Erosion, Debris Flows and Environment in Mountain Regions (Proceedings of the Chengdu Symposium, July 1992). IAHS Publ. no. 209, 1992.

Use of caesium-137 to investigate sediment sources and sediment delivery in a small glacierized mountain drainage basin in eastern Greenland

B. HASHOLT
Institute of Geography, University of Copenhagen, Copenhagen, Denmark
D. E. WALLING
Department of Geography, University of Exeter, Exeter EX4 4RJ, UK

Abstract The suspended sediment yields of glacierized drainage basins have attracted increasing attention in recent years, but most existing information relates to alpine rather than arctic environments. Measurements of sediment transport by proglacial streams have, however, been included in a long-term investigation of contemporary environmental processes within the area around the Mitdluagkat Glacier in eastern Greenland, undertaken by the Institute of Geography at the University of Copenhagen. During the 1990 field season an attempt was made to use ^{137}Cs measurements to determine the main sediment sources and to elucidate sediment delivery processes. The work undertaken demonstrated that the fallout radionuclide ^{137}Cs offers considerable potential as a sediment tracer in this environment. Some of the preliminary findings relating to the relative importance of glacier-derived sediment and sediment mobilized from the proglacial area to the overall sediment yield from the basin, and to rates of sediment deposition along the valley of the Mitdluagkat stream are presented.

INTRODUCTION

Recent years have evidenced a growing interest in the sediment yields of glacierized drainage basins (cf. Gurnell & Clark, 1987). This interest has been promoted by a number of factors, including, the potential for using measurements of suspended sediment transport by the stream issuing from a glacier to obtain information on glacial processes (cf. Collins, 1979); the practical problems associated with using sediment-laden water from glacier-fed rivers, particularly for hydroelectric power production (cf. Ostrem, 1975); and by the possibility of using measurements of sediment yield to estimate rates of erosion and landform development (cf. Lawler, 1991). In the latter context, some glacierized basins have been shown to generate very high suspended sediment yields which in turn reflect high rates of denudation. For example, Lawler (1991) documents an extremely high suspended sediment yield of 14 482 t km^{-2} year^{-1} for a 78 km^2 glacierized basin in Iceland, Gurnell (1987) reports a value of 1896 t km^{-2} year^{-1} for the small (4.8 km^2) Tsidjiore Nouve basin in Switzerland, Bogen (1988) cites a value of *c*. 1300 t km^{-2} year^{-1} for the small basin of the Trollbergdalsbreen glacier in Svartisen, Norway, and Ferguson (1984) reports a yield of 4800 t km^{-2} year^{-1} for the 13 200 km^2 basin of the Hunza River in the Karakoram region of Pakistan.

Most currently available information on the suspended sediment yields of glacierized basins, however, relates to alpine areas, and much less attention has been given to arctic regions. In consequence, studies of suspended sediment transport by proglacial streams have been initiated as part of a long-term field investigation of contemporary environmental processes in the area around the Mitdluagkat Glacier in eastern Greenland undertaken by the Institute of Geography of the University of Copenhagen (cf. Hasholt, 1976). Measurements reported by Hasholt (1976) for part of the 1972 melt season indicated that suspended sediment yields in parts of this glacierized area are again high and could be well in excess of 1000 t km^{-2} year^{-1}. Further work is currently in progress, as a contribution to the Northern Research Basins Project, to elucidate the processes of erosion and sediment transport operating in the area. In order to determine the main sediment sources and to study sediment delivery processes in more detail, an attempt was made during the 1990 field season to exploit the potential for using the fallout radionuclide caesium-137 as a sediment tracer. Some of the preliminary findings of that work are presented in this paper as a contribution to improving the understanding and geomorphological interpretation of suspended sediment generation in arctic glacierized basins.

THE STUDY AREA

The study area is situated on the western margin of the Mitdluagkat Glacier, which is located on Angmagssalik Island, close to the coast of southeast Greenland (Fig. 1). Geologically, the area is part of the Nagssugtoqides belt and the rocks are dominantly gneisses with some basalt inclusions. The terrain has been deeply dissected by glacial valleys and there are a large number of smaller geologically-controlled fissure valleys criss-crossing the area. The maximum elevation of the area delimited on Fig. 1 is 973 m. The proximity of the Greenland Ice Cap exerts a dominant control on the climate of the locality, which is characterized by cold stable weather conditions. Lows centred over western Greenland may, however, give rise to gale force foehn winds which cause severe drifting of snow, and lows tracking along the east coast of Greenland can result in warm spells and periods of rainfall, even during the winter. The annual mean temperature at Angmagssalik is −1.2° C and monthly mean temperatures range between a minimum of −8.2° C and a maximum of 7.5° C. The mean annual precipitation at Angmagssalik is 826 mm, but runoff measurements within the study area itself suggest that annual precipitation received by the glacier surface is of the order of 2000 mm. The monthly

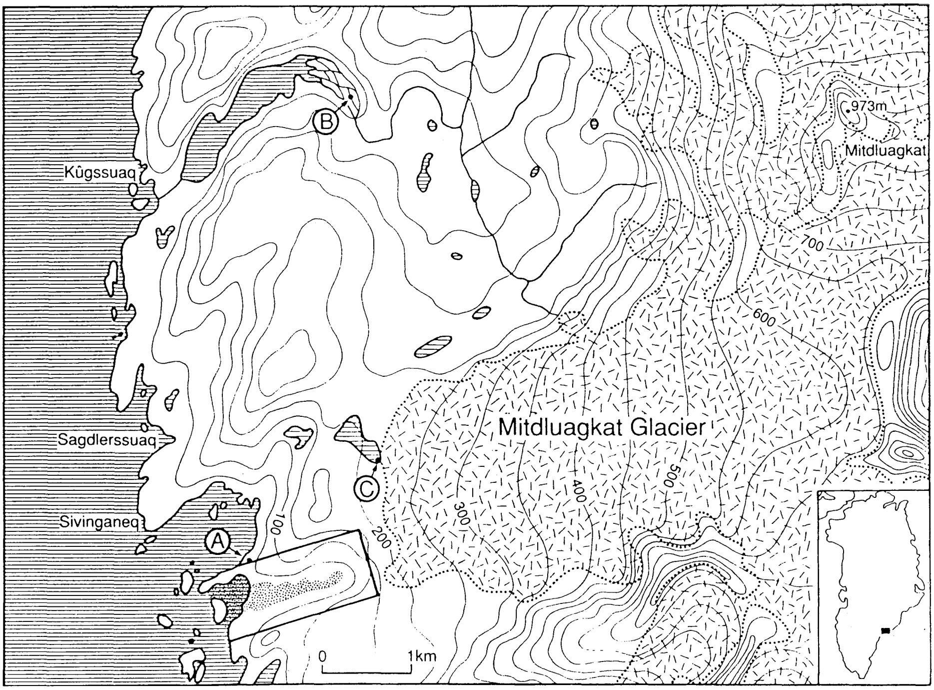

Fig. 1 The study area. Sampling sites identified on the map are referred to in the text. The area covered by the map presented in Fig. 3 is marked by the box.

precipitation at Angmagssalik ranges between 40 and 90 mm, with a maximum in October-November and a minimum in June-July. However, monthly totals exhibit substantial variability, with the values for October ranging between 35 and 470 mm. The Mitdluagkat Glacier (30 km^2) is the largest glacier on the island and the area investigated includes the two main meltwater outlets draining to Sermilik Fjord (Fig. 1). In the northern area, meltwater passes through a series of small lakes near the ice margin and after traversing about 6 km of undulating terrain enters a large lake at Kugssuaq through a well-developed delta. Water finally drains to the sea through a short fissure valley with numerous rapids. At the southern outlet, which has been studied in greater detail, the meltwater feeds the Mitdluagkat stream which flows in a well-developed braided channel across an outwash plain stretching *c.* 1.5 km from the glacier terminus to the sea, where a substantial delta has been formed. Since the Little Ice Age (*c.* 1700), the glacier has retreated from a point close to the shore, to the head of the short valley.

The area is characterized by a glacio-nival hydrological regime. Melting normally starts in May and reaches a maximum in June or July. Periods of rainfall during this period can cause substantial increases in flow. From October until the end of April the runoff is normally very low, but minor peaks may occur during the winter in association with warmer spells. The valley floor of the southern outlet is inundated by floodwater every year during the spring melt due to icing. A much larger discharge was recorded in 1958, when a jokulhaup flood occurred as a result of the draining of an ice-dammed lake. Jokulhaups have not occurred since that time due to glacier retreat. The suspended sediment transported by the streams in the study area is predominantly coarse (sand and coarse silt), but clay-sized ($< 2\ \mu m$) particles, largely comprising primary feldspars and micas (biotite), but also including some secondary vermiculite and smectite, have been reported by Petersen & Rasmussen (1980). Suspended sediment concentrations measured in the stream draining the southern outlet exhibit marked diurnal variation and reach a maximum of *c.* 1000 mg l^{-1} during storm events. As indicated above, the suspended sediment yield from this drainage basin is estimated to be in excess of 1000 t km^{-2} $year^{-1}$.

CAESIUM-137 AS A SEDIMENT TRACER

The radionuclide caesium-137 (^{137}Cs) is present in the environment primarily as a product of the atmospheric testing of nuclear weapons during the late 1950s and early 1960s which caused radiocaesium to be globally distributed within the stratosphere. Fallout to the land surface, which is primarily associated with precipitation, was first documented in 1954, reached a maximum in 1963, and declined rapidly after the nuclear test ban treaty (cf. Ritchie *et al.*, 1975), although in many areas of Europe there were further significant inputs of ^{137}Cs in 1986 as a result of the Chernobyl disaster. Existing evidence indicates that fallout reaching the surface of most soils is rapidly and strongly adsorbed by the upper horizons of the soil and that further downward translocation by physico-chemical processes is limited (cf. Frissel & Pennders, 1983). Subsequent movement of ^{137}Cs is therefore generally associated with the erosion, transport and deposition of sediment particles (e.g. Rogowski & Tamura, 1970; Campbell *et al.*, 1982). Caesium-137 has a half-life of 30.2 years and approximately 50% of the total input of this radionuclide since fallout began in 1954 could still remain within the environment. Considerable potential therefore exists for tracing the movement of sediment over the past 30 years by measuring the current distribution of ^{137}Cs within the landscape (cf. Walling & Bradley, 1990).

CAESIUM-137 MEASUREMENTS IN THE STUDY AREA AND THEIR INTERPRETATION

No significant input of Chernobyl fallout was detected in the study area during this investigation, and the measurements of the ^{137}Cs content of soils and sediment undertaken relate solely to "bomb test" fallout of ^{137}Cs, most of which occurred more than 25 years ago.

Sampling and measurement techniques

Collection of soil and sediment samples from the study area for measurements of ^{137}Cs activity has involved four approaches:

(a) Information on the distribution of ^{137}Cs within the profile has been obtained by sampling from an area of 640 cm^2 at 1 or 2 cm increments down to depths of up to 25 cm, using the scraper plate technique described by Campbell *et al.* (1988).

(b) Several 6.5 cm diameter cores were collected from the sampling site using a steel cylinder corer to depths of up to 30 cm. These cores were subsequently sectioned into 1-5 cm slices and the slices for specific depth increments from the individual cores were combined for subsequent analysis. This approach again provided information on the distribution of ^{137}Cs in the profile.

(c) Individual whole cores were collected using a 6.5 cm diameter corer to depths of up to 30 cm for subsequent analysis of the total ^{137}Cs inventory of the sampled material.

(d) Samples of specific surface sediments (*c.* 250 g) were collected in order to determine their ^{137}Cs content. In this case no attempt was made to collect from a pre-defined surface area.

All samples were transported to the Department of Geography at the University of Exeter, where they were air dried, disaggregated and sieved to separate the <2 mm fraction for analysis. The ^{137}Cs content (mBq g^{-1}) of this fraction was measured by gamma spectrometry using high purity coaxial germanium detectors. Count times were typically of the order of 30 000 s, providing an analytical precision (2 s.d.) of *c.* $\pm$ 5%. Results relating to samples collected using approaches (a), (b) and (c) listed above, were also expressed in terms of the surface area of the original sample in units of mBq cm^{-2}.

Caesium-137 inventories in the study area

In order to obtain information on the magnitude of total ^{137}Cs fallout inputs to the study area, 10 whole core samples were collected from an essentially flat undisturbed area with a good cover of grassy vegetation where fallout inputs are unlikely to have been remobilized (point A on Fig. 1). The average ^{137}Cs inventory of these cores was 250 mBq cm^{-2}. Other individual cores collected from equivalent sites elsewhere in the study area yielded similar values and it has therefore been assumed that the current ^{137}Cs fallout inventory for the area is 250 mBq cm^{-2}. It is likely that values may be somewhat greater at higher altitudes in the study area, since existing evidence from other areas of the world indicates that regional variations in fallout inputs closely reflect variations in annual precipitation (cf. Cambray *et al.*, 1982). The value of 250 mBq cm^{-2} is consistent with estimates of fallout inputs to areas of northern

Europe with similar annual precipitation totals. Total fallout at the time of deposition in the late 1950 s and the 1960s would have been greater due to the effects of radioactive decay during the intervening period. In using ^{137}Cs as a sediment tracer within the study area, it is therefore assumed that stable sites which have experienced neither erosion nor deposition during the past 30 years should exhibit current inventories close to 250 mBq cm^{-2}, that eroding sites should be characterized by reduced inventories, and that sites where deposition of fine sediment has occurred should exhibit increased inventories. It must, however, be accepted that the original fallout inputs may have been characterized by some local variability associated with drifting snow.

Caesium-137 redistribution by erosion and deposition processes

In order to confirm that ^{137}Cs can be used as a meaningful sediment tracer within the study area, it was necessary to demonstrate that radiocaesium fallout inputs had been firmly bound within the upper horizons of soils and surface materials and that depositional areas exhibited both increased ^{137}Cs inventories and profile distributions consistent with sediment accretion. Some uncertainty existed regarding the ability of the poorly developed coarse-grained soils of the study area to fix ^{137}Cs fallout inputs, but Fig. 2(a), which depicts the vertical distribution of ^{137}Cs within a soil profile at the location used for sampling fallout input inventories (site A, Fig. 1), demonstrates that the majority of the ^{137}Cs is held within the upper 2 cm of the profile. The extent of downward translocation is indeed much less than normally encountered in soils from more temperate environments (cf. Walling & Quine, 1991), and this feature has been tentatively ascribed to reduced biological activity. The total ^{137}Cs inventory associated with the profile shown in Fig. 2(a) is in close agreement with the average fallout inventory for the study area of 250 mBq cm^{-2} presented above.

Figure 2(b) presents the ^{137}Cs profile distribution for a set of adjacent

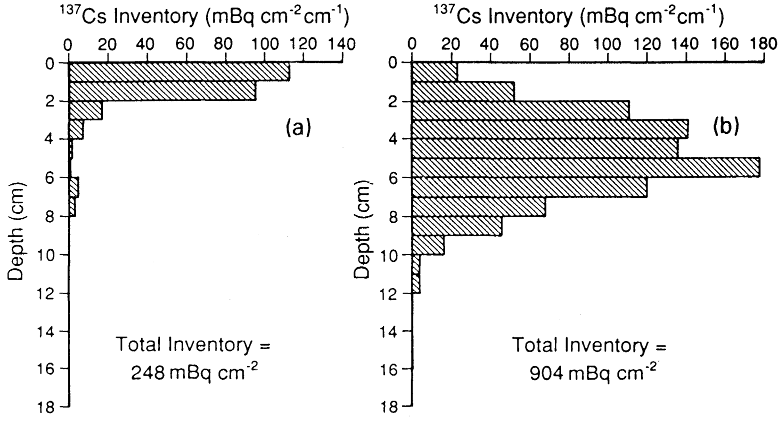

Fig. 2 Caesium-137 profiles associated with an undisturbed input measuring site and the delta at the head of Kugssuaq lake.

cores collected from an accessible site within the delta at the head of the large lake near Kugssuaq (site B, Fig. 1). Both the total ^{137}Cs inventory recorded for this site and the profile distribution are consistent with a rapidly accreting environment. Assuming that all direct ^{137}Cs fallout at this point was incorporated into the sediment, the site has received an additional ^{137}Cs input of *c.* 650 mBq cm^{-2} through deposition of radiocaesium-bearing sediment eroded from the upstream drainage basin. If it is assumed that the delta surface at the time of maximum fallout in the early 1960s, which is marked by the peak levels of ^{137}Cs in the profile, was located about 6 cm below the current surface, the deposition rate at this point can be estimated as approximately 2 mm $year^{-1}$. The reduction in the ^{137}Cs content of the delta sediments towards the surface reflects the lack of significant direct fallout since about 1970 and the reduced radiocaesium content of sediment eroded from the drainage basin. As erosion proceeds within the main source areas, surface layers containing relatively high levels of ^{137}Cs will be removed, exposing subsurface material with a progressively lower ^{137}Cs content.

Suspended sediment sources

In attempting to identify the major sources associated with the high suspended sediments yields reported for the study area by Hasholt (1976), several possible scenarios can be advanced. In many studies of glacierized basins (*c.* Ostrem, 1975; Gurnell & Clark, 1987) it has been shown, or at least assumed, that the major source of suspended sediment is either material entrained within or beneath the glacier by meltwater, or glacial debris released from the melting ice. In this situation the sediment is essentially a product of glacial erosion transported to the river system by meltwater. Alternatively, situations may exist where the major source of sediment lies in the proglacial area bordering the glacier front, where the recently-exposed unconsolidated sediments, largely unprotected by vegetation, are easily eroded by fluvial processes. In this case the main periods of sediment transport will be associated with storm runoff events, whereas in the former sediment transport will be essentially continuous, although reflecting the intensity of glacier melting. Richards (1984) introduces a third scenario, which incorporates elements of both the former situations. In his study of suspended sediment transport by the stream draining from the Storbreen Glacier in the Jotunheimen region of Norway, he concluded that fine sediment was transferred from the subglacial to the proglacial environment during low flow (melt-dominated) periods and subsequently removed from that area during high flow (rainfall-controlled) events. The ultimate source of the sediment was, however, material released by the glacier. In the study area, existing measurements of suspended sediment concentration in the Mitdluagkat stream draining from the southern outlet of the glacier have been shown to exhibit marked diurnal variation in response to variations in the intensity of ice melt. This suggests that glacier-derived sediment represents an important source. Equally, however, the large areas of unconsolidated sediment exposed by the recent retreat of the glacier could also be expected to provide a substantial contribution to the overall sediment load, particularly during periods of snowmelt and heavy rainfall.

Caesium-137 measurements offer potential for testing the applicability of the three potential scenarios outlined above and for assessing the relative importance of subglacial and proglacial sediment sources in the study area. Sediment contained within and beneath the glacier will have been effectively "protected" from ^{137}Cs fallout and is unlikely to exhibit significant levels of radiocaesium. Conversely, sediments located in those parts of the proglacial zone that were exposed during the main period of "bomb" fallout should contain appreciable amounts of ^{137}Cs in their surface horizons. Sediment released from the glacier and stored temporarily in the proglacial zone before being remobilized will, however, be very unlikely to contain significant amounts of radiocaesium because of its short residence time in the proglacial zone.

Confirmation of this potential for differentiation between sediment sources is provided by the following results. Sediment collected from dirt bands within the melting glacier front and from the base of the glacier at location C (Fig. 1) contained extremely low levels of ^{137}Cs and confirmed the absence of significant levels of radiocaesium in glacier-derived sediment. Fine sediment deposits collected from a nearby stream fed by meltwater from the glacier front also contained very low levels of ^{137}Cs, confirming its glacier origin. However, fine sediment collected from the margin of several small lakes receiving drainage from the proglacial area contained appreciable levels of ^{137}Cs (15-75 mBq g^{-1}) confirming a source within the proglacial area itself. Although it has not proved possible to collect bulk samples of the suspended sediment transported by streams in the study area in order to "fingerprint" its likely source, some preliminary conclusions can be advanced based on available surrogate information.

As indicated above, the ^{137}Cs inventory associated with a sediment core retrieved from the delta at the head of the Kugssuaq lake was approximately 3.6 times greater than the local reference fallout inventory. The excess ^{137}Cs can only be accounted for by deposition of ^{137}Cs-bearing sediment which in turn must have been eroded from the proglacial area during flood events. Sediment cores collected from a range of depositional environments on the floor of the valley of the Mitdluagkat stream and which will be discussed in greater detail in a subsequent section (cf. Fig. 4), were in most cases also characterized by ^{137}Cs inventories substantially in excess of the local reference inventory. This again suggests that the deposited sediment was derived primarily from the proglacial area, rather than the glacier itself. Collection of bulk suspended sediment samples from the river over a range of flow conditions and analysis of the ^{137}Cs content of the resultant sediment samples would provide further confirmation of the relative importance of proglacial and subglacial and englacial sources to the suspended sediment yields of the study area, but the evidence outlined above suggests that material eroded from the proglacial area represents a major, if not the dominant, source. Data presented by Hasholt (1976) indicate that suspended sediment concentrations in the Mitdluagkat stream increased markedly during periods of high discharge caused by rainfall inputs. During such periods, which will account for a substantial proportion of the total suspended sediment yield, sediment is likely to be eroded from the slopes of the proglacial zone.

The behaviour of depositional environments in the valley of the Mitdluagkat stream

A more detailed assessment of the potential for using caesium-137 measurements to investigate the behaviour of depositional environments focussed on the outwash train in the valley of the Mitdluagkat stream (Fig. 3). The depth distributions of ^{137}Cs activity were measured in cores from four characteristic environments. The sampling sites are located on Fig. 3 and represent firstly, the surface of an exposed bar within the braided river system (site 1); secondly, the floor of a shallow distributary channel within the lower outwash plain, which functions only during periods of high discharge (site 2); thirdly, a mid-channel bar associated with the aggrading reach of a small stream draining from a tributary valley (site 3); and finally a flood plain bench bordering the main channel (site 4). The ^{137}Cs profiles obtained for these four sites are presented in Fig. 4.

The ^{137}Cs profiles for sites 1 and 2 exhibit many similarities. Both demonstrate a general upward decrease in ^{137}Cs activity from the layer immediately overlying the coarser basal material containing no ^{137}Cs. This suggests that the finer sediment has been deposited since the early 1960s, because, if deposition had commenced prior to that time, some evidence of a gradual increase in ^{137}Cs levels towards a sub-surface peak would have been expected. The presence of ^{137}Cs in the deposited sediment again points to a proglacial source for a substantial proportion of the material. Figure 3 indicates that the glacier front retreated rapidly during the 1950s and 1960s. The areas of unconsolidated sediment exposed both in the valley floor and on the slopes would have received inputs of ^{137}Cs fallout and it is this ^{137}Cs-labelled sediment that has been mobilized and deposited at these sites. Assuming that deposition of the ^{137}Cs-bearing sediment commenced in the 1960s, an average deposition rate of *c.* 3 mm $year^{-1}$ can be postulated. The abrupt commencement of deposition of finer sediment, evidenced by the clear boundary between coarse and fine sediment would suggest a sequence whereby the coarser basement must aggrade to a certain height above the adjacent river channel before deposition of fines can commence. The lower total inventory and the lower ^{137}Cs levels associated with the base of the core from site 2 further suggests that the surface on which deposition of ^{137}Cs-bearing sediment occurred was not exposed during the main period of "bomb" fallout and that deposition did

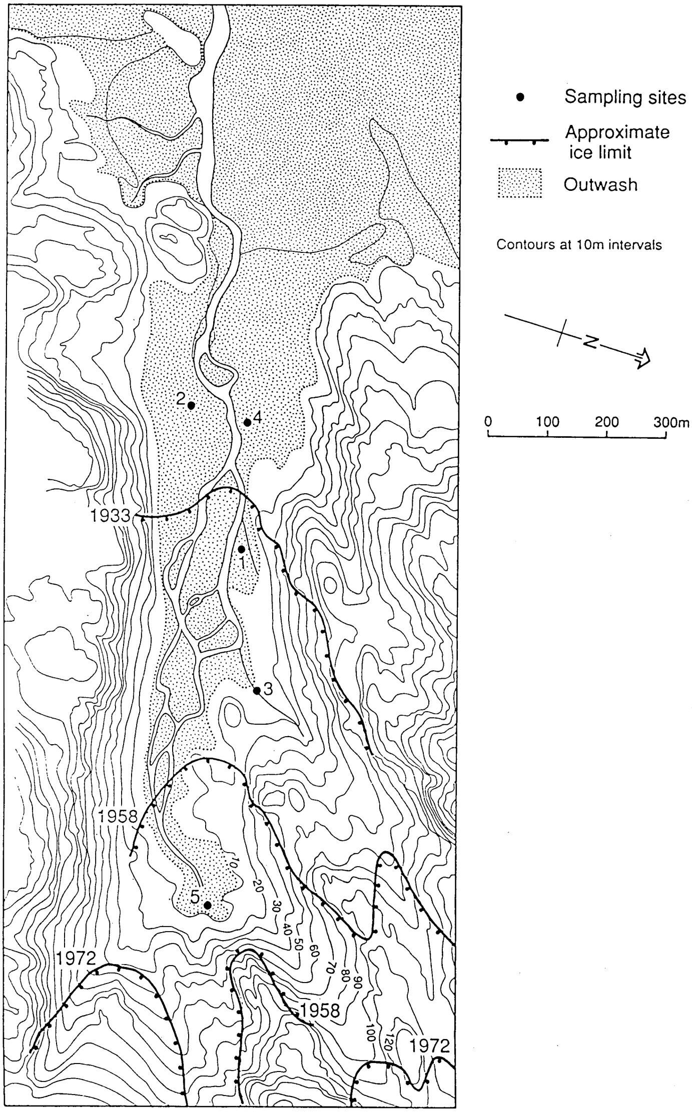

Fig. 3 The valley of the Mitdluagkat stream showing the approximate location of the receding glacier front in 1933, 1958 and 1972 and the location of the depositional sites examined in detail.

not commence until the mid or late 1960s.

The ^{137}Cs profiles for sites 3 and 4 also exhibit strong similarities in terms of their overall shape. In this case, maximum radiocaesium levels are found towards the middle of the profiles and levels decline both above and below the peak. Assuming that the peak levels correspond with the surface exposed at the time of maximum fallout in the early 1960s, of the order of 18 and 10 cm of deposition have occurred at sites 3 and 4 since that time,

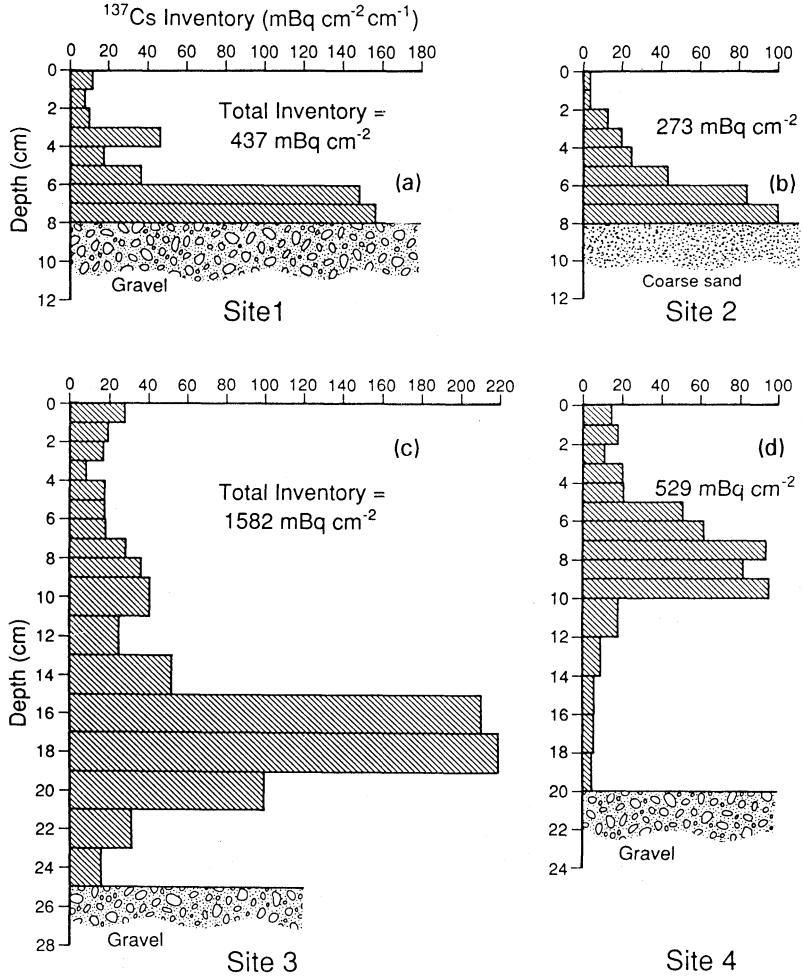

Fig. 4 Caesium-137 profiles associated with four depositional sites sampled within the valley of the Mitdluagkat stream. (a) represents site 1, (b) site 2, (c) site 3 and (d) site 4 on Fig. 3.

representing average deposition rates of approximately 7 mm year^{-1} and 4 mm year^{-1} respectively. Site 3 is located at the bottom of a tributary valley which was exposed by the retreating ice front in the 1940s and 1950s. The slopes within this area would have provided a major sediment source, which is in turn reflected in the high rates of deposition evident at site 3. The high levels of ^{137}Cs associated with the profile peak and the very rapid decline of radiocaesium levels towards the surface are indicative of rapid erosion of fine sediment from the surface of the upstream sediment-contributing areas.

The ^{137}Cs measurements obtained from the cores collected in the Mitdluagkat valley evidence a dynamic depositional environment with accretion rates for fine sediment of the order of 3 mm year^{-1} within the braided channel system itself and of 5 mm year^{-1} on flood plain benches and on the small alluvial fans at the outlets of tributary valleys. The measurements are also consistent with the previous hypothesis that proglacial areas recently exposed by the retreating ice provide the major source of fine sediment. Some additional short sediment cores collected from the recent alluvial/outwash deposits at the upper limit of the flat valley floor, in an area that was exposed by the retreating ice during the late 1960s (site 5, Fig. 3), produced total ^{137}Cs inventory values that were close to the local reference inventory. This is somewhat unexpected since the area would not have been exposed when a significant proportion of the "bomb" fallout was received. The presence of significant radiocaesium inventories can, nevertheless, again be ascribed to the deposition of ^{137}Cs-bearing sediment eroded from the surrounding slopes, further emphasising the importance of proglacial sediment sources. Several cores were also collected from depositional environments adjacent to the main river which carries meltwater from the northern outlet of the Mitdluagkat Glacier to the Kugssuaq Lake. The total inventories of these cores were similar to the local reference value, indicating that rates of sediment deposition are much lower than found bordering the Mitdluagkat stream. This can in turn be related to the "older" nature of the drainage basin, of which only a small proportion has been recently exposed by the retreating glacier margin. Erosion rates, and therefore the sediment concentrations carried by this river in flood events are likely to be much lower than in the Mitdluagkat stream (cf. Hasholt, 1976).

The information on sediment deposition rates obtained for the Mitdluagkat stream also has important implications for the efficiency of the sediment delivery system operating in this environment. The substantial rates of deposition indicate that significant conveyance losses must occur as sediment is transported through the system. On-site rates of erosion or sediment mobilisation will be appreciably greater than indicated by the downstream sediment yields. In order to ascertain if the deposition process was associated with a significant change in the grain size of transported sediment, the grain size distribution of fine sediment collected from slackwater sites in the channel of the main river and its tributaries (Fig. 5(a)) was compared with that of the deposits sampled at sites 1 to 4 (Fig. 5(b)). If, in the absence of more direct evidence, it is assumed that the grain size distribution of the slackwater deposits (Fig. 5(a)) is representative of transported sediment, it is evident that the deposited sediment (Fig. 5(b)) is significantly depleted in the silt- and clay-sized fractions. However, these fractions represent a very small proportion of the total mass and the overall distribution is little changed. There is, therefore, some evidence for a preferential delivery of fines but, in general, deposition evidences relatively little grain size selectivity.

PERSPECTIVE

Although most work on the application of ^{137}Cs measurements in hydrological and geomorphological investigations has been undertaken in temperate environments, the results presented above indicate that caesium-137

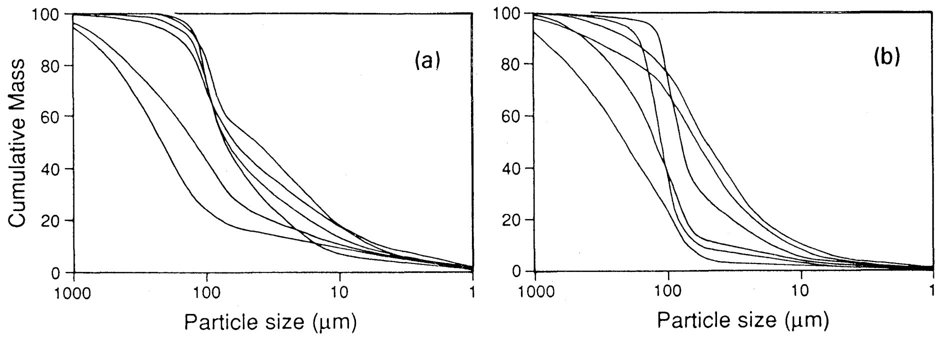

Fig. 5 Representative grain size distributions associated with fine channel sediments (a) and the sediment deposits collected from sampling sites 1-4 along the Mitdluagkat stream (b).

measurements can also provide useful information regarding the operation of contemporary geomorphological processes in arctic glacierized drainage basins. The effects of drifting snow in giving rise to spatial variability in fallout inputs and the coarse nature of the sediment in such environments inevitably constrain the potential of the approach, but these limitations must be set against the operational problems of employing more traditional monitoring techniques in these frequently remote areas. Of particular value is the possibility of assembling information on the basis of a single visit to an area. As in other environments, however, the use of ^{137}Cs measurements should be seen as a complement to traditional monitoring techniques, rather than as an alternative. One application which appears to offer particular potential is the possibility of determining whether the major source of the suspended sediment yield of a glacierized basin is material transported from within and under the glacier by meltwater or material eroded from the surrounding proglacial area by fluvial processes. The former will inevitably be of significance, since there are numerous studied reported in the literature which show that glacier-fed streams can transport relatively high suspended sediment concentrations, even during periods of stable flow. However, the importance of the latter may have been underestimated in many studies, particularly where short periods of observation have failed to document the role of relatively infrequent storm events in the overall sediment budget.

Acknowledgements The authors gratefully acknowledge the financial support for fieldwork in East Greenland provided by the Danish Natural Science Council, and the assistance of Mr J. Grapes in undertaking the gamma spectrometry measurements, and of Mr R. Fry in producing the diagrams.

REFERENCES

Bogen, J. (1988) A monitoring programme of sediment transport in Norwegian rivers. In: *Sediment*

Budgets (ed. by M. P. Bordas & D. E. Walling)(Proc. Porto Alegre Symp., December 1988), 149-159. IAHS Publ. no. 174.

Cambray, R. S., Playford, K. & Lewis, G. N. J. (1982) Radioactive fallout in air and rain: results to end of 1981. *UK Atomic Energy Authority Report AERE-R 10845.*

Campbell, B. L., Loughran, R. J. & Elliot, G. L. (1988) A method for determining sediment budgets using caesium-137. In: *Sediment Budgets* (ed. by M. P. Bordas & D. E. Walling)(Proc. Porto Alegre Symp., December 1988), 171-180. IAHS Publ. no. 174.

Campbell, B. L., Loughran, R. J. & Elliot, G. L. (1982) Caesium-137 as an indicator of geomorphic processes in a drainage basin system. *J. Austral. Geogr. Studies* **20**, 49-64.

Collins, D. N. (1979) Sediment concentration in meltwaters as an indicator of erosion processes beneath an alpine glacier. *J. Glaciol.* 23, 247-257.

Ferguson, R. I. (1984) Sediment load of the Hunza River. In: *The International Karakoram Project* (ed. by K. J. Miller), vol. 2, 581-598. Cambridge University Press, Cambridge, UK.

Frissel, M. J. & Pennders, R. (1983) Models for the accumulation and migration of ^{90}Sc, ^{137}Cs, ^{239,240}Pu and ^{241}Am in the upper layers of soils. *Spec. Publ. Brit. Ecol. Soc.* no. 3, 63-72.

Gurnell, A. M. (1987) Fluvial sediment yield from alpine, glacierized catchments.In: *Glacio-fluvial Sediment Transfer* (ed. by. A. M. Gurnell & M. J. Clark), 415-420. John Wiley, Chichester, UK.

Gurnell, A. M. & Clark, M. J. (eds) (1987) *Glacio-fluvial Sediment Transfer*. John Wiley, Chichester, UK.

Hasholt, B. (1976) Hydrology and transport of material in the Sermilik area 1972. *Geografisk Tidsskrift* **75**, 30-39.

Lawler, D. (1991) Sediment and solute yield from the Jokulsa a Solheimasandi glacierized river basin, southern Iceland. In: *Environmental Change in Iceland: Past and Present* (ed. by J. K. Maizels & C. Caseldine), 303-332. Kluwer, Dordrecht.

Ostrem, G. (1975) Sediment transport in glacial meltwater streams. In: *Glaciofluvial and Glaciolacustrine Sedimentation* (ed. by A. V. Jopling & B. C. McDonald), 101-122 Society of Economic Palaeontologists and Mineralogists Special Publication no. 23.

Petersen, L. & Rasmussen, K. (1980) Mineralogical composition of the clay fraction of two fluvio-glacial sediments from East Greenland. *Clay Minerals* **15**, 135-145.

Richards, K. S. (1984) Some observations on suspended sediment dynamics in Storbregrova, Jotunheimen. *Earth Surf. Proc. & Landforms* **9**, 101-112.

Ritchie, J. C., Hawks, P. H. & McHenry, J. R. (1975) Deposition rates in valleys determined using fallout caesium-137. *Geol. Soc. Am. Bull.* **86**, 1128-1130.

Rogowski, A. S. & Tamura, T. (1970) Erosional behaviour of caesium-137. *Health Physics* **18**, 467-477.

Walling, D. E. & Bradley, S. B. (1990) Some applications of caesium-137 measurements in the study of fluvial erosion, transport and deposition. In: *Erosion, Transport and Deposition Processes* (ed. by D. E. Walling, A. Yair & S. Berkowitz)(Proc. Jerusalem Workshop, March 1987), 179-203. IAHS Publ. no. 189.

Walling, D. E. & Quine, T. A. (1991) The use of caesium-137 to investigate rates and patterns of soil erosion on arable fields in the UK: potential applications and limitations. *J. Soil Sci.* **42**, 147-165.