THE ROLLS ON THE ELLESMERE ICE SHELF*

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In a paper on arctic ice islands (Koenig *et al.*, 1952) it was pointed out that surface rolls are characteristic features of both the Ellesmere Ice Shelf and the floating ice islands. From this it was inferred that the ice islands almost certainly originated by calving from the Ellesmere Ice Shelf. The shape of one large ice island did in fact prove its former contiguity with the ice shelf off the mouth of Markham Bay. Comparison of roll patterns of other ice islands with the roll pattern on the ice shelf may indicate the exact areas from which the ice islands have calved. It is therefore of interest to discuss the origin and evolution of these surface features.

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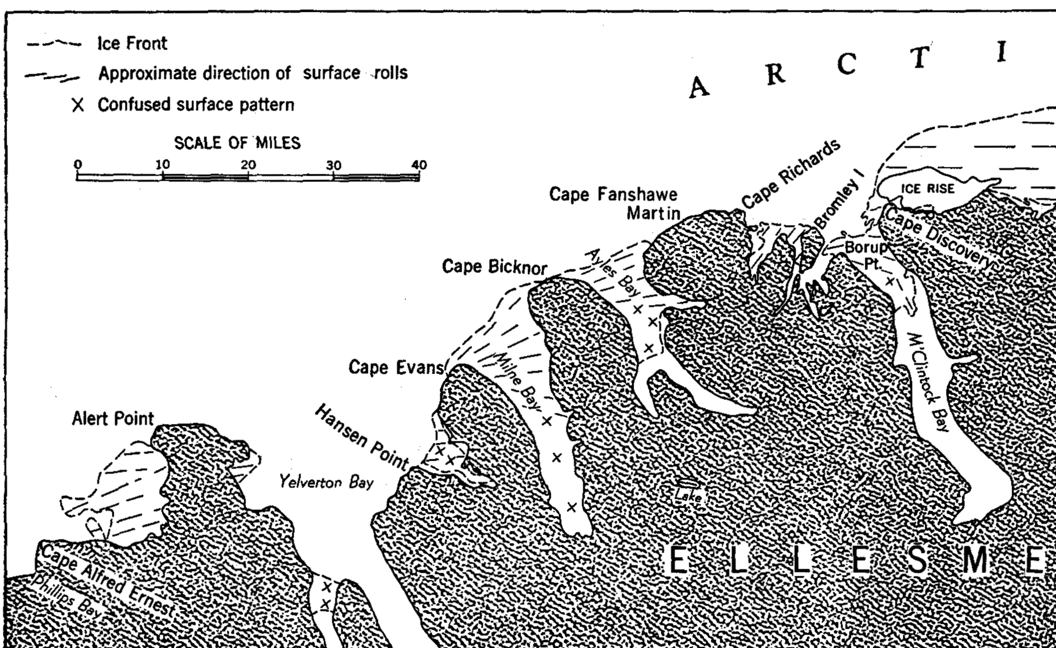
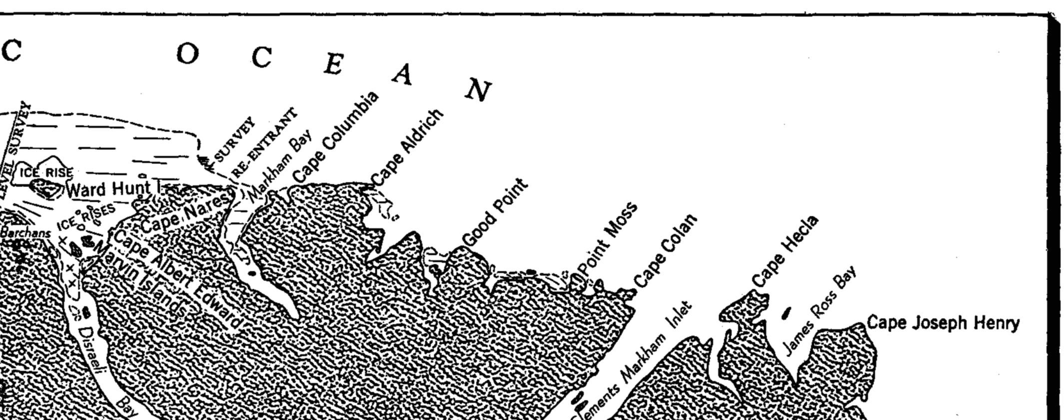


Fig. 1. Sketch map of the coas

The ridges and troughs that constitute the rolls on the surface of the Ellesmere Ice Shelf (Hattersley-Smith *et al.*, 1955, p. 12) show a general parallelism to the outer coast, but inside the fiords they tend to swing southward or to become disorganized (Fig. 1). In 1954 a transit level survey was carried from the mainland shore to the ice front on a south-north line, one mile west of Ward Hunt Island ice rise (Crary *in* Hattersley-Smith *et al.*, 1955, p. 27); the results of the survey are shown in Fig. 2, in which the vertical scale has been greatly exaggerated. The greatest difference in elevation between the bottom of a trough and the crest of an adjacent ridge was observed to be 21.2 feet, with allowance for the different amounts of snow at the two places.

Since the ice shelf is floating and in isostatic equilibrium, it may be expected to be proportionately thinner beneath the troughs and thicker beneath the ridges. The difference in thickness beneath a trough and an adjacent ridge should be equal to more than the difference in elevation between the bottom of the trough and the crest of the ridge, for it seems unlikely that the rigidity of the ice is sufficient to support a ridge and trough pattern on the surface without a reciprocal pattern on the underside. The tendency of the ice islands to break off from the ice shelf along lines parallel to the ridges and troughs may be due to the fact that the troughs, where the ice shelf is thinner, are lines of structural weakness (cf. Koenig *et al.*, 1952, p. 81).



of northern Ellesmere Island.

The ice thicknesses obtained seismically near the edge of the ice island T3 give some indication of rolls on the under surface; the convex-upward troughs on the under surface seem to be vertically beneath the troughs on the upper surface (Crary, 1954, p. 300). Robin (1954, p. 200) has postulated similar conditions for the Maudheim Ice Shelf in western Dronning Maud Land. The effect of isostatic forces on a mass of floating ice of irregular thickness has been demonstrated by Russian work. Thus "a hummock was demolished on an ice field to the north of Laptev Sea in the preparation of an airdrome. After several days, a bulge appeared at the place of the razed hummock as a result of isostacy, ruining the airdrome." (Zubov, 1938, p. 11).

The temperature of the lower surface of the ice shelf is between -2° and -3°C., according to the salinity of the water. The temperatures measured in the ice shelf (Crary, *in* Hattersley-Smith *et al.*, 1955, p. 30) indicate a considerable temperature gradient from the lower to the upper parts of the shelf. Heat flows from the water to the ice. If the water is above its freezing point, the transfer is accompanied by freezing (Simpson, *in* Debenham, 1948, p. 213). There should be less melting and more freezing beneath the troughs, where the ice shelf is thinner, than beneath the ridges. Rolls on the under-surface should therefore tend to be flattened out. It must be assumed that this tendency is more than offset by the isostatic effect resulting from the deepening of the surface troughs by melt-water, whose warming effect persists throughout the winter, as shown by the higher ice temperatures beneath a trough (Crary, *in* Hattersley-Smith *et al.*, 1955, p. 30). The increase in the depth of the troughs toward land is due partly to increased melting near land, and hence to a greater flow of melt-water. Two other factors may also be partly responsible for the greater depth of the troughs on the landward part of the ice shelf—the greater thickness of the shelf, giving the trough rivers and lakes a higher gradient and a faster flow toward the tidal cracks draining to the sea; the probably greater age of this part of the shelf, which has allowed more time for the troughs to develop.

Secondary troughs near the crests of some of the major ridges suggest that modification of the primary drainage pattern may have taken place from time to time. Modification could be due to blocking of drainage channels and filling up of some troughs by lake ice or it could be due to melt-water overflowing from the trough lakes to form new lakes in depressions on the ridges. The general shallowness of the troughs on the ice islands T1 and T2, as seen in air photographs (Koenig *et al.*, 1952, pp. 70, 72), may perhaps be due to filling by lake ice since the time when the ice islands broke away from the ice shelf. In a trough lake on T3 blockage of outlet led to an increment of 35 inches of ice (Goldstein, *in* Crary *et al.*, 1955, No. 8, p. 3).

Undulations have also been described near the seaward edges of antarctic ice shelves (Wright and Priestley, 1922, p. 208; Siple, 1945, p. 57; Debenham, 1948, p. 210; [Roscoe], 1953, p. 58; Swithinbank, 1955, p. 72). On the relatively thin Ellesmere Ice Shelf the rolls have a shorter wave length than the undulations on the much thicker antarctic ice shelves, as the following figures show. In the vicinity of Ward Hunt Island (Koenig *et al.*, 1952, p. 66), where the thickness of the ice shelf is at the most 120 to 150 feet, the ridges are 200 to 300 yards apart, and the troughs 5 to 20 feet deep; near Point Moss, where the thickness of the ice shelf is probably much less, the ridges are about 100 yards apart, and the troughs not more than 5 feet deep (Hattersley-Smith, 1956, p. 233). In Dronning Maud Land, where the ice shelf is about 190 metres (620 feet) thick, the ridges are said to be about 1 kilometre (1,100 yards) apart, and the troughs about 10 metres (30 feet) deep (Swithinbank, 1955, pp. 64, 73). In describing the undulations on the Ross Ice Shelf, Debenham (1948, p. 210) observed that "their direction and symmetry seem to indicate a factor operating with regularity from seaward", but Swithinbank (loc. cit.) states that "the origin of such depressions is quite unknown".

Under present conditions in northern Ellesmere Island undulations originating from any cause would be perpetuated by the drainage of melt-water, which does not occur in the Antarctic. The original siting of the ridges and troughs on the Ellesmere Ice Shelf could have been due to any one of the following possible causes: movement of the ice shelf, movement of the land glaciers, temperature changes, pressure of the pack ice, tidal action, or wind action.

At the present time no glaciers exert large scale lateral pressure on the Ellesmere Ice Shelf, and there is no sign of any *en masse* movement of the ice shelf away from the coast, except when ice islands break away along lines of fracture. It has been stated that antarctic ice shelves have a general surface elevation of between 37 and 45 metres (120 and 150 feet) above sea level, and it has been shown that they are subject to spreading under their own weight (Swithinbank, 1955, pp. 64, 72). It may be that this sort of movement would be negligible on the Ellesmere Ice Shelf, whose surface elevation probably nowhere exceeds 25 feet above sea level (Fig. 2). Measurements on the ice shelf in Markham Bay are inconclusive on this point, but they do show that between May 1953 and September 1954 any movement along a north-south line did not exceed 5 feet.

Pressure by a glacier has been stated to be the cause of folded bay ice in Marguerite Bay, Graham Land (Nichols, 1933, p. 130-3). It has been suggested that during the history of the Ellesmere Ice Shelf the glaciers along the *outer* part of the coast have never extended much beyond their present limits (Hattersley-Smith, 1955, p. 23-5). As Debenham (1954, p. 497) has pointed out, it is unwarranted to suppose that the rolls on the outer part of the ice shelf are due either to movement of the land glaciers or movement of the ice shelf. However, inside the fiords, as at the head of Milne Bay, rolls on the ice shelf have undoubtedly resulted from glaciers moving out into the fiord. The air photographs suggest that the rolls are mainly due to crevasses in the floating glacier tongues that merge with the ice shelf (see also Marshall, 1955, p. 112), rather than to buckling of the ice shelf under the pressure of the glaciers. On the outer part of the coast between Alert Point and Cape Alfred Ernest the remnant of ice shelf is partly composed of a floating ice tongue, which has well developed surface rolls (Fig. 4). But glacier pressure cannot be regarded as the main cause of the rolls even in the fiords, because the whole series of rolls from the fiords to the outer edge of the shelf, which is 12 miles from the mainland north of Ward Hunt Island, show a remarkable uniformity (Fig. 1).

Rolls have been explained as due to temperature changes, in order to account for their parallelism to the shore. Wright and Priestley (1922, p. 344) gave this explanation for ridges and troughs parallel to the shore on the east side of McMurdo Sound, South Victoria Land: "a rise of temperature, acting over a very large area, causes expansion in the ice-sheet, especially when the latter is thick. This, in turn, sets up considerable pressure which is usually concentrated along shore lines, or against immovable objects such as islands and stranded bergs." Zubov (1955, p. 5) has suggested a similar explanation of the rolls on the Ellesmere Ice Shelf. "The temperature of the lower surface of ice, when it is afloat, is always close to the freezing point, while on the top surface it fluctuates, in the course of the year, over a range from zero to 40-50° below zero [centigrade]. If we take it that the ice shelf is at some times resting on the bottom so that its lower surface is immovable, then temperature fluctuations might cause either fissures or folds in the ice, and . . . they will be parallel to the shore line."

Measurements on the ice shelf in 1954 showed that seasonal variations in temperature occur only in the upper 40 feet of ice (Crary, *in* Hattersley-Smith *et al.*, 1955, p. 30). Permanently grounded ice, as the ice rises (Koenig *et al.*, 1952, p. 66), can be recognized by the lack of rolls and by the strand cracks that mark the junction with the ice shelf. The observations and soundings east and west of Ward Hunt Island (Crary, 1956) strongly suggest that the ice shelf in this region is floating throughout its extent, except possibly over limited areas near its edge, where it may intermittently be grounded. No fissures, as postulated by Zubov, were observed on the ice shelf, unless the troughs themselves are to be regarded as fissures that have been enlarged by melt-water. The floating nature of the ice shelf and the complete lack of rolls on the ice rises constitute the principal objections to Zubov's hypothesis.

Debenham (1954, p. 504) and Zubov (1955, p. 5) have suggested that the pressure of the pack ice may be responsible for producing the rolls in the coastal fringe of the ice shelf. But it is difficult to see how pressure of the pack could in any way influence roll formation at the present time, because, north of Ward Hunt Island for example, the pressure can only act on a thin edge of the 12-mile wide ice shelf. At its edge the ice shelf is believed to be not more than about 35 feet thick, whereas near the mainland it is as much as 150 feet thick, according to seismic soundings by A. P. Crary. Under these conditions pressure of the pack could hardly cause folding. It is possible, however, that the pressure of the pack may have influenced the original siting

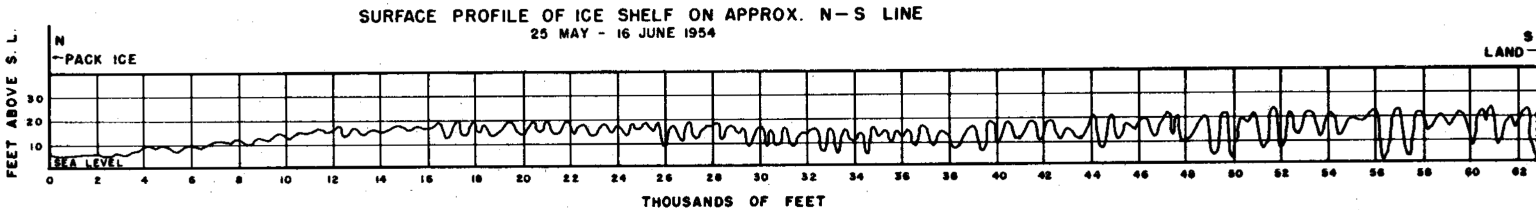


Fig. 2. Surface profile of ice shelf west of Ward Hunt Island.

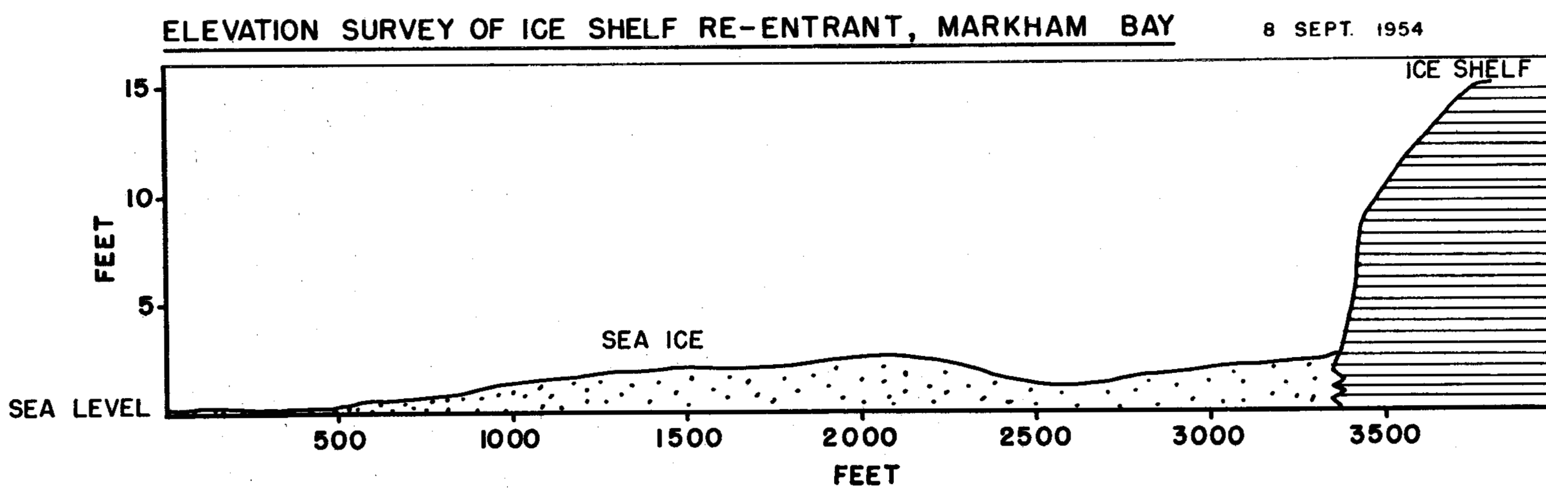


Fig. 3. Surface profile of ice shelf re-entrant off Markham Bay.

of the rolls at the bay ice stage of ice shelf formation, as exemplified by the ice that has formed in the Markham Bay re-entrant to a thickness of 20 feet since 1946 (Hattersley-Smith *et al.*, 1955, p. 23) (Fig. 3). A slight tendency toward a linear arrangement of the melt-water lakes between low pressure ridges was observed on the ice of the Markham Bay re-entrant, and could possibly represent an early stage in ridge and trough development, on the assumption that the lakes are subsequently deepened by melt-water flow. In Yelverton Bay more or less regularly spaced "hedges" of pressure ice, separated by a few hundred yards of smooth ice, probably about 15 feet thick, were observed in May 1954, and suggested a way in which a system of rolls might be started. Continual snow accumulation on the surface during the upward growth of the ice shelf might smooth out the rough ridges of the pressure ice to give a series of gentle undulations. An incipient ridge and trough pattern that could possibly have been formed in this way can be seen in an air photograph of sea ice off Phillips Bay (Fig. 4) (but see p. 42).

Photo: R.C.A.F.

Fig. 4. Cape Alfred Ernest and Phillips Bay.

Tidal action has been invoked to explain the origin of the rolls on the Ross Ice Shelf (Siple, 1945, p. 57; Poulter, 1947, pp. 377-83; Debenham, 1948, pp. 210-11). Debenham envisages a series of parallel cracks being formed by tidal action near the seaward edge of the ice shelf. Sea-water fills the cracks, and, since the temperature of the ice shelf is low, freezes up to sea level. The sea ice remains as a permanent line of weakness and tends to keep open the crack, which in its upper part becomes filled with drift snow. In Dronning Maud Land depressions along the seaward margins of the ice shelves are also thought to represent lines of structural weakness (Swithinbank, 1955, p. 73). The bottoms appeared to be "falling out" of these depressions, and Swithinbank concluded that this vertical movement is "normal and continuous", for otherwise no depression could survive filling-in by drift snow. Evidently the spreading of an antarctic ice shelf under its own weight plays a part in the formation of the depressions, but it is doubtful whether the Ellesmere Ice Shelf has any significant movement of this kind (p. 35).

In relatively thin ice tidal action can cause a system of parallel transverse cracks to develop; an air photograph of Hare Fiord off Nansen Sound shows such cracks in bay ice probably not more than 6 to 8 feet thick. If further cracks were to develop in the ice of this fiord, differential melting, due to penetration of sea-water, and melt-water erosion might conceivably combine to produce a system of ridges and troughs, as on the Ellesmere Ice Shelf. That cracks may occur in the lower part of the ice shelf is suggested by the influx of salt-water into the bottom of the 80-foot bore-hole at the 1954 main camp, where seismic soundings by A. P. Crary showed the ice shelf to be about 120 feet thick. But a crevasse was observed in only one place on the surface of the ice shelf.

The rolls could perhaps also be regarded as expressing the plastic response of the ice shelf to the tide, which acts gradually and progressively toward the land, so that there is a definite time interval between its effect near the edge of the shelf and its effect, say, along the latitude of Ward Hunt Island. The tidal effect could perhaps be measured by simultaneous levelling at various points along the north-south line. In the early days of the ice shelf, when it was relatively thin, tidal stresses might have been taken up by rafting and buckling of the ice. Later, as the ice shelf became thicker, perhaps with the worsening of the climate and increased accumulation at the surface, the tidal stresses may have been taken up by actual plastic deformation. Debenham (1954, p. 499) considers that deformation, caused by tidal action, is responsible for the rolls on the ice shelf in the fiords, on the assumption that the ice shelf is grounded at the sides of the fiords.

To each of the various possible explanations of the rolls, involving fracture or deformation of the ice shelf, that have been mentioned above, certain objections have been raised. Furthermore, none of these explanations can account for the astonishing regularity of direction and spacing of the rolls over the whole extent of the ice shelf.

It remains to examine the possible connection between wind action and rolls on the Ellesmere Ice Shelf. At the present time, wind does not have any important effect on the form of the ridges and troughs, because they are features of the ice and not of the superficial snow, which alone could be readily affected by the wind and which in fact tends to be slightly deeper in the troughs than on the ridges. Moreover the snow has provided no net increment at the surface during at least the last 45 years, as is shown by the finding of relics of a Peary expedition on the surface of the shelf (Hattersley-Smith *et al.*, 1955, p. 23). A minor effect of the prevailing westerly winds has been the promotion of drainage by the driving of melt-water eastward in the trough lakes in summer. But any connection between wind and original development of the troughs must be sought not under present day conditions, but under conditions prevailing when the shelf was being built up and all the winter snow did not melt in summer.

If the rolls were initiated by wind action, their east-west trend indicates that they began as elongated snow dunes parallel to the direction of the dominant westerly winds. Their tendency to swing southward into the fiords could be due to deflection of the winds, and their tendency to become disorganized at the heads of the fiords could be due to strong winds of variable directions induced by the local topography (Fig. 1), including katabatic winds from the ice cap parallel to the axes of the valleys. The fact that parallel ridges and troughs occur on the ice of a lake in a valley, 15 miles south of the head of Ayles Bay (Fig. 1) (Montgomery, 1952), strongly suggests that the ridges and troughs on the ice shelf are in no way associated with forces acting from the sea. A similar pattern of ridges and troughs occurs on another lake a few miles south of Cape MacMillan to the west of Phillips Bay (Fig. 5).

The following observations may support the hypothesis of wind origin. On the ice island T3 deep borings gave evidence of a migration of the surface rolls during the growth of the ice shelf (Crary *et al.*, 1955, No. 7, p. 2). If the rolls originated as a system of snow dunes, it would not be surprising to find that they migrated like sand dunes.

According to Bagnold (1941, pp. 178-9), there is a tendency for sand to be deposited in longitudinal strips under the influence of a strong wind from the same direction, blowing over a surface of absolute uniformity. Bagnold suggests that a large scale rotary movement in the air tends to scour the sand from the area between the strips, depositing it on either side. When the wind regime includes a strong wind from one direction with gentler winds from transverse directions, the sand is driven laterally into the sand-covered strips, and the conditions are right for the formation of longitudinal or *seif* dunes (Bagnold, 1941, p. 195). *Seif* dunes may grow to as much as 300 feet in height and may be as much as 60 miles long. The distance between the dunes remains approximately the same over a large area, and "is probably a statistical effect dependent on the sand supply". (Bagnold, 1941, pp. 229, 232). The ratio of this distance to the height of the dune varies widely from one region to another.

Fig. 5.

Glacier-dammed lake south of Cape MacMillan.

Photo: R.C.A.F.

Fig. 6. Ice barchans on mainland, south of Ward Hunt Island. July 30, 1954.

It is believed that some such processes may have been responsible for the development of the rolls on the Ellesmere Ice Shelf, where the strong winds and the bulk of the precipitation come from a general westerly direction, but where gentler winds blow from other quarters, chiefly the northeast. It could be expected that the form of the individual snow-flakes is also important. The more rounded and compact the snow-flakes—or the more they resemble sand grains—the more favourable are the conditions for *seif* dune formation.

Ice barchans occur on the mainland south of Ward Hunt Island (Fig. 6); their horns point eastward. Similar features occur near Hansen Point. Dune bedding was observed in the steep trough walls on the ice shelf in Disraeli Bay (Marshall, personal communication, 1954). Undoubted wind-drift formations occur near the Marvin Islands (Hattersley-Smith *et al.*, 1955, p. 14), and on the mainland south of Cape Albert Edward. These features are probably in equilibrium with the wind strength and the supply of snow.

Of special significance are the rolls, attributed to snow dunes, that occur on the smooth bay ice of the Markham Bay re-entrant formed since 1946 (cf. p. 38). They run parallel to the rolls of the adjacent ice shelf, but appear to have about half the "wave length" of the latter (Fig. 7). They were not noticed during the elevation survey (Fig. 3), which was made after the snow had melted. Similar rolls can also be seen on the bay ice in air photographs of Phillips Bay (Fig. 4), and Baird (1955, p. 104) has drawn attention to similar features on fiord ice in northeast Baffin Island. The presence of these features constitutes a strong argument in favour of a wind origin of the rolls on the ice shelf. The longer wave length on the ice shelf could be due to a difference in wind strength and snow supply during formation. The absence of rolls on the ice rises is attributed to the slope of the ice rises, which would cause the rolls to be obliterated by the surface drainage of melt-water. The absence of rolls on the hummocky ice of Clements Markham Inlet and on the broken bay ice of the outer part of the Markham Bay re-entrant suggests that the wind will not form rolls unless the ice surface is absolutely level and smooth. Such a surface also implies less snow cover, and hence a greater potential thickness of ice.

Of various possible agencies that may have caused the rolls on the Ellesmere Ice Shelf, wind action appears the most likely. It is suggested that the original development of the rolls was analogous to the formation of *seif* dunes in the desert. Since the wind is not forming rolls on the ice shelf today, they should be regarded as "fossil" snow dunes that have been perpetuated by the annual drainage of melt-water.

Field work by R. L. Christie, A. P. Crary, and E. W. Marshall provided much of the material on which this paper has been based.

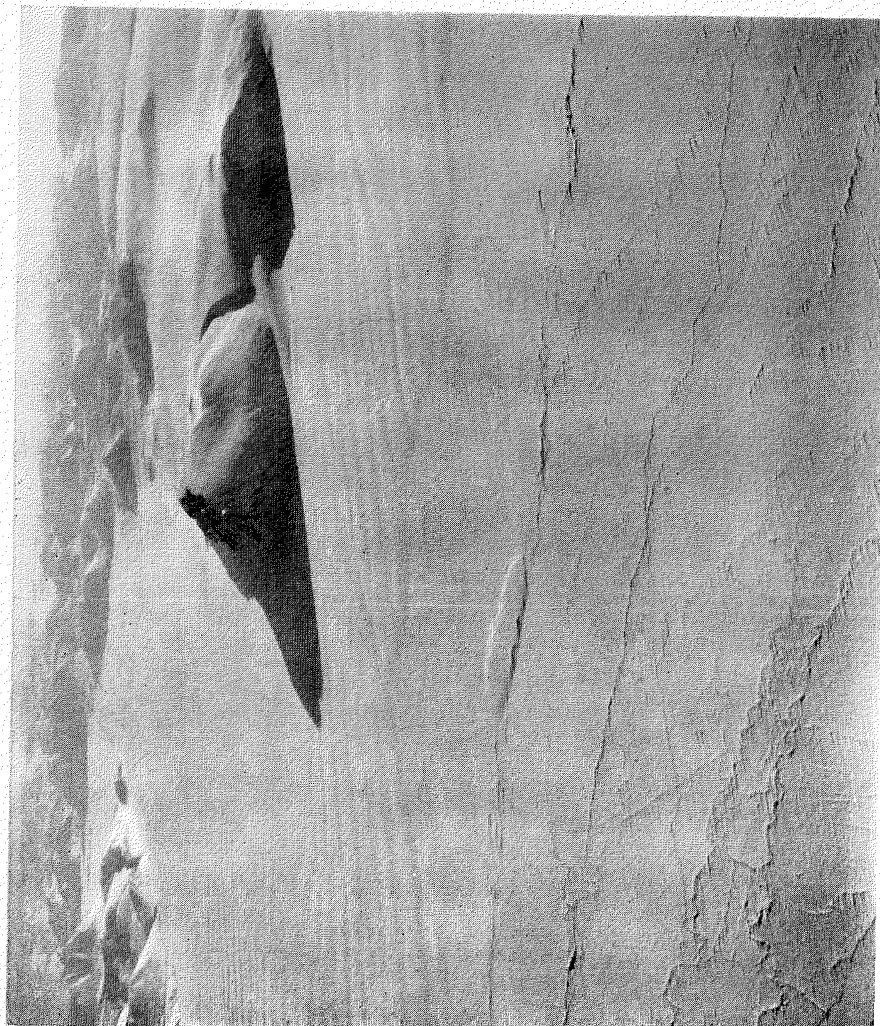


Fig. 7. Re-entrant of ice shelf off Markham Bay. Cape Nares in centre. *Photo: R.C.A.F.*

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