Composition and dispersal of debris by modern glaciers, Bylot Island, Canada

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INTRODUCTION

1.1 Location and geography

Bylot Island lies opposite the settlement of Pond Inlet, off the northeastern tip of Baffin Island, about 400 km southwest of Thule, Greenland and 430 km east of Resolute Bay (Fig. 1). The central, northwest-trending spine of the 180 km long by 100 km wide island is mountainous, with peaks averaging 1400 m a.s.l. up to a maximum altitude of about 2000 m a.s.l. in the Byam Martin Mountains. The highlands (Fig. 2) are aptly described by Jackson and Davidson (1975:1) as - "...mostly ice-covered, and the bedrock, much of which is deeply weathered, is exposed in a myriad of jagged nunataks, aretes, cols, tors, and cirques which appear like islands in a white sea. Innumerable glaciers flow outward from the backbone of the Byam Martin Mountains; ...".

In 1977, the authors chose several glaciers on the southwest side of Bylot Island as sites to study the composition of debris in lateral moraines and debris entrained in ice. Bylot Island was selected for these studies specifically because of its bedrock geology — highly metamorphosed, crystalline, Precambrian-terranes in the rugged, high-altitude accumulation areas is surrounded by a gently rolling apron of unmetamorphosed, late Proterozoic sediments and poorly consolidated, coal-bearing, Cretaceous-Tertiary sediments in the dispersal area (Jackson and Davidson, 1975). Glaciers chosen for sampling cross at least two of these lithologically distinct bedrock terranes.

1.2 Objectives and methods

The principal objectives of the study are: (1) to determine the proportions of "far-travelled" and "local" components in various size fractions of the debris; (2) to determine the nature of entrainment and transport processes; and (3) to determine how compositions of debris change according to vertical or areal position within or around a glacier. To achieve these objectives the lateral moraines of five contiguous glaciers (Fig. 1) from two major drainage basins have been sampled systematically, and four vertical profiles of samples have been collected from two glaciers, the largest of the five, located less than 15 km apart. (In 1978 two additional profiles were collected from the upper reaches of Aktineq glacier and profiles of englacial debris were collected from glacier C-55 and from a glacier located wholly on crystalline terrane. Additional ice samples were also collected from several glaciers. None of these 1978 materials have been analyzed at this writing.)

The lateral moraines of the five glaciers (numbered or named with reference to map area 46201, Bylot Island, Inland Waters Branch, 1969) were sampled by collecting 2 kg samples of diamicton from the crest of the moraines at approximately 1.5 km intervals around each glacier.

At Aktineq and "Camp" glaciers (B-17 and B-7, Fig. 2) debris bands were sampled at sections that exposed debris (accessible without special climbing equipment) from near the base of the glacier to a height of several metres. The fragments of ice and debris were stored in 1000 ml polypropylene bottles where they remained during shipment and at room temperature.
for an average of two months in Ottawa. The supernatant water in each sample bottle was filtered and analyzed for trace and major elements by atomic absorption methods. It is thought to have had ample time to equilibrate with the sediment in the bottles.

The <4µm fraction was removed from all mineral sediment samples by centrifugation techniques. This fraction was analyzed by atomic absorption for several trace and minor elements after a hot HCl-HNO₃ leach.

Suspensions containing the <4µm fractions were also mounted on glass slides which were analyzed by X-ray diffraction first at room temperature and humidity and later after saturation with ethylene glycol. Because significant data were derived from these treatments, no further treatment of the slides was performed. Thus, the identifications of the 17 Å, 14 Å, 10 Å, and 7 Å peaks can be no more precise than montmorillonite group, montmorillonite-chlorite, micas, and chlorite-kaolinite, respectively. For the purpose of this paper, a more
Baffin Bay

Baffin Island

BYAM MARTIN MOUNTAIN

B-17 AKTINEQ GLACIER

B-17 Aktineq Glacier

Pond Inlet

Eclipse Sound

Figure 2. View southeast of Bylot Island. Contact of Gneissic and Mesozoic-Tertiary terrain marked by prominent escarpment in central part of photo. Hummocky moraine in foreground and in front of "Camp" Glacier probably greater than 8,000 years old. Tall Martin mountains include peaks over 2,000 m a.s.l. (EMR T344R-198).

Emphatic breakdown is required.

Heavy minerals (s.g. >3.3) were separated from the fine sand (64 to 250µm) fraction of all moraine samples. Weight percentages of heavy minerals (weight heavy minerals/weight heavy plus light minerals times 100) were calculated.

3 Outline of glacial history

Bylot Island is located at or near the presumed northeastern edge of the Laurentide ice sheet. The complex temporal and spatial relationships between local highland ice bodies and the continental ice sheet are presently in the initial stages of study by R.A. Klassen. From the reconnaissance studies of Klassen, Dilabio and Shilts (1974), and Hodgson and Haselton (1974), it is apparent that at least the lower parts of the island were covered by continental ice during the Wisconsinan age. Several "old" dates (>50,000 yr. B.P.) on shells from undisturbed raised deltaic beds at Pond Inlet, only 25 km from Bylot Island (Hodgson and Haselton, 1974), suggest that the last episode of continental glaciation affected Bylot Island several tens of thousands of years ago, probably in the early to middle Wisconsinan. On terrain underlain by Cretaceous-Tertiary bedrock drift deposited by continental ice differs from drift deposited by glaciers originating on Bylot Island in its higher content of erratics with lithologies found in late Proterozoic and Paleozoic formations of northern Bylot Island and Baffin Island.

As noted by Hodgson and Haselton (1974:8) the glaciers of Bylot Island appear to have advanced recently and many have begun to retreat, leaving massive, ice-cored moraines covered by lichen-free bouldery detritus. The outermost lichen-free boulders of the modern moraine that surrounds Aktineq glacier lie on a section exposing wind-deposited sands bearing peaty layers as young as 450±70 14C years B.P. (GSC-2597). About 2 m lower in the same section, a peat in growth position lies on a till-like diamicton and associated fluviatile (?) gravels; this peat is 7860±100 14C years old (GSC-2541).
Figure 3. Trace elements in clay and relative amount of expansible clay in profile 2, Aktineq glacier. Concentrations in ppm, higher 17 Å/14 Å ratios equal higher amounts of expansible clay.

Figure 4. Relative amounts of expansible clay in four ice profiles studied. Higher 17 Å/10 Å ratios equivalent to higher concentrations of expansible clay.

2.1 Clay mineralogy

2.1.1 Expansible minerals

The clay-sized detritus of the debris in transport in Aktineq and "Camp" glaciers is a mixture of expansible, montmorillonite group clay minerals and well crystallized 10 Å micas and chlorite-kaolinite. In general, Aktineq glacier seems to be richer in expansible minerals than "Camp" glacier. The probable source for the expansible minerals is the Cretaceous-Tertiary bedrock that underlies the sample sites at "Camp" and Aktineq glaciers. The well-crystallized chlorites and micas are typical for till derived from crystalline rocks of the Canadian Shield and are most likely derived by glacial comminution of phyllosilicates eroded from the crystalline Precambrian substrate in the upper reaches of "Camp" and Aktineq glaciers.

In profile 2 (Fig. 3) on Aktineq glacier, the apparent concentration of montmorillonite group minerals is greatest near the base of the profile (an undetermined distance above the base of the glacier) and decreases upward in a 12 metre vertical distance. In other profiles, however, the amount of montmorillonite group minerals is less obviously related to height of sample above the base of the glacier (Fig. 4). All but two debris samples from "Camp" and Aktineq glaciers contain some expansible clay, but the sites sampled on Aktineq are greatly enriched in expansible minerals, if the ratio of 17 Å to 10 Å peaks is considered to be a valid measure of relative concentrations (Fig. 4).

2.1.2 Green layers

In "Camp" glacier, several distinctly green debris bands were noted as high as 30 m above the base of the glacier.
In the field, they seemed to be associated with pink gneissic erratics containing abundant epidote that apparently occurs as fracture fillings or as coatings on fracture surfaces. Numerous angular erratics of this type were lying on the glacier and on the lateral moraines, and pink and grey gneisses are common about 5 km up-ice from where the green bands were sampled. The clay fraction of the green bands is predominantly chlorite with little or no montmorillonite and relatively small amounts of 10 Å mica, which is the dominant component of the clay suite in all other samples. The chlorite may occur in the pink gneisses as a product of retrograde metamorphism associated with their epidotization.

More than 95% of the coarse clasts from the green bands are fragments of epidotized pink gneiss. The gneissic debris was either picked up from outcrops of glacier or comprises detritus derived from individual blocks that were transported on the surface of the glacier, dropped from the sides or snout, and ultimately picked up again at the base. The peculiar mineralogy and monolithologic nature of the debris indicates that a large block (or blocks) of gneiss was crushed and sheared into place with little or no dilution by superadjacent debris. The lack of other types of debris supports an origin within the outcrop area.

2.2.1 Comparison among glaciers

Figure 5 indicates that the clay fractions of lateral moraines around "Camp" glacier and glacier C-93 are similar in their trace element content, but that they differ markedly from the other three glaciers which, in turn, differ among themselves. The moraines of "Camp" glacier and glacier C-93 are markedly enriched in Cu, Ni, and Cr, elements usually enriched in basic or ultrabasic intrusive or extrusive rocks or in their metamorphic equivalents. A volcanic-sedimentary bedrock unit that may include such rocks is mapped by Jackson and Davidson (1975) between these adjacent glaciers, about 10 km up-ice from their termini. Numerous sulphide-bearing gneissic boulders with significant amounts of Cu, Ni, and Cr were found on and adjacent to the moraines of "Camp" glacier (DiLabio and Shilts, 1978). Whether the boulders are derived from the volcanic-sedimentary unit or are related to unknown zones of sulphide mineralization is not known at present.

Because the Cretaceous-Tertiary bedrock is impoverished in trace elements (averages: Cu= 7 ppm, Pb=14 ppm, Zn=37 ppm, Co=3 ppm, Ni=11 ppm, Cr=3 ppm, Mn=96 ppm) it is assumed that most of these metals in the clays in the moraines are derived ultimately from the Precambrian terrane, either as cations leached from labile minerals and sorbed onto clay-sized phyllosilicates, as part of the silicate structures of clay-sized particles, or as very finely ground non-silicate minerals.
2.2.2 Variations within lateral moraines of individual glaciers

A complex set of factors affects the composition of till at a given location within a lateral moraine. These include (1) the amount of supraglacial debris falling onto the moraine, (2) the amount of proglacial sediments sheared upwards in debris bands within ice adjacent to the moraine, (3) the amount of meltwater erosion of local bedrock and contribution of water-eroded bedrock to outwash, which could then be incorporated into the glacier, (4) the degree of weathering or age of the moraine, (5) the nature and degree of reworking of morainic material (slump, collapse, washing, inundation, etc.), and, most importantly, (6) the chemical, mineralogical, and physical nature of the bedrock that supplies debris to the ice and the distance of a sample site from specific source rocks.

In this study, it is the latter influence on the composition of lateral moraines or debris in transport that the authors are attempting to distinguish from the other, secondary factors.

Two types of element dispersal patterns are illustrated by Figure 6. Glacier C-93 is intersected by a tributary glacier, the lateral moraines of which outline effectively the part of the main lobe that it comprises. In this figure, it can be seen that the southeastern part of the glacier has lateral moraines with Zn, Ni, Pb, and Cr compositions that are significantly higher than concentrations within the snout and northwestern parts of the glacier. In effect, these trace elements are distributed in the moraine of this glacier in bimodal fashion, the higher metal contents being associated with the southeastern tributary glacier. That tributary drains bedrock terrain near "Camp" glacier, the debris of which has already been shown to be enriched in these metals.

2.2.3 Variations in long profile of trace elements, lateral moraines of Aktineq glacier

The moraines of Aktineq glacier also have a bimodal metal distribution in the clay sizes. In this case, the metal values are highest in the moraines within the Precambrian terrain and seem to decrease in a regular manner toward the snout of the glacier (Fig. 7). This appears to reflect dilution by increasing contents of metal-poor clays derived from the Cretaceous-Tertiary rocks on which the lower 12 km of the glacier lie. These examples serve well to show the advantage of studying composition on the contrasting bedrock terranes of Bylot Island. They also show how studies of modern glacier debris can point up the complexities liable to be detected in ancient glacial deposits, particularly in areas of high relief.

2.2.4 Variations in vertical profiles of Aktineq glacier

Although the profiles of trace-element variations in Aktineq glacier show discrete zones of enrichment or dilution that are inversely related to amounts of expansible clays, the range of variation in a given profile is within the range of variation of the adjacent lateral moraine. Thus, the average composition of in-ice debris is as characteristic of a glacier as is the average composition of its lateral moraines.

By comparing the chromium and zinc contents of clays from the profiles to the amount of montmorillonite group minerals within the clay fraction (as represented by 17 Å/14 Å ratios) (Figs. 3, 8) one can see that trace element content generally decreases with increasing amounts of montmorillonite. If the same relationship holds for samples from lateral moraines, the regular down-ice decrease in trace elements noted above (Sec. 2.2.3) can be similarly related to dilution by metal poor debris from bedrock in the dispersal area.

2.3 Mineralogy of sand-sized fractions

Compared to tills formed elsewhere on the Canadian Shield, the sand-sized debris of these glaciers is greatly enriched in heavy minerals, reflecting the large amounts of garnet and magnetite in the high-grade metamorphic rocks that form the Precambrian "core" of the island. It is rare, in the authors' experience, to encounter more than 5 weight per cent heavy minerals (s.g. >3.5) in the sand fractions of Canadian tills, but these tills range from 5.5% to 24.6% heavy minerals by weight. The fact that heavy mineral percentages are high reflects derivation from the Precambrian terrain. The observation that the percentages do not seem to decrease down-ice in a manner similar to the trace elements in clay, reflects the fact that much of the
Figure 6. Comparison of trace element contents (ppm) of clay from lateral moraines on Aktineq glacier and glacier C-93. Average values at each sample site are underlined. Dashed line marks contact between Mesozoic-Tertiary and Precambrian crystalline rocks.
Cretaceous-Tertiary sediment is very immature and contains large amounts (5-6 weight per cent) of angular heavy minerals. Thus, dilution by incorporation of sand from the younger "rocks" does not affect the concentration of heavy minerals in the sand sizes noticeably. It is interesting to note that the fluvial beds of the Tertiary-Cretaceous formations are nearly as immature as the modern glacial debris.

2.4 Rock types in coarse fractions

The pebble and boulder fractions of the debris in transport and in morainal accumulations are composed almost exclusively of Precambrian rock types. The lack of apparent influence of the Cretaceous-Tertiary substrate on the coarser fractions at Aktineq is at least partially due to the unconsolidated nature and fine grain size of the younger rocks — they simply do not have enough strength to survive as large fragments. The rock types in moraines and in the ice are mostly light-coloured gneisses and garnetiferous gneisses. Fragments of late Proterozoic sedimentary rocks are present but rare in modern glacial sediment of all glaciers except for C-55, which lies on Proterozoic rock.

2.5 Composition of clean and debris-rich ice

Although the data are limited, some comparison may be made of the major element content of clean glacier ice vs. melted ice allowed to equilibrate with its included debris. Water filtered from debris-rich ice is markedly enriched in dissolved major elements compared to water derived from clean ice in a nearby glacier. For example, Ca ranges from 4 to 35 ppm in melted debris-rich ice from Aktineq glacier whereas clean ice from an adjacent glacier contains 1/5 to 1/10 these amounts (pers. comm. L. Johnston and G. Holdsworth, Inland Waters Directorate). A sample of meltwater from a stream draining a glacier near Aktineq is enriched in Ca and other elements to the same order of magnitude.
as water allowed to equilibrate with its included debris, suggesting that cations are readily exchanged between sediment and ice on melting.

3 DISCUSSION

3.1 Textural fractions

From data presented in the previous section and from field observations, it is clear that the debris of the glaciers studied comprises three textural fractions that are fundamentally different in composition. The compositional differences can be used to derive basic information about the nature of entrainment and distance of transport of detritus. The three fractions, to be discussed from coarsest to finest, will be called the (1) Coarse fraction, comprising polymineralic (rock) fragments in the coarse sand, granule, gravel, and boulder size ranges (>250µm); (2) Sand fraction, comprising monomineralic particles dominated by quartz-feldspar with significant amounts of heavy minerals in the sand, fine sand, and silt sizes (250µm-4µm); and (3) Clay fraction, comprising dominantly phyllosilicate minerals (micas and clays) in the very fine silt and clay sizes (<4µm). These are essentially the same textural/compositional classes long recognized in the study of till and are slightly modified from those recently discussed by Shilts (1971, 1975).

3.1.1 Coarse fraction

The coarse fractions of all lateral moraine and glacier samples consist almost entirely of crystalline rock from the Precambrian highlands. The rare exceptions to the highland source are occasional (<1%) fragments of Proterozoic sediments from northwestern Blyot or from Baffin Island and occasional pieces of coal from the Cretaceous beds.

The coarse fragments vary from very angular to well rounded. The most angular fragments seem to have fallen onto the ice in the highlands and are scattered about on the surface of the ice tongues. They fall continuously onto the lateral moraines, often splitting further or splitting and scarring the other rocks.

The more rounded particles are mostly reworked proglacial outwash which is incorporated as individual particles or as cross-bedded "rafts" as the glacier advances. Many undeformed, boulder-sized "rafts" of outwash were observed near the snouts of the glaciers, suggesting that slabs of sediment, frozen onto the base of the glacier in its outer portions, are dragged up to the surface of the glacier along shear planes. One undeformed "raft" of cross-bedded gravel, covered with peat 120±120 years old (GSC-2529, uncorrected), was found over 30 m above the base of "Camp" glacier. This "raft" must have been lifted from the glacier bed within a kilometer of the site where it was found because such vegetated outwash does not occur much further than that up ice. Similar "rafts" within 10 m of the one that was dated were deformed and disrupted, being smeared out by shearing.

That there is almost no contribution to the coarse fraction by the Cretaceous and Tertiary beds is not surprising in view of the fact that these sediments are generally very poorly consolidated and are not likely to produce coarse rubble under any condition. Also, the younger beds lie beneath the sole of the glaciers in broad valleys so that no debris from them could fall onto the glacier.

3.1.2 Sand fraction

The sand fraction contains one component, the heavy mineral fraction, that can be linked to a source within the Precambrian highlands. The metamorphic grade of the highlands is such that garnet and magnetite are abundant in the Precambrian gneisses and granulitic rocks. The few samples of Cretaceous-Tertiary sandstones studied, however, also contain abundant heavy minerals of >3.3 specific gravity.

Their heavy mineral suite is remarkably immature, consisting of a fairly wide compositional range of very angular heavy grains, reminiscent of the same size grains in the superadjacent glacial deposits.

Thus, in the case of Aktineq glacier, the unusually high concentration of heavy minerals in the Cretaceous-Tertiary rocks does not allow any firm conclusion to be drawn as to the ultimate source of the sand fraction. The fact that a significant proportion of the clay fraction comes from the younger rocks of the dispersal area (see below) does suggest, however, that the sand portion of the moraine and in-ice debris does contain a Cretaceous-Tertiary component.
3.1.3 Clay fraction

The clay fraction shows systematic variations in trace element chemistry and in mineralogy that lead to several important conclusions relating to entrainment and transport of debris. Data from scanning electron microscopy and X-Ray Diffraction indicated that the particles in the clay fraction from ice profile samples of "Camp" and Aktineq glaciers are almost all (>95%) phyllosilicates. The profiles of clay mineralogy from sites directly over montmorillonite-bearing bedrock on Aktineq glacier show significant amounts of montmorillonite group clays in debris bands, indicating that the material in the bands is at least partially derived from the sole of the glacier, regardless of the height of the bands above the base. Almost all debris bands in "Camp" glacier also contain montmorillonite, but they are much less enriched in this component than those in Aktineq glacier (Fig. 4). Although in one profile on Aktineq glacier the bands closest to the base are most enriched in the montmorillonite group minerals, indicating that they are most greatly diluted by the underlying montmorillonite-bearing Cretaceous bedrock, the vertical location of greatest dilution is more erratic in other profiles, sometimes occurring in the uppermost samples.

The trace element concentration of profile number 2 on Aktineq glacier shows a trend opposite to that of the clay minerals (Fig. 3). Because most of the trace element component is derived from the Precambrian highlands this reflects either increasing dilution by Cretaceous bedrock toward the base of the glacier or increasing amount of Precambrian components upward in the glacier, or both.

The long profile of trace elements in the clays of the lateral moraines of Aktineq glacier (Fig. 7) shows a regular decrease in element levels from the Precambrian-Cretaceous contact out onto the Cretaceous terrane. This is taken as an indication of down-ice dilution by debris derived basally from the Cretaceous rocks. In the case of Aktineq glacier, the clay fraction reflects this dilution much better than the sand fraction, as discussed above.

In general, the dilution of Precambrian debris is best shown by the negative correlation of montmorillonite and trace elements in the clay (Fig. 8). This relationship is presumed to hold for debris from the lateral moraines as well as for the debris collected directly from the ice. Finally, the comparison of trace element variations in the clays of the moraines of the five glaciers sampled shows that each one is influenced by a distinctive chemistry within its catchment area (Fig. 5). Around glacier C-93 (Fig. 6), in fact, one can clearly detect the lateral morainic debris of one of its major tributaries by the strong contrast in trace element chemistry with the rest of its moraines. The tributary, which drains an area near "Camp" glacier, shows much more chemical affinity for the moraines of "Camp" glacier than for adjacent morainic debris on the northwest side of its snout.

These latter observations have important practical implications for mineral prospecting in regions presently or formerly covered by Alpine-type glaciers. Sampling of lateral moraines might be used in the same way as stream sediment geochemistry is used in mountainous regions to detect potential ore bodies lying within the drainage basin.

4 CONCLUSIONS

Based on the preceding discussion, a number of preliminary conclusions can be proposed:

(1) The composition of coarse englacial or morainic debris cannot necessarily be used as an indicator of entrainment, transport, or depositional processes as has been attempted elsewhere (Boulton, 1970; Souchez, 1971). The contrasts in apparent sources among the coarse, sand-sized, and clay-sized fractions of debris in and around Aktineq glacier clearly demonstrate this (i.e., examination of only the coarse fraction would lead to the false conclusion that all debris was derived from the Precambrian highlands).

(2) Material in the debris bands in the Bylot Island glaciers, although including a high proportion of components ultimately derived from several kilometers up-ice, includes significant amounts of debris dragged up from the base of the glacier from sites a few hundred metres or less from the profiles studied. On Bylot Island, the most distinctive component of the "local" debris is montmorillonite group clay from the Cretaceous-Tertiary beds that underlie the lower portions of the glaciers.

(3) There are significant vertical variations in the physical and chemical nature of debris bands. Some variation is systematic with respect to height above the glacier base and some is
erratic, probably due to the presence of bands containing debris eroded from unusual lithologies at or near the glacier base some distance up ice from the sites of study. The "green bands" of chlorite-rich debris in "Camp" glacier are examples of the latter situation. These vertical variations may be related to similar ones noted in ancient tills deposited by continental glaciers (Shilts, 1978; Podolak and Shilts, 1978).

(4) The finest debris carried by Aktineq glacier is diluted in a regular way in the down-ice direction, a feature best shown by the trace element content of the clay fraction.

(5) The chemical composition of glacial debris can be used, under conditions on Bylot Island, to characterize the drainage basin of individual glaciers or even to distinguish among the morainic materials of tributary ice streams. Apart from the sedimentological and glaciological uses of such information, these contrasts may be useful in mineral exploration in Alpine areas.

(6) Detailed compositional studies of modern glaciers, located in areas where distinctive differences exist among bedrock types in their accumulation and dispersal areas, can shed much light on the nature of glacial sedimentation, erosion, and transportation processes.

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6 REFERENCES


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