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Sedimentation of fluted moraine in forefields of glaciers in Wedel Jarlsberg Land, Spitsbergen

ABSTRACT: Fluted ground moraine deposits in the forefield zones of the Blomli, Scott and Renard glaciers were investigated. It was found that the fluted moraine crests, especially the stone-rich ones, continue on the glacier front surface as cones or stony belts. The linear ablation forms, partly filled by the supraglacial sediment, are the extensions of the crests formed from the finer material. Thus, the opinion is expressed that the ribs and furrows at the top surface of the ground moraine are the result of the supraglacial material deposition and that they reflect the differentation of the ablation relief of the front surface of the recessing glacier. Till now the fluted relief origin was joined exclusively with the subglacial conditions and such forms were considered as the indicators of the glacier movement direction.

Key words: Arctic, Spitsbergen, sedimentology, fluted moraine.

Introduction

The field studies were performed in June—August 1987 during the 2nd Polar Expedition organized by the Maria Curie-Skłodowska University of Lublin, Poland.

The forefield sediments of Blomli, Scott and Renard glaciers in the north-western part of Wedel Jarlsberg Land in Spitsbergen (Fig. 1) were the object of the author's studies. Special attention was paid to the so-called fluted ground moraine deposits and their relation to the supraglacial sedimentary covers of the glaciers fronts.

The mentioned glaciers occupy three neighbouring valleys in the studied area. The smallest western valley, partly occupied by Blomli Glacier, opens to the north, to Bellsund Fjord. The other two valleys: the vaster one with Scott Glacier and the largest one with Renard Glacier, open to NE, to Recherche Fjord (Fig. 1). All the mentioned valleys have a distinct slope asymmetry: steep western slopes with most intensive development of talus cones (Nitychoruk and Dzierżek 1988), and easier eastern slopes. The rockfalls from the steep valley slopes submit in a significant degree the clastic material on the glacier surface (Fig. 1). The valleys were cut in rocks of the epimetamorphic Hecla Hoek Formation (Hjelle *et al.* 1969, Flood *et al.* 1971). The following mountain ridges rise above this area, from the west to the east: Halvorsenfjellet, Wijkanderberget, Bohlinryggen and Activekammen, being the waters and ice divides.

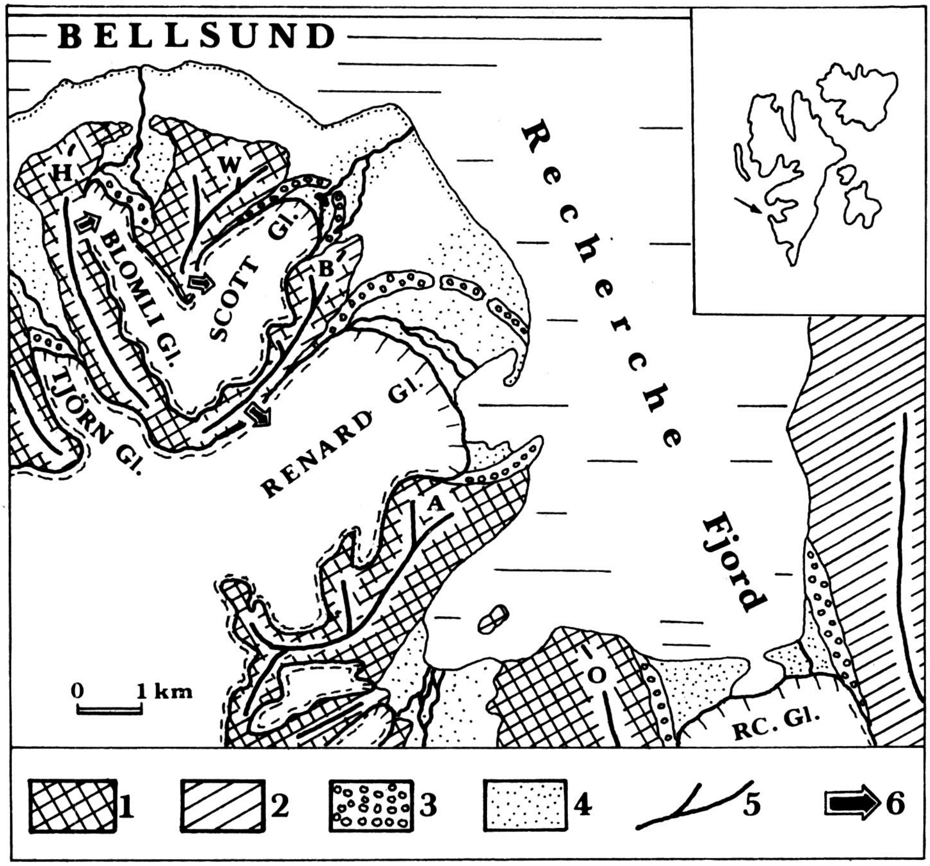

Fig. 1. Location map of the investigated area (arrowed) in Spitsbergen; 1 — rock outcrops of the Hecla Hoek Formation, 2 — outcrops of the Permian-Mesozoic rocks, 3 — moraines, 4 — sedimentation area of the gravel-sandy deposits, mainly sandurs and beaches, 5 — mountain ridges: H — Halvorsenfjellet, W — Wijkanderberget, B — Bohlinryggen, A — Activekammen, O — Observatorfjellet, 6 — places of the intensive slope processes submitting the clastic material on the glacier surface, RC Gl — Recherche Glacier

The glaciers of the NW part of Wedel Jarlsberg Land have been retreating since years, continuously enlarging their forefield areas.

Field observations

Blomli Glacier

Glacier front zone. — The bilobate front of the Blomli Glacier occupies presently a position in the valley bend. Thus the glacier front has an oblique position with respect both to the valley and glacier axes (Pls 1, 2). The western valley frame in the glacier front region is a steep, several-tens-meters high wall of the Halvorsenfjellet massif (Pl. 2). Frequent rockfalls coming from this wall deposit (Fig. 2) on the glacier surface in its near-front part appreciable amounts of angular debris. The Blomli Glacier front of a concave-convex surface has significant decline about 30—35°. Its surface in the higher part is cut by ablation furrows, altering downwards into larger hollows filled with

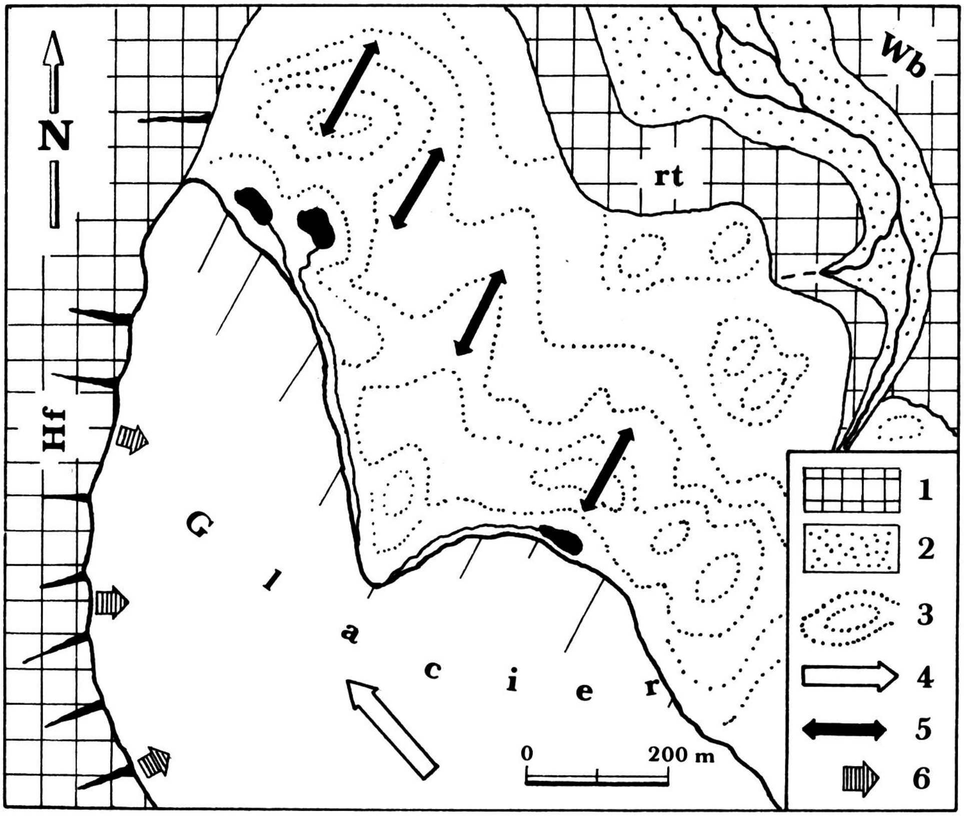

Fig. 2. Sketch map of the front zone and the forefield area of the Blomli Glacier: Hf — escarpment of the Halvorsenfjellet, Wb — Wijkanderberget, rt — rock threshold, 1 — Hecla Hoek Formation, 2 — sandur deposits, 3 — morainic morphology outline in the forefield zone, 4 — glacier movement direction, 5 — crest elongation, 6 — slope material yields

rock fragments (Pl. 3, Fig. 1), and finally into typical supraglacial debris cones (Fig. 3A). Such situation makes reasonable the supposition that the small linear ablation forms (Fig. 3B, a-b) visible in the upper part of the glacier front, transform gradually down the glacier front in ablation depressions of increasing dimensions (Fig. 3B, c-f).

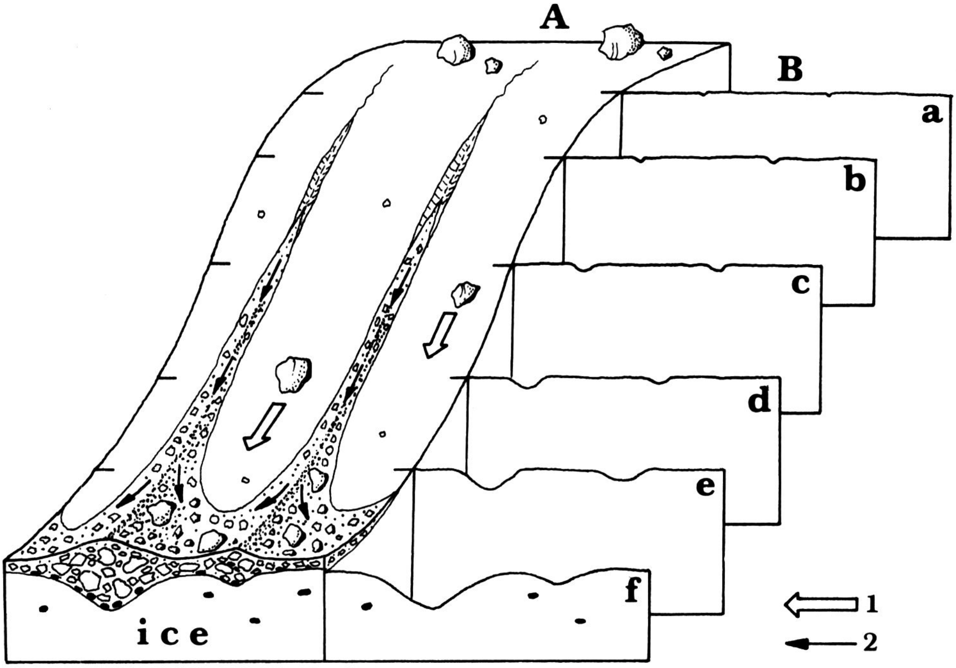

Fig. 3. Blockdiagram of a part of the Blomli Glacier front (A) and a sequence of the parallel cross-sections (B) showing the glacier surface with the supraglacial deposits omitted: 1 — gravitational rolling of boulders down the glacier surface, 2 — distribution of clastic material within the talus cones on the top surface of the glacier ice

During his field works the present author has observed twice the rockfalls from the steep wall of Halvorsenfjellet. The rockfalls of the evaluated volume of several cubic meters, crushed on the glacier surface to form smaller boulders and debris. Part of this material rolled down to the glacier foot. Another part, however, when rolling down, has met the proximal sides of the above mentioned cones, building them upward the glacier front.

During the arctic summer small marginal streams flow along the foot edge of the glacier in opposite directions and they supply in water small flood water basins (Fig. 2, Pl. 2) with underground outflows (Merta 1988a). Main outflow of proglacial waters from the Blomli Glacier takes place in the eastern part of the glacier front, leaving the forefield zone out of the effective glaciofluvial processes.

Forefield zone. — Forefield of the Blomli Glacier is an area of variable morphology (Fig. 2) covered with boulders and debris. Some of the boulders achieve the diameter over 2 m. This kind of material causes the morphologic features of a lower range are not recognizable during the direct penetration of the area. Only during the photogrammetric works (Ozimkowski and Merta 1988) on the phototheodolite images it was found, that the hills in the Blomli Glacier forefield are covered with a sequence of collinear ribs and furrows with the amplitude exceeding 1.0 m (Pl. 3, Figs 1, 2). Crest spacing is irregular. Orientation of these forms, as determined from glacier surface, is approximately parallel to the valley axis and independent of the surface shape they occur on (Fig. 2). Locally this fluted relief become obliterated in the zones of the zigzag channels, going generally across the crests (Pl. 3, Fig. 1). It is distinctly visible that above mentioned crests with boulders and coarse debris continue to the glacier front and, in spite of small break caused by a flow zone of the present-day marginal stream, they meet distinctly the supraglacial debris cones bases, occurring on the glacier front ice (Pl. 3, Fig. 1). Possibly the mentioned transversal zigzag channels indicate the previous glacier front positions and they were eroded by small marginal streams.

Undoubtedly the sedimentary cover with fluted relief in the Blomli Glacier forefield zone is a sediment formed mainly on the expense of the eroded wall of the Halvorsenfjellet massif. The sediment material formed originally the supraglacial debris cones, which are deposited on the forefield as crests during the succesive glacier recession.

Scott Glacier

Glacier front zone. — The Scott Glacier front is a smoothly sloping surface of the decline of few degrees. Its marginal edge goes along a long-radius curve across the valley, being over 1 km long in the front part (Fig. 4). Top ice surface in the front zone is furrowed by linear ablation to form a system of the trough-shaped forms and gutters of irregular spacing. These linear forms run down the glacier perpendicularly to its front. Approaching the glacier front, the described forms are filled in increasing degree by a supraglacial material with prevailing sandy and muddy fraction which remained after the glacier ice melting.

The most marginal part of the glacier front is covered by a thin continuous cover of the supraglacial deposits without any relief of the top surface. The border of this cover forms on the ice surface a "seismogram-like" line (Fig. 5A), what would suggest a continuation of the ablation forms under the sediment (Fig. 5B). In the NW peripheral part of the glacier front, the stone-rich supraglacial deposit is arranged in belts, which are slightly convex in the transversal cross-sections. The mean outflow of the proglacial waters takes place in the external SE part of the glacier front.

Forefield zone. — The Scott Glacier forefield is an amphitheatre-shaped depression bordered by frontal moraine, passing laterally in the lateral moraine arches (Fig. 4). Frontal moraine sediments form an accumulative superstructure of the rock threshold (Pękala 1987). Approximately in its central part, an erosional incision occurs, allowing the outflow of the proglacial waters from Scott Glacier to the sandur of Calypsostranda, and further to Recherche Fjord.

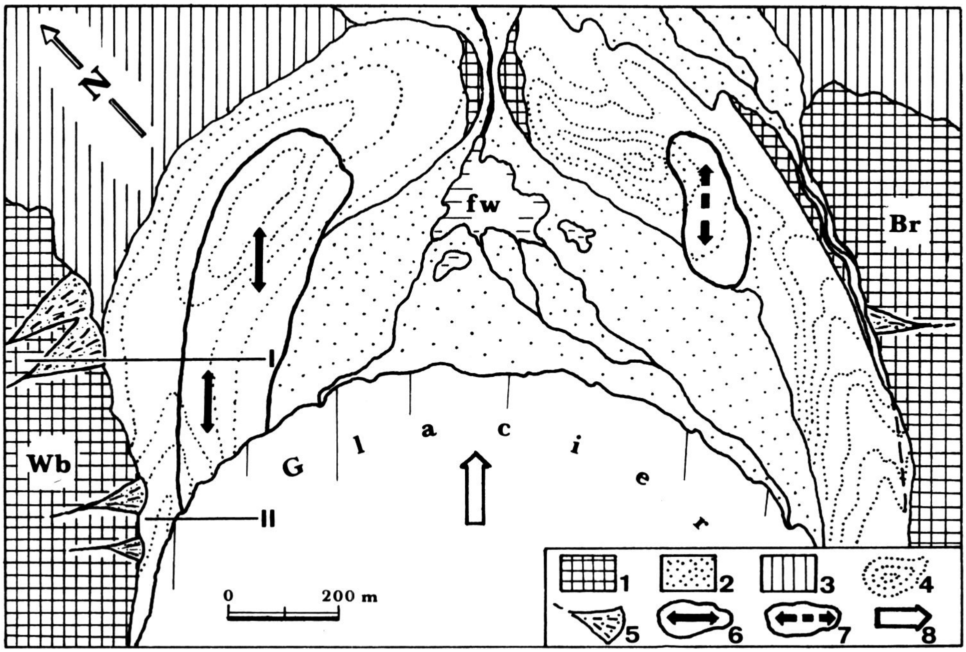

Fig. 4. Sketch map of the front zone and forefield area of the Scott Glacier: Wb — Wijkanderberget, Br — Bohlinryggen, fw — flood water basin, 1 — Hecla Hoek Formation, 2 — sandur deposits, 3 — surface of the raised marine terrace, 4 — morphological outline of the moraine ridge, 5 — talus cones, 6 — fluted maraine area with the distinct relief, crest elongation is bi-arrowed, 7 — area of the fluted moraine relic crests, crest elongation is given by the dashed bi-arrow, 8 — direction of the glacier movement, I and II — cross-sections, *see* Fig. 6

In the summertime a flood water basin occurs in the central part of the forefield (Merta 1988b), swollen by the main proglacial river and subordinate streams. This basin continuously changes its extent due to the "day-and night" changes of the water flow (*cf.* Bartoszewski 1988).

Fluted moraine. — The forefield area, except the fluvioglacial sedimentation zone, is covered with the ground moraine deposits with a characteristic

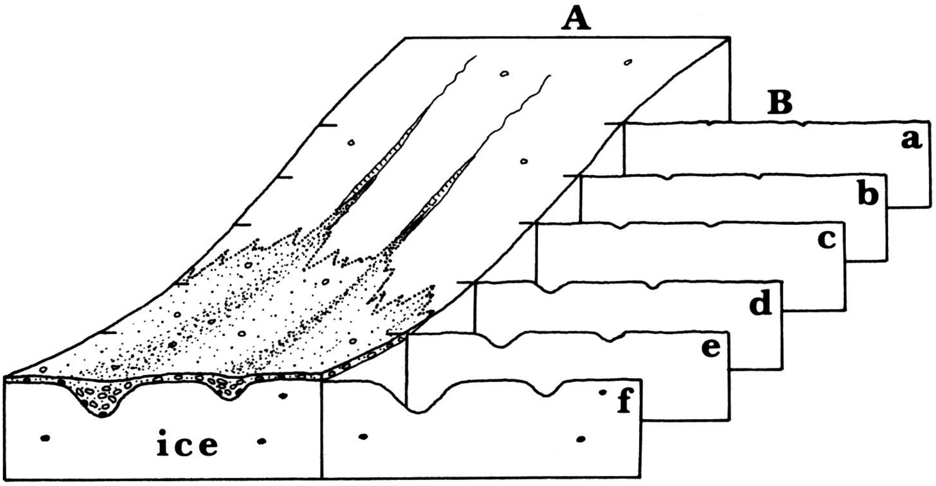

Fig. 5. Blockdiagram of the Scott Glacier front (A) and a sequence of the parallel cross--sections (B) showing the ice surface ablation relief with the supragalacial deposits omitted

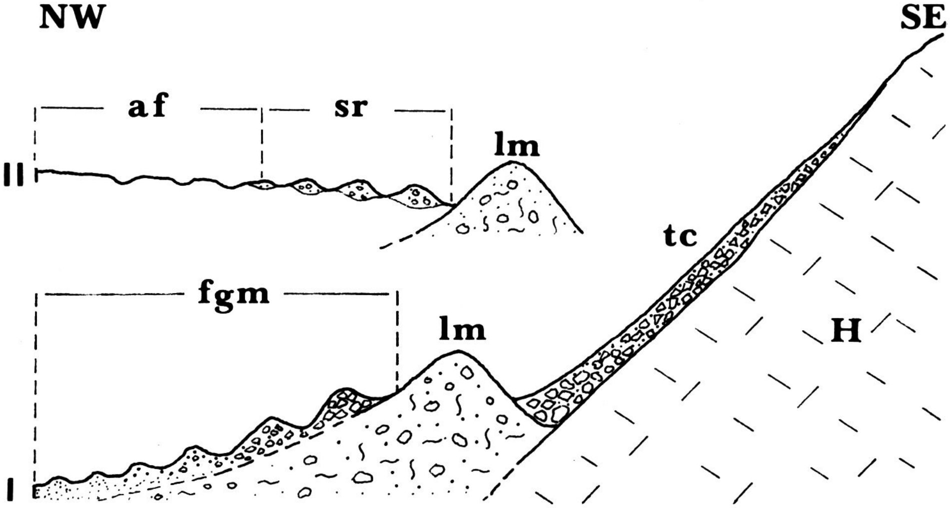

Fig. 6. Superimposed cross-sections through the forefield zone (I) and through the Scott Glacier (II), for the cross-sections location — see Fig. 4: H — Hecla Hoek Formation of the Wijkanderberget massif, lm — lateral moraine, tc — talus cone, fgm — fluted ground moraine, af — ablation furrows on the ice surface, sr — stone ridges or belts on the ice surface

fluted relief of the top surface. Fluted moraine with distinct ribs and furrows occurs only in the NW part of the forefield area. The ribs climb by a traverse up the stoss side of the moraine ridge, maintaining continuously the same direction approximately parallel to the valley axis (Fig. 4; Pl. 4, Fig. 2). Morphometry and lithology of the mentioned ribs are variable. The external crests, up to 50—60 cm high, are formed essentially from the angular and subangular boulders and debris, however, the crests closer to the axial zone of the forefield become distinctly lower, and their material is significantly finer (Fig. 6). The fluted moraine crests mentioned above approach the marginal edge of the glacier front; the external boulder-and-debris bearing crests extend on the front surface as the stone-rich belts, but the internal crests formed from the finer sediment fractions join the supraglacial deposits and on the glacier front surface they extinct as individual forms. Nevertheless, the linear erosional ablation forms appearing in the upper part of the glacier front, are presumably a continuation of such crests (Fig. 5). This direction convergence of linear ablation relief of the ice front top surface and ground moraine crests in the forefield zone is visible especially distinctly when one observes the glacier front and its forefield from the lateral moraine (Pl. 4, Fig. 1). In the SW part of the Scott Glacier forefield only the relic fluted ground moraine is noted (Pl. 4, Fig. 1, *see also* Fig. 4).

It is worth noting that the Scott Glacier top surface in its upper part is strongly enriched in the rocky material coming from the slope of the Wijkanderberget massif (Fig. 1). This material is transported in the supraglacial position to the glacier front region. The earlier mentioned stone-rich belts consist exactly of this material.

Renard Glacier

Glacier front zone. — This is the representative of the glacier type with the gradually decreasing ice thickness; it causes the top surface decline of the glacier front equal several degrees. The ice top surface shows a variable ablation relief, where besides the common linear troughs, there occur also sinusoidal channels *ca* 1.5 m wide and *ca* 1.0 m deep. Such larger forms usually do not achieve the glacier front marginal zone but they end earlier in the deep wells or fissures. Smaller ablation forms approaching the glacier front marginal zone, become gradually filled in increasing degree by a supraglacial sediment that formed during the glacier ice melting. The most frontal glacier zone, several tens meters wide, is covered continuously by supraglacial deposits. The border of this cover on the ice surface forms a "seismogram-like" line, similarly as on the Scott Glacier.

The mean outflow of proglacial waters occurs as a large subglacial river in the peripheral SE part of the glacier front, directly to Joseph Bay. Smaller proglacial streams flow out from under the glacier in several points. One of such stream, flowing out through a small glacier snout in the NW part of the front, at a significant distance runs along the ice marginal border as a proglacial marginal stream (Fig. 7).

Forefield zone. — The area in front of the Renard Glacier has several square kilometers. It is generally flat, slightly inclined toward the Recherche Fjord,

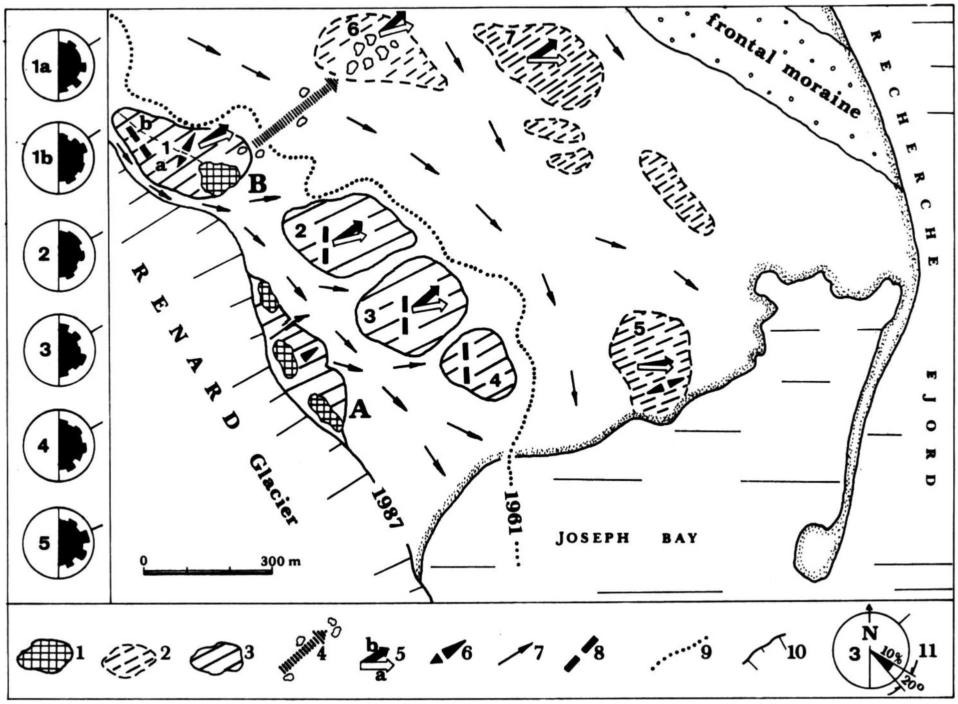

Fig. 7. Sketch map of the Renard Glacier forefield zone: 1 — exposed Hecla Hoek Formation rocks of the southeast (A) and northwest (B) thresholds, 2 — patches of the ground moraine with the degradated top surface fluted relief; dashed lines indicate the crest directions, 3 — ground moraine area with the distinct top surface fluted relief; the lines indicate the crest directions, 4 — boulder transport direction from the glacier-eroded threshold B, 5 — drumlin-like forms; a — boulder long axis orientation, b — tail orientation, 6 — slope decline, 7 — proglacial stream flow direction in the area of the sandur sedimentation, 8 — transverse crest orientation, 9 — glacier front position in 1961, 10 — glacier front position in 1987, 11 — measurements of the long axes orientations of boulders and stones in the half-circle projections; the number indicates the domain of the measurements and the external bar shows the crest elongations

thus in different direction than the glacier valley. From NE the forefield area is limited by a ridge of the frontal moraine (Fig. 1, Pl. 7). Eastern part of the forefield is flooded by Joseph Bay waters. The forefield fragment exposed due to recession of the Renard Glacier during the last twenty six years is especially interesting because of the distinct, fresh forms of the glacier accumulation. Directly before the glacier front, two large thresholds, the eastern and the western one (*A* in Pl. 5, Fig. 1, and *B* in Pl. 5, Fig. 2, respectively, *see also* Fig. 7), have been exposed. The thresholds are formed from rocks of the Hecla Hoek Formation. These rock thresholds are covered by a moraine deposit 50—60 cm thick. A part of the western threshold has no moraine cover (Pl. 6, Fig. 1). Boulders, glacier-derived from there, have been transported by the glacier over a significant distance. Appreciable amount of these boulders has been deposited several hundred meters from the threshold as a boulder mass (Fig. 7). Some of the boulders have probably come from more distant parts of the glacier valley bottom, because they have strong signs of the ice transport (Pl. 6, Fig. 1).

The forefield area is cut by a system of proglacial streams having migrating beds, that indicate an area of present-day sandur sedimentation (*cf.* Łanczont 1988). Extensive, several dozen centimeters high erosional remnants of an older sedimentary cover (Fig. 7, Pl. 5, Figs 1, 2) with typical fluted relief on the top surface protrude above the surface of the presently formed sandur (*a* in Pl. 9, Fig. 1).

Fluted moraine. — Ground moraine has got distinct parallel crests and grooves on the top surface. Average height of the crests ranges from 20 to 30 cm. Differences in the sediment structure can be observed; crests are formed from the material enriched in stones, whereas grooves have predominantly sandy and clayey material. The ground moraine with the fluted relief is present in the flat area of the forefield zone as well as on the stoss and lee sides of the thresholds. The fact should be emphasized that any difference neither in lithology nor in directions or height of the crests has been observed between the stoss and lee sides of the thresholds.

The crests have usually length of several dozen meters, and their spacing is irregular. Certain crests begin from an anchored boulder (*cf.* "flute initiating boulder" *sensu* Boulton 1976). Better developed crests have been observed in the part of the forefield area left by the glacier after 1961. Generally, the crest distinctiveness gradually decreases with the increasing distance from the glacier.

In the flat forefield part, the fluted ground moraine forms a cover *ca* 40 cm thick, protecting the underlying gravelly and sandy sandur deposits of an older stage (*c* and *b* in Pl. 9, Fig. 1, 2, respectively). The cover/sandur contact is a horizontal plane surface. The vertical sequence of the ground moraine deposits shows the distinctly higher content of stones in its upper part (Pl. 9, Fig. 2).

The fluted relief of the ground moraine in the most distal forefield part — *i.e.* left by the Renard Glacier before 1961 — is strongly degradated and the crests are marked only by linear concentrations of stones.

Orientation of the crests. — General orientation of the crests seems to be perpendicular to the present-day margin of the Renard Glacier front. Measurements of the crest orientation in various parts of the forefield indicate however, that the crest elongation directions fall in a certain azimuth range. In the forefield part exposed before 1961, the crests have azimuths 57—68°, and in the forefield area exposed after 1961 — 57—65° (Fig. 7). Thus, the conclusion made on the basis of the crest orientation measurements from larger areas shows that the crests are not exactly parallel, but they show a slightly radial orientation. The range given above for the fluted moraine crest azimuths differs distinctly from the general direction of the glacier movement as determined by the axis of the Renard Glacier valley with its azimuth *ca* 50.

Orientation of stones. — Only the stones with long axes exceeding 10 cm were measured. This study included stones that were visible on the ground moraine surface, both in crests and in grooves. The measurements were made essentially in the forefield area exposed by the glacier from 1961 till 1987 (the measurement domains 1—4 in Fig. 7). Special attention has been paid to the stone orientation measurements in fluted moraine of the different parts of the sedimentary cover of the threshold B, *i.e.* on the stoss and lee sides (domaines *1a* and *1b* in Fig. 7, respectively). As a comparison, the same measurements were made for stones from the fluted ground moraine with poorly visible crests (domain *5* in Fig. 7). A minimum of 150 measurements has been taken to construct each domain. The results are given on half-circle diagrams, with the projection of the stone long axes onto the horizontal plane (Fig. 7).

Fairly uniform distribution of the measurements indicates the absence of any preferred orientation of stone in ground moraine both with the distinct fluted relief and with the strongly modified one. Besides, stones on the stoss and lee sides of the threshold moraine cover have no preferred orientation as well.

Drumlin-like type forms. — In several places of the Renard Glacier forefield zone there occur giant boulders with tails of till sediments (Pl. 8, Fig. 2, Pl. 10, Figs 1, 2). These forms with a convex profile are similar to the so-called "crag-and-tail" forms of the drumlin type of the subglacial origin (Glückert 1973). The "crag-and-tail" forms are treated as the exact indicators of the glacier movement direction (Dionne 1987).

In the Renard Glacier forefield the discussed forms have the length of several meters. The orientations of the boulder long axis and of the "tail" are distinctly different. It should be mentioned that the subglacial boulder long axes have almost never the same orientation as the glacier movement direction (Boulton 1970 a, b, Lawson 1979). Therefore, only the tail direction of the drumlin-like form may be here an indicator of the glacier streamline.

In the forefield zone of the Renard Glacier, the drumlin-like forms exhibit only little deviations of azimuth from 45 to 57°, except the one form near Joseph Bay with the azimuth 84°, what can be, however, an erroneous measurement (see domain 5 in Fig. 7). It is worth noting that the general trend of the drumlin-like forms is conformable to the direction of the line linking the threshold B with the boulder mass (*see* Fig. 7), and the both above directions are comparable with the valley axis azimuth equal 50°. Therefore, the small variation of the discussed directions and the assumption of the subglacial origin of the drumlin-like forms would be the basis to establish the glacier movement direction.

Transversal crests. — Such forms occur only in this part of the forefield, which was exposed by the recessing glacier after 1961. They are oblique to nearly perpendicular to the crests of the fluted moraine (Fig. 7, Pl. 7), few to more than ten meters long and with height comparable to the height of the fluted moraine crests. Relationship of the transversal crests and the fluted moraine crests is ambiguous, it seems, however, that they may be equivalent forms (Pl. 7). Such forms reported from the forefields of other present-day glaciers are usually interpreted as annual moraine ridges (Stankowski 1979, Sharp 1984). In the investigated area, the present author supposes on the basis of his personal observations that the mentioned forms, especially these with the oblique orientation, represent fillings of ice crevasses (*cf.* Merta 1988c).

Comprehensive attributies of the investigated fluted moraines

The studies performed in the glacier forefield areas in northwestern Wedel Jarlsberg Land in Spitsbergen permit the expression of some general regularities describing not only the fluted ground moraine features, but also the relation of this moraine to the glacier front. The regularities are as follows:

— ground moraine with fluted relief on the top surface in the glacier forefield occurs in the flat parts and in the parts with differentiated morphology;

— the fluted relief is characterized by parallel rows of crests slightly radial when a large area is considered, independently to the area morphology;

— the convergence of the direction of the crests and of the linear ablation forms on the ice top surface is distinct;

— the relationship: crest height versus stone size, is noted as the higher crests, the larger stones occur in;

— smaller crests join with the supraglacial cover of the glacier front, the larger ones continue on the top surface as stone belts or talus cones;

— any preferred orientation of stones is absent;

— a limited but not complete convergence of the ground moraine crest directions and the directional trends of the drumlin-like forms is noted;

— the sharp plane contact of the ground moraine and the underlying sandur deposits is visible.

Previous concepts of the fluted ground moraine origin

The unusual fluted moraine relief long since is a subject of studies of its origin conditions. This relief is formed by an alternating sequence of ribs and furrows and it is the top surface of the ground moraine in the forefields of the present-day glaciers.

An opinion used to be expressed that most frequently the ground moraine with the fluted relief occupies flat surfaces (Czerwiński 1973) and at the glacier-facing-side of the frontal moraine (Price 1973, Krüger and Thomsen 1984). Sometimes the crest climb up the stoss sides of such moraines (Schytt 1963). The crests have different height in various areas of their occurrence, from *ca* 0.2 m in the ground moraine of the Blomstrand Glacier forefield, Spitsbergen (Paul and Evans 1974) to *ca* 2.0 m in the fluted moraine of Brúarjökull, Iceland (Todtmann 1952). The crest height depends on the sediment grain class: the lower crests consist usually of finer material than the higher ones (Morris and Morland 1976). In each case, however, the crests are seemingly richer in stones than sediment in between (Gravenor and Meneley 1958, Kłysz 1983). The average crest length equals several dozen meters, scarcely decreasing in the downstream direction (Hoppe and Schytt 1953, Kozarski and Szupryczyński 1973, Price 1973). But Boulton (1976) reports crests up to 500 m long and with the constant height. Some authors indicate the great regularity of the crest spacing (Baranowski 1970, Gravenor and Meneley 1958, Boulton 1976). Many crests of the fluted moraine start from the lee sides of boulders (Dyson 1952, Hoppe and Schytt 1953, Boulton 1976). Near convergence of the striae directions on the uncovered bedrocks and the fluted moraine crest directions is mentioned (Dyson 1952, Schytt 1963).

Ray (1935) suggested, when he considered the genesis, that the fluted relief of the ground moraine resulted from the grooving of the subglacial till by the glacier base ice. Dyson (1952) has written that the crests form due to pressing of the subglacial deposits into tunnels furrowed in the bottom glacier surface by the irregularities of the underlying bedrock, especially by the boulders protruding from the lodgement till. Boulton (1976) presents a similar interpretation, indicating that boulders were transported in englacial position and next, retarded by ploughing into the subglacial till, subsequently developed ridges of till on their lee sides by squeezing of till into cavities. Appropriately to the above presented dynamic crest genesis, Morris and Morland (1976) consider theoretically the conditions of origin of such forms. Taking into account the constant crest height, Todtmann (1952) suggests, that the crests could be formed by pressing of the lodgement till into subglacial crevasses. The pressing of the watered material could occur only to the level determined by the isotherm 0°C position, where the sediment froze (Hoppe and Schytt 1953). The above concepts join the genesis of the fluted moraine crests with the linear relief of the glacier ice lower surface, developed mainly by the interaction of the moving ice and obstacles, *i.e.* boulders and/or bedrock knobs. A different idea on the crest origin is presented by Gravenor and Meneley (1958). They suggest that crests have been developed by the action of the alternating parallel high- and low-pressure zones at the glacier base; the observed enrichment of crests in stones may be explained in this manner.

Taking into account the regularity of the crest spacing, Baranowski (1970) interprets the fluted moraine crests as an effect of the rhythmic changes of thermal regime under the glacier base. It may be noted that Boulton (1976) explains the crest spacing regularity as a probable result of the random boulder placement.

A completely different explanation of the crest origin is presented by Kłysz (1983a, b). After studies of the fluted ground moraine within the forefield zone of the Hans Glacier in Spitsbergen, he concludes that ribs and furrows are the multiplication of the morphology of the underlying bedrock, consisting here of the monoclinally occurring Hecla Hoek Formation layers, which have a variable mechanical resistance. He assumes that such irregularity of bedrock covered by a layer of the subglacial till gives an analogous relief of its top surface with crests and furrows. Kłysz (*op. cit.*) adds however, that the crest sediment bears somewhat more stones than the furrow sediment.

All the concepts of the fluted moraine genesis presented above and made on the basis of the observations of the exposed sediments of the forefield zones of the existing glaciers assume the subglacial environment of the fluted moraine origin, although the extension of the crests under the glacier still remains only a supposition (*cf.* Hoppe and Schytt 1953). Assuming a significant weight pressure of ice, the subglacial area of the crest initiations should be located in an appreciable distance from the glacier front (Dyson 1952). Only Czerwiński (1973) joins the crest origin with the subglacial conditions existing in the area adjacent to the glacier front.

Remarks on the crest-like forms on the bottoms of the subglacial tunnels (Schytt 1963) or caves (Boulton 1976) are not an unambiguous evidence that the crests on the ground moraine top surface within a forefield zone extend under the glacier.

As the supposed subglacial forms, the crests are treated as a streamlines indicating the glacier movement direction (Kozarski and Szupryczyński 1973, Boulton 1976, Krüger and Thomsen 1984 and others), and consequently, the ground moraine top surface may be interpreted as a cast-image of the glacier base surface (Hoppe and Schytt 1953, *cf. also* Price 1973).

A confirmation of the subglacial origin of the fluted ground moraine was expected as resulting from the studies of the stone orientation. Such studies were performed for the fluted moraine deposits of the forefield zones of the existing glaciers among other in Iceland and Norway. They indicated that although the stone long axes within the lower parts of the ground moraines display a significant ordering degree, however in the subsurficial parts "... parallel ridges lack every preferred orientation of the stones" (Hoppe and Schytt *op. cit.*, p. 111). A similar regularity has been reported by Kozarski and Szupryczyński (1973) in their study of the fluted moraine sediments within the forefield zone of Siduijökull in Iceland. The absence of the stone preferred orientation in the superficial part of the fluted moraine these authors explain as a result of the epigenetic reorientation of the sediment components due to the creeping of the crest material. Other reports on the stone orientation either are pertinent to a statistically insignificant number of measurements or they do not specify if the data have been collected for the crest debris or for the whole fluted ground moraine cover (*cf.* Morris and Morland 1976).

If one considers the origin of the fluted ground moraine crests in a subglacial environment, the crests may be treated as similar forms with fluting assemblage (*sensu* Aario 1977, *cf. also* Menzies 1987) and narrow linear drumlins (*sensu* Lemke 1958). An opinion was also expressed that the crests of the ground moraine may result from the same process as that which formed the drumlins (Gravenor 1953). It must be added that the typical drumlins often have a thin cover of till with flutes on the top surfaces (Boulton 1987), which are commonly named the superimposed flutes (Rose 1987). It should be noted, however, that such crests have somewhat different direction than the general direction of the drumlin elongation (Rose *op. cit.*, Boulton 1987). Thus, such flutes "... although indicating the general direction of ice movement, they are not a reliable indicator of the precise ice flow direction" (Dionne 1987, p. 152). Such different registration of the glacier movement in the same area (drumlin orientation and its superimposed flute direction), in the Boulton's opinion (1987) has been achieved through the modification of the topmost part of the drumlin deposits due to a rheological contrast between the stiff basal ice and underlying deposits, or by a secondary redistribution of the formerly deposited material (Rose 1987).

It should be distinctly emphasized that the subglacial interpretation of all the crest types does not take into account in the deposition any contributions of the supraglacial material, although the presence of this material during the formation of the frontal moraine ridges or small annual transversal ones causes no doubts (*cf.* Stankowski 1979, Sharp 1984).

Discussion

Some facts are difficult to explain on the basis of the above summarized concepts on the subglacial environment of the fluted moraine origin. The observed discordance of the directions of the crests and drumlin-like forms is one of such facts most important. If the both form groups should indicate the glacier movement direction when they occur on the same surface, this results in a paradoxical picture of a glacier moving isochronically in different directions. Moreover, the selective activity of the subglacial factors seems to be unreasonable. A reason should be found that would explain why in certain cases a stabilized boulder has stimulated the formation of a groove in the glacier base resulting in a long crest with its initiating boulder, and in other cases similar but larger boulders stimulated the till deposition only in a short distance, giving drumlin-like forms.

The accordance of the drumlin-like form elongation with the transport direction of boulders glacier-derived from the threshold **B** (*see* Fig. 7) and with the valley axis should indicate the glacier movement streamline. A question appears; if the fluted moraine crests indicate a different direction, could they form under the subglacial conditions? Additional troubles rise during attempts of the subglacial explanation of (i) the crest enrichment in stones and (ii) the lack of the stone preferred orientation even in very fresh crests, *i.e.* near the glacier front. Serious doubts appear due to the sharp contact of the fluted ground moraine with the underlying sandur deposits: probably this contact should be deformed during pressing of the subglacial till in the grooves of the glacier base. Moreover, taking into account the glacier movement dynamics, different habits of the ground moraine crests should be expected for the sediment cover of the differently located sides of the bedrock forms, *i.e.* stoss and lee sides of thresholds. However, the till cover crests are in both cases the same, as it was found in the Renard Glacier forefield.

The subglacial interpretation of the fluted moraine origin causes also problems of the sedimentation nature. If the fluted relief would be a cast product of the glacier base, that means that in the forefield area the whole surface of its occurrence is occupied exclusively by the "subglacial" till, thus there is no place for the deposition of the sedimentary cover of the recessing glacier front.

A new interpretation: supraglacial origin of the crests

The concept of the supraglacial conditions of fluted moraine crest origin has resulted from present author's observations of large crests in the Blomli Glacier forefield and their relation to the talus cones occurring in the ablation gullies of the glacier front (Pl. 3, Fig. 1). There were no doubts, that during the glacier recession and the succesive extension of the cones mainly by the supraglacial rock debris from the Halvorsenfjellet escarpment (Fig. 3A), the proximal parts of these cones (Fig. 8A) transform into the crests of the forefield sedimentary cover (Fig. 8a). A similar interpretation of genesis of the

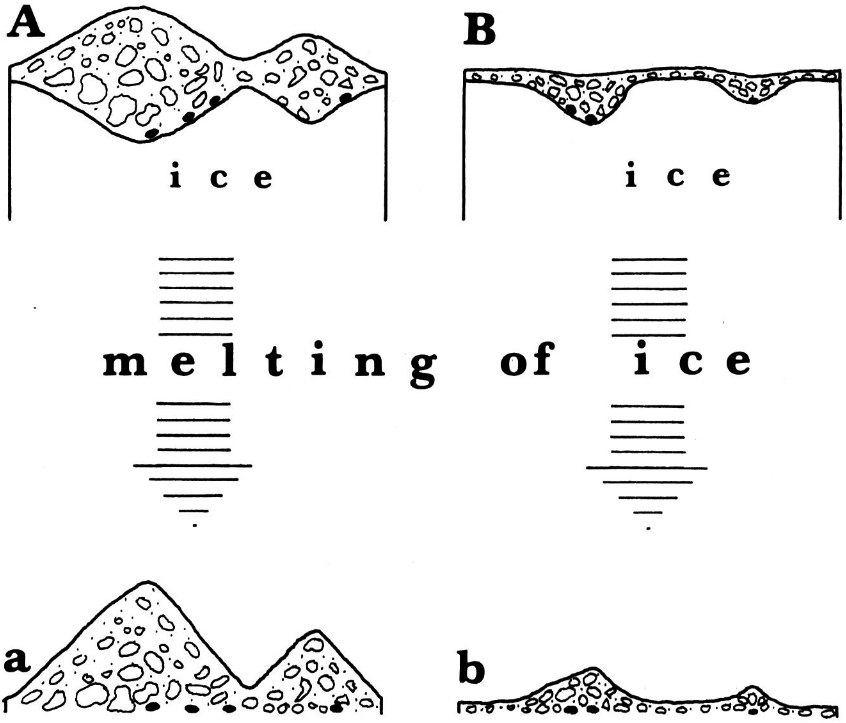

Fig. 8. Explanation of fluted moraine crest origin: A — position and features of the supraglacial sediments on the ice surface, with the strong submitting of clastic material, a — the fluted relief after ice melting, formed beneath the glacier front, B — supraglacial deposits formed mainly from the englacial material and covering the ablation relief of the ice top surface, b — the reflief of the ground moraine after complete melting of the formerly underlying ice

large ridges, perpendicular to the glacier front has been presented by Drozdowski (1988), who studied the forefield sediments of K2 Glacier in Karakorum Mountains, but without linking these forms to the fluted moraine.

Similarly, the origin of the crests of distinctly smaller sizes and being the typical ground moraine fluted relief (*e.g.* in more internal part of the Scott Glacier forefield zone and in the Renard Glacier forefield one) can be connected, in the present author's opinion, with the distribution of the supraglacial sediment on the glacier front surface determined by the ablation relief.

Initial forms of the linear ablation relief form in the upper part of the glacier front due to the gravitational dripping of the supraglacial water streamlets. This linear erosion of ice leads to a concentration of mineral material released from ice. Partial filling of the ablation furrows by this sediment stimulates both the incising and lateral erosion of ice due to the strong albedo decrease. Increase of the ablation furrows causes a linear axial concentration of the englacial stones released from the furrow walls. The enrichment of the ablation furrow sediment in coarse material may be also caused by partial washing out the fine-grained components.

The apparently uniform supraglacial sediment cover in the marginal part of the glacier front has in fact in its transversal section a variable thickness due to filling the deeper and shallower depressions of the ice morphology (Fig. 8B). The variable relief of the glacier surface under the supraglacial sediment cover can be inferred *e.g.* from the seismogram-like upper border of the glacier front sediments (Fig. 5A). After ice melting the supraglacial material is deposited in the forefield area forming ribs and furrows, what depends on the sediment thickness modelled respectively by furrows and ribs of the ice surface (Fig. 8b).

According to the above interpretation, the ground moraine fluted relief is not a cast product of the glacier base but contrary, it is a negative-type reflection of the ablation top surface in the glacier front zone. The convergence of the directions of the linear ablation forms and crests of the fluted moraine deposited immediately in front of Scott and Renard Glaciers is an additional argument confirming the above genetic model. In the supraglacial model of the fluted moraine crest genesis a special attention should be paid to the so-called flute-initiating boulders. Such forms probably most dramatically "support" the subglacial theory of their origin, determined by the "traction way", the "stop point" and the "tail sedimentation" as a given crest (*a*, *b*, *c* respectively, *see* Fig. 9). Although the ridge width at the stone-adjacent side is approximately the same as the diameter of the stone (*II* in Fig. 9), however the groove at the glacier-facing side of the stone is much wider (*I* in Fig. 9). It seems thus, that the mentioned groove did not form due to

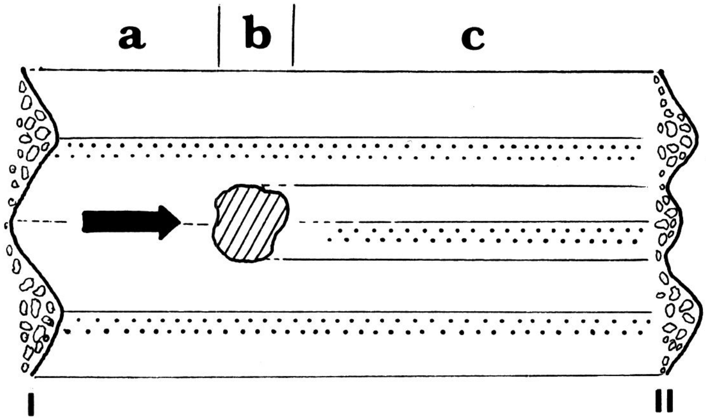

Fig. 9. Development of the boulder tail crest: a — "traction route" of the boulder, b — "stabilization point", c — deposition of the tail sediment, I — cross-section in front of the boulder, II — cross-section behind the boulder; the arrow indicates the "glacier movement" direction

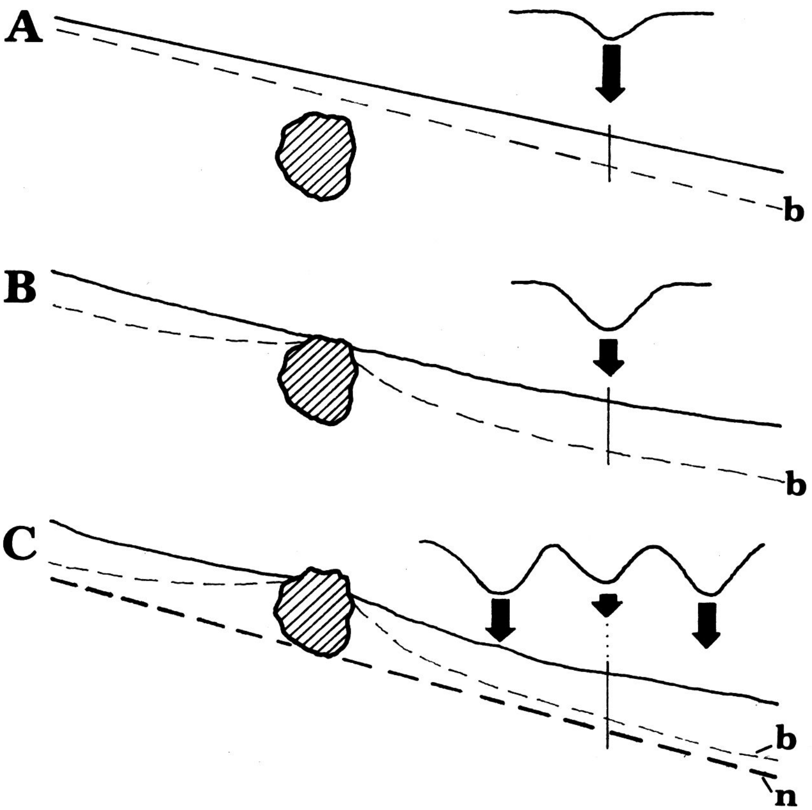

Fig. 10. A probable sequence of events explaining the origin of the boulder tail crest in the supraglacial interpretation: A — englacial position of the boulder, free water flow in the ablation gutter; a — gutter bottom, B — emerging of the boulder from the ablation gutter bottom, impeded water flow, C — development of the two parallel ablation gutters with the free water flow; black arrows indicate relative rates of the vertical erosion extent caused by ablation, n — position of the bottom of a new ablation gutter

furrowing of the subglacial till by the stone sticking in the glacier base. In the present author's opinion the above mentioned crests with the flute-initiating boulders are the supraglacial forms, too.

The incising of a linear ablation form on the ice surface (Fig. 10A) continues uniformly along its extension to the point where it meets a larger englacial boulder. Such boulder protruding from the ablation furrow bottom is a local erosion basis for proglacial water flowing along this furrow (Fig. 10B). Such situation causes: (i) decrease of flow behind the obstacle and the same a slower incision of the ablation furrow, (ii) formation of flows along both sides in parallel associated furrows (Fig. 10C). The filling of the furrows by the supraglacial sediment and its deposition on the forefield surface gives the crest arrangement with the central crest as the boulder initiated flute. From this reconstruction it is evident that the boulder does not start the crest formation but it finishes its deposition.

Developmental stages of the glacier forefield

A glacier covering a given area, hides under its mass various bedrock forms *i.e.* thresholds, roches moutonnées or products of subglacial accumu-

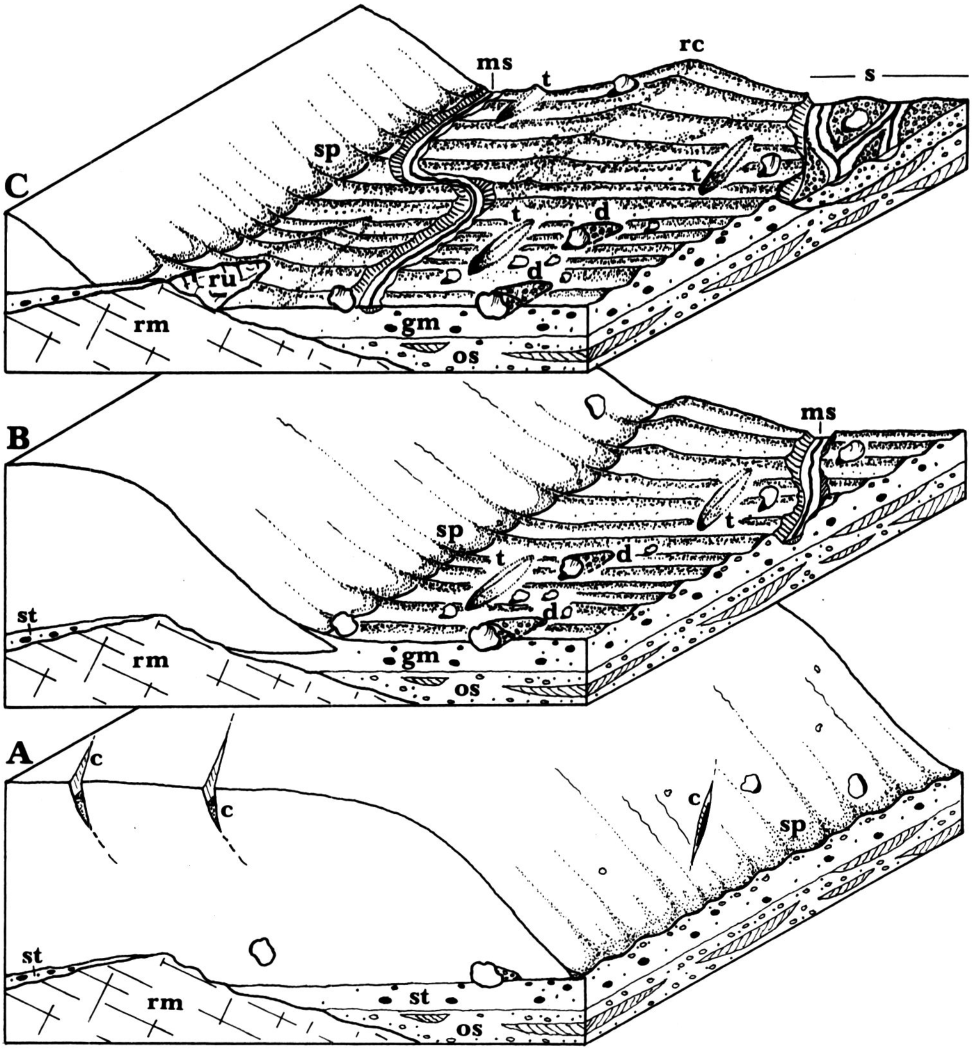

Fig. 11. Hypothetical developmental stages of the forefield area during the glacier recession mainly based on the observations of the Renard Glacier forefield: A — the glacier completely covers investigated area, B — the forefield area partly exposed, C — exposure of the almost whole forefield surface, c — sediment-filled crevasse, st — subglacial till, sp — supraglacial deposits, rm — roche moutonnée (threshold), os — older sandur deposits, gm — ground moraine being of the supraglacial origin in its uppermost part, d — drumlin-like forms of the subglacial origin, t — transversal crests, rc — ground moraine cover on the threshold, ru — uncovered part of the threshold (glacier-eroded niche), ms — marginal proglacial stream, s — contemporary sandur deposits

lation (drumlins or drumlin-like forms) with elongation according to the glacier movement and a layer of the subglacial till (Fig. 11A). All the above forms are gradually exposed during the glacier recession and they are covered by supraglacial till directly in front of the recessing glacier margin. The supraglacial till cover develops the habit of the fluted deposits. The possibly present crevasse fillings and transversal ridges of "annual" moraines are deposited isochronally (Fig. 11B). The further glacier recession (Fig. 11C) with contemporaneous covering of the forefield area with supraglacial till causes, that the lee side slopes and next the stoss side ones of the thresholds, gradually exposed by the recessing glacier are covered by supraglacial till with the same feature of the flutes. The deposition process of the supraglacial cover with the fluted relief may be ceased if the marginal stream flow is formed (Fig. 11C). Such situation is observed presently along the NW part of the Renard Glacier front (Fig. 7).

The presented above supraglacial origin of the fluted moraine gives the explanation of the identical direction and the identical habit of the sedimentary cover crests on the differently declined surfaces of the underlying bedrock forms. Moreover, it explains well the absence of the perfect coincidence of the directions determined by elongation of the subglacial accumulates *i.e.* the drumlin-like forms and the crest extension of the fluted moraine.

If the subglacial forms are small, their occurrence together with the supraglacial till crests on the forefield surface may suggest an isochronous origin of these two groups of forms and *eo ipso* the same origin conditions.

The presented interpretation of the supraglacial origin of the flutes in the author's opinion is also appropriate for explanation of the flute genesis on the drumlin top surface. Such superimposed flutes with the elongation deviation from the drumlin direction trends were linked till now with the subglacial conditions (Boulton 1987, Rose 1987, and others) but in fact they may be the flutes of the supraglacial till cover, deposited on the top surfaces of the subglacial drumlins during the glacier recession. Those crests of the fluted moraine does not indicate the glacier movement direction, but they determine the general trend of the glacier recession.

Ground moraine sequence

As it was mentioned earlier, the subglacial concepts of the fluted ground moraine genesis either omitted or even excluded the presence of the supraglacial sediment in the area of the glacier forefield. The connection of the fluted relief with the supraglacial conditions and sediments according to the new concept, does not mean, however, that the present author treats the ground moraine layer as the material genetically homogeneous. The lithological variation in the vertical cross-section of the ground moraine seems to indicate its duality. Only the upper part with the top surface fluted relief can be identified with the supraglacial ablation till. The lower part is probably a sediment layer deposited as the subglacial till. These two genetically different sediment portions connect directly in the recessing glacier front, when the supraglacial sediment is deposited on the subglacial till (Fig. 12). In the author's opinion, this duality of the ground moraine deposit may be a reason of the noted preferred stone orientation (Hoppe and Schytt 1953, Kozarski and Szupryczyński 1973) in the lower part (subglacial division) of ground moraine sequence (*A* in Fig. 12), and absence of any stone orientation in the upper one (supraglacial division) of the sequence with the fluted moraine relief (*B* in Fig. 12).

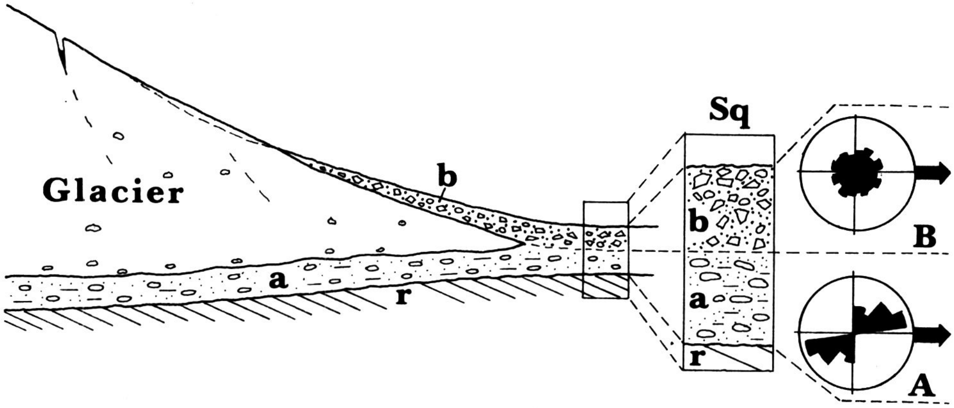

Fig. 12. Idealized scheme of the stratigraphic relationship between the subglacial till (a) and supraglacial deposits (b) in the ground moraine sequence (sq) and the plausible primary orientation of stones (A and B, respectively); r — sandur deposits of an older stage

Approximate convergence of the supraglacial crest and the subglacial forms

Polarity of the deposition forms (*i.e.* obstacle-mark deposits of the drumlin-like type, nose-to-tail position of boulders — *cf.* Boulton 1987) or the glacier-erosion features (striae), a subglacial genesis of which causes no doubts and their approximate convergence with the elongation of the ribs and furrows of the fluted ground moraine (Dyson 1952) were probably the reason of attribution of the fatter ones to the subglacial conditions.

The new interpretation of fluted ground moraine does not exclude, however, such convergence, although the origin environments are extremely different. The subglacial forms were formed due to the action of the moving glacier on the underlying sediments or the bedrock. The glacier movement direction was generally determined by the extension of the glacier-occupied valley. Similarly, the valley extension determines the direction of the recessing glacier front migration, opposite, with respect to the movement of the glacier ice.

Thus one can expect that the directions of the sub- and supraglacial structures including the fluted moraine not only may be almost convergent as it was observed, but locally they may be the same. However, they also may be distinctly different, if the migration direction of the glacier ablation front is clearly other than the glacier ice movement direction. It seems that such situation occurs presently in the Blomli Glacier front region. The subglacial form *e.g.* drumlin-like type are absent here, but the general glacier movement direction determined by the valley long axis above the glacier front differs distinctly from the migration direction of the glacier ablation front, determined by the normal to the marginal line of the glacier front or by crest elongation near the glacier front.

The present author in his earlier publication (Merta 1988c) on the directional elements of the fluted ground moraine in the forefield of the Renard Glacier has accepted also the subglacial hypothesis of the crest origin, because that study has been prepared on the literature data basis, till now joining the crest origin with the subglacial conditions only. Thus, the fluted ground moraine crests have been treated as indicators of the glacier movement direction. The fact of the subglacial form occurrence in the studied area which are named in the present paper the drumlin-like ones, and determining somewhat different direction of the glacier movement than that deduced from the above crests, has been the reason of the hypothesis on the layered ice movement of this glacier.

In the light of the presented supraglacial interpretation of the ground moraine crest genesis, the previous interpretation of the glacier movement is erroneous. The present author, discarding his hypothesis on the layered ice migration and the resulting different directions of the deposition structures, explains his error by the very old but still true Roman proverb *Errare humanum est.*

Conclusions

The origin of the fluted relief of the ground moraine is generally caused by the existence of the linear ablation forms on the glacier front top surface. The crests of the fluted moraine related to the supraglacial sediment-filled furrows on the ice top surface are not the indicators of the glacier movement direction, but they are commonly situated perpendicularly to the ice front marginal line. They determine the general direction of the ice front recession due to the ablation processes. The possible coincidence of the directions of the glacier movement (determined by the directional forms of the subglacial origin) and his front recession (marked by the ground moraine crests) appears from the limiting of the both directions by the extension of the glacier-occupied valley.

Joining the crest formation with the intensive ablation zone of the glacier front, one may conclude that such forms can associate only with glaciers having gradually thinning front zones and without an abundant crevasse network. Probably the crest size depends on the en- and supraglacial material amount transported by a glacier and on the front ablation rate. The same material amount and quicker glacier front recession results in lower crests. Abundant submitting of the clastic material from the abraded valley slopes on the glacier surface strongly increases the crest sizes. The supraglacial material is deposited with formation of the fluted relief on the newly exposed subglacial till giving jointly the ground moraine cover of the forefield area.

The coating process of the forefield area with the supraglacial till may be ceased, if a marginal flow of the proglacial stream is formed.

The fluted moraine crest are probably unstable forms. The stone-enriched crests of the upper part of the ground moraine supraglacial division and prevailing of the clayey-sandy material in its lower part probable subglacial division result in a typical unstable density system (*cf.* Dżułyński 1966, Anketell *et al.* 1970). The crest sediment sinking into the underlying deposit leads to the degradation of the fluted relief. Hence, although there exists a small chance of preservation of the crests in its original habit in the fossil state, it is probable that they are hidden in older glacial sequences as forms remaining ice-wedge casts or those interpreted as cross-sections of the pattered grounds (*cf.* Butrym *et al.* 1964).

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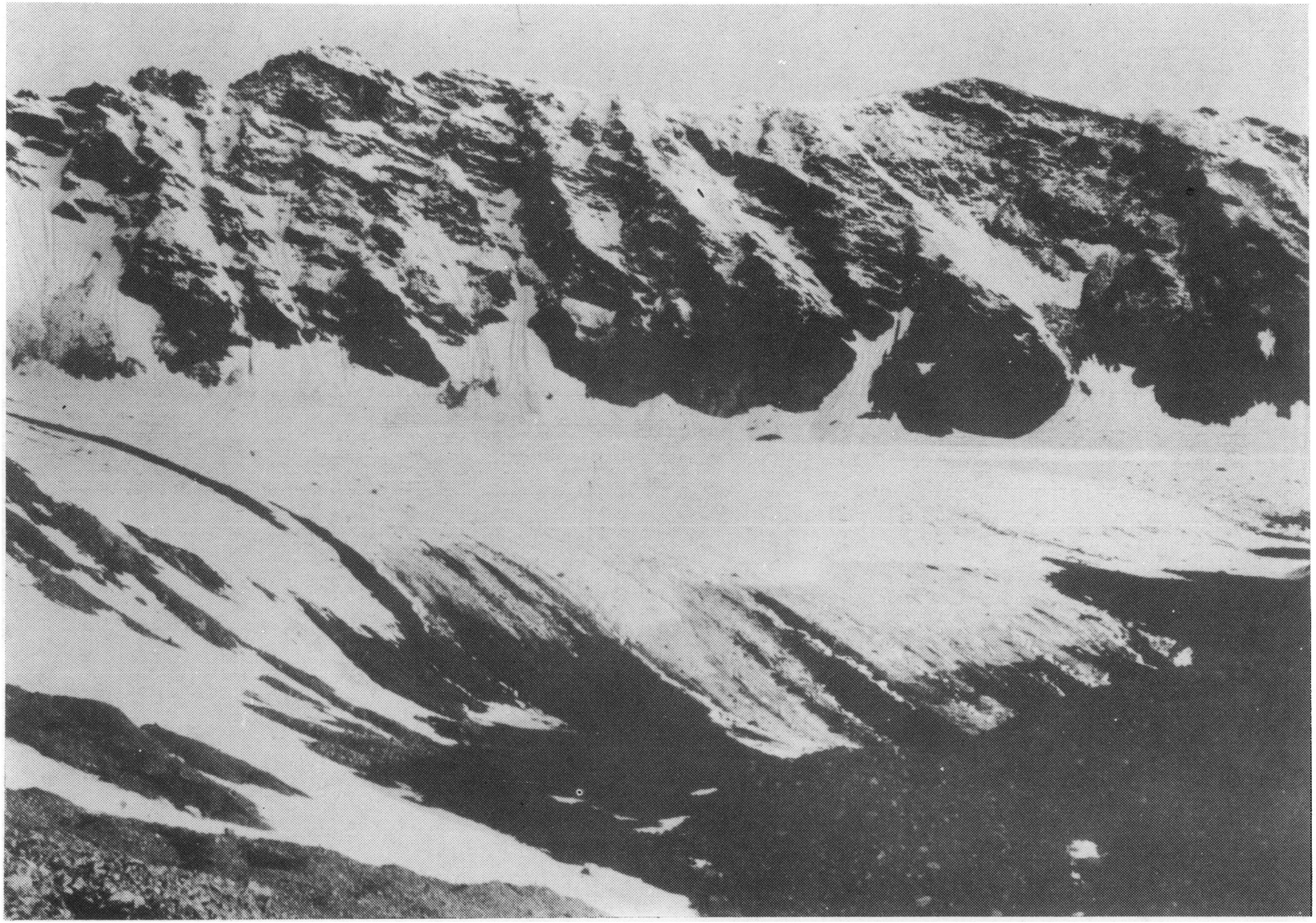
Streszczenie

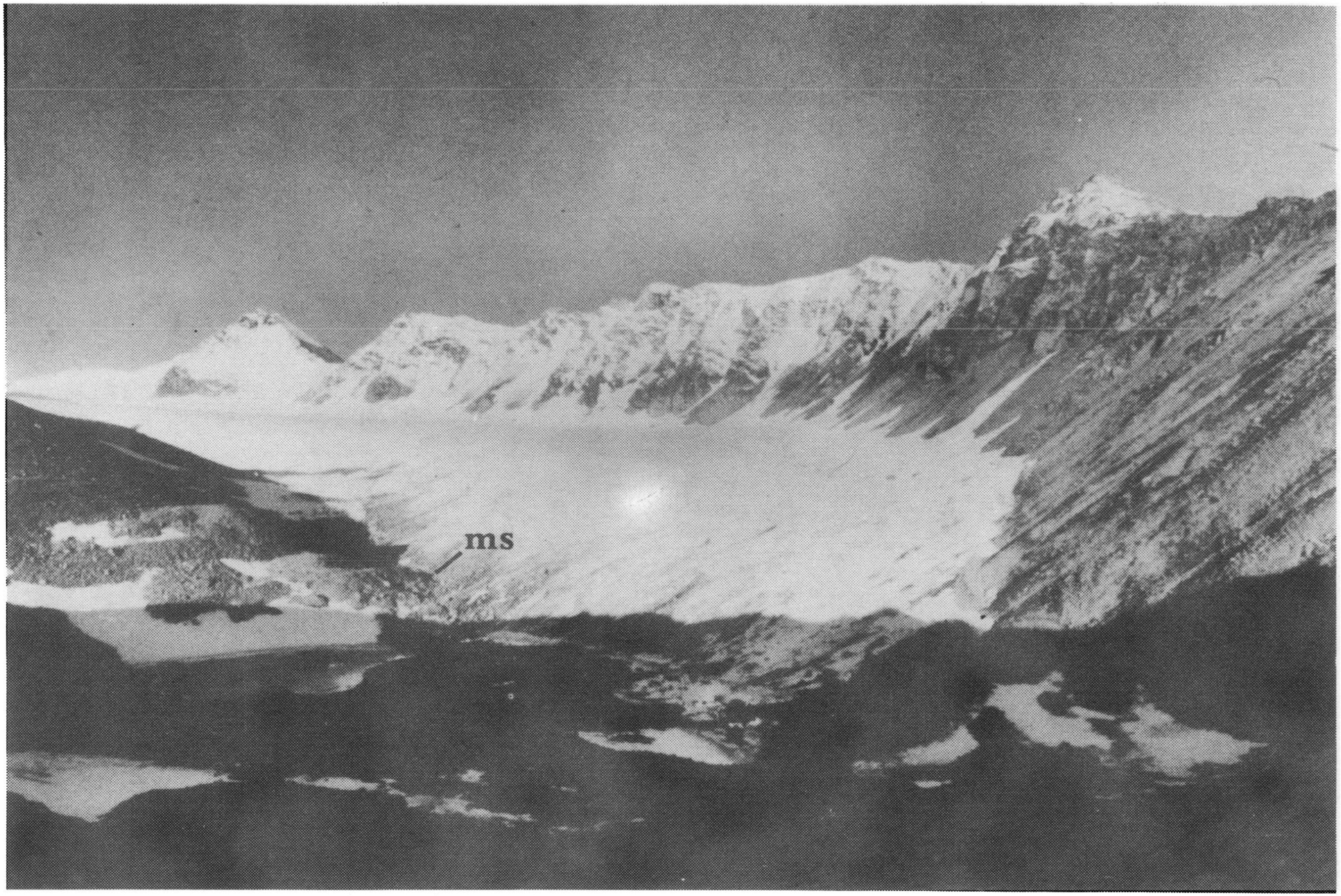
Przedmiotem pracy jest analiza środowiska sedymentacji moreny żłobkowanej, dokonana na podstawie badań przeprowadzonych w obszarze przedpól trzech współczesnych lodowców w NW części Ziemi Wedel-Jarlsberga na Spitsbergenie (fig. 1). Na przykładzie lodowców Blomli i Scotta wykazano wyraźny związek grzbietów moreny żłobkowanej przedpola z linijnym reliefem ablacyjnym powierzchni czół lodowcowych (fig. 2—6, pl. 1—4). Szczególną uwagę poświęcono formom z przedpola lodowca Renarda (pl. 5), gdzie oprócz typowej moreny żłobkowanej (pl. 6, fig. 2, pl. 7) występują drumlinopodobne formy (pl. 8, fig. 2, pl. 10) oraz liczne głazy (pl. 8, fig. 2) rozwleczone przez lodowiec wskutek egzaracji progu skalnego (pl. 6, fig. 1). Przeprowadzono analizę rozkładu struktur kierunkowych dowodząc, że jedynie t.zw. formy drumlinopodobne i kierunek rozwleczenia głazów mają w tym obszarze rangę wskaźnika ruchu lodowca (fig. 7), zaś grzbiety moreny żłobkowanej są względem wspomnianych form kierunkowych akumulatem heterochronicznym.

Uwzględniając zgodność orientacji grzbietów moreny żłobkowanej z linijnymi, częściowo wypełnionymi osadem supraglacjalnym zagłębieniami ablacyjnymi na powierzchni czoła lodowca, przedstawiono nową interpretację genezy grzbietów moreny "fluted". Grzbiety owe stanowią „odlew" reliefu powierzchni czoła lodowca (fig. 8), a ich rozciągłość wyznacza kierunek wycofywania się czoła lodowca. Grzbiety wykształcone za dużymi głazami (fig. 9) zinterpretowano jako efekt zahamowania rozwoju rynny ablacyjnej (fig. 10).

Opierając się głównie na danych z przedpola lodowca Renarda, przedstawiono hipotetyczną sekwencję formowania się obrazu przedpola w trakcie wycofywania się lodowca (fig. 11). Zgodnie z kreowaną, supraglacjalną koncepcją genezy żłobkowanego reliefu moreny przedpola, jej profil pionowy (pl. 9) uznano za poligenetyczny, traktując dolną jej część za osad subglacjalny, górną zaś za nałożoną morenę supraglacjalną (fig. 12).



South-eastern lobe of the Blomli Glacier front. The Halvorsenfjellet escarpment is visible in the background (photo from colour slide by A. Niedek)

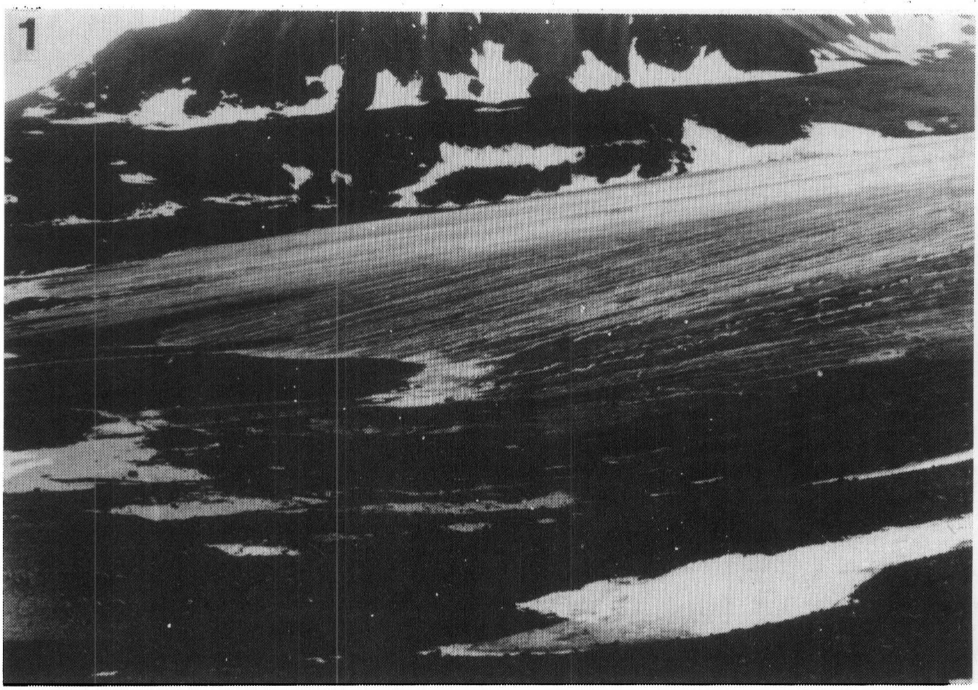


North-western lobe of the Blomli Glacier front. The oblique position of the front with respect to the glacier-valley axis is visible. On the foreground of the glacier margin two small reservoirs occur: ms-marginal proglacial stream (photo from colour slide by A. Niedek)

1. Blomli Valley, the zone of the glacier forefield area; the lower level of ice is arrowed. Dashed line indicates the previous route of the marginal proglacial stream (phototheodolite image)

2. Preceeding photo continued. Flutings of debris on the hill slopes of the forefield zone (phototheodolite image)

1



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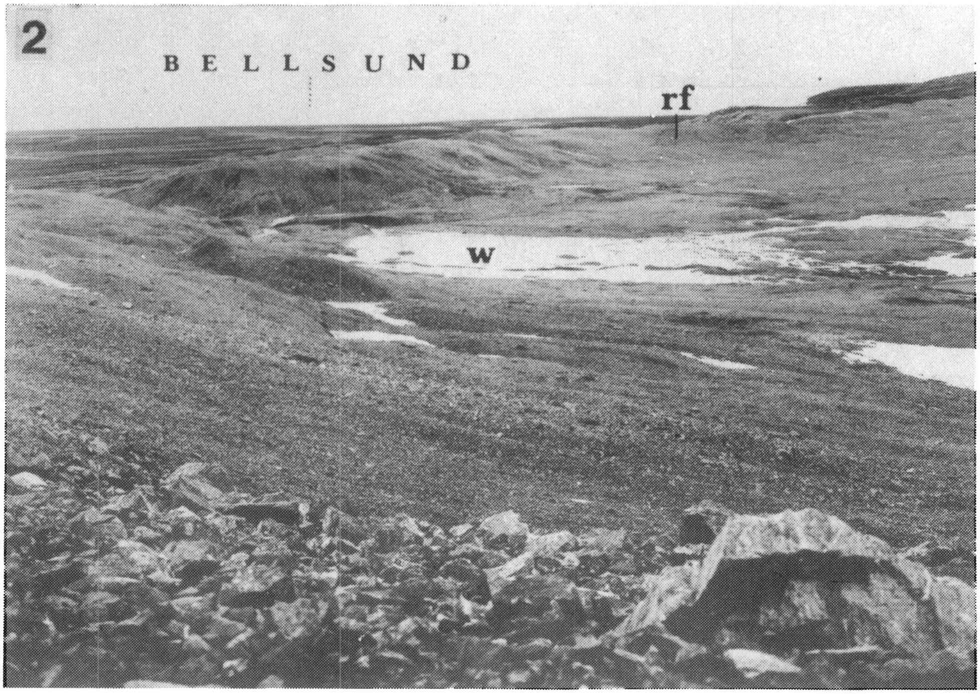
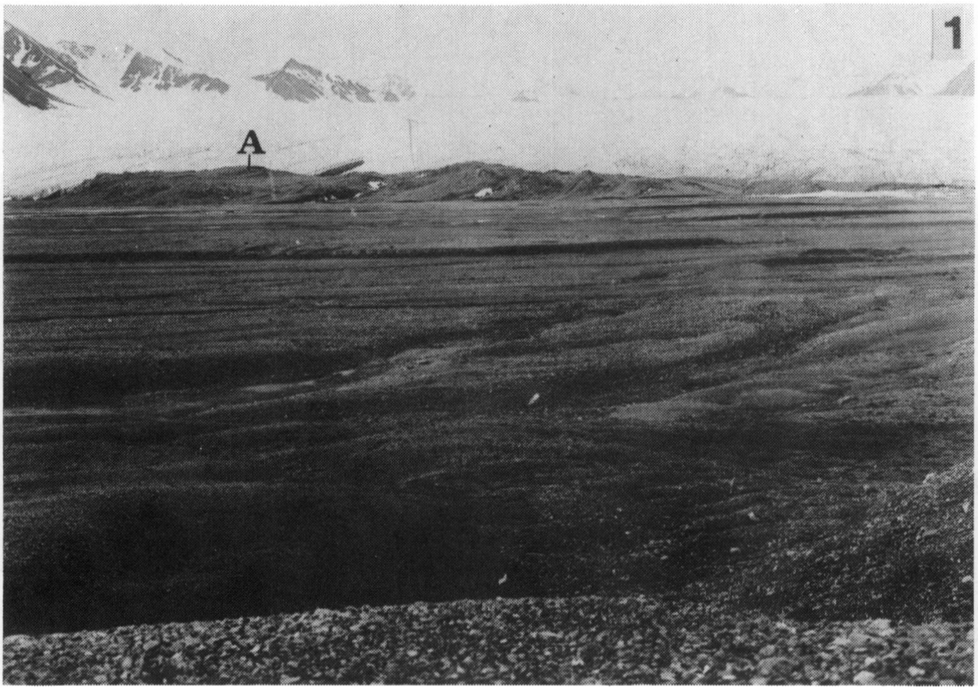
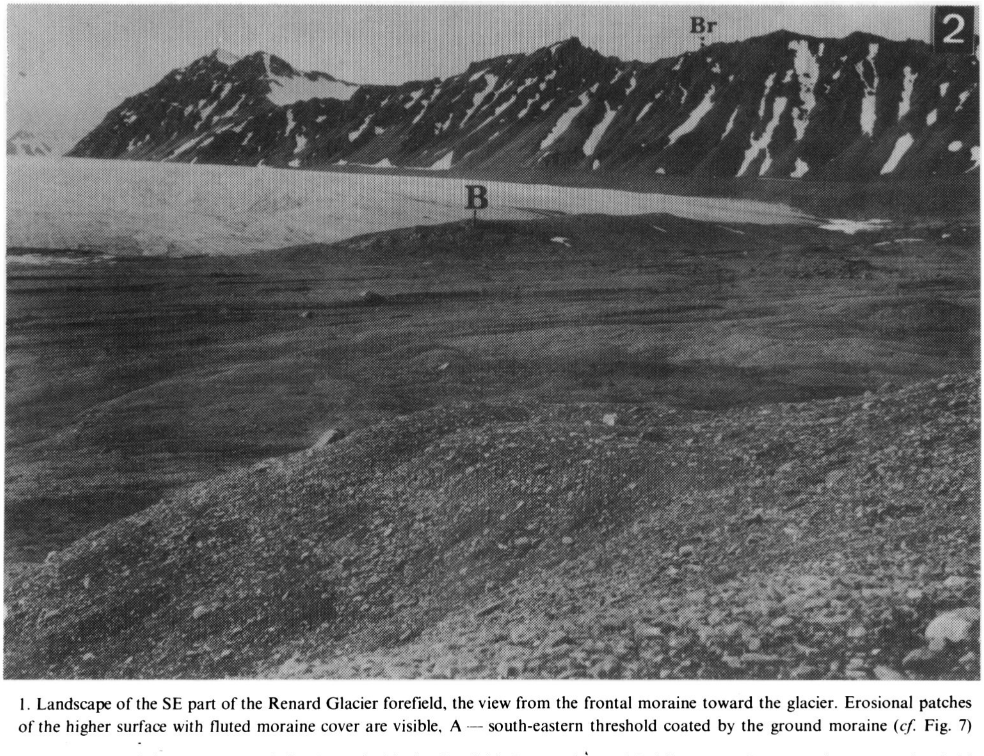


1. Scott Glacier, the zone of the glacier forefield area; crests of the fluted ground moraine passing in ridges of debris on the top surface of the ice. The convergence of the crests with the linear ablation relief of the ice surface is visible
2. External part of the forefield zone of Scott Glacier; the crests of the fluted ground moraine occur in the first plan; w — flood water basin. rf — ground moraine cover with the relic flutings (phototheodolite view)





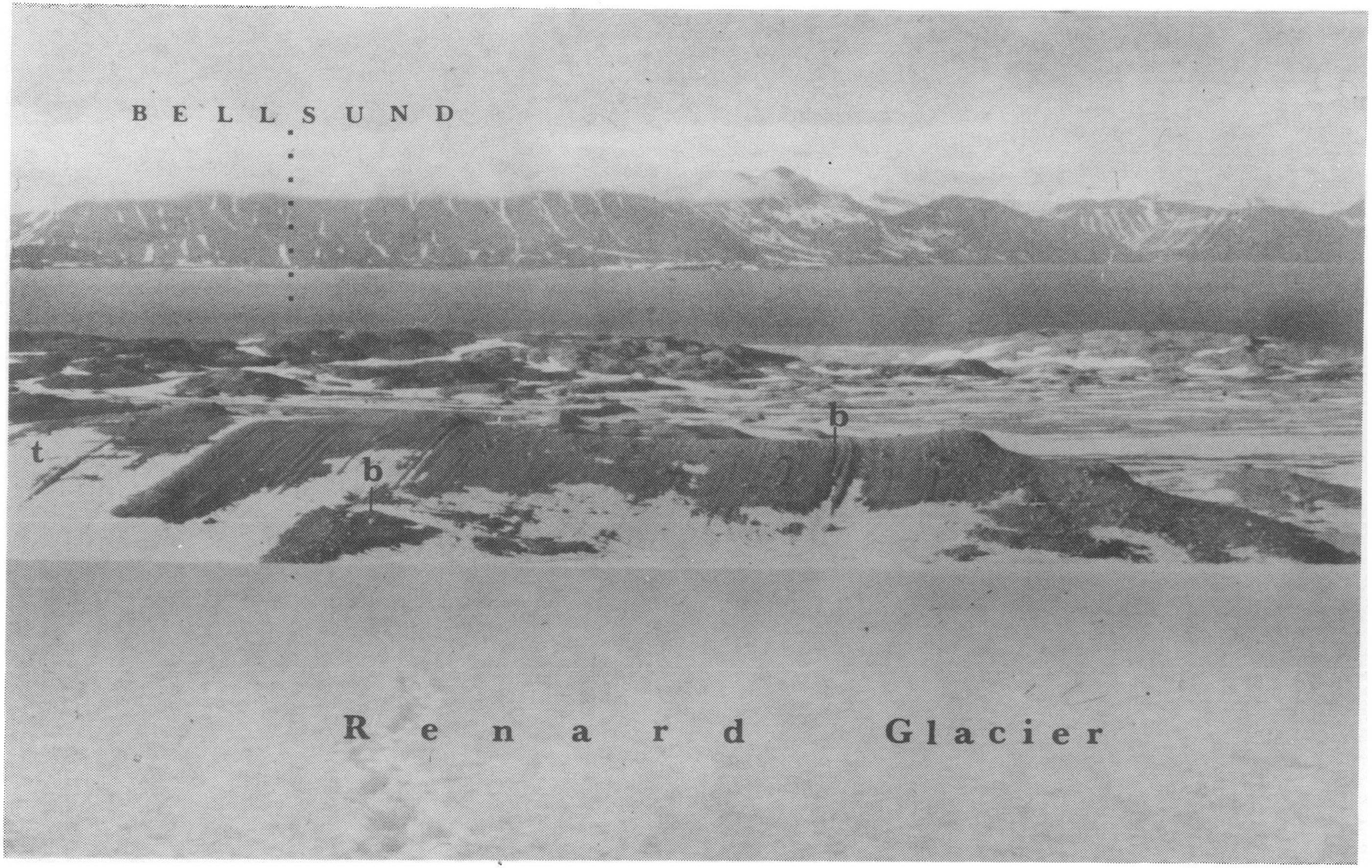
1. Landscape of the SE part of the Renard Glacier forefield, the view from the frontal moraine toward the glacier. Erosional patches of the higher surface with fluted moraine cover are visible, A — south-eastern threshold coated by the ground moraine (*cf.* Fig. 7)

2. Landscape of the NW part of the Renard Glacier forefield: Br — ridge of Bohlinryggen, B — north-western threshold (*cf.* Fig. 7, *see also* Pl. 6, Fig. 1)

1

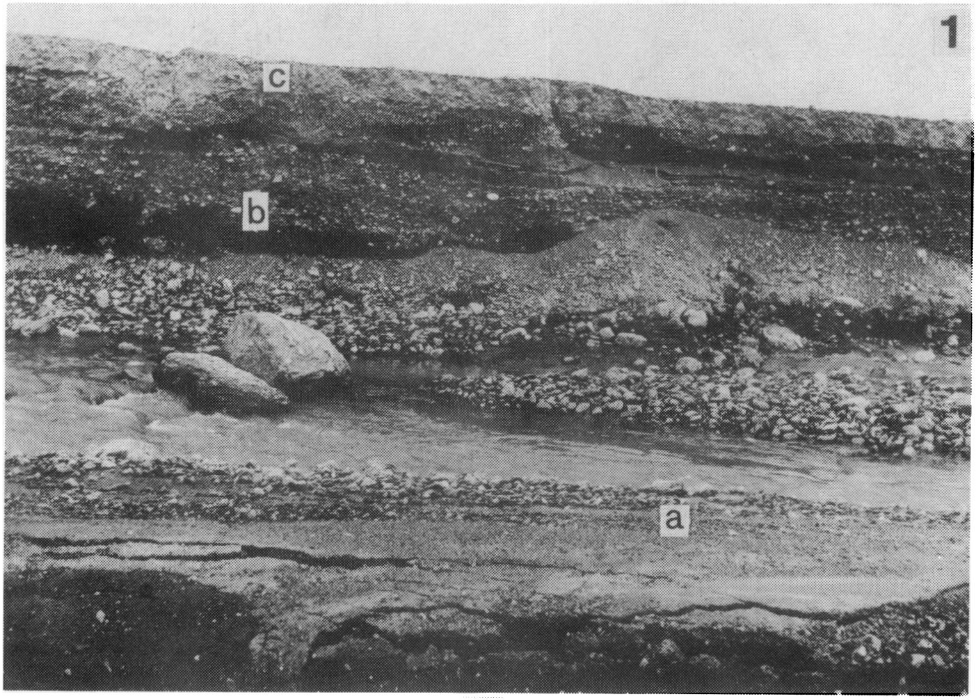
2

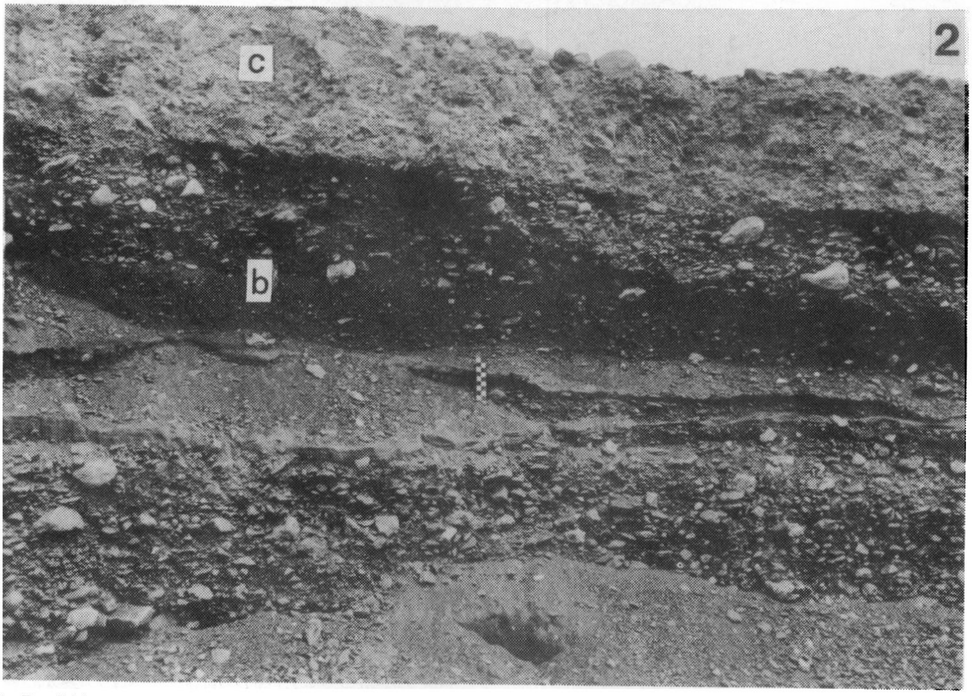
1. Uncovered part of the NW threshold (*B* in Pl. 5, Fig. 2); RG — Renard Glacier, Br — ridge of Bohlinryggen
2. Renard Glacier marginal zone with the slightly degradated crests of the fluted ground moraine. The rifle forms the scale



View of the stoss-side slope of NW threshold, coated by the fluted moraine; t — transversal crests, b — crest initiating boulder (photo from colour slide by A. Niedek)

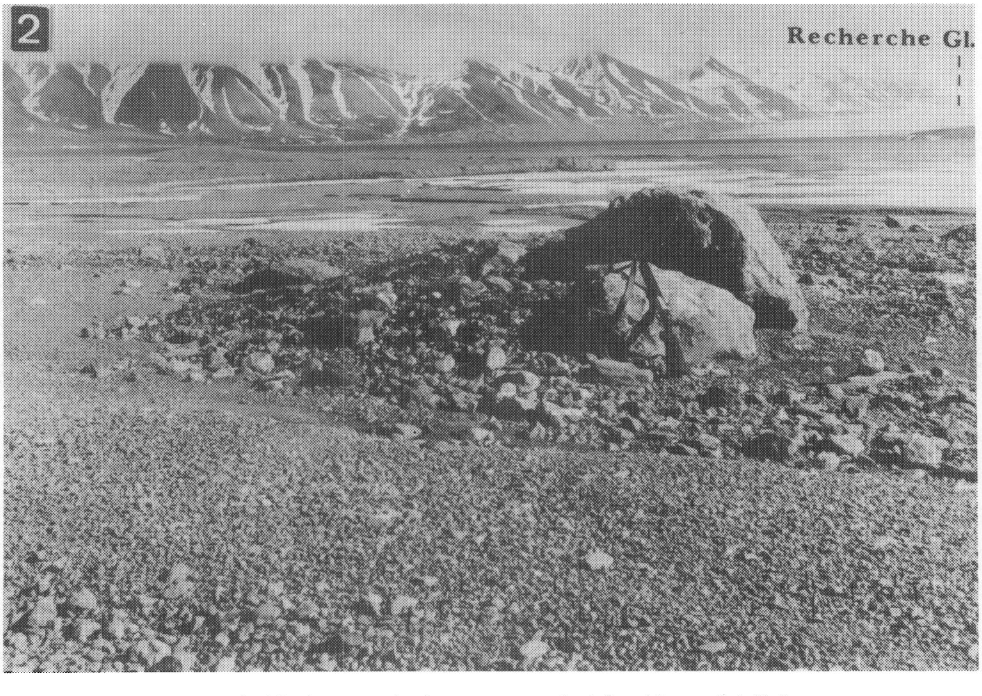
1. Renard Glacier, forefield zone, the area of erratics. Scale in the lower left corner in cm
2. Boulder-end tail, an example of the drumlin-like form. The rifle forms the scale





1. Forefield zone of the Renard Glacier; the lithological sequence of the forefield sedimentary cover; a — present-day sandur deposits, b — sandy-gravel deposits of sandur of an older stage, c — till of the ground moraine cover
2. Enlarged fragment of the preceeding photo. The sharp, plane contact of the till and underlying sandur deposits is visible. Scale in cm

1


2


1. Renard Glacier marginal zone; a typical boulder-end tail form
2. Two boulders with short tail of the till deposit. The rifle forms the scale