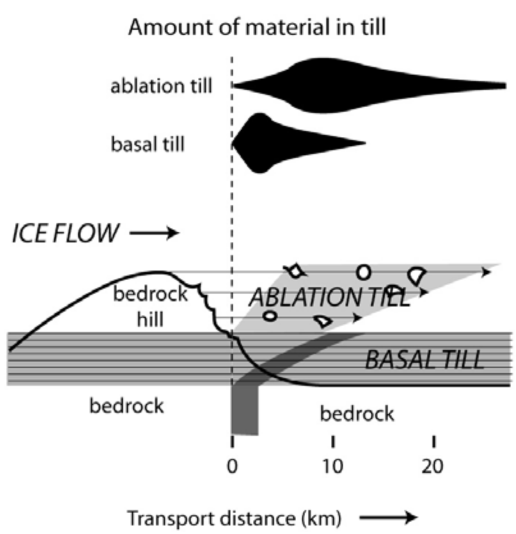
Puranen, R. 1990. Modelling of glacial transport of tills *in* Kujansuu, R. and Saarnisto, M. (eds.), Glacial Indicator Tracing, Balkema, Rotterdam, p. 15–34.

Synopsis. *Conceptual model of the development of glacial (till) dispersal trains. Presents a geological model for improved understanding of the likely extent of geochemical or lithological anomalies from eroded bedrock. Focus is on dispersal in till with a secondary element of the paper on boulder trains in ablation till*.

Exploration significance. *Most boulders in till in Finland appear to be locally sourced; less than 20% are displaced farther than 6 km from their bedrock source. If numerous boulders of ore are found in an esker, and if one assumes they were not dispersed far in the esker-depositing stream, the bedrock source may be close by (especially if the boulders are large and difficult to transport).*

Key quotes

- *"In glaciology, physical models have been presented both for growth of large ice sheets (dimension > 1000 krn), and for erosion caused by small grains (dimension < 1 m). Models with intermediate dimensions of about 10 km have not been presented, as pointed out by geologists in their inspiring dialogue with glaciologists (Hallet, 1981). Since the following model has a horizontal dimension of about 10 km, a geologically reasonable 1 % resolution is obtained with the model even if the distance steps are raised to 100 m."*
- *Boulder trains: "Tills contain on the average less than 10 wt % stone and boulder fraction with a clast size exceeding 2 cm in diameter (Soveri, 1964). The number of boulders (diameter over 20 cm) is thus low, which makes it difficult to establish their distribution within basal tills."*
- *"Rough estimates can, however, be made on the basis of the numerous observations compiled by Salonen (1986). Thus, about 50% of the boulders in a typical till cover derive from a distance of less than 3 km, 30% have travelled 3-6 krn and 20% more than 6 km."*



Conceptual model of boulder dispersal downflow of a hill.

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Rampton, V.N. 2000. Large-scale effects of subglacial meltwater flow in the southern Slave Province, Northwest Territories, Canada. Canadian Journal of Earth Sciences, v. 37, p. 81–93.

***Synopsis**. Study of the landscape near Lac de Gras, NWT. Concludes that "Broad corridors in the southern Slave Province of the Northwest Territories are marked by meltwater-scoured bedrock, irregular and transverse gravel ridges, gravel bars, crag and tail features (tails formed of gravel), drumlins, boulder lags, potholes, plunge pools, meltwater-sculpted slopes (in some cases defining till plateaus), and eskers. Most of the above features can either be attributed to the subglacial erosion of till by high-velocity, turbulent meltwater under high pressures and (or) meltwater transport and deposition of the eroded material… Features and deposits owing their origin to subglacial meltwater can lead to complex dispersal patterns of minerals and metals contained within both till and glaciofluvial deposits."*

***Exploration Significance**. This paper makes a compelling argument for the need for increased recognition of the role of subglacial meltwater processes in eroding and distributing sediment and indicator minerals and the need for increased consideration of these processes in drift exploration. One key question that arises is whether the mineralogical content and geochemistry of near-surface till in areas affected by subglacial meltwater erosion and in adjacent areas unaffected by meltwater can differ.*

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Reesink, A.J.H. and Bridge, J.S. 2007. Influence of superimposed bedforms and flow unsteadiness on formation of cross strata in dunes and unit bars. Sedimentary Geology, v. 202, p. 281–296.

***Synopsis**. Review of superimposed (composite) bedforms and the strata they generate. Concludes that the "Formation of angle-of-repose cross strata on the lee side of dunes and unit bars is dependent on three main grain-sorting mechanisms: (1) presorting of sediment that arrives at the lee side of the bedform, related to superimposed bedforms and longerterm variations in water flow and sediment transport; (2) sorting due to differential deposition of sediment on the lee side and associated grain flows, and; (3) movement of sediment on the lee side by the water currents in the lee side flow-separation zone. Although most emphasis has been put on mechanism (2), recent field and experimental studies of the dynamics of sandy and gravelly dunes and unit bars show that mechanism (1) is at least as important."*

***Exploration Significance**. Heavy mineral concentration is known to be affected by fluvial bedforms. Mechanims of sediment transport and bedform development and cross-strata preservation are pertinent to the interpretation of potential variation in heavy mineral results and improved targeting of sample locations.*

========

Rothlisberger, H. 1972. Water pressure in intra- and subglacial channels. Journal of Glaciology, v. 11(62), p. 177–203.

***Synopsis**. Theoretical paper on water flow through glaciers (and specifically flow in closed conduits under cryostatic pressure). Argues that the equilibrium size of subglacial conduits will reflect a balance between ice inflow, which works to close the conduit, and melting from heat generated by viscous dissipation of the turbulent water, which works to enlarge the conduit. Concludes that pressure in the conduits decreases with increasing discharge, which means that subglacial water must flow into the largest conduits (see Boulton et al., 2007a for a documentation of this in the field).*

***Exploration Significance**. Glacier ice and subglacial water should flow into subglacial stream conduits. These processes may feed sediment into esker sedimentary systems.*

Key quotes

- *"Water flowing in tubular channels inside a glacier produces frictional heat, which causes melting of the ice walls. However the channels also have a tendency to close under the overburden pressure."*
- *"It is shown that pressure decreases with increasing discharge, which proves that water must flow in main arteries"*
- *"In a typical temperate valley glacier a main stream emerges at the lowest point o the terminus, and there is little doubt that it extends backwards for at least some distance under the glacier. From the fact that the water carries a fair amount of sediment, it can be further inferred that the stream is located at the glacier bed."*

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Rubey, W. W. 1933a. The size distribution of heavy minerals within a water-laid sandstone. Journal of Sedimentary Petrology, v.3, p. 3–29.

***Synopsis**. Concludes that "Factors such as differences in the density and hardness of the various minerals, differences in the original size of the various mineral grains in the source rock, the amount of abrasion that all grains have undergone during transportation, the different settling velocities of the various grains at the site of deposition, and the degree of sorting to which all grains were subjected there-all these factors seem competent to cause large variations in the relative abundance of various minerals in different samples of deposits that have been derived from exactly the same source rock and also in different size fractions of each of the samples."*

***Exploration Significance**. Highlights the role of sedimentary transport and depositional processes in the preferential concentration of heavy minerals. Defines the term settling equivalence. Notes that the ratio of heavy minerals in a concentrate will vary with grain size.*

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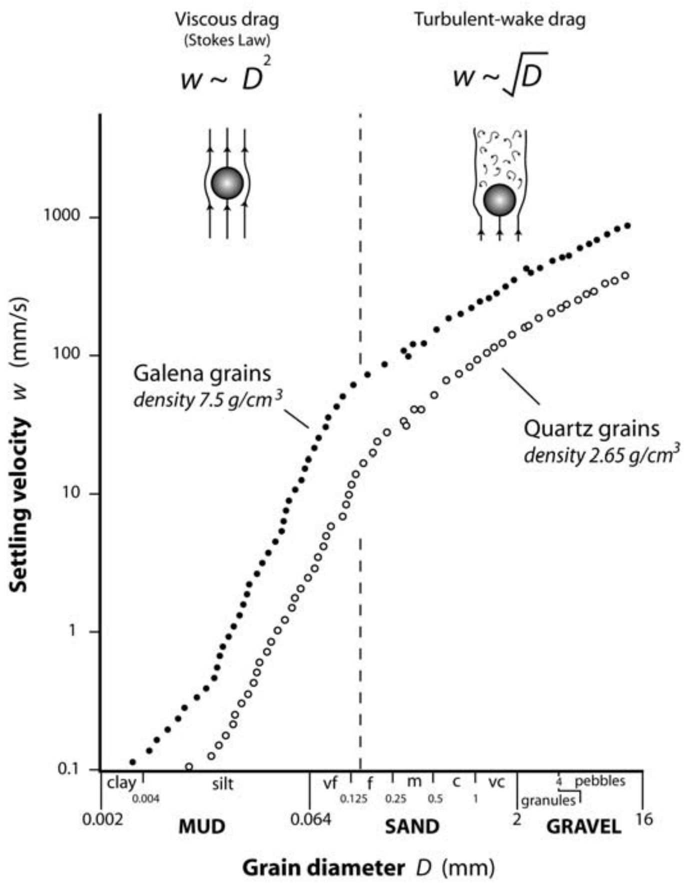
Rubey, W.W. 1933b. Settling velocities of gravel, sand and silt particles. American Journal of Science, v. 225, p. 325–338.

***Synopsis**. An experimental study of the settling velocities of different-sized quartz and galena grains through water. Concludes that larger grains settle faster than smaller ones, and that denser grains settle faster than lighter ones.*

***Exploration Significance**. Smaller, lighter grains will travel farther in streams than larger, denser ones. This leads to the downflow partitioning of grains based on size and density—for example, it is the reason why deltas pass from sand onshore to mud in deeper water. Dispersal trains in eskers should likewise fine downflow. All other things equal, the denser the indicator mineral, the shorter its dispersal train.*



Experimentally determined settling velocities through water for quartz and galena grains. Each point represents the average of a large number of experimental runs. Note that galena in the medium to very coarse sand fraction—the most commonly analyzed heavy mineral fraction for diamond exploration—settles at the same speed as granules and small pebbles. Because of their high density, kimberlite indicator minerals (3.3–4.7 g/cm^3) and gold grains (19.3 g/cm^3) will also settle faster than quartz particles of the same size, at rates that are respectively slower (KIMs) and faster (gold) than galena. Note, however, that pristine gold grains are typically flat and silt sized; they may therefore be prone to travelling in suspension rather than as bedload, despite their ultra-high density (Stu Averill, personal communication, 2010).

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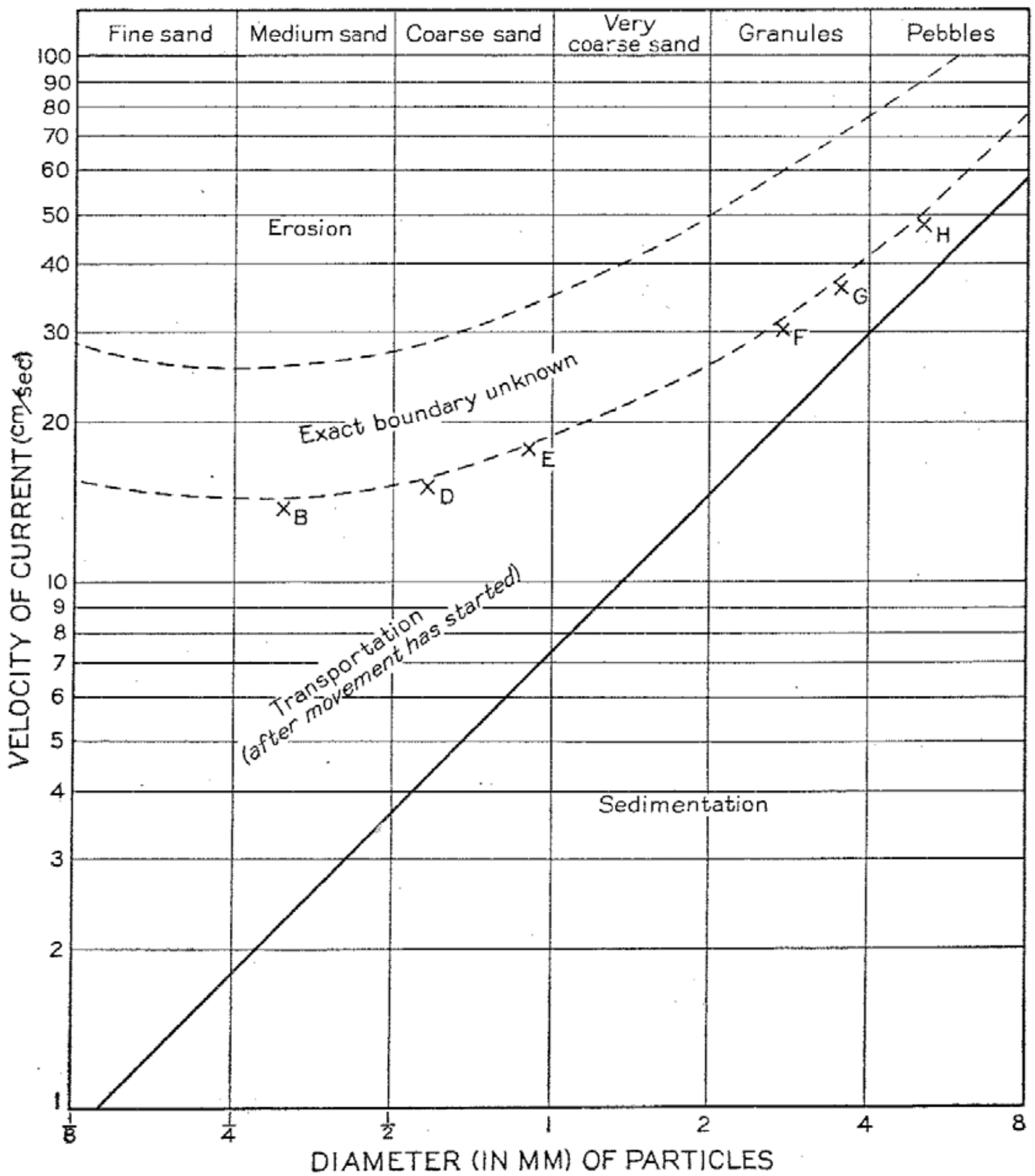
Rubey, W. W. 1938. The force required to move particles on a stream bed. United States Geological Survey, Professional Paper 189-E, p. 121–141.

Synopsis. *Reviews a number of concepts considered responsible for the entrainment of particles by a flow. A good review of process seen as responsible for entrainment at the time of the article and still applicable to an understanding of sediment transport today. The study emphasizes the role of "bed" velocity, as opposed to mean stream velocity, in governing the entrainment of sediment from a stationary bed.*

Exploration significance*. Larger grains are easier to entrain than smaller ones. This, among other things, leads to downstream fining. However, this trend reverses itself for cohesive sediments, which are harder to entrain.*

Key quotes

- *"…the "bed" velocity increases with an increase of mean velocity, hydraulic radius, and slope and with a decrease of the roughness ratio (increase of channel smoothness). The relationship is such that the "bed" velocity is most sensitive to changes of the mean velocity and only very slightly sensitive to changes of the roughness ratio."*
- *"For laboratory streams flowing over transportable debris, it was found that approximately 2.5 percent of the total energy of the stream was spent in transportation. For a few natural streams on which the necessary data were available, the proportion was about 4 percent."*
- *"If the average settling velocity of debris transported should remain the same, then the weight of debris per unit width of stream carried past a given point would vary roughly as the fourth power of the "bed" velocity."*



A portion of Hjulstrom's diagram with Gilbert's experimentally determined entrainment data for various sediment sizes (B to H) plotted over top (from Rubey, 1938).

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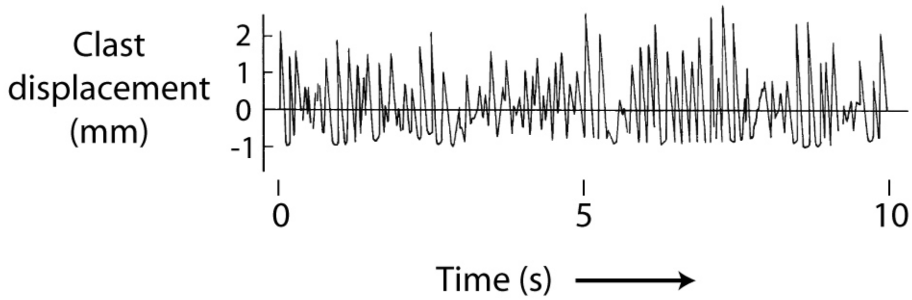
Schumm, S.A. and Stevens, M.A. 1973. Abrasion in place: A mechanism for rounding and size reduction of coarse sediments in rivers. Geology, v. 1(1), p. 37–40.

***Synopsis**. Suggests that in-place vibration of gravel clasts can cause significant rounding, and that this can account from discrepancy between "downstream fining" rates observed in lab experiments and real streams.*

***Exploration significance**. Esker gravel tends to be rounded (even friable lithologies like shale tend to be rounded). If in-place rounding is in part responsible for this—which is debatable—gravel rounding may be poorly correlated to transport distance.*



Vertical motion of a cobble over 10 seconds in water flowing at 2 m/s. These vibrations, which are common near the threshold for gravel motion (e.g., Frostick et al., 2006), may cause in-place rounding. (<u>Aside:</u> They may also lead to infiltration of sand into gravel pore spaces. See Frostick et al., 2006.)

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Shilts, W.W. 1973. Drift prospecting; geochemistry of eskers and till in permanently frozen terrain: District of Keewatin, Northwest Territories. Geological Survey of Canada, Paper 72-45, 34 p.

***Synopsis**. A classic esker – till study from the eastern part of the Keewatin. A number of points regarding both geochemical and heavy mineral sampling are derived from the study results, particularly pertaining to mud boils, wave washing, and esker spacing. Concludes that gravel is similar to that in the till, and that these clasts were derived from bedrock up to 100 km up-glacier. Suggests that eskers formed in segments, and that segments are 5 miles long.*

***Exploration significance**. If the eskers formed in five-mile-long segments, as Shilts suggests, dispersal trains within them should extend no more than 5 miles downflow of the end of the till dispersal trains from which they were sourced. This should apply for clastic indicators of all size (gravel, sand and mud).*

Key quotes

- *"It is concluded that some potentially interested ore minerals (sulphides and carbonates) are removed from the active zone of eskers and till by intense chemical weathering."*
- *heavy mineral percentages (s. g. > 3.3) vary rapidly and rather randomly in the wave-washed upper portions of both eskers*
- *… a significant proportion of the sand and cobble-size fractions of Kaminak Esker samples was not derived from underlying bedrock is apparent from high proportions of specular hematite and red volcanic rock fragments in the samples. These components were transported by the glacier from sources at least 60 miles (100 km) from any portion of the esker.*
- *"Most eskers are probably built in short segments by streams extending a few tens of feet to a few miles back from the ice margin. As the ice margin retreats, the stream segment building the esker retreats, maintaining more or less constant length by extending itself headward."*
- *"In Keewatin, ice marginal retreat is thought to have taken place largely during the summer (B.C. MacDonald, pers. comm., 1972) so that spacing of identifiable segments can be related to rate of yearly retreat."*

- *"The implication of the segmented sedimentation hypothesis of esker formation is that, unlike normal drainage systems where sediment at any point is partially derived from points upstream to the limits of the drainage basin, sediment at any point in a segmented esker can only be derived from as far as the head of the short stream segment associated with its formation. Thus, although an esker may be traceable as a continuous ridge from 100 miles, if it is composed of sedimentation segments that average only five miles in length, five miles is the maximum distance of transport that may be expected."*
- *Despite the strong assertions made above, results are inconclusive with respect to how the two eskers formed.*

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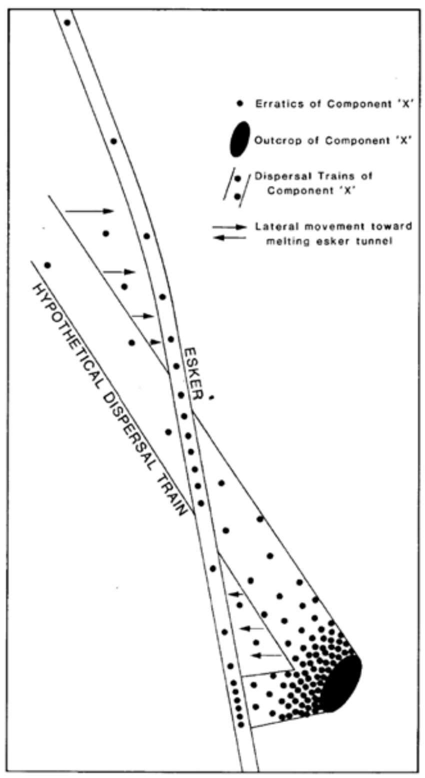
Shilts, W.W. 1984. Esker sedimentation models, Deep Rose Lake map area, district of Keewatin. Current Research, Part B, Geological Survey of Canada, Paper 84-1B, p. 217–222.

***Synopsis**. This paper constitutes an important contribution to the philosophical debate of how eskers may disperse sediments, and especially eskers in the Northwest Territories and Nunavut, the areas where Shilts worked. As the author acknowledges, this is a conceptual paper. It contains ideas, but no dispersal data to back them.*

***Exploration Significance**. An important paper for Keewatin esker studies as it raises a number of hypothesis on how eskers may have been deposited and some controls on esker geometry. One of the classic sites from the 1980's work on the Keewatin eskers by Aylsworth and Shilts.*



Conceptual model of esker indicator dispersal

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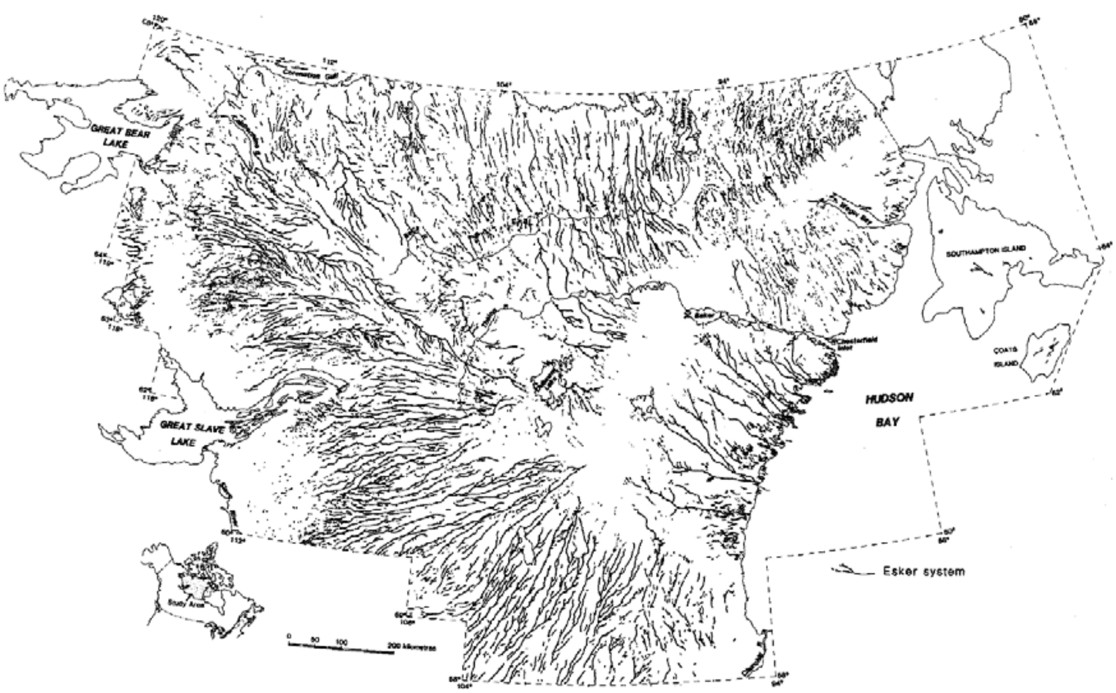
Shilts, W. W., Aylsworth, J. M., Kaszycki, C. A., and Klassen, R. A., 1987, Canadian Shield, in Graf, W. L., ed., Geomorphic systems of North America: Boulder, Colorado, Geological Society of America, Centennial Special Volume 2. p. 119-150.

__Synopsis__. An essential paper on the glacial geology of the Canadian Shield and the esker networks. Shilts and Aylsworth discuss Keewatin, Kaszycki central Canada and Klassen the Ungava with an emphasis on the Labrador sector. All of the Keewatin examples discussed in the text are from the Hudson Bay drainage area. The study concludes, among other things, that sediment supply (as opposed to accommodation space) is the main control on the nature and volume of glacial sedimentary cover in North America. In other words, in places where there is little sediment, it is thought that the bedrock yielded little sediment, not because there was little accommodation space for sediment beneath the glacier.

__Exploration significance__. If the analysis by Shilts et al is correct, the differential resistance of bedrock lithologies to subglacial erosion by ice and meltwater will skew clast assemblages toward the more easily eroded lithologies. Resistant lithologies will be under-represented, and non-resistant lithologies over-represented, in till and eskers.

Key quotes

- *"A typical esker system begins as a series of hummocks or short, flat-topped segments that pass downstream into continuous large eskers joined by areas of outwash or meltwater channels. Along a section measured across [the trend of the eskers]…eskers are spaced approximately 13 km apart, with spacing varying from 2 to 27 km. Throughout most of the area eskers are sharp ridges and up to 40 m high, with occasional conical knobs projecting well above the average elevation of the esker crest. Along their length they may be interrupted periodically by bulges where the single ridge splits into multiple ridges that coalesce downstream."*
- *"North of the Thelon River, eskers are associated with prominent outwash terraces, and the tops of the eskers are in some places flat, planed off by subaerial meltwater flowing on a stagnant ice floor into which the esker ridge was temporarily frozen after the ice front had retreated…"*
- *"Although the number of eskers and their tributaries increase [moving outward from the Keewatin spreading centre], the average size (height and width) of individual eskers decreases…"*
- *"As meltwater streams descended to the base of the ice near the outer margin of an ice sheet, sediment for esker deposition would have been largely limited to debris in the basal ice. Therefore, the size of the esker can be used as a rough indication of the amount of basal debris…The small size of eskers and the paucity of drift cover in Zone 4 indicate that the ice in that area may have been relatively clean. This implies that dispersal trains of sediment from the east had been depleted and little erosion occurred within this zone."*



Distribution of eskers, northwestern Canadian Shield.

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Shreve, R.L. 1972. Movement of water in glaciers. Journal of Glaciology, v. 11(62), p. 205–214.

Synopsis.

Exploration Significance.

Key quotes (paraphrased)

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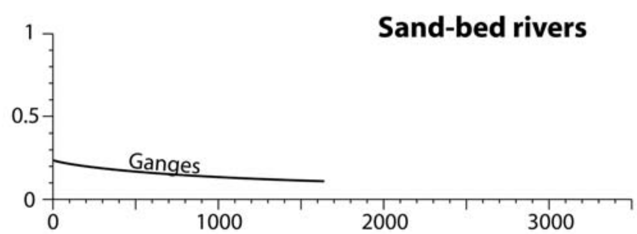
Singh, M., Singh, I.B., Müller, G. 2007. Sediment characteristics and transportation dynamics of the Ganga River. Geomorphology, v. 86, p. 144–175.

Synopsis. *Study of the bed material in a long sand-bed river. Highlights the energy gradient and tributary controls on downstream fining. In addition, it emphasises a two phase model of sediment transport, flood and post flood.*

Exploration Significance. *The downstream fining trend in this sand-bed river is subtle and it occurs over hundreds of kilometers. Downstream fining trends for sand in eskers may therefore be very difficult to detect. Downflow fining of gravel in eskers, by contrast, may be easier to detect, given that downstream fining in gravel-bed streams occurs over the scale of kilometers to tens of kilometers (e.g., Knighton, 1980). Identification of downstream fining trends is important because it may resolve whether eskers form in segments or not (e.g., St. Onge, 1984), which has direct implications on dispersal distance for all grain sizes (gravel, sand and mud) in esker sedimentary systems.*

Key quotes (paraphrased)

- *At the base of the Himalaya, a very sharp gravel–sand transition is present in which median grainsize of bedload sediments decreases from over −0.16 Φ to 2.46 Φ within a distance of 35 km.*
- *Downstream fining is a result of selective transport phenomena rather than of abrasion, the condition attributed to channel competence with low gradient of 70 to 25 cm/km.*
- *… model for sediment transportation dynamics in active channel of the Ganga River during monsoon flow is proposed in which two prominent characteristic flow zones are recognised: peak monsoon flow and post-monsoon flow.*



Downstream fining of bed material, Ganges River (noise filtered out)

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Slingerland, R. and Smith, N.D. 1986. Occurrence and formation of water-laid placers. Annual Review of Earth and Planetary Sciences, v. 14, p. 113–147.

Synopsis. *An excellent review on the fluid mechanics behind placer or heavy mineral concentrations.*

Key quotes

- *"… heavy-mineral segregations in water-laid deposits occur on hierarchically different scales (from millimeters to kilometers)."*
- *"The sorting circuits rely upon different responses of heavy and light grains to local fluid forces acting on a sediment bed."*
- *"Sorting by density may occur during entrainment, transport, settling from suspension, or dispersion by grain-to-grain interactions, and natural heavy-mineral enrichments often involve combinations of these processes."*
- *"Pure settling behavior, embodied in the classical idea of "hydraulic equivalence," probably does not playas important a role in placer origins as is believed by some workers."*

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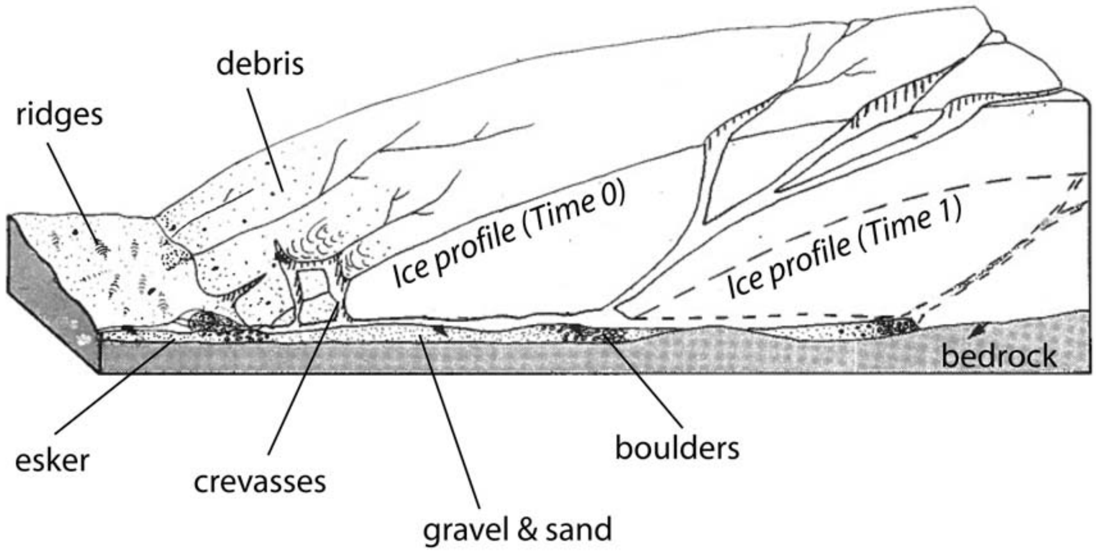
St. Onge, D. 1984. Surficial deposits of the Redrock Lake area, District of Mackenzie *in* Current Research, Part A, Geological Survey of Canada, Paper 84-1A, p. 271–276.

Synopsis. *Field study of eskers and esker corridors (i.e., glaciofluvial corridors). Presents a model for short esker segment development. This paper is one of the early papers recognizing the erosional corridors adjacent to eskers.*

Exploration significance. *If the eskers formed as St. Onge suggests, dispersal of all grain sizes (mud, sand and gravel) should be limited to 1.5–2 km from source (the "source" being the underlying till dispersal train). In other words, dispersal trains in these eskers should not overshoot the underlying till dispersal trains by more than 2 km.*

Key quotes

- *"The melting of glacial ice produced enormous amounts of water that entrained sediments which were redeposited as gravel and sand. These powerful meltwater streams not only deposited sediments, in places they removed all but the largest boulders in their path. Thus corridors were created in which stretches of bare bedrock alternate with ice contact features, which include esker ridges, transverse and circular ridges, and minor morainic ridges."*
- *"Glaciofluvial corridors occur at regular intervals…spacing averages 12–15 km. They represent the formed beds of major meltwater streams which have lost all their tributary streams as a result of the melting of the ice. The frequency of the corridors indicates a high drainage density, and the size of the transported material, commonly 60–80 cm diameter, implies powerful streams."*
- *"Eskers are the most prominent components of glaciofluvial corridors"*
- *"Esker material ranges from coarse sand to boulders 60–80 cm in diameter. Boulders are not distributed randomly through the esker material but form the principal component of short esker segments, averaging 10–30 m in length. These segments of extremely coarse openwork structure…commonly occur at intervals of every 1.5–2 km. It is likely that boulders did not travel far along the esker tunnel; carried by fast moving water flowing down steeply dipping ice tunnels, they were deposited as soon as the gradient flattened, i.e., when the water reached the main tunnel at the base of the ice. Gravel and coarse sand were deposited downstream. This interpretation of grain size distribution implies that, although esker ridges may be continuous for several tens of kilometres, they are in fact constructed of successive, comparatively small segments."*
- *"Flat-topped terraces, commonly fan shaped, occur along the eskers. These outwash terraces were formed when meltwater was no longer confined to an ice tunnel."*



"Short conduit" depositional model for eskers in the Redrock Lake region, east of Great Bear Lake. St. Onge (1984) suggests that the eskers are composed of multiple, short depositional segments, each 1.5–2 km long and defined by a bouldery proximal zone. Down-esker dispersal of both sand and gravel in such an esker would be limited to 1.5–2 km.

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Surian, N. 2002. Downstream variation in grain size along an Alpine river: analysis of controls and processes. Geomorphology, v. 43, p. 137–149.

***Synopsis**. A well documented study using field and aerial photographic documentation of discharge impact on bedforms to channels. Concludes that the main and the secondary channels underwent a high degree of activity (total removal of the painted gravels) during small floods, which are 20–50% of the bankfull discharge, and with recurrence interval lower than one year. Full activity of high bars and islands likely takes place for floods with recurrence intervals of five years or possibly less.*

***Exploration Significance.** Is coarse material in esker sedimentary systems moved at a similar frequency (i.e., every few years)? What about sand-sized indicator minerals? Might they be expected to move more often? Flow magnitude is a critical component of bed mobility in fluvial systems and this is likely the case for eskers also. An important difference in subglacial conduits is the ability (or inability) to maintain conduit full flow conditions over a large range of discharge values.*

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Sutherland, D.G. 1982. The transport and sorting of diamonds by fluvial and marine processes. Economic Geology, v. 77, p. 1613–1620.

***Synopsis**. An interesting review paper that is focused on diamond placers. It comments on the downstream change in diamond size and quality and the spatial extent of diamond placers.*

***Exploration significance**. Diamonds in the earth surface environment are extremely resistant to chemical weathering, physical weathering, and abrasion during transport. As such, they can be dispersed hundreds of kilometers from source and survive for hundreds of* *millions of years. Isolated diamonds in glacial deposits—eskers or otherwise—should therefore be treated with skepticism. They may form part of huge, dilute dispersal trains generated over millions on years and multiple transport events involving both water and glacier ice (e.g., Prest, 2000).*

Key quotes

- *"Consideration, however, of the Zaire-Angola and Sierra Leone examples establishes that diamonds can be widely distributed from relatively limited source areas."*

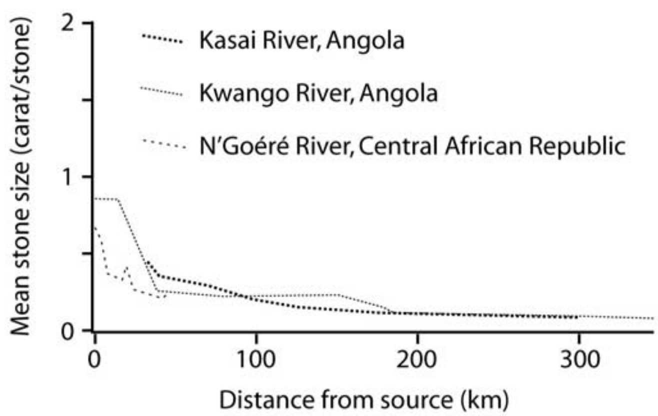

Figure showing fining of diamonds downstream of known kimberlite sources

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Swift, D.A., Nienow, P.W., and Hoey, T.B. 2005. Basal sediment evacuation by subglacial meltwater: suspended sediment transport from Haut Glacier d'Arolla, Switzerland. Earth Surface Processes and Landforms, v. 30(7), p. 867–883.

Synopsis. *Study of fluvial sediment flux in a glaciated catchment. Suggests that (1) ice–bed separation and scavenging of sediment from outside the subglacial tunnel during floods and (2) creep of basal sediments toward tunnel were important in delivering sediment to the subglacial stream (the authors argue basal-ice inflow likely did not contribute sediment because it operates too slowly to explain the sediment-discharge peaks observed). States that "…subglacial streams fed by abundant supraglacial melt will be exceptionally efficient at transporting sediment, the flux from which is more likely to be limited by sediment availability than flow capacity…".*

Exploration significance*. Is most sediment delivered to esker sedimentary systems by creep of till into subglacial streams and/or by extra-stream meltwater scavenging during flood-related ice–bed decoupling, as the authors suggest for this glacier? If so, how far does this sediment capture zone extend out from the subglacial stream? What about inward-pointing striae near some eskers? These suggest an addition mechanism—namely ice inflow toward the subglacial stream—can also contribute sediment to eskers.*

Key quotes

- *"Sub-seasonal changes in relationships between suspended sediment transport and discharge demonstrate that the structure and hydraulics of the subglacial drainage system critically influenced how basal sediment was accessed and entrained."*
- *"Flow capacity is inferred to have increased more rapidly with discharge within subglacial channels because rapid changes in discharge during highly peaked diurnal runoff cycles are likely to have been accommodated largely by changes in flow velocity."*

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Tomkins, M.R., Baldock, T.E. and Neilsen, P. 2005. Hindered settling of sand grains. Sedimentology, v. 52, p. 1425-1432.

Synopsis. *Reviews formula for the estimation of settling velocity of irregular shaped particles and conditions of hindered settling.*

Exploration significance. *Fall velocity of particles in hyperconcentrated flows is reduced compared to that of clear water flows. For example, hyperconcentrated flow deposits commonly contain outsized clasts that were transported farther from source than would be expected in a clear water flow. Hyperconcentrated flows are believed to occur in esker sedimentary systems based on sediment facies observed. If anything, this may lead to enhanced downstream transport of indicators.*

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Trefethen, J.M. and Trefethen, H.B. 1944. Lithology of the Kennebec Valley esker. American Journal of Science, v. 242(10), p. 521–527.

Synopsis. *This classic study of an esker in Maine has some good data on entrainment of bedrock lithologies downflow of lithological contacts. It also has a number of valuable observations on the nature of heavy minerals in the esker. Concludes that most material in the esker has been transported less than 8 miles from its bedrock source.*

Exploration significance. *If this example is representative, gravel and heavy minerals in eskers may commonly be of local origin—in this case, the authors suggest these materials have been transported less than 10 miles from its bedrock source.*

Key quotes

- *"The heavy minerals show some degree of rounding, but not enough to indicate extensive transportation. Subangular fragments dominate, numerous angular fragments are present, well rounded grains are rare."*
- *"In general, the majority of the minerals has been transported for distances of three to eight miles, hence it is principally of local origin."*
- *"Because of the varying stream competency the larger sizes tended to drop out earlier than the small. Thus the finer sizes have a wider range of distribution than the larger."*
- *"Reference to the map (Fig. 1) brings out another problem. It will be seen that the esker passes between the granite outcrops of the Hallowell batholith but, itself, rests on schists, which separate the granite exposures…How then does the granite from these lateral areas become so quickly incorporated into the stratified drift? Prest (1917–1918) has suggested that eskers are a result of lateral movements of the ice towards the esker ridges. Marginal troughs have been cited as evidence of such lateral shove."*

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Van Beever, H.G. 1971. The significance of the distribution of clasts within the Great Pond esker and adjacent till. Unpublished MSc thesis, University of Maine at Orono, 66 p.

Synopsis and exploration significance. *This MSc thesis sampled along a ~60 km section of the Ketahdin esker, near Bangor, Maine. The esker segment was chosen for the general transeverse relationship of the esker and ice flow to bedrock. Sampling was completed on both esker and till to ascertain transport distances of different size fractions and to deconvolve glacial (till) from glaciofluvial (esker) dispersal. Gravel was investigated, not sand. Four factors are identified as controlling the clast lithology: (1) the surface area of the bedrock source, (2) the resistance of the bedrock source to stream erosion, (3) the downstream distance from a bedrock source, and (4) the size of the fragments. The values of transport distance "K" for any particular component vary according to the size examined.*

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Virkkala, K. 1958. Stone counts in the esker of Hameenlinna, southern Finland. Bulletin de la Commission geologique de Finlande, v. 180, p. 87–108.

Synopsis and exploration significance. *An integrated till and esker pebble study from a 40 km section of esker. Concludes that esker material is further traveled than till; that transport distances in the esker are variable; that 40 % of the esker material has travelled less than 40 km; and that transport distance is associated with the resistance of the respective lithologies to abrasion.*

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Wadell, H. 1934. Shape determinations of large sedimental rock fragments. Pan Am Geologist, v. 61, p. 187–220.

Synopsis. *An early study of settling velocity of sediment grains. A formulation for shape of pebbles is developed and its relationship to the coefficient of resistance as a function of the Reynolds number presented. Examples are drawn from three samples one o f which is an esker gravel sample. This is a classic early paper demonstrating the relationship between shape and fluid dynamic processes.*

Exploration significance*. Spherical indicator minerals will settle faster through water than non-spherical indicator minerals of equal size and density. As such, all other things equal, spherical indicator minerals will be deposited closer to source in esker sedimentary systems than non-spherical ones.*

Key quotes

- *"…the sphere has a greater average settling velocity than any other solid of the same volume and specific gravity, because a sphere has (a) the greatest relative volume with the smaller surface area, (b) the smallest cross-sectional area taken as an average of a great number of such sections, and (c) a maximum degree of circulatiry in all cross-sections…"*

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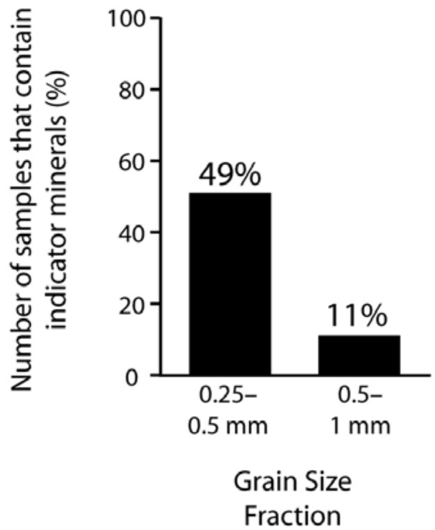
Ward, B.C., Dredge, L.A., Kerr, D.E. and Kjarsgaard, I.M. 1997. Kimberlite indicator minerals in glacial deposits, Lac de Gras area, N.W.T. *in* LeCheminant, A.N. et al (eds), Searching for Diamonds in Canada. Geological Survey of Canada, Open File 3228, p. 191–195.

Synopsis*. Assesses a till sampling program in a well known kimberlite camp. Provides an over view of heavy mineral distribution, grain size and mineralogy. Concludes that more indicator minerals were found in finer (0.25–0.5 mm) than coarser (0.5–1 mm) fraction. (Note that Nixon (1980) finds the opposite in data from non-glaciated settings).*

Exploration significance*. Are there generally more indicator minerals in the finer sand fractions? Do these finer (<0.5 mm) indicator minerals exhibit different dispersal distances in eskers relative to coarser (> 0.5 mm) ones?*

Key quotes

- *"The majority of the indicator minerals were found in the 0.25 to 0.5 size fraction. In this size fraction, 95 of the 194 samples contained indicator minerals confirmed…In the 0.5 to 1 mm size fraction only 22 samples contained indicator minerals. These data suggest that subtle anomalies will be missed when only the coarser grain size is picked."*
- *"The relative proportion of indicator minerals for the entire…data set is ~73% pyropes, ~24% Cr-diopsides, ~2% Mg-ilmenites, ~1% chromites, and <<1% eclogite garnets"*



Kimberlite indicators in medium vs coarse sand, Lac de Gras

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Werritty , A.1992. Downstream fining in a gravel-bed river in southern Poland: Lithologic controls and the role of abrasion *in* Billi, P. et al (eds.), Dynamics of Gravel-bed Rivers, Wiley, p. 333–350.

Synopsis. *A study in the change of clast size and lithologic abundance. Concludes downstream fining is related to attrition (abrasion, chipping, splitting, cracking and chemical weathering) and selective transport, and that the significance of attrition versus selective transport changes longitudinally along the river.*

Exploration significance*. In some fluvial systems, such as this one, downstream fining of gravel is less pronounced. However, such examples are in the minority. Nonetheless, it offers an interesting point of comparison to eskers, which tend to not exhibit net downstream fining. (Whether this applies to individual lithologies within eskers, however, is debatable.)*

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Wheatcroft, R.A. 2000. Oceanic flooding: a new perspective. Continental Shelf Research, v. 20(16), p. 2059–2066.

Synopsis. *A discussion of sediment delivery to the ocean by small rivers.*

Exploration significance. *This paper offers an interesting perspective of how quickly small, steep fluvial systems transfer sediment and water to the basin following storm events. A specific focus here is on the role of floodplains as sedimentary capacitors. Given that eskers lack floodplain-like sediment-storage sites, at least in any appreciable quantity, there is hypothesized to be a parallel between eskers and the small, high-gradient streams discussed in this paper, which are characterized by flashy discharges and rapid, efficient transfer of fluid and sediment to the basin. For the other end of the stick, see Goodbred and Kuehl (1999), who investigate a large river system, and show that extensive floodplain development causes rivers to be extremely inefficient at transferring their sediment load to the basin.*

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Wiberg, P.L. and Smith, J.D. 1985. A theoretical model for saltating grains in water. Journal of Geophysical Research, v. 90(C4), p. 7341–7354.

Synopsis. *Presents a theoretical model that is an improvement and more widely applicable than previous semi-empirical model for the paths of single grains moving as bedload. It is primarily a saltation model, but rolling is included as a limiting case as the boundary shear stress approaches its critical value. The model, given appropriate input parameters such as boundary shear stress and grain size and density will yield the trajectory of a grain as a function of time.*

Exploration significance*.* *This paper provides some basic context for understanding the mechanics sediment dispersal in esker systems. Notably, it contains one of the best explanations of how non-cohesive (i.e., sand and gravel) grains are entrained and deposited by flowing water.*

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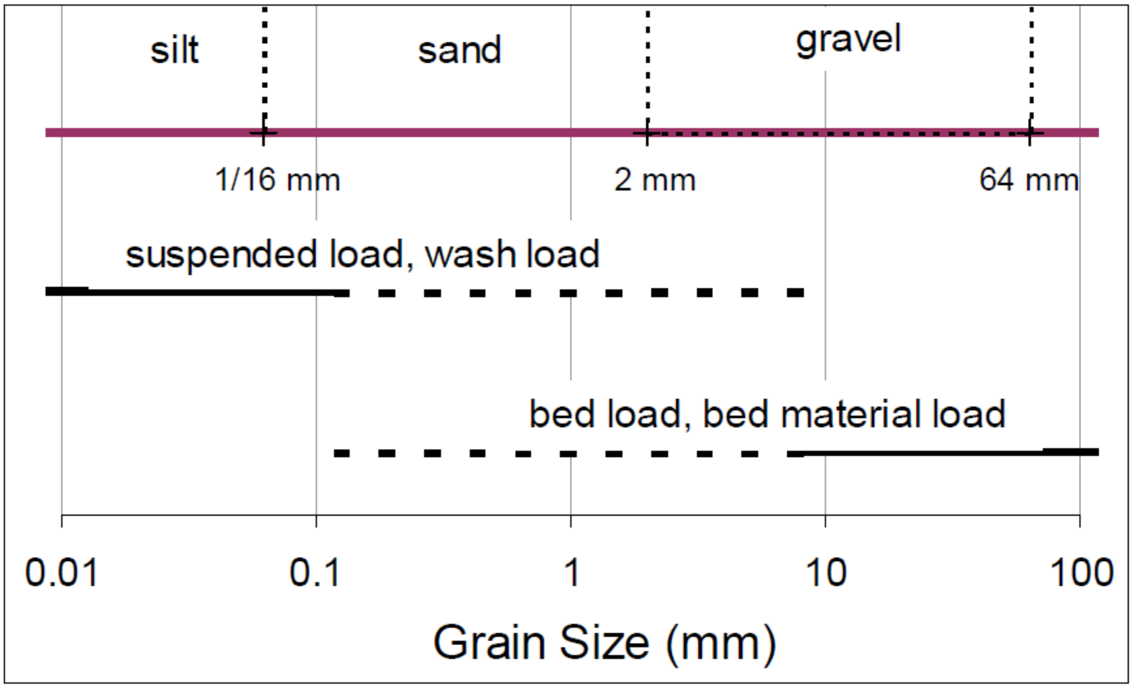
Wilcock, P. 2004. Sediment Transport in Gravel-Bed Rivers with Implications for Channel Change. Short Course Notes, January 26–28, University of California–Berkeley. http://calm.geo.berkeley.edu/geomorph/wilcock/wilcock.html

Synopsis*.* *A comprehensive review of sediment transport in gravel-bed streams.*

Exploration significance*.* *Most ideas in this chapter represent testable hypotheses of how sediment is dispersed in esker sedimentary systems.*



Typical mode of transport for different grain-size fractions in gravel-bed streams

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Wolfe, W. J., Lee, H. A. and Hicks, W. D. 1975. Heavy Mineral Indicators in Alluvial and Esker Gravels of the Moose River Basin James Bay Lowlands, District of Cochrane; Ontario Division of Mines, Geoscience Report 126, 60 p.

Synopsis. *Documents a reconnaissance-scale heavy mineral sampling program of till, eskers, and alluvium. Portions of five eskers were sampled for heavy minerals along with the collection of pebble samples (200 pebbles per sample; 8–16 mm fraction). Over 2 million grains were examined under the microscope. Concludes that the heavy mineral concentrates from all media sampled (till, eskers, stream samples) contain about the same heavy mineral assemblages; that heavy minerals are typically angular, irrespective of media sampled; and that streams contain most heavy minerals per sample, followed by eskers, then till.*

***Exploration significance**. The eskers in this study, like the alluvium, consist essentially of winnowed fill. The till, eskers and streams contained similar heavy mineral assemblages. Grain shape and roundness are poor proxies for transport distance in this setting, irrespective of the media (till, eskers or stream samples) (see also Averill, 2001). Eskers contained 2 to 3 times the amount of heavy minerals per volume than the till.*

Key quotes

- *"…pyrope garnets have been recognized in eskers situated southeast of the Kapuskasing structure."*
- *"The pre-Barlow-Ojibway eskers have been overridden by the Cochrane re-advance and are identifiable as topographic features only in the southern half of the map-area…"*
- *"Samples of coarse sand and gravel alluvium were collected from riffled gravel bars spaced at intervals of 2 to 8 miles (3 to 13 km) along the major north-flowing drainage systems…*
- *"Samples [in the streams] were collected from areas of maximum natural heavy mineral concentration in riffled parts of the river beds and under boulder and cobble-sized material."*
- *"Approximately…28 to 140 litres of sand and gravel material was wet screened on site in the river to produce a 4.5 litre sub-sample of the 0.5 to 1.23 mm size fraction… …sieving of each sample too from ½ to 3 hours."*
- *"At intervals of 0.8 to 6 km along the esker ridges, samples of massive gravel were collected near the crest and on the upstream edges of esker nodes or beads that occur intermittently along the medial ridge of the esker train and tend to be coarsest gravel. At each site, a pit was excavated to expose the massive esker gravel and a sample of the 0.5 to 1.23 mm size fraction was obtained by screening the gravel."*
- *"…the amount of heavy minerals recovered from material in the 0.595 mm to 2.0 mm size range…were calculated for each sediment type as follows: Lower Till – 3.88 g; Adam Till – 2.29 g; Kipling-Cochrane Till – 2.54 g; Eskers – 7.34 g; Alluvium – 27.52 g. These averages reflect 1) differences in the heavy mineral content of Precambrian, Paleozoic and Quaternary source rocks, 2) differences in the ability of glacial, glaciofluvial and alluvial processes to concentrated high density minerals, and 3) postglacial weathering processes which move less resistant material into finer fractions."*
- *"The heavy fractions of the samples, no matter what their origin (esker, till or alluvium) contained generally the same minerals."*
- *"…it is estimated that over 2 million grains were examined" under the microscope.*
- *"Angularity of grains was a dominant feature of all the heavy mineral fractions. Well rounded grains were a rarity and these included only limonite and a few garnets."*
- *"The light fraction also had little variation in mineralogy from sample to sample. Quartz was generally the dominant mineral. In most cases, either limestone or feldspar occurred abundantly after quartz, but the presence of one seemed to almost preclude the presence of the other. The remainder of the sample usually contained red and/or black shale, fossils and assorted lithic fragments. Quartz grains varied from angular to very well rounded and spherical. Feldspar grains and limestone and shale fragments were all generally well rounded."*
- *"In drift covered interfluve areas, a kimberlite diatreme subcropping less than a kilometre from a major river valley, might not be sampled directly by the drainage system."*

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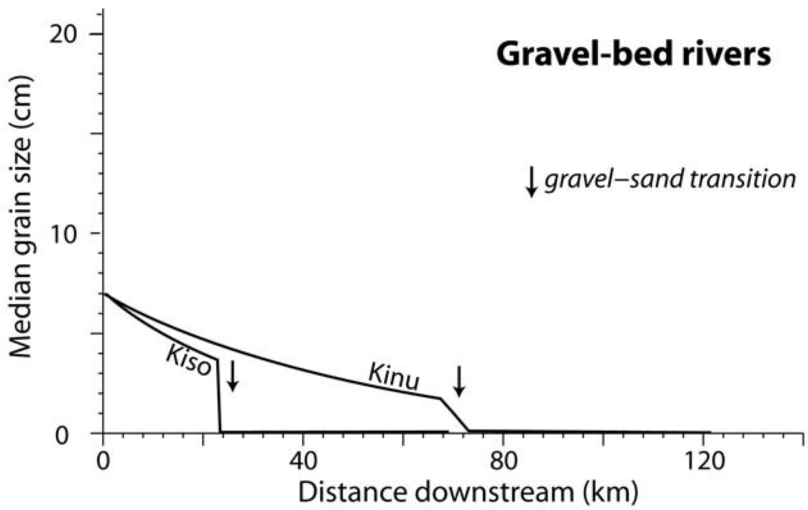
Yatsu, E. 1955. On the longitudinal profile of the graded river. Transactions of the American Geophysical Union, v. 36(4), p. 655–663.

Synopsis. *Documents downstream fining in nine gravel-bed rivers in Japan, including gravel–sand transitions. Nice dataset—possibly still the most extensive on this subject. The work focuses on graded rivers, rivers that are mature and have obtained an equilibrium longitudinal profile.*

Exploration significance. *Like the gravel in these Japanese rivers, gravel indicator of different lithology that comprise esker dispersal trains are suspected to fine downflow. The size of the gravel clast may therefore be a proxy for distance to source (in most cases, the "source" will be an underlying till dispersal train).*



Downstream fining in two of the Japanese rivers studied by Yatsu (1955) (noise filtered out). Other rivers he studied show similar trends. Note rapid gravel–sand transitions.

ACKNOWLEDGEMENT

Dan Kerr is thanked for his constructive review.