APPENDIX

Consider a detached floating ice sheet which is free to creep in both the x and z direction. Consider the situation far from the edge of the sheet. Assume again that the various stresses are independent of x and z. Eqs. (2), (3), and (4) will still be valid. It is reasonable in this situation to take σ_{xx} equal to σ_{zz} since an arbitrary rotation of the axes about the y axis ought not to change the form of the solution. Eq. (10) now takes the form

$$K=\dot{\epsilon}_{xx}=\dot{\epsilon}_{zz}=-2\dot{\epsilon}_{yy}=A^n\left|\frac{\sigma_{xx}-\sigma_{yy}}{\sqrt{3}}\right|^{n-1}\left(\frac{\sigma_{xx}-\sigma_{yy}}{3}\right) \quad . \quad . \quad . \quad . \quad (16)$$

Proceeding as before we find for K

$$K=\frac{1}{\sqrt{3}}\left(\frac{\rho_I g h^2}{2\sqrt{3}}\right)^n\left(1-\frac{\rho_I}{\rho_W}\right)^n\Big/\left[\int_0^h A\,dy\right]^n \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

The creep rate predicted by Eq. (17) is a factor $(2/\sqrt{3})^n/\sqrt{3} \sim 1{\cdot}1$ larger than that predicted by Eq. (14). The creep rate predicted by Eq. (17) is isotropic. That is, any base line on the shelf, regardless of its orientation, will stretch at this rate. For Eq. (14) only a base line perpendicular to the sea front will stretch. In any actual situation in the Antarctic the truth probably lies somewhere between Eqs. (14) and (17).

When the density of ice, ρ_I, is a function of the depth, the term $\frac{1}{2}\rho_I h^2(1-\rho_I/\rho_W)$ in Eqs. (14) and (17) should be replaced by

$$\int_0^h\int_x^h \rho_I(y)\,dy\,dx-\frac{1}{2\rho_W}\left[\int_0^h \rho_I(y)\,dy\right]^2.$$

THE OLD MORAINES OF PANGNIRTUNG PASS, BAFFIN ISLAND*

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ABSTRACT. The "old moraines" of Pangnirtung Pass were constructed by trunk glaciers, tributary glaciers, glacial streams, rockfalls, talus-creep and other agents and processes. Rivers have since reworked or removed the deposits lying along the axis of the Pass and have begun to dissect the remainder. The old moraines have ice cores, which have tended to melt, collapse and flow downhill, thus further complicating the drift topography. The freshness of many old-moraine fronts implies a recent warming up of the climate, which is also reflected in the decay of the modern glaciers; but erosional undermining may also cause fresh fronts. Although no accurate date can be assigned to the disappearance of the trunk glaciers, A.D. 500 is given as a tentative estimate. There have since been at least two main advances of the tributary glaciers, of which the first followed close on the disappearance of the trunk glaciers and the second occurred not later than 1850.

ZUSAMMENFASSUNG. Die ,,alten Moränen" des Pangnirtungpasses wurden durch Hauptgletscher, Seitengletscher, Gletscherflüsse, das Kriechen von Schutthalden und andere Agenzien und Vorgänge aufgebaut. Flüsse haben seitdem die entlang der Achse des Passes liegenden Ablagerungen verändert oder beseitigt und haben begonnen, den Rest zu zerschneiden. Die alten Moränen haben Eiskerne mit der Neigung zu schmelzen, einzufallen und bergab zu fliessen, wobei sie die Topographie des Gletscherschutts weiter komplizieren. Die Kahlheit vieler Altmoränestirnen lässt auf eine kürzliche Erwärmung des Klimas schliessen, die sich auch im Schmelzen der jüngsten Gletscher zeigt; Unterwaschung kann jedoch auch kahle Stirnen erzeugen. Obgleich für das Verschwinden der Hauptgletscher kein genauer Zeitpunkt angegeben werden kann, wird das Jahr 500 n.Chr. vorgeschlagen. Seitdem kam es zu mindestens zwei Hauptvorstössen der Seitengletscher. Der erste von ihnen folgte dicht auf den Schwund der Hauptgletscher, der zweite kam spätestens 1850.

INTRODUCTION

Several papers have already appeared in this Journal under the general title, "Studies in glacier physics on the Penny Ice Cap, Baffin Island, 1953"[12,19]. Complementary to the expedition's glaciological programme was a geomorphological study of Pangnirtung Pass, the great through-valley that cuts across Cumberland Peninsula a few miles to the east of the Penny Ice Cap[2,14,15].

* Substance of a paper read before the Society, 1 June 1955.

The Pass is 85 km. long, 1–3 km. wide and as much as 1½ km. deep. It is lined by hanging valleys, most of them containing glaciers, of which several derive from the Penny Ice Cap. Pangnirtung Pass itself is unglacierized, but striated *roches moutonnées* and other land forms show clearly that there were once trunk glaciers flowing NE and SW from the divide, where the four largest "tributary" glaciers still converge (Fig. 1, p. 45). But the most convincing signs of glaciation in the Pass are the so-called "old moraines", with which this paper is concerned and the precise origin of which is difficult to determine.

Morphology, Lithology and Structure of the Old Moraines

The old moraines are to be seen over a distance of 130 km. from near Pangnirtung Post to North Pangnirtung Fiord. They occur as irregular and discontinuous terraces above, below and at the break of slope between valley floor and mountainside. While they seldom have a vertical extent exceeding 70 m., their summits may lie 130 or 160 m. above the bottom of the Pass (Fig. 2, p. 45). Individual crest lines are inconsistent in altitude, being particularly high beside the present "tributary" glaciers, but a general down-valley trend is detectable. The crests are composed of angular and sub-angular boulders and cobbles, richly lichened, but lying in perched and otherwise unstable positions.

In many cases the moraine crest is separated from the adjacent hillside by a longitudinal depression averaging 3 m. in depth. Such "inner depressions" (Fig. 2) are richly vegetated and are generally floored by a deposit of fine sediments. They seem to form base levels for both modern and old screes and are clearly being filled in at the present time.

By contrast, the outer face of each patch of moraine is poorly or not at all vegetated and consists of sub-angular and semi-rounded debris of all sizes from sand to large boulders. No sorting is visible and fully-rounded blocks are rare, but there is generally a larger proportion of fines here than on the crest. Striated and faceted boulders occur, but are no more plentiful than in the modern moraines of Pangnirtung Pass. The instability of the valleyward face is also proclaimed by the sliding of its debris, both naturally and under a man's weight (Fig. 3, p. 49).

Just as the crests of adjacent moraines may be of unequal height, so may their lateral extent outward from the valley side range from 50 to 400 m. Some of the broadest moraines lie beneath the highest rock cliffs and all are associated with screes (Fig. 4, p. 49). Some moraines cling like isolated shelves to the Pass flanks; some occur in tiered groups; many have several closely spaced crests. Others—particularly those of Weasel Valley—are still broader and more complex, including massive lobate forms trending downhill, closed depressions containing ponds or bedded sediments, small alluvial fans, and irregular rivulet systems.

Lying unconformably upon the normal bouldery drift are "whaleback" or "mesa" features, made of coarse sand and pebbles, moderately to well rounded and occasionally bedded (Fig. 5, p. 49). Locally these sediments are related to stream channels on nearby hillsides, but in most cases they are true erosional remnants of a former more continuous cover. The "rivulet systems" just mentioned are also no more than remnants, truncated as they are by the steep outer faces of the moraines.

Between the moraines and the modern floodplain and lakes lies almost invariably a smooth, richly vegetated slope. In places this "green slope" is broken by *roches moutonnées*, but more often it consists of semi-rounded boulders and cobbles, partially hidden beneath rudely stratified sands and gravels. The protruding boulders are well lichened but are consistently more rounded than those of the old moraines. The surface sands and gravels dip toward the modern floodplain and not down-valley.

Bedrock knobs appear within the old moraines on either flank of Turner Glacier but nowhere else. The moraine beside the southern margin of Turner Glacier is significant for another reason: it slopes gradually downward in the direction of present ice flow and then curves round towards the line of Pangnirtung Pass. Similar trends are noticeable on the south side of Glacier 32, on both

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sides of Glacier 30 (Fig. 6, p. 49), and in numerous other places. Conversely, some empty cirques are fronted by loops of drift identical to that of the old moraines.

Because of the extremely complex nature of the old moraines and also because similar features have been explained in varying ways by previous writers, the origin of the Pangnirtung moraines will be discussed by the analytical method. Although only Hypothesis No. 5 explains all the morphological, lithological and structural details, the others are either locally valid or have appeared in earlier literature.

Hypothesis No. 1

The features are nivation ridges

Behre[3], Bird[4], and Bretz[5] have described how a transverse ridge may develop at the base of a talus slope: a snow bank lying against the talus acts as a chute for falling stones, which therefore accumulate at its lower margin. Although seasonal waxing and waning of the snow bank must cause some dispersal of the debris, it is likely that a ridge would eventually be constructed by this process. Both the ridges and their component blocks seen by Bird were quite small, whereas those described by Behre were massive.

Since most of Pangnirtung Pass and Pangnirtung Fiord is lined by talus slopes, it is possible that some of the features here described as moraines originated as nivation ridges. But such ridges would be more likely to develop *below* the break of slope between hillside and valley bottom than in higher, "perched" locations. Nor can Hypothesis No. 1 explain the "whalebacks" and "mesas" of sand and gravel, the closed depressions, the fresh outer faces, and other peculiarities of the Pangnirtung features.

Hypothesis No. 2

The features are slumped scree

The constant association of old moraines with talus slopes cannot be too firmly stressed. Not only do both new and old scree fans terminate in the moraines' inner depressions, but sometimes the moraine crests are actually continuous with, though at right angles to, prominent lines of scree. Since much of the talus is sub-angular or semi-rounded, there is no way of distinguishing it from the nondescript drift of the modern moraines. Moreover the walls of Pangnirtung Pass are generally so steep and smooth that the possibility arises that the "old moraines" may have been piled up by the mass-settling of scree.

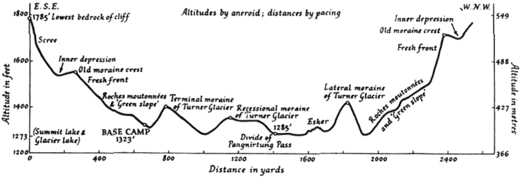
Sharpe[13] states (p. 68) that " . . . backward rotation during slip is also very common in unconsolidated soil or coarser debris, as is well known to excavation contractors". Such movements, known as "slumps", usually occur slowly and intermittently along one or more slip-planes well below the surface. But Sharpe adds, in a comment unfavourable to the hypothesis, that slumps, including "talus-slumps", involve only small displacements relative to the size of the moving block.

W. H. Ward's paper on "The stability of natural slopes"[17] offers little support to the hypothesis. Assuming that instability is caused primarily by undercutting below and by deposition above, Ward argues that actual slope failure depends on the type and structure of the material involved, and on climatic conditions. The movements resulting from failure include the mass movement of cohesive material and the particle movement of fragmental. The failure of scree involves shearing or rolling of the surface fragments only and is classified by Ward as a "dry fragmental slide". According to this authority, rotational slipping is essentially confined to cohesive materials, especially clays.

It seems that Hypothesis No. 2—often the most attractive in the field—must be rejected for want of evidence of the processes supposedly involved.

Fig. 1 (left). Pangnirtung Pass and its flanking glaciers. Old moraines line the Pass from Pangnirtung Post to North Pangnirtung Fiord. The regional erosion surface, lying at 5000–7000 feet, has been deeply dissected by alternating rivers and glaciers, generally along lines of structural weakness. Stipple represents glaciers; line shading, water; and blackness, bare land

Fig. 2 (below). Cross-section of Pangnirtung Pass at the divide, showing the location of the old moraines and the land forms often found with them



Hypothesis No. 3

The features are impeded scree

Under this hypothesis the fact that two of the moraines have partial bedrock cores is extended by analogy to all such features. It is assumed that rock knobs obstruct the down-slope migration of scree, causing increasingly large piles to develop. But it is difficult to imagine how upstanding ridges of scree ten or twenty feet high can attain adequate stability, even on long rock benches; nor can most of the complex details of the old moraines be accounted for.

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Hypothesis No. 4

The features are creeping talus and rock glaciers derived from hanging valleys and cirques

In an oft-quoted paper, Capps[6] described Alaskan "rock glaciers" as being composed of rather coarse and angular debris, and having clear ice in their interstices as far down as he could penetrate. The rock glaciers ended in transverse ridges with steep outer slopes—the former were well lichened and the latter fresh. Although the rock glaciers headed in "cirque-like valleys" and graded into the moraines of ordinary glaciers, Capps believed that slow movement of the debris itself was occurring "in a glacier-like way". It was to this mass movement that he ascribed the fresh outer slopes.

The whole question was re-examined by Kesseli[7]. The features described by him were similar to the old moraines of Pangnirtung Pass, with the following exceptions: all his "rock streams" headed in cirques and similar features; they occurred especially with northern, north-eastern, and eastern orientations; none had bedded or unbedded sands and gravels lying unconformably on top of them; they were not stated to have vegetated upper surfaces and fresh outer slopes; and they had multiple ridges parallel to and at much the same elevation as the outermost ridge.

Because of these differences it is not possible to apply Kesseli's explanation—that the rock streams resulted solely from past cirque-glacial transport—to all the old moraines of Pangnirtung Pass. Nevertheless there are some features, especially in Weasel Valley, that were undoubtedly the products of former advances of hanging and cirque glaciers, of which some have now vanished.

Sharpe[13] believes that rock glaciers are not necessarily of glacial origin, but claims that their parallel "wrinkles" are evidence of slow flowage or rock-glacier creep. As an example of this process he cites movements in a spoil pile near Grand Coulee Dam. But he adds (p. 98) that "creep is common in moraines perched on the sides of glacial troughs and parts of these deposits occasionally come down as landslides or debris-avalanches". Rock-glacier creep grades into both talus-creep and true glacier flow.

A feature very similar to the old moraines of Pangnirtung Pass was photographed in East Greenland by Bretz[5]. In his caption on page 255 Bretz described the mass of drift as "flowing talus", though he gave no evidence for this assertion.

Hypothesis No. 4 is a great advance over its predecessors, for old moraines of tributary glaciers, intermingled with scree and flowing downhill, must have accounted for many of the land forms enumerated at the beginning of the chapter. And yet there are long stretches of valley-side which lack cirques or hanging valleys of any significance—it is to explain them that the final hypothesis, strengthened as it is by the evidence of glacial markings[15], is stated and elaborated.

Hypothesis No. 5

The features are of complex origin, but consist predominantly of moraines deposited by trunk glaciers flowing in Pangnirtung Pass

It is only by this hypothesis that all the morphological details may be explained. The general irregularity of the deposits is in accord with the chaotic state of the modern moraines, subject as they are to differential downwasting and collapse[14, 16]. In particular, the occurrence of tiered old moraines may be ascribed to successive stages in the downwasting of a trunk glacier. Some of the old drift, particularly that flanking the Great Moraine Gorge (Fig. 5), may be derived from recessional moraines, but most of it must be of lateral, superglacial and subglacial origin. No doubt rockfalls, steady talus-creep and water-washing over many years have increased the predominance of angular and sub-angular blocks on the moraine crests. The patches of fine sand, medium sand and gravel appear as remnants of marginal (kame) terraces, intramorainal terraces, kames, outwash and pond deposits. In some places streams from the hanging glaciers and from unglacierized cirques have likewise contributed sediments.

Rich has described, in a paper on the Catskill Mountains[10], old lateral moraines similar to those of Pangnirtung Pass. He makes two pertinent comments (p. 25–26) on "inner depressions":

There are all gradations, from moraines that stand out from the hillsides and are tens or hundreds of feet high, to those which can be seen only under favorable conditions of light. . . .

Whether the steeper slope of the embankment is on the side of the ice contact or on the side toward the hill depends on the relative load of the ice and the position with respect to the end of the [moraine] loop.

Although this principle is more relevant to the modern tributary glaciers than to a trunk glacier in Pangnirtung Pass, it is nevertheless a reminder that "inner depressions" are both characteristic and intermittent features of lateral moraines.

It now becomes clear that the better rounding of the boulders on the "green slopes" is due primarily to their origin as ground moraine or coarse outwash and secondarily to their maltreatment by Owl and Weasel Rivers during the dissection of the drift masses. The veneer of bedded sand and gravel upon the "green slopes" has been laid partly by rivulets flowing toward the main rivers from the old moraines and partly, in phases of aggradation, by the main rivers themselves. The "slopes" are now no longer graded to the active floodplains, because of recent downcutting that has left its mark in low, bedded river terraces, very different in appearance and in composition from the older, lichened ones incorporated in the "green slopes".

The most striking aspect of the old moraines is the freshness of their outer faces, as compared with the rich vegetation of their crests and "inner depressions". Since the fresh faces are so common we must presumably search for a widely applicable cause—nor is one far to seek. For if the modern moraines have glacial ice as their predominant constituent (Fig. 6)[16], there is no reason to believe that past moraines were different. It is therefore suggested that the cause of the fresh fronts on the old moraines lies in the melting of buried ice. The closed depressions, disrupted drainage systems, and chaotic micro-topography of the moraines may also be explained in this way.

Now, Matthes[8], Odell[9], and Rich[11] have all claimed that ice may be preserved for many years under a blanket of detritus. W. H. Ward[18] has pointed out that ice-cores may remain indefinitely, provided the mean annual temperature of the adjacent air is below 0° C. and the annual range of temperature and cover are such that the temperatures of the boundaries of the buried ice masses do not reach the melting point. He considers that three or four feet of rock debris provide adequate insulation in most parts of Baffin Island.

Ward himself* saw large masses of glacial ice in old moraines near the snout of Coronation Glacier (Fig. 1). The ice was exposed for a quarter of a mile down Coronation Fiord, beyond which the old moraines had fresh-debris fronts of the usual type. The vegetation cover on top of the moraines was progressively richer away from the ice front and was interrupted by many round ponds. The Coronation example was also instructive in that it illustrated the stages by which a lateral moraine became "old" in appearance. But Ward's cardinal observation was that the faces of the old moraines were fresh because the buried ice was there least insulated and the debris least stable, because of undercutting and undermelting by waves. Comparable observations were made by the writer in the moraines beside Glacier 25, though here there was no undermining.

Since so many old moraines have fresh faces, without any undermining, it is necessary to assume not only that those moraines have ice cores but that the ice is melting because of increased external temperatures. The important possibility then emerges that the present climatic fluctuation around the North Atlantic Ocean[1] has affected Pangnirtung Pass†.

The ice-core hypothesis may be carried further still. In order to explain the very low elevations, the irregular vertical and lateral distributions, the occurrence on top of alluvial fans and the massively lobate appearance of the old moraines, it is necessary to assume not only differential melting and collapse of the ice core but a general downhill migration and spreading of all the materials concerned‡.

* Personal communication. † The same conclusion was reached after an examination of the modern glaciers[15].

‡ Even allowing for such a redistribution of the drift, the fact remains that the old moraines, particularly at the Great Moraine Gorge (Fig. 5), give a strong impression of being part of a former valley fill covered by organized stream systems and alluvial deposits. Such conditions may well have obtained when the last Pangnirtung Pass glacier was dying beneath its cloak of drift—the ice itself provided most of the "valley fill".

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The processes involved in the downhill migration are physically quite simple. According to Ward a massive ice core might itself flow downhill at a velocity approximately proportional to the fourth power of the ice thickness. Meanwhile the shrouding detritus would tend to slip downward whenever the melting isotherm penetrated far enough to affect the ice. By these two processes—and even by the second one alone—the whole moraine would become flattened and extended downhill. There is evidently something in common between Ward's ideas and those of Capps, Kesseli and Sharpe, already discussed.

Moraine Chronology

From the close intermingling and similar vegetation of their deposits, it is clear that an advance of many of the tributary glaciers took place shortly after Pangnirtung Pass itself was deglacierized. Another tributary advance occurred some time before 1850[15]. Neither of the earlier glacierizations can be dated; but G. C. Riley* states that in local Eskimo legends there is no mention of Pangnirtung *Fiord* being filled with ice. In Bulletin No. 118 of the National Museum of Canada, H. B. Collins writes (p. 29) that the "Thule" culture of Frobisher Bay, 200 miles to the south, prevailed about 650–1000 years ago or more. The modern Eskimo culture of Frobisher and Pangnirtung postdates that period and it may therefore be permissible to believe that Pangnirtung Fiord has been ice-free for at least 600–700 years. But even this tenuous "evidence" does not necessarily apply to Pangnirtung Pass itself.

F. H. Schwarzenbach's ecological studies have provided only a minimum estimate for the age of the old moraines, namely 300 to 500 years*. The general condition of the moraines, as well as the lack of deep weathering of bedrock and drift, make the geomorphologist unwilling to accept dates too remote from the present. Perhaps A.D. 500 is not too wild a guess for the deglacierization of Pangnirtung Pass, but the figure is offered as a guide rather than a conclusion.

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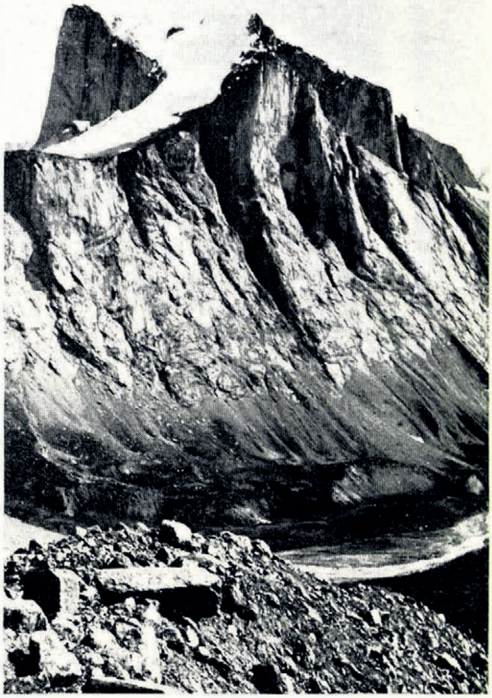

Fig. 3 (above, left). Old moraines, with vegetated tops and fresh fronts, cling to the side of the Pass. Glacier 28 on left and Glacier 26 on right

Fig. 4 (above, right). Old moraines lie at the base of massive granite slabs and extensive screes. Grey valley-train terraces are seen between the old moraines and Weasel River

Fig. 5 (below, left). Old moraines near the Great Moraine Gorge (left). "Green slope" in right centre. Glacier 20a and its new moraine on the right

Fig. 6 (below, right). Glacier 30 and its new moraine loop. Glacial ice crops out at several points and underlies every type of deposit. Old moraines to right and in foreground

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