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GRADIENTS OF PAST AND PRESENT OUTLET GLACIERS

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Jane T. Buckley

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ABSTRACT

Gradients have been calculated for a large number of outlet glaciers entering fiords in Alaska, Greenland, Antarctica and Arctic Canada. A linear relationship exists between the overall length and the gradient of these glaciers. This method finds application in the reconstruction of ice surfaces of former outlet glaciers in areas previously glaciated, and an example is taken from Baffin Island.

GRADIENTS OF PAST AND PRESENT OUTLET GLACIERS

INTRODUCTION

Current interest in the 'nunatak hypothesis' (Dahl, 1966; Ives, 1966) and discussion concerning the vertical extent of the Laurentide glaciation in northeast Arctic Canada suggested the possibility of reconstructing former outlet glaciers by comparison with glaciers existing today. Study of the implications of high-level moraines at the mouth of Sam Ford Fiord (Ives and Buckley, 1969) included trend surface analyses of former outlet-glacier ice-surfaces reconstructed from the position of their moraines. The results, along with those obtained from Ekalugad Fiord (Andrews, et al.), suggest that the terminal part of the outlet glacier was relatively steep, but that above 500 or 600 metres the ice surface rapidly flattened. How far this gradient continued inland was not discernable for lack of data. Previously, from a study of moraines at the head of Sam Ford Fiord, Smith (1966) concluded that lateral moraines, related to the long profile of the glacier in that fiord, could be interpreted as having a constant gradient of 1:66. If this argument were correct, then the existence of an excessive thickness of ice over Baffin Island at the maximum advance during the Wisconsin would have to be accepted.

To establish some means of comparison, attention was turned to glaciers existing today in analogous positions. Most of the glaciers measured in this study originate from ice caps and terminate either in a fiord or close to its head. The resulting relationship between the measured length and the overall gradient might be applied to the prediction of the extent of the ice cover at the last glacial maximum in Baffin Island. Previous work on the reconstruction of glacier profiles (Mathews, 1967) depended on knowing the depth of the glacial ice. However, in fiord situations, submarine-floor profiles are often not available, and in many cases morainic evidence is non-existent or unobtainable from the sides of the fiord. Much work on theoretical ice-profiles has been concerned with 'perfect' shapes, which while providing limits within which to work, do not necessarily reproduce forms which exist in the natural world. Generally the surfaces dealt with have been those of inland ice rather than of outlet glaciers (Bull, 1957; Nye, 1952, 1959).

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GLACIER MEASUREMENTS

Study Areas and Sources of Material

Four areas were chosen for study:

- the coastal part of Alaska bordering the gulf of Alaska, and including the entire 'panhandle';
- the complete coastal area of Greenland;
- that part of coastal Antarctica bordering the Ross Ice Shelf and the Ross Sea;
- coastal areas of the northeast islands of the Canadian Arctic Archipelago.

These areas have the following features in common:

- mountainous coastal areas;
- outlet glaciers that extend from interior ice caps to any part of a fiord;
- numerous glaciers flowing from headwalls in the mountains to the fiords.

The areas contain examples of many different stages in the 'life' of fiord glaciers. As a result, the study includes glaciers in which the ice extends as far as the outer limit of the coastline - although in no case as far as the continental shelf - and also, examples in which the glacier terminus now lies at the head of the fiord. However, the Greenland figures include many glaciers which do not flow through or from mountains, and these glaciers appear to have a more gentle gradient, which influences the final result of this group.

Data were measured from maps, at the scale of 1:250,000, in the following series:

Alaska	- AMS series Q 501 (1st edition)
Greenland	- AMS series C 501 (1st edition)
Antarctica	- USGS - reconnaissance series
Arctic Canada	- ASE series A 501 (1st edition)

Most of these maps are contoured at 200-metre intervals, although a few have 500-foot contour intervals. The accuracy of the contours varies, depending on the amount of data available, but the maps, nevertheless, present coverage of the areas in similar terms and thus measurements may be readily compared. It is recognized that errors are likely to occur in working with small-scale maps of, in some cases, relatively poorly documented areas, but by using the same scale throughout the study, the comparative values for the gradients are considered valid.

Grouping and Measurements

Within each of the four areas the glaciers were classified into the following major groups:

A) all the glaciers included in B, C and D;

B) glaciers flowing from ice caps into fiords, including any which continue as far as an ice shelf;

C) glaciers flowing from mountain headwalls to fiords or onto ice shelves;

D) glaciers flowing from ice caps or headwalls to the heads of fiords, where it is clear that the snout is on land and not more than 200 metres asl;

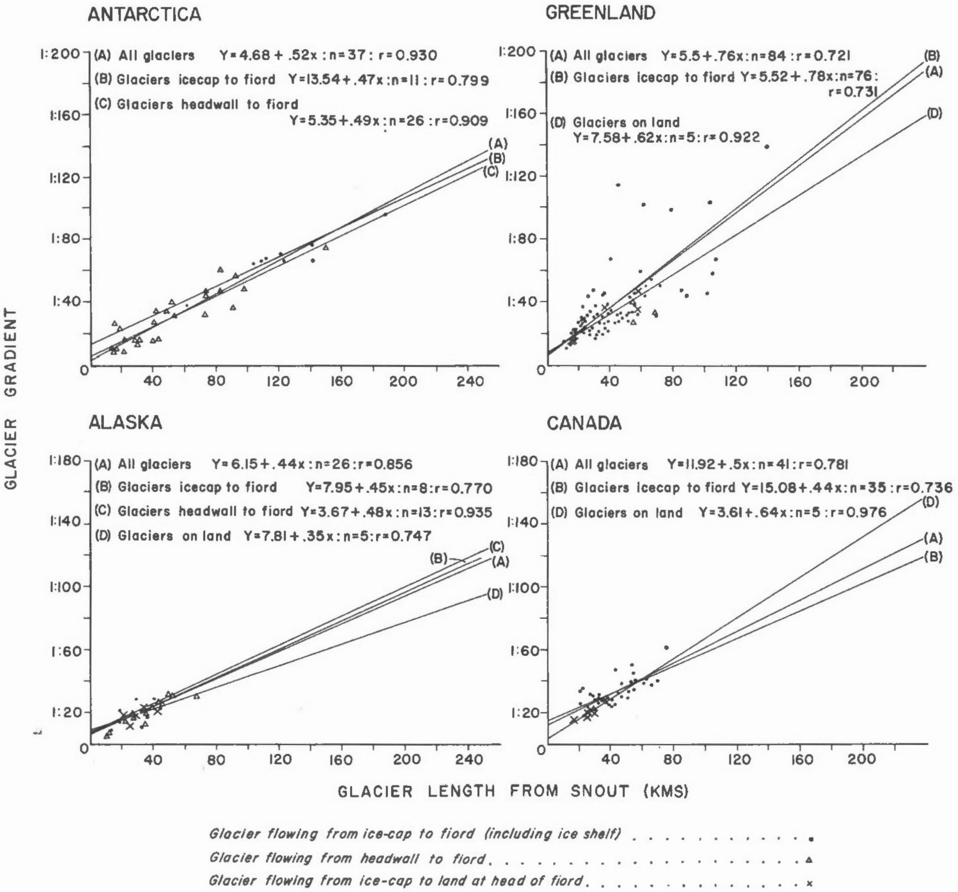

Figure 1. Overall gradient versus glacier length for four selected areas, showing least-squares line for specified groups.

Also measured but not considered in the final comparisons, were the following groups, none of which were common to all the areas:

E) distributary glaciers flowing into fiords or onto ice shelves;

F) the head-sections of tributary glaciers;

G) complete profiles of tributary and main glaciers.

The profile of each glacier was plotted, with elevations (in metres) along the y axis and distances from the snout (in kilometres) along the x axis. In the case of glaciers originating from an ice cap, the height was taken from the highest contour on the ice that showed distinct indentation indicating ice flow into the outlet glacier. Distributary glaciers were measured from the first contour above the junction or at a suitable spot height in mid-glacier. In a few cases, it was not possible to measure the complete length nor the total height, due to the lack of mapped information in some areas. In such cases, the gradient of the measurable length was used, and all were found to agree well with the other results.

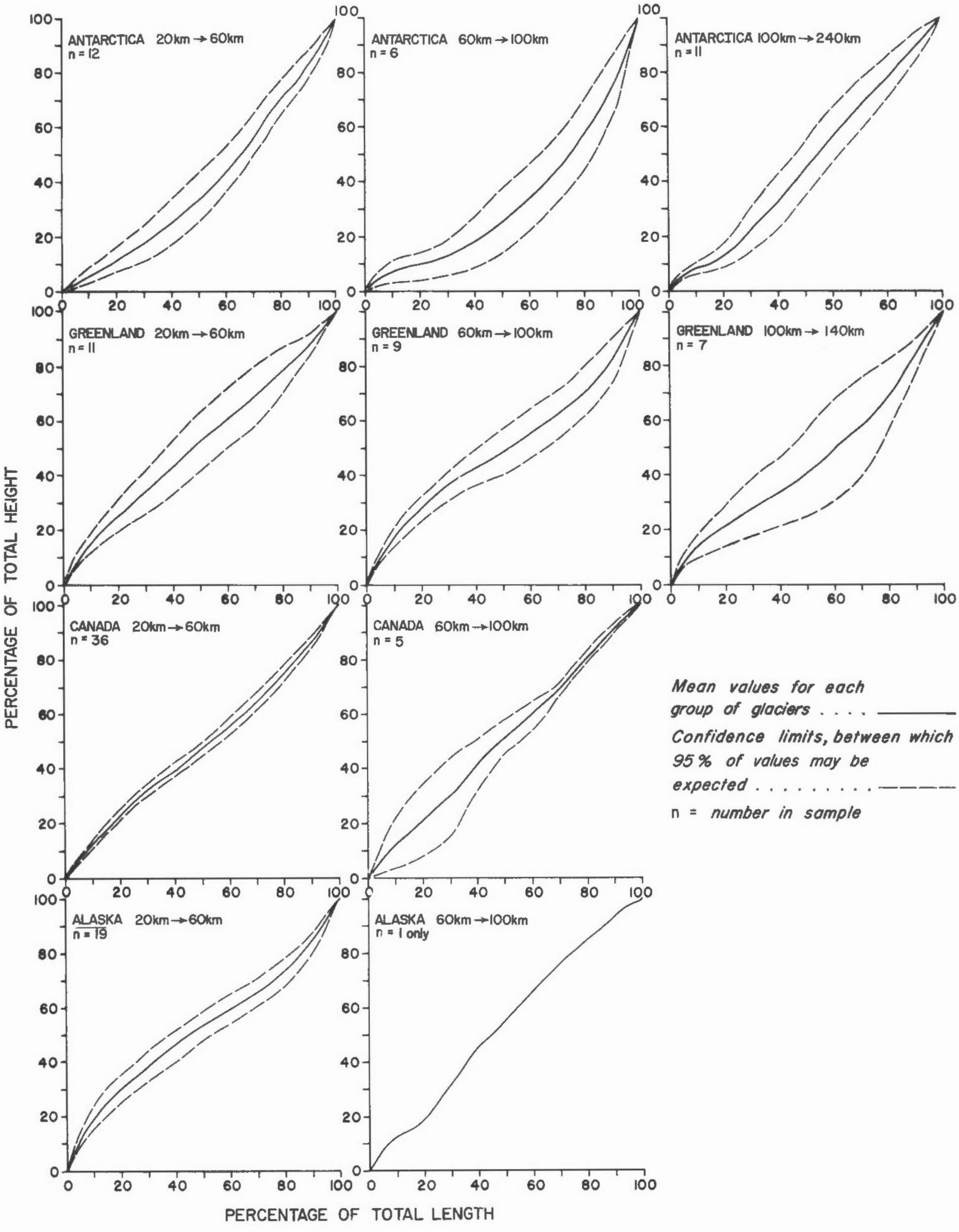

Figure 2. Grouped glacier-profiles plotted with cumulative percentage of height against distance from the snout expressed as a percentage

The overall gradient of each glacier was plotted on a graph against its length (Fig. 1). The least-squares line for each group of glaciers was computed using a program called 'Tilt' which fits an equation of the type $y = a + bx$ in which a and b are constants calculated on the basis of observations, x is the length and y the gradient. The program also calculates values for r (the correlation coefficient) and S (the standard error). Table I shows each of these values for glacier groups A to D inclusive.

The height gained every five kilometres up from the snout was measured and expressed as a percentage of the maximum or total height of the ice at its greatest measured distance. These figures were plotted on the y axis against percentage of glacier length on the x axis, and the curves were grouped according to the total measured length, to provide a visual means of comparison. Each group, varying in size between the areas, is represented in Figure 2 by a solid line joining mean values derived from the plotted curves. Broken lines represent the upper and lower confidence limits within which lie 95 per cent of the observed values.

RESULTS

From Figure 1 it is clear that a high degree of correlation exists between the total length of a glacier and its overall gradient. Figure 3 shows the comparison between the length/gradient relationship for each of the areas studied. A close similarity is seen between results from Alaska, Canada and Antarctica, whereas Greenland shows more gentle gradients. These results provide the best indication of existing conditions. Figure 4 is constructed in a similar way, but represents only those glaciers that flow from interior ice caps to fiords or, in the case of Antarctica, onto an ice-shelf (group B). The results of this particular group are of special interest in considering former glaciation in areas such as Baffin Island. Because of lack of data toward the upper reaches of 5 of the 26 Alaskan glaciers, only the lower sections of these glaciers could be included in this study. This may result in the calculated gradients being slightly steeper than the real ones. In the Greenland measurements, 4 glaciers out of 84 similarly lacked complete data. Table I details the least-squares line for each group of data, and, besides giving the values for the constants (a. b), it also shows the values for each correlation coefficient (r), the standard error (S), and the number of glaciers (n) included in each sample. The correlation coefficient for group A varies between 0.930 for a sample of 37 glaciers in Antarctica, to one of 0.721 for a sample of 84 glaciers in Greenland. In group B all the r values lie below 0.8, whereas in group C (glaciers flowing from headwalls) the r values are above 0.9.

Figure 1 shows that in Canada glaciers with their termini on land at the head of a fiord have an average gradient less steep than those which terminate in water. This is contrary to the general trend shown in all the other examples, where the gradient becomes steeper as the distance to the terminus decreases.

The diagrams showing cumulative percentages of total height and total length were constructed by grouping together glaciers with similar cumulative profiles. Figure 2 shows the curves representative of the groups obtained for each area.

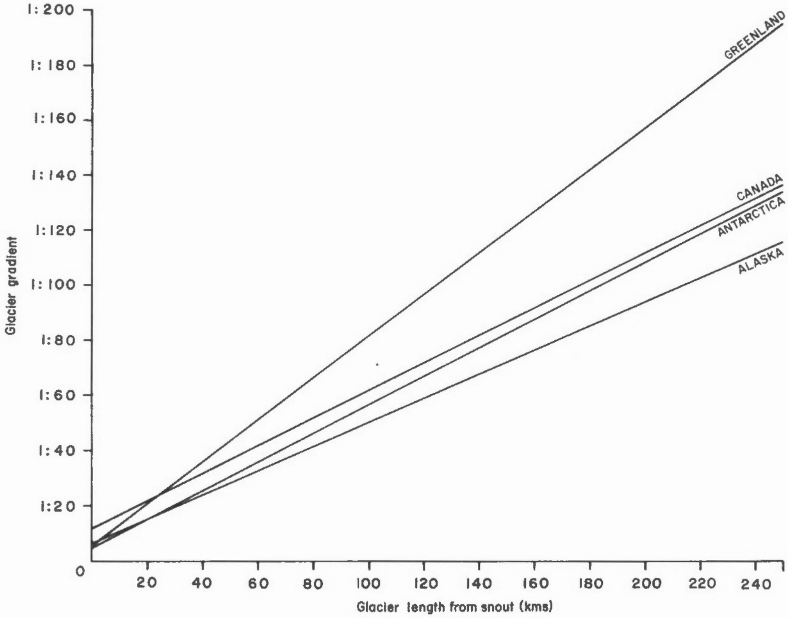

Figure 3. Comparison of the gradient/length results for all glaciers measured in each area.

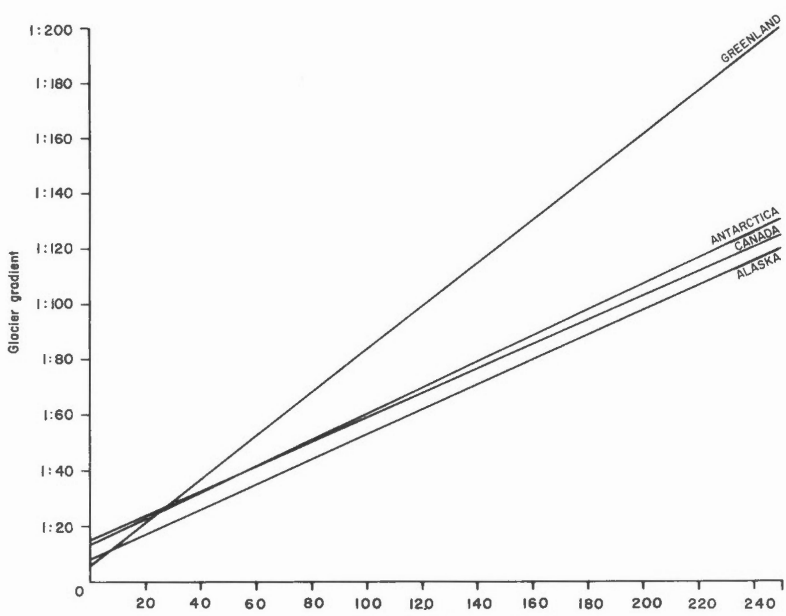

Figure 4. Comparison of the gradient/length results for glaciers flowing from ice caps to fiords in each area.

<u>Table I</u>

Results of least-squares line calculations for glacier groups measured in each area*

		Alaska				Canada				Antarctica				Greenland			
		A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
a value	A	6.15				11.92				4.68				5.5			
	B		7.95				15.08				13.54				5.52		
	C			3.67				-				5.35				-	
	D				7.81				3.61				-				7.58
b value	A	0.44				0.5				0.52				0.76			
	B		0.45				0.44				0.47				0.78		
	C			0.48				-				0.49				-	
	D				0.35				0.64				-				0.62
r value	A	.856				.781				.930				.721			
	B		.770				.736				.799				.731		
	C			.935				-				.909				-	
	D				.747				.976				-				.922
s standard error	A	3.84				5.97				11.54				18.26			
	B		5.15				6.08				18.52				19.08		
	C			3.12				-				7.68				-	
	D				2.95				1.14				-				6.28
n No. in class	A	26				41				37				84			
	B		8				35				11				76		
	C			13				1				26				3	
	D				5				5				-				5

* A) – <u>all</u> measured glaciers, that is, groups B, C, D.
B) – glaciers flowing from ice cap to fiord and/or ice shelf
C) – glaciers flowing from headwall to fiord and/or ice shelf
D) – glaciers with snouts on land at head of fiord

In each graph, the solid line represents the mean of all the glacier profiles measured in that particular length range. The broken lines indicate the upper and lower confidence limits at 95 per cent. Thus the Antarctica diagrams suggest that the glaciers conform fairly closely to a concave profile, which is especially pronounced in glaciers between 60 kilometres and 100 kilometres in length. At all lengths, Antarctic glaciers exhibit a flatter profile near the snout than do those in any of the other areas. Profiles from Greenland, Canada and Alaska are slightly concave at their greatest length but become progressively straighter and then more convex as the measured length decreases. In Alaska the suggestion of concavity lacks the weight of evidence of a large sample.

DISCUSSION AND CONCLUSIONS

Much discussion concerning the shape of ice cap profiles is based on the calculations of hypothetical values, and on the profile of the 'perfect' ice cap, which is generally envisaged as lying on relatively flat or, in some places, depressed ground. Even though some sectors of existing ice caps may conform closely to predicted shape, this paper is concerned mainly with the profile of the ice-cap edge where it lies against a mountain barrier and flows through the mountains as outlet glaciers. The Trans-Antarctic Mountains form just such a barrier to the inland ice through which outlet glaciers flow to Ross Ice Shelf and the Ross Sea. In a cross-section profile of Antarctica, Bentley (1965) shows the contrast between the smooth, convex ice-surface at the edge near Mirnyy, and the broken, concave surface where the ice flows through the mountains on the opposite side of the continent. The Antarctic ice is believed to have thinned only a few hundred metres from its maximum extent (Gow, 1965), and thus, as a working 'model', represents today conditions similar to those which may have existed over northeastern Canada at the time of the Wisconsin maximum. Exact parallels cannot be drawn because, of the two, the Antarctic ice is regarded as cold polar in origin, whereas the Laurentide Ice is considered to have formed under more temperate conditions. However, the results of gradient measurements suggest that there is little difference in the long profiles of glaciers from the two areas when they are compared length for length.

There has been considerable argument concerning the existence of coastal mountains of Northeastern Canada as nunataks during the Wisconsin glaciation. Dahl (1947) suggested that the maximum marginal slope of an inland ice sheet bordering a deep ocean would be 1:100 and that peaks in excess of 1,000 metres altitude and within 100 kilometres of the coast would have remained as nunataks - or have been capped only by local ice patches and glaciers. Mercer (1956) reiterated this argument and applied it in Baffin Island, where he found evidence that the highest parts of the Kingnait Peninsula had <u>not</u> been glaciated. However, he recognized that the existence of a wider continental shelf that exists further south along the Labrador coast allowed for a greater accumulation of ice, and that the slightly lower summits to the north had definitely been submerged beneath the ice. Ives (1957) concluded that the highest mountains in the central Torngats could have been submerged by more than 300 metres, but that the coastal mountains would have had only a very thin covering of ice.

To test the results presented in this paper and thus to formulate a working hypothesis, reconstruction of the outlet glacier in Sam Ford Fiord, Baffin Island has been attempted (Fig. 5). Here, the continental shelf extends 50 km off the outer coast, and the height of land, >1800 metres, lies 50 km inland from the outer coast. On the outer coast, at the mouth of Sam Ford Fiord is a series of old moraines, most of which are believed to date from 36,000 radiocarbon years B. P., by their relationship to the position of one dated sample (I-2581 (GB-69-66)), (Ives and Buckley, 1969). The total length was measured to the head of the fiord, above which it is assumed that the ice would have begun to show signs of flow into the fiord. The mean glacier profile and the upper and lower confidence limits taken from the cumulative height/length results obtained from the longer of the Antarctic glaciers (see Fig. 2), were superimposed onto the submarine profile of Sam Ford Fiord and the land profile of the peninsula to the north (Fig. 5). From this it appears highly unlikely that the mountain tops at the height of land were beneath the outflowing inland ice, although it does seem probable that those close to the coast and further inland near the head of the fiord would have been under the ice at some time. It is generally assumed that the ice edge lay no further offshore than the edge of the continental shelf at any time. The highest of the coastal moraines can be fitted to an ice profile (line A_1, Fig. 5), the limit of which lay close to the edge of the continental shelf. The ice thickness over the outer coast at this maximum position would have been little greater than that suggested by these moraines, and it seems likely, therefore, that they relate to a retreat phase very early in the deglaciation of the area. The lowest moraines in the series fit the profile only after ice retreat brought the ice edge within 7 kilometres of the coast (line A_2, Fig. 5). It is likely that some mountains projected through the inland ice as nunataks, (Fig. 5) but no conclusions can be drawn regarding the existence of local ice caps on the high mountains.

Shear stress values have been calculated at 10 km intervals along Sam Ford Fiord, using the formula $\tau = \rho g h \alpha$ (Nye, 1952) where:

- τ = sheer stress
- ρ = density of ice
- g = acceleration due to gravity
- h = thickness of ice between fiord floor and the ice surface (reconstructed from the Antarctic mean ice surface as obtained from the cumulative percentage of height and length measurements on glaciers between 120 and 240 kilometres in length)
- α = numerical expression of surface slope obtained by dividing the sloping length of the glacier into the difference in height.

The slope of the mean ice surface between the head of Sam Ford Fiord and the outer coast was taken as uniform, and a constant value of $\alpha = 0.01078$ was used in the calculation of shear stress for that section. Between the outer coast and the continental shelf, the value $\alpha = 0.00343$ was used for the flatter part of the profile and $\alpha = 0.00864$ was used for the steeper terminal section.

The calculated shear stress values for the fiord section may appear to be high, but result from the great depth of the midsection of the fiord which greatly influences the measurement of ice thickness. Table II shows the mean shear stress between the fiord-head and the outer coast as being 1.39 bars. Between the coast and the edge of the continental shelf, where no

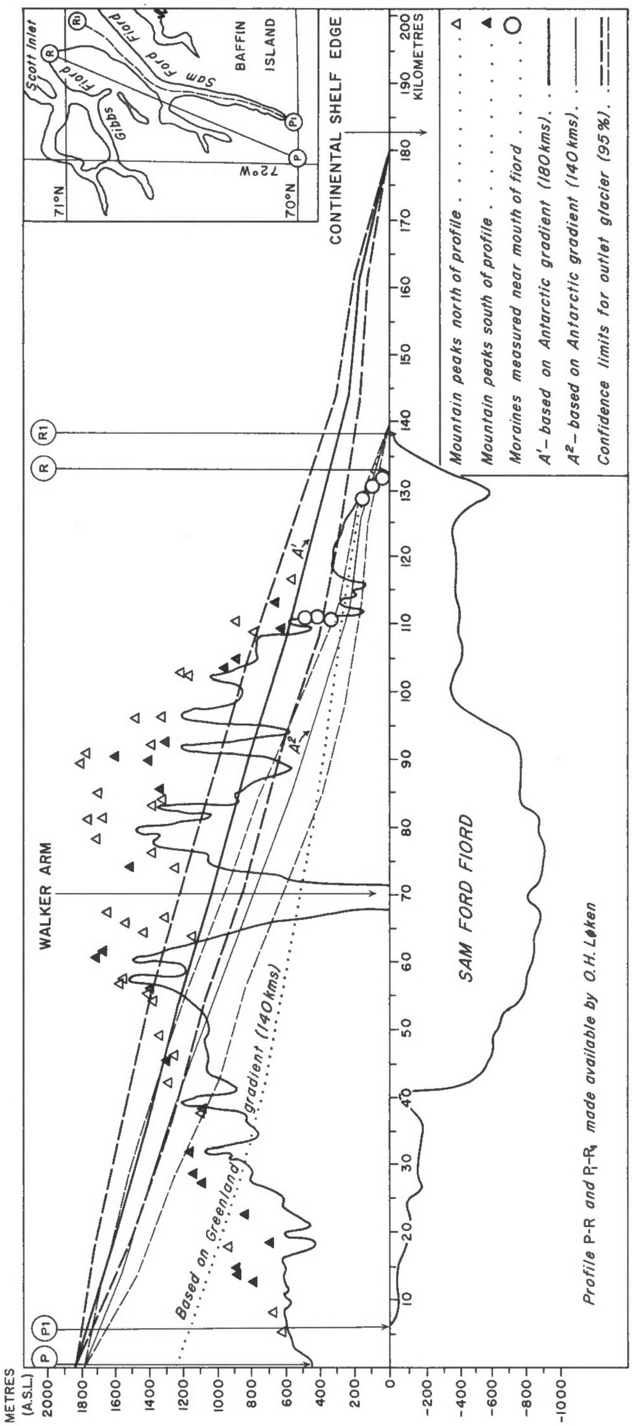

Figure 5. Ice surfaces reconstructed in Sam Ford Fiord, Baffin Island, based on Antarctic data.

Table II

Ice thickness and shear stress values for reconstructed glacier in Sam Ford Fiord

Distance from fiord-head (kms)	Calculated ice thickness between mean ice surface and fiord floor (metres)	Calculated shear stress: $\tau = \rho g h \alpha$ (Nye, 1952) expressed bars (1 bar = 10^6 dynes/cm^2)
0 (fiord-head)	1775	1.68
10	1700	1.61
20	1685	1.60
30	1580	1.50
40	1920	1.82
50	2000	1.90
60	1965	1.87
70	1875	1.78
80	1645	1.56
90	1265	1.20
100	1040	0.99
110	890	0.85
120 (outer coast)	830	0.79
130	360	0.34
		$\bar{\tau}$ = 1.39
	Ice thickness where submarine profile unknown (metres)	
140	215+	>0.065
150	180+	>0.054
160	120+	>0.092
170 (continental shelf edge)	40+	>0.030
		$\bar{\tau}$ = >0.06

submarine profile was available, the mean shear stress was calculated to be >0.06 bars. This should be considered as a minimum value, since the depth of the ice (unknown) below the water-level would tend to increase the shear stress value.

The conclusions drawn from this reconstruction of a former ice surface may be summarized thus: between the gradient of a glacier profile and its length, there exists a close relationship such that the longer the glacier, the more gentle its gradient. As the glacier becomes progressively shorter its gradient or surface slope becomes proportionately steeper. Profiles of similar length show close resemblance to each other and exhibit characteristics which may be indicative of their length and of their position within the confines of a fiord. In most cases, outlet glaciers have mainly concave profiles in which the ice surface drops steeply from the head-wall or ice cap before flattening out in the mid-section and steepening again near the snout or terminus which itself is more convex in profile.

It should be remembered that, of the glaciers measured in this study, those in Antarctica, Alaska and Arctic Canada all exist in what today appear to be comparable situations. Greenland introduces slightly different conditions in that the mountains around the coast are not so prominent and the measurements were made on all the glaciers reaching the coast rather than on only those flowing through mountains. The Greenland ice cap is not so pronouncedly 'banked-up' against the mountains as is the case in Antarctica where the Transantarctic Mountains form an appreciable barrier. Consequently the Greenland ice cap slopes down gently to a lower height before the outlet glaciers flow out. Over comparative distances the Greenland gradients are all much more gentle than those for any of the other areas (see line G, Fig. 5).

The reconstruction of former ice surfaces of outlet glaciers has, in this paper, been based on the results from Antarctica. Had the Greenland gradients been used instead, the results would have shown more rather than less of the mountains remaining above the main ice surface.

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