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Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry

ABSTRACT: In Northwestern and Central Spitsbergen geomorphological and botanical data were collected on slope deposits associated with infrequent meteorological events. In hillslope debris flows triggered by heavy rainfall, compact volumes of debris range from 1 to 600 m^3. Recurrence intervals of major episodes are tentatively estimated from lichenometry at 80 to 500 years. Such debris flows are widespread in Spitsbergen and induce conspicuous geomorphological effects. Nevertheless, typical levées and lobes are small-sized because of the thinness of permafrost and they rarely survive more than one century. In contrast, catastrophic slush avalanches mobilize 1300 to 7000 m^3 of rock debris every 500 years, forming long boulder tongues and fans. Such accumulations can been observed in much more restricted sites. In Central Spitsbergen at least three generations of slush avalanche deposits have been identified and lichenometry suggests that such boulder tongues survive for at least 2000 years. So the geomorphic impact of sporadic slush avalanches appears much more important than the effects of recurrent spring snow avalanches which do not generate original and long-lasting landforms. Botanical studies show that investigations of *saxicolous* lichen communities allow more reliable chronological reconstructions than observations of phanerogamic and bryophytic vegetation cover. *Rhizocarpon* diameters are partly interpreted from growth curves from Baffin Island and North Alaska. The results will be refined when a curve is published for Spitsbergen. Nevertheless, recurrence intervals proposed here seem to be consistent and are fruitfully compared with previous evaluations from Swedish Lappland and Colorado.

Key words: Arctic, Spitsbergen, geomorphology, lichenometry.

Introduction

Attention has been drawn to slope deposits resulting from extreme meteorological events by Rapp and Washburn in the 1950's (Rapp 1959, 1960; Washburn and Goldthwait 1958). These pioneer studies were followed by contributions concerning Swedish Lappland (Nyberg 1985) and Spitsbergen (Jahn 1976; Elfström 1978; Larsson 1982) as well as by general reviews (Starkel 1976; Innes 1983a). This paper focuses on new estimates of the recurrence intervals of debris flows and slush avalanches, based on a combination of geomorphological and botanical methods. Such evaluations can be compared to results from other Arctic areas and to the morphogenic impact of continuous processes which modify Arctic slopes with annual frequency. Such processes and especially small spring avalanches were recently examined and tentatively quantified (André 1988).

Five field seasons (1982—86) were carried out in Spitsbergen, the main island of the Svalbard archipelago characterized by a polar oceanic climate. In Longyearbyen (78°13'N, 15°35'E, 37 m a.s.l.) temperatures range from $-15°.3$C in February to $+6.3$°C in July, with an average annual temperature of -5.8°C (Steffensen 1982). Precipitation amounts to 208 mm. On the more exposed northwest coast, temperatures are about the same but precipitation is almost

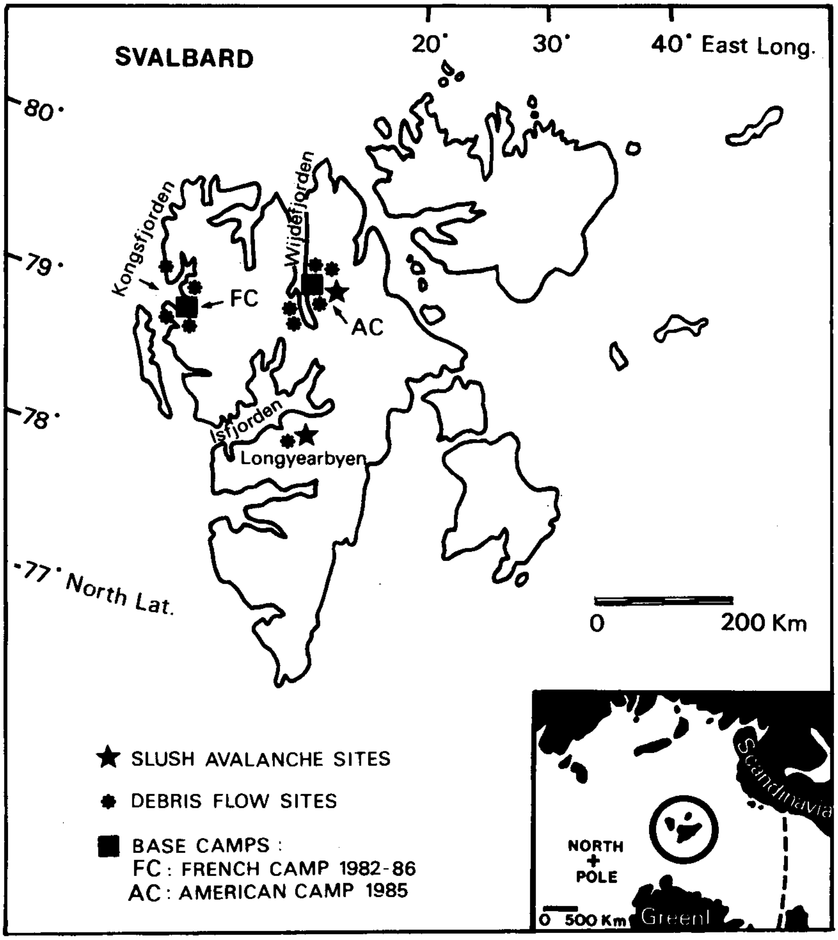

Fig. 1. Location map

double (385 mm in Ny-Ålesund, 78°55′N, 11°56′E, 8 m a.s.l.). Previous studies have been performed in the easily accessible Longyear Valley which provides striking landforms. Most of the author's observations have been done in two other parts of Spitsbergen located approximately at 79°N (Fig. 1). The northwest coast has been investigated from the French Base near Ny-Ålesund. In the Kongsfjorden area, summit elevations range from 600 to 900 m. The bedrock is composed mainly of Precambrian mica schists, quartzites and marbles, and secondarily of Permo-Carboniferous limestones. In the inner part of Spitsbergen, slope deposits were examined from the University of Washington base camp, settled along the Wijdefjorden. Here, most of the summits exceed 1000 m and include Perriertoppen (1717 m a.s.l.), the highest point of Svalbard. Rock walls are developed in Devonian red and green sandstones on the west side of the fjord and in Precambrian gneisses, amphibolites and quartzites on the east side.

Methods

An interdisciplinary approach. This magnitude-frequency study of debris flows and slush avalanches on Spitsbergen was performed by connecting geomorphological and botanical data. Such an approach has been used previously in Colorado (Curry 1966), Swedish Lappland (Karlén 1973; Rapp and Nyberg 1981), the Canadian Rockies (Sauchyn *et al.* 1983) and the Scottish Highlands (Innes 1983b). Fieldwork included classical studies of representative profiles, measurements of slope angles, calculations of surface covered with slope deposits, and detailed mapping (André 1987). Particular attention was given to the topographical and geological setting. Laboratory analysis of regolith and rock samples led to a better knowledge of parent materials of slope deposits. Relative chronology was established from the stratigraphy of these deposits, from their correlations with moraines and ^{14}C — dated marine terraces and from lichenometry. Moreover, vegetational data were systematically collected and concern:

— vegetation cover: estimates of the percentage of both the vegetation and the lichen cover led to the conclusion that the latter is far more reliable as a chronological indicator. Crustaceous lichens covering boulders are less dependent than phanerogams and mosses on variations in ecological conditions within a deposit, *e.g.* grain size and consequently water content (André 1989).

— floristic composition of plant communities, methods of reproduction and rates of colonization of different species: the Norwegian botanists I. Brattbakk and O. I. Rønning provided valuable help for the identification of numerous vegetal samples.

Lichenometry in Spitsbergen. — In 1984, both A. Werner (INSTAAR, University of Colorado) and the author initiated lichenometric studies in Spitsbergen. Werner is about to publish a preliminary growth curve for *Rhizocarpon* species (*pers. comm.*). Some taxonomy work has been done by the author with the valuable help of lichenologists Cl. Roux (University of Marseille) and S. Déruelle (University of Paris VI). The main results are presented here.

Lichen species. — Chemical tests and microscopic examination of spores reveal the occurrence of three groups of yellow *Rhizocarpon* in Spitsbergen:

a — *Rhizocarpon* section *Geographicum* (Runem.) Thoms.: this group is represented by the common species *Rh. geographicum* (L.) DC. (spores multiseptate, 20–70 × 10–25 microns, medulla I+ indigo). Three subspecies were identified: ssp. *arcticum* (Runem.) Hertel, ssp. *diabasicum* (Räs.) Poelt and ssp. *geographicum* Vezda.

b — *Rhizocarpon* section *Superficiale* (Runem.) Thoms.: this group seems to be widespread in Spitsbergen (Pl. 3, Fig. 1) where it is mainly represented by species Rh. superficiale (Schaer.) Vainio (spores 1 — septate, 11–18 × 6–8 microns, medulla P+ brick-red). Other species were identified like *Rh. effiguratum* (Anzi) Th. Fr., *Rh. pusillum* Runem, and probably Rh. *crystalligenum* Lynge (medulla K+ red).

c — *Rhizocarpon* section *Alpicola* (Runem.) Thoms.: this group is represented by a rather pale species, *Rh. inarense* (Vainio) Vainio (spores 1 — septate, 19–28 × 9–13 microns, medulla I–, P+ yellow), previously called *Rh. chionophilum* Th. Fr. This lichen can present unusual multiseptate spores scattered among typical 1 — septate spores as noted on Amsterdamöya (Hertel and Ullrich 1976). *Rh. alpicola* (Hepp.) Rabh. was reported in 1980 by lichenologist S. Déruelle at two sites in the Kongsfjorden area (*pers. comm.*). Nevertheless it was not found in the author's collection.

Sampling techniques have been described in previous papers (André 1985, 1986). Because of the small size of slope deposits investigated, the sampling area was only of 100 m^2. In every site, fifty of the largest thalli were measured, and for elliptical thalli, the minor axis was recorded. According to Lock *et al.* (1979), the maximum diameter was determined from the five largest diameters after eliminating anomalous lichens. Measurements of *Rhizocarpon* belonging mainly to *Geographicum* and *Superficiale* sections were completed with observations of a faster growing black filamentous lichen, *Pseudephebe minuscula* (Nyl. *ex*Arnold) Brodo et Hawksw. previously *Alectoria minuscula* (Nyl. *ex* Arnold) Degel.

Control points. — *Rhizocarpon* was not yet visible in 1984 on a moraine deposited by the surge of Kongsvegen in 1948. So it seems to require more than 30 years to colonize a substrate in Spitsbergen. Moreover, two control points were established by the author:

— a 100 year-old moraine behind the French Base in Kongsfjorden bears lichens reaching a 10 millimeter diameter (moraine photographed by Hamberg in 1892, Liestøl (*pers. comm.*);

— a maximum diameter of 22 mm was obtained on thirty-eight 350 year-old graves of English whalers on Prins Karl Forland.

These control points are consistent with the preliminary growth curve based on whaling stations and various monuments being established by Werner for Spitsbergen (*pers. comm.*). This curve is similar to those from Baffin Island (Miller and Andrews 1972) and North Alaska (Calkin and Ellis 1980), although lichen growth seems to have been faster in Spitsbergen at least for the last 100 years. The older part of the growth curve concerning periods older than 350 years is not controlled. Awaiting Werner's curve, the chronological data presented in the text and tables rafer to Baffin and Alaska curves. So these data only provide rough orders of magnitude for recurrence intervals of catastrophic events. For recent deposits, estimated ages must be regarded as maximum values.

Recurrence intervals of debris flows

Debris flow site and morphology. — Debris flows in Spitsbergen have been observed on slopes with different orientations and are associated with steep slopes exceeding 30–35° rather than with specific climatic conditions. In Wijdefjorden for example, the steep western side in Devonian sandstones is affected by a large number of debris flows. In contrast, the gentle eastern side is covered with moraines affected by gelifluction. Moreover, most of the flows investigated lie below the outlet of gullies and funnels, themselves usually aligned with fault lines. Debris flow cones present a concave profile, with slope gradients ranging from 4 to 25°.

Debris flows in Spitsbergen are characterized by typical levées extending alongside channels. Length of channels is 40 to 150 m, width 0.3 to 5 m and depth 0.3 to 2 m. Channels are at least temporarily drained from snow patches persisting late in the summer inside gullies upslope. Surface water rapidly seeps into lobes and cones, emerging downslope where fine-grained colluvial deposits are colonized by hygrophilous vegetation. Plant communities are frequently characterized by mosses like *Aulacomnium palustre*, horse-tails such as *Equisetum variegatum* and cotton grass like *Eriophorum scheuzeri* (André 1989). Levées are 0.5 to 2 m wide and 0.1 to 0.5 thick. At the distal end of many flows, single or finger-like lobes are developed. They often present a convex front, well outlined when overlying subhorizontal vegetated marine terraces (Pl. 2).

Length of lobes varies between 10 and 100 m, width is 2 to 35 m and thickness 0.1 to 1.5 m, most often about 0.3 m. It corresponds to an accretion of debris ranging from 65 to 1000 mm, or 200 mm on average.

Total volume of lobes varies between 1 and 600 m^3. These flows belong to the small-scale hillslope flow type defined by Innes (1983a). Their small size can be explained by the proximity of the permafrost table to the ground surface during the summer on the west coast of Spitsbergen. A thin active layer then provides only small volumes of debris for remobilization and deposition. As shown by many authors such as Nyberg (1985), permafrost is one of the internal factors of debris flow processes because it prevents water from percolating. When heavy rainfall occurs, the excess of water which cannot be absorbed by a too thin regolith initiates slides and flows like those which crossed roads in Longyearbyen in 1972 (Fig. 2, from Larsson 1982): on 10 – 11

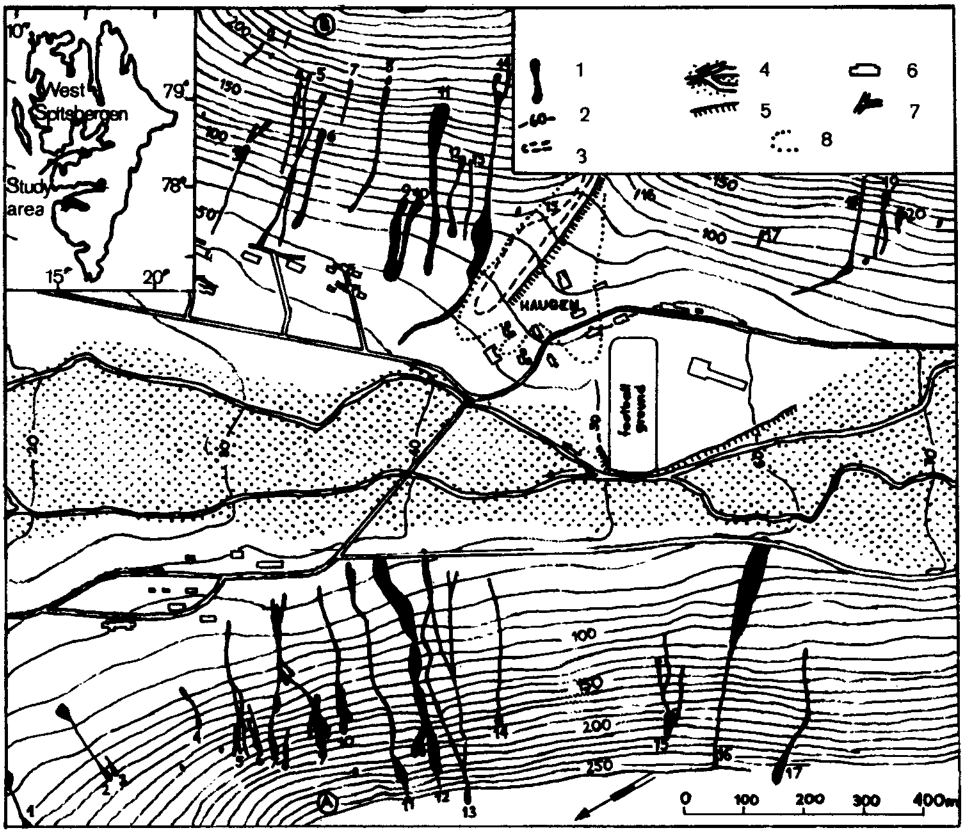

Fig. 2. Debris flows in Longyear Valley, Spitsbergen 1972; map by Stig Larsson
1 — slide scar with debris flow and colluvial fan, 2 — contour line, 3 — approximate flow margin 1972, 4 — stream sandur area, 5 — artificial fill, 6 — house, 7 — road, 8 — limit of slush avalanche 1953

July, a 12-hour rainstorm brought 31 mm of rain, *i.e.* 10 mm more than the average monthly fall for the period 1957–1976 (Steffensen 1982). Meteorological and geological conditions of this extreme event were analyzed by Thiedig and Kresling (1973). The morphogenic impact of this spectacular event has also been described by Jahn (1976), Elfstrøm (1978), Larsson (1982) and Rapp (1985).

The granulometric heterogeneity of the regolith is another condition which favours the mobility of the loosely interlocking clasts (Nyberg 1985). Lobes and levées resulting from the mobilization of frost-shattered debris present poorly sorted material consisting predominantly of sand, gravel and boulders up to 0.3 m in length for mica schist and 1 m for gneiss and amphibolite. Some small lobes are composed of sand and gravel, most debris ranging from 1 mm to 5 cm. Nevertheless, most of the flows observed comprise many boulders in a sandy matrix. Granulometric analysis of the fine-grained part of the lobes (less than 2 m) reveals 75 to 95% of sand and a low clay content: 1% or less in metamorphic Precambrian rocks, 5% in soft Permo-Carboniferous limestones and up to 20% in Tertiary coal-bearing shales. No preferred orientation of blocks has been generally observed, except in two sites where elongated stones tend to be aligned in the flow direction of the lobes.

Vegetation and chronological data. — In Spitsbergen most of the small-scale lobes and levées investigated seem to be short-lived landforms. In this widely glaciated arctic island, we observed no equivalent of debris flow cones showing many generations of distinct lobes like those from Swedish Lappland (Rapp and Nyberg 1981). Levées are rapidly obliterated by spring avalanches. Moreover, because of the evacuation of their fine-grained matrix by active throughflow, lobes tend to collapse and to be incorporated within the cones. Life duration of these small-scale landforms usually does not exceed one century and even thirty years. No slow growing lichens such as *Rhizocarpon geographicum* can be observed on the majority of these distinct lobes. Some exceptions do exist but they involve only the largest debris flows. In Longyearbyen for example, smooth 600-year old lobes are preserved below a dense tundra vegetation (coverage up to 75%) composed of *Dryas octopetala, Cassiope tetragona* and *Salix polaris,* with boulders colonized by *Rhizocarpon* of 30 mm in diameter. In Central Spitsbergen at the bottom of a large alluvial cone with debris flow morphology, old channels are mantled with *Cassiope tetragona.* Boulders bear *Rhizocarpon* up to 63 mm indicating a possible age of *ca.* 1,800 B. P. Such exceptions are rare and botanical studies are necessary to distinguish the different generations of deposits forming the cones.

Plant colonization of debris flows. — On large scale aerial photographs, differences in colour intensity due to variations in plant cover can be seen. To interpret them, it is necessary to take into account the type of rock. On light-coloured rocks such as limestone and leucocratic gneiss, slope deposits appear darker as they are more vegetated. In contrast, in dark mica schist and amphibolite, very dark debris flows are very fresh, with lichen-free boulders and much fine-grained matrix, especially in schists. The floristic composition of plant communities is interesting to follow the stage of colonization in the most recent deposits. Within the first thirty years after the deposition of mica schistous and quartzitic debris flows, three stages can be observed:

1. No vegetation at all (only a few years?).
2. Scattered pioneer species such as the moss *Rhacomitrium canescens* and the phanerogam *Saxifraga cernua*, of which small bulbs behaving like small stones are adapted to the mobility of the environment .
3. A pioneer plant community comprising the two species already mentioned as well as *Stereocaulon* sp., *Oxyria digyna, Saxifraga oppositifolia* and *Papaver dahlianum.* These two last plants show well-developed root-systems and runners allowing them to resist burial (André 1989).

Later on fast and slow-growing lichens will start colonizing boulders and these saxicolous lichen communities will be more useful than the rest of the vegetation, as chronological indicators. When evolving, the phanerogamic and bryophytic vegetation depend on local ecological conditions which strongly vary within a slope deposit. For example, in the same distal end of an old cone, the vegetation coverage ranges from 0% where no fine-grained matrix appears, to almost 100%. For as soon as such a matrix is present, the flow is colonized by an abundant vegetation associating phanerogams like *Dryas octopetala, Saxifraga oppositifolia, Pedicularis dasyantha, Silene acaulis* and *Cassiope*

Debris flow lobes tentatively dated by lichenometry in Spitsbergen. Estimated ages partly refer to 1980) in

Location	Elevation	Orientation	Lithology	Slope gradient	EPISODE A		
					Lichen cover	Max. Diam. Rhizocarpon	Age BP
ISFJORDEN Longyeardalen	150–200 m	ESE	Sandstone	3–25	-	-	-
AUSTFJORDEN Tryggvebreen			Gneiss Amphibolite Quartzite	18–25	-	-	-
KONGSFJORDEN Feiringfjellet	80–200 m	SSW	Mica schist Quartzite	10-18	55%	61 mm	1780 *1740*
WIJDEFJORDEN Reinsbukkdalen *Alluvial cone*	75–140 m	S	Gneiss Quartzite Amphibolite	5–10	70%	63 mm	1870 *1810*

tetragona, fruticose lichens such as *Cetraria nivalis* and *Thamnolia vermicularis* and mosses like *Rhacomitrium lanuginosum.* Variations in the colonization pattern due to textural differences are common. Sandy and gravelly levées may be vegetated whilst the central channel is floored by lichen-free boulders. In contrast, blocky levées are frequently lichen-free while sandy material trapped in the central channel is densely vegetated. Another disturbing factor for the interpretation of vegetation data is the frequent occurrence of bird-cliffs inducing an abundant nitrophilous vegetation. On cones located below, vegetation cover close to 100% is devoid of chronological meaning, for it corresponds to a 20-cm carpet of mosses and *Cochlearia officinalis* induced by the abundance of guano. The pattern of plant colonization also depends on the existence of a removal agent downslope. When cones are distorted and removed as lateral moraines by glacial tongues like Pedersenbreen, very little vegetation can be seen at the surface of cones, for they are continuously reactivated, and too rapid a material turnover prevents boulders from colonization by slow-growing lichens. In contrast, debris flow cones happen to overlie marine terraces or "Little Ice Age" moraines separated from the present-day glacier, as along Midre Lovenbreen. In that case plants have enough time to colonize slope deposits, and vegetation covering is usually far superior.

Generations of debris flows. — As chronological indicators, the percentage of lichen cover and the lichenometric data seem to be much more reliable than the floristic composition of the whole plant community. *Rhizocarpon* species are

Table 1

growth curves from Baffin Island (Miller and Andrews 1972) and North Alaska (Calkin and Ellis italics

GENERATIONS OF DEBRIS FLOWS								
EPISODE B			EPISODE C			EPISODE D		
Lichen cover	Max. Diam. Rhizocarpon	Age BP	Lichen cover	Max. Diam. Rhizocarpon	Age BP	Lichen cover	Max. Diam. Rhizocarpon	Age BP
50%	30 mm	600 *680*	20%	10 mm	60 *80*	0%	0 mm	0
40%	27 mm	480 *560*	15%	12 mm	80 *120*	0%	0 mm	0
35%	27 mm	480 *560*	15%	13 mm	100 *130*	0%	0 mm	0
40%	33 mm	730 *800*	10%	11 mm	70 *100*	0%	0 mm	0

represented in Spitsbergen on all substrates except carbonates. Three and sometimes four generations of debris flow deposits have been distinguished in Spitsbergen (Table 1, Fig. 3), namely starting from the present-day well-defined flows:

1 — EPISODE D: characterized by the absence of lichen cover on boulders and by sparse pioneer phanerogams and mosses if any, these recent lobes and levées are not older than 30 to 40 years. This corresponds to the minimal period required in Spitsbergen for a substrate to be colonized by *Rhizocarpon*.

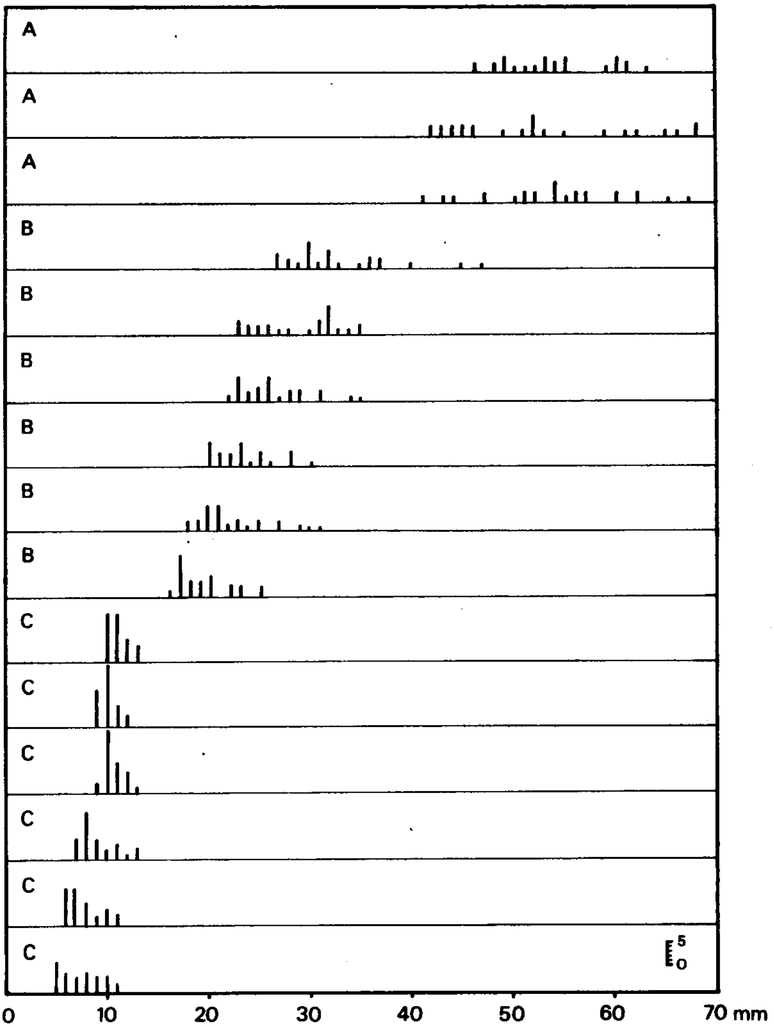

Fig. 3. Diagrams of largest diameters of *Rhizocarpon* on three generations of debris flows from Spitsbergen (Wijdefjorden, Isfjorden and Kongsfjorden areas). The twenty largest diameters recorded in every 100 m^2 plot are presented

2 — EPISODE C: from lichenometric data showing *Rhizocarpon* up to 10–13 mm in diameter, this episode dates back to *ca.* 80 B.P., namely the end stage of the "Little Ice Age". An average lichen cover of 15% is associated with the occurrence of a typical community on siliceous boulders characterized by the following species: *Pseudephebe minuscula, Umbilicaria decussata* and *U. cylindrica, Parmelia* sp. and *Rhizocarpon* sp.

3 — EPISODE B: boulders are colonized by *Rhizocarpon* of up to 30 mm providing an estimated age of 600 years B.P., which coincides with an early stage of the "Little Ice Age". Lichen cover rises up to 40%, with similar species locally associated with a type of *Usnea, Neuropogon sulphureus.*

4 — EPISODE A: this older generation is little represented in Spitsbergen, only at the base of some well-developed cones. In such locations, *Rhizocarpon* diameters exceed 60 mm and lichen cover reaches 70% except on weathered mica schistous boulders. The saxicolous plant community remains the same, together with abundant rusty crustaceous lichens such as *Lecidea dicksonii.* These oldest deposits possibly date back to *ca.* 1,800 B.P. Lignified and whitened tufts of moss have been found in an old flow. They had been uprooted and mixed with the mineral debris during the transport. No radiocarbon dating has been obtained from moss samples as yet. More generally, it is noticeable that this kind of uprooted moss frequently visible in debris flows seems to remain green-coloured even in 100-year deposits, probably because of the slowness of organic decomposition in cold areas. Nevertheless, the possibility of contamination by recent vegetal debris cannot be excluded.

Anyway, this *ca.* 1,800 B.P. estimated age for oldest debris flows appears reasonable. Indeed, these deposits frequently dissect or overly lobate rock glaciers tentatively dated using lichenometry to 3,400–3,200 B.P. in Central Spitsbergen and on the northwest coast (André 1987, 1989). The initiation of rock glacier activity might date back to the Neoglacial episode of 3,500–2,000 B.P. following the Holocene climatic optimum (Baranowski 1977, Punning *et al.* 1982). In other places, debris flow cones rest on marine terraces situated in the southern part of Bröggerhalvöya between 29 and 37 m. These raised shorelines date back from 11,940 ± 180 to 9,745 ± 155 B.P. (Forman *et al.* 1987). On the west side of Austfjorden, debris flows overly marine deposits at various altitudes. ^{14}C datings provide ages ranging from 8,620 ± 90 to 7,470 ± 90 B.P. (Mann *et al. in press*). Assuming that data concerning old flows are insufficient, recurrence intervals of major debris flows can be estimated at 80 to 500 years. These catastrophic events do not exclude the occurrence of minor episodes in the meantime. One of those less spectacular morphological events took place in Longyearbyen in 1981, namely nine years after the major 1972 episode (Akerman *pers. comm.*, Rapp and Nyberg 1981, Larsson 1982). It is noteworthy if not surprising that rain-triggered debris flows cannot be connected with climatic variations since they occur as much during "temperate" as during Neoglacial Holocene stages.

Frequency of major slush avalanches

Site factors and depositional forms. — While a helicopter flight over Spitsbergen reveals that debris flow tracks are widespread in Spitsbergen, slush avalanche sites appear much more restricted. Those have been described previously in the Hornsund and Longyearbyen areas (Czeppe 1966, Jahn 1967). In this area, the 1953 disastrous slush avalanche destroyed the buildings of a hospital, killing three people and injuring twelve others. Two new sites have

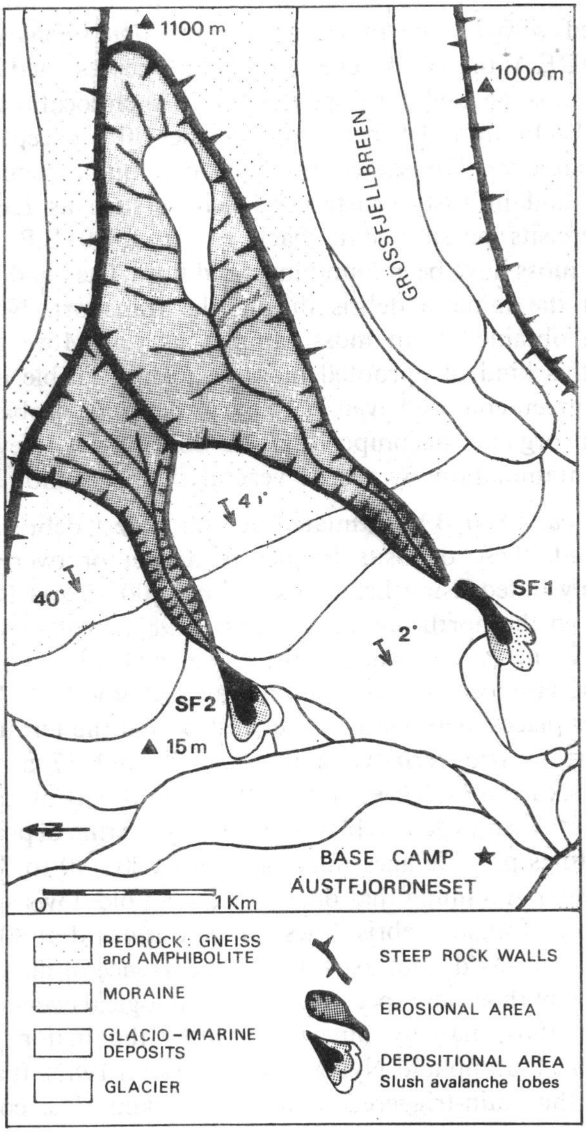

Fig. 4. Site of two slush avalanches in Central Spitsbergen, east side of Wijdefjorden

been investigated in Central Spitsbergen in 1985 from the Base Camp of the University of Washington (Fig. 1). Located on the east side of Austfjorden, which is the southern branch of Wijdefjorden, slush avalanche sites are two kilometers apart, allowing a direct comparison of data. As in most similar deposits (Rapp 1960, Jahn 1967, Nyberg 1985), the two avalanche deposits are developed at the outlet of narrow gullies locking a glacial cirque or a wide funnel located upslope (Fig. 4). The retention of spring meltwaters in such a collecting basin is known to be followed by the sudden release of water-saturated snow. It takes place as soon as the ice jam blocking the basin gives way.

The depositional area consists of fans formed by superimposed avalanche boulder tongues. These extremely flat accumulations are developed on very gentle slopes of about 2° in glacio-marine deposits. The global size of slush avalanche deposits ranges from 400 to 600 m in length and 30 to 300 m in width. The surface of single tongues varies between 10,000 and 60,000 m^2. Their thickness is highly variable, from 0.1 to 1.3 m. Because of the loose interlocking of the very heterometric debris which include scattered boulders, 0.2 m seems a reasonable average thickness. This corresponds to an approximate accretion of debris of 130 mm. Assuming this evaluation is correct, that would mean an average debris volume for each individual slushflow ranging between 1,300 and 7,000 m^3. The chaotic surface of slush avalanche deposits comprises gneissic and amphibolitic boulders up to 2.6 m in length and 1.5 m in width. More generally, the average size of boulders is 0.3 m. They are mixed with gravel and fine-grained material. This matrix (less than 2 mm) is composed of 86% sand, 11% silt and less than 3% clay.

Vegetation cover and lichenometry. — Differences in vegetation within slush avalanche deposits have been reported in Steinvikdalen – Southwest Spitsbergen, close to the Polish Base of Horsund (Jahn 1967). Nevertheless, accurate vegetational data are lacking. In 1985, detailed observations were collected in the two slushflows (SF 1 and SF 2) from Austfjorden. The floristic composition of plant communities, and above all lichen cover studies and measurements of *Rhizocarpon* diameters led to distinguish three and even four generations of flows (Table 2; Pl. 3, Fig. 1; Pl. 4, Figs. 1 – 2) starting from the most recent one:

1 — EPISODE D: the youngest slushflow is dissected by drained channels phasing into throughflow within the deposit. Numerous vegetal debris like tufts of uprooted moss have been mixed with rock debris during the transport. Boulders are lichenfree, which means that the avalanche took place within the last thirty years. Between the boulders vegetation is sparse, with a coverage ranging from 0 to 25%. When vegetation is not completely lacking, it is characterized by pioneer phanerogams like *Festuca* sp. A more complex plant community can be present, including *Saxifraga cernua, S. oppositifolia, S. cespitosa, Polygonum viviparum* and *Draba* sp. Alongside drained channels grows an hygrophilous plant community with typical species like horse-tails

Tentative datings of slush avalanche deposits

Elevation	Orientation	Lithology	slope gradient	Site	EPISODE A		
					Lichen cover	Max. Diam. Rhizo-carpon	Age BP
15 m	SW	Amphibolite Gneiss	2°	SF 1	≥ 50%	≥ 60 mm	≥ 1740 ≥ *1700*
				SF 2	≥ 50%	55 mm	1530 *1530*

(*Equisetum arvense*) and mosses such as *Orthothecium chryseon* and *Aulacomnium turgidum.*

2 — EPISODE C: the fine-grained matrix does not show any significant change in the granulometry of the deposit. Its $CaCO_3$ content is twice as high as in the most recent slushflow (1.6% instead of 0.8%). Nevertheless such a difference may be explained by variations in ecological conditions. Vegetational data appear more significant from a chronological point of view: lichen cover on boulders rises up to 20% and corresponds to the same saxicolous community as in debris flows: *Rhizocarpon geographicum, Pseudephebe minuscula, Umbilicaria decussata* and *Parmelia intestiniformis. Rhizocarpon* maximum diameters reach 25 mm providing a possible age of *ca.* 400 B.P. Vegetation cover between boulders is very high, up to 75%. The most common plant community is dominated by phanerogams (*Dryas octopetala, Pedicularis hirsuta, P. dasyantha, Salix polaris, Carex rupestris, Polygonum viviparum, Draba* sp., *Saxifraga oppositifolia* and *S. cespitosa*) and terricolous lichens (*Stereocaulon* sp., *Ochrolechia frigida* and *Leciophysma finmarkicum*).

3 — EPISODE B: present only on SF 1—probably because preserved from burying—this slushflow bears *Rhizocarpon* up to 38 mm in diameter, indicating a possible age of *ca.* 900 B.P. Lichen cover rises up to 40% while vegetation cover is decreasing from 75% (episode C) to 40% because of aeolian deflation. The plant community is similar to the one from episode C.

4 — EPISODE A: lichen cover exceeds 50% on blocks in the oldest slushflows, with *Rhizocarpon* diameters reaching 55 to 60 mm. Therefore such deposits possibly date back to *ca.* 1,700—1,500 B.P. Plant communities both on and between boulders do not differ from those colonizing younger slush avalanche deposits. Longer wind deflation led to the clearing of the vegetation cover, lowering coverage to less than 35%, with wind-eroded and necrosed tufts of *Dryas octopetala.*

The similarity of the two slushflows both in their site and morphology suggests that they were originated during the same four episodes. In one case

Table 2

from lichenometry. Austfjordneset, Wijdefjorden

GENERATIONS OF SLUSH FLOWS								
EPISODE B			EPISODE C			EPISODE D		
Lichen cover	Max. Diam. Rhizo-carpon	Age BP	Lichen cover	Max. Diam. Rhizo-carpon	Age BP	Lichen cover	Max. Diam. Rhizo-carpon	Age BP
40%	38 mm	900 *940*	25%	24 mm	390 *480*	0%	0 mm	0
-	-	-	15%	25 mm	420 *510*	0%	0 mm	0

(SF 1) each of them left traces. In the second deposit (SF 2) it seems highly probable that episode B took place, but that the corresponding slushflow deposit has been either removed or fossilized below the following avalanche deposit. In Wijdefjorden the return period of such major slush avalanches can be estimated to 500 years. Such deposits connected with specific site conditions appear to be less frequent than debris flows. No slushflow seems to have occurred in the investigated area at the end of the "Little Ice Age" while such an episode is usually expressed in debris flow cones. No correlation of slush avalanches with climatic variations can be inferred since such deposits took place just as well during the "Viking period" as during an early stage of the "Little Ice Age".

Discussion and conclusions

1 — Frequency and geomorphological effects of debris flows

Deposits investigated in Spitsbergen belong to the small-scale hillslope flow type (Innes 1983), with compact volumes ranging from 1 to 600 m^3. Debris flows have clearly originated during infrequent meteorological events (Rapp 1960) rather than in connection with recurring spring snowmelt (Jahn 1976). Lichenometry provides evidence for such an interpretation. Recurrence intervals of major rainfall-triggered debris flows vary in Spitsbergen from 80 to 500 years. Such an evaluation is consistent with previous results: 50 to 400 years in Swedish Lappland (Rapp and Nyberg 1981), 150 to 400 years in the Tenmile Range, Central Colorado (Curry 1966) and 300 years in Japan (Iso *et al.* 1980). Nevertheless in certain sites of the Japanese Alps where climatic and geological conditions are favourable, debris flows become "normal" events. Indeed, in such locations return periods are reduced to five years (Ono and Watanabe

1986) and even a few months (Okuda *et al.* 1980). In Spitsbergen the average debris accumulation has been evaluated to 200 mm every 80 to 500 years. That corresponds to an annual accretion rate of debris ranging from 0.4 to 2.5 mm per year coinciding with the occurrence of one major debris flow episode per century. As hillslope flows are widespread in Spitsbergen, their geomorphic impact is important. In Swedish Lappland evaluation of the density of debris flow (7 per km^2, according to Nyberg 1985) shows that such deposits are 45 times more abundant than slush avalanche deposits. In Spitsbergen geomorphological effects are all the more striking as between major events, channels and lobes are reactivated during secondary episodes. Nevertheless, when debris flows are located at the outlet of gullies frequently scoured by spring avalanches, lichenometry shows that small-scale lobes and levées are short-living forms, their life span rarely exceeding 30–40 years. Recurrent avalanches scrape the surface of cones, supplying 0.04 to 2.5 mm of debris every spring (André 1988) and tend to rapidly smoothen debris flow morphology. In contrast when hillslope flows are developed on slopes without avalanche chutes above, deposits can be preserved longer, for several centuries and locally more than a millenary.

2 — Recurrence intervals and geomorphic impact of slush avalanches

Deposits observed in Central Spitsbergen present a compact volume of 1,300 to 7,000 m^3. They belong to the same type as catastrophic slush avalanches reported in the Alps (Allix 1924) and Norwegian mountains (Gaddefors in Rapp 1960). Lichenometry provides evidence for recurrence intervals of about 500 years for major episodes, agreeing with rough evaluations from Lappland (Nyberg 1985. In Svalbard few sites have been investigated because slush avalanche deposits are related to much more specific conditions than are debris flows, *e.g.* to drainage conditions. This has been previously reported in Lappland where the density of slushflows is very low, namely 0.15 per km^2 (Nyberg 1985). In Spitsbergen the average accumulation of debris can be estimated to 130 mm every 500 years. This corresponds to an annual accretion rate of about 0.3 mm. Such an evaluation agrees with results from Swedish Lappland: 0.4—0.5 mm/yr on average (Nyberg 1985), and 1 mm/yr as a maximum accumulation for Postglacial times (Rapp 1960). Such results are also comparable to the values which concern continuous processes like spring avalanches occurring annually in Spitsbergen (André 1988). If numerical values obtained for sporadic slushflows and annual spring avalanches are similar, geomorphological effects of these two types of avalanche are quite different. While spring avalanches continuously, albeit slightly reshape debris slopes, major slush avalanches create typical and long-lasting landforms. Lichenometry indicates that such landforms can survive about 2,000 years and possibly more, mainly because of their protected position. Indeed boulder tongues and fans extending on flat areas are frequently disconnected from the steep slopes and rock walls located above. Consequently, they are protected against frequent processes like avalanching and rock falling. Their morphology is globally preserved for they are only subject to frost-shattering and evacuation of some fine-grained material by throughflow. These processes together with plant colonization do not substantially modify the landforms, the surface of which is only slightly smoothened. The occurrence of a new major slush avalanche is the only type of geomorphological event able to remove or fossilize such deposits. On the whole slush avalanche deposits result from sporadic processes, locally important, originating long-lasting landforms.

These new results concerning the frequency of debris flows and slush avalanches will be refined when a lichen growth curve is published for Spitsbergen (Werner *in press*). Nevertheless, the orders of magnitude proposed here appear consistent and can be fruitfully compared with previous results from other Arctic and Alpine areas.

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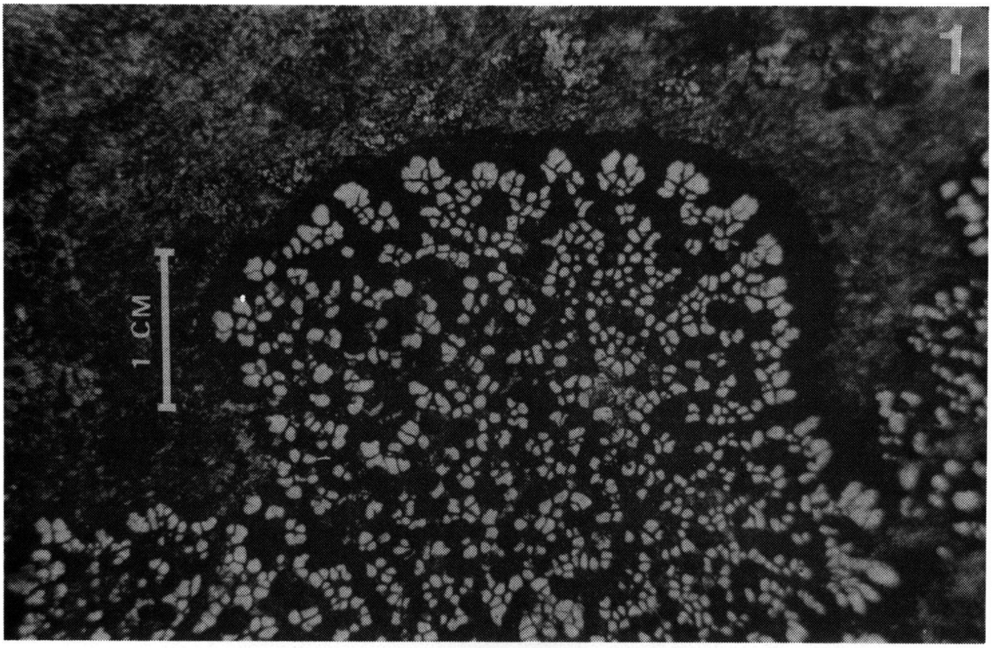
Streszczenie

W artykule przedstawiono dane geomorfologiczne i botaniczne zebrane z osadów stokowych północno-zachodniego i centralnego Spitsbergenu (Fig. 1). Spływ gruzowy spowodowany obfitymi opadami deszczu niesie ze sobą gruz, którego zwarte objętości wahają się od 1 do 600 m^3. Przedziały rekurencyjne głównych epizodów wstępnie oszacowano za pomocą lichenometrii na 80 do 500 lat (fig. 3, tab. 1). Takie spływy gruzowe występują często w całym Spitsbergenie wpływając na powstanie zauważalnych zmian geomorfologicznych (pl. 1—2, fig. 2). Należy jednak pamiętać, że typowe formy liniowe i loby są niewielkie i rzadko istnieją dłużej niż 100 lat. Natomiast katastrofalne spływy roztopowe występujące co 500 lat, niosą ze sobą od 1300 do 7000 m^3 gruzu skalnego i tworzą długie jęzory rumowiskowe i stożki. Taką akumulację można zaobserwować tylko w nielicznych miejscach (fig. 4). W centralnej części Spitsbergenu zostały oznaczone co najmniej trzy generacje osadów z lawin roztopowych (pl. 3—4); a pomiary lichenometryczne wykazują, że tego typu jęzory rumowiskowe mogą istnieć co najmniej 2000 lat (tab. 2). Tak więc geomorfologiczny wpływ sporadycznych lawin roztopowych okazuje się być ważniejszy niż efekt powtarzających się lawin śnieżnych, w wyniku których nie powstają trwałe formy lądowe.

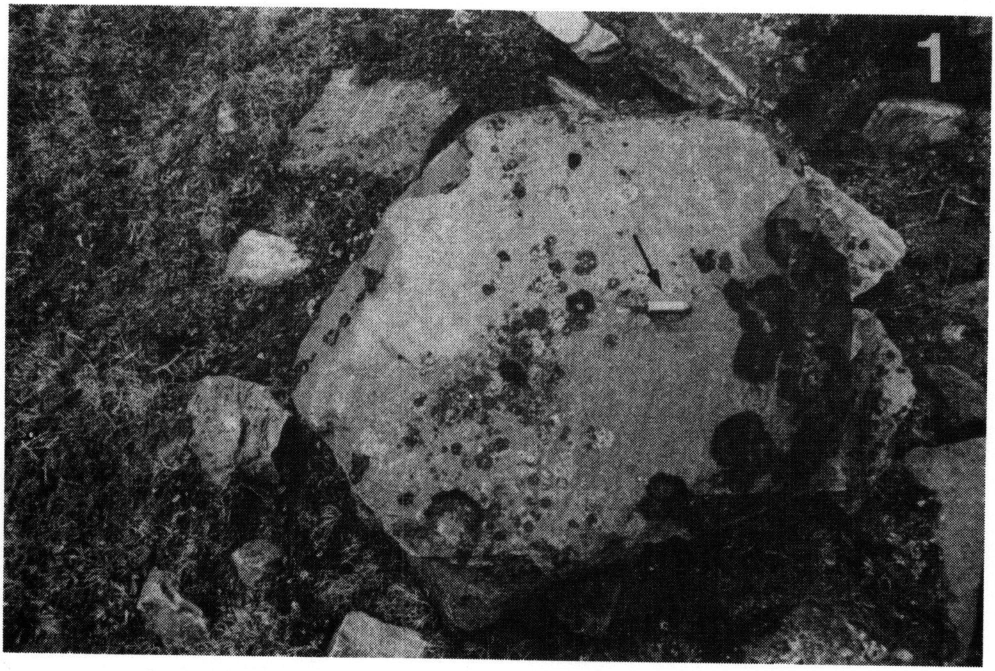
Studia botaniczne dowodzą, że badania zbiorowisk porostów *saxicolous* pozwalają na bardziej wiarygodną rekonstrukcję chronologiczną niż obserwacje pokryw roślinnych utworzonych przez mszaki i rośliny nasienne. Interpretację *Rhizocarpon* (pl. 3) przeprowadzono częściowo w oparciu o krzywe wzrostu z Wyspy Baffina i Północnej Alaski. Wyniki te zostaną zweryfikowane gdy taka krzywa będzie opublikowana dla Spitsbergenu. Pomimo tego przedziały rekurencyjne (cykle) zaproponowane tutaj wydają się być zgodne i w pełni porównywalne z wynikami uzyskanymi w szwedzkiej Laponii i Kolorado (USA).

Recent rainfall-triggered debris flows at the outlet of gullies developed in Carboniferous limestones, Engelbukta, Northwest Spitsbergen

Distal end of a recent debris flow lobe overlying a vegetated marine terrace, west side of Wijdefjorden



1 — *Rhizocarpon* Group *Superficiale,* id. Cl. Roux, Univ. of Marseille. 2 — lichen-free boulder in the most recent slushflow (Episode D)



1 — fast-growing black lichen *Pseudephebe minuscula* colonizing the intermediate slushflow (Episode C), 2 — slow-growing *Rhizocarpon* species reaching a maximum diameter of 55 mm in the oldest slushflow (Episode A)