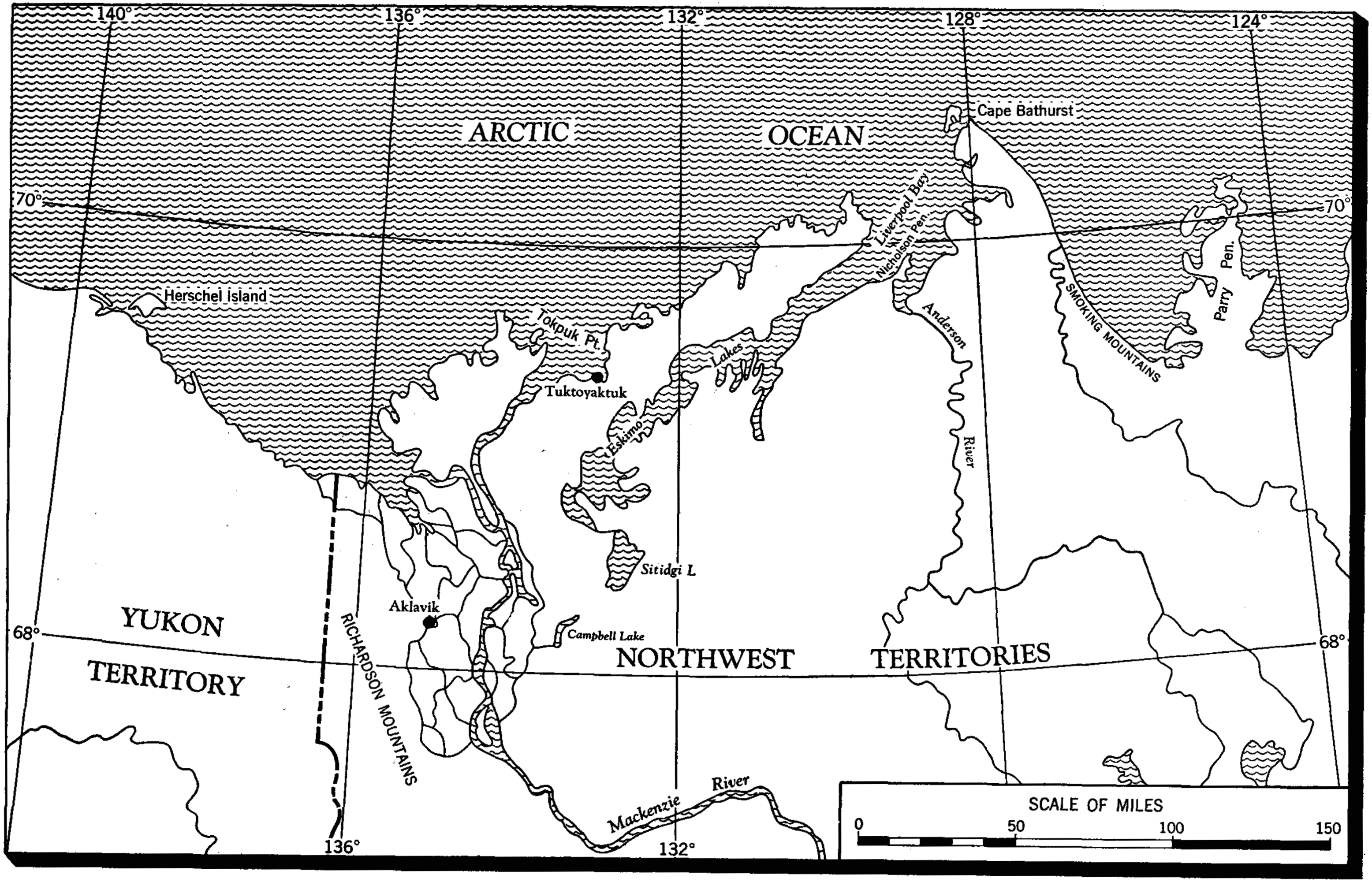

Fig. 1. Mackenzie Delta and Liverpool Bay area.

DEFORMATION BY GLACIER-ICE AT NICHOLSON PENINSULA, N.W.T., CANADA*

J. Ross Mackay†

Introduction

The capability of glacier-ice to deform consolidated and unconsolidated sediments on a regional scale has been well established, although there are relatively few good examples to show it. The action of glacier-ice has produced various types of deformation, such as broad flexures, warps, folds, and thrust faulting. Deformation by glacier-ice is superficial and has no deep-seated tectonic significance. There are at least two excellent examples of deformation by glacier action in the Western Arctic of Canada, one at Nicholson Peninsula at the southern end of Liverpool Bay, and the other at Herschel Island, Yukon Territory, 250 miles to the west (Fig. 1). It is the purpose of this paper to discuss the effects of deformation by glacier-ice at Nicholson Peninsula. Field work was done in the summer of 1954 in the Eskimo Lakes-Tuktoyaktuk area; in 1955 at Nicholson Peninsula and vicinity; and in 1956 a brief stop was made by W. H. Mathews and the writer at Herschel Island. The writer would like to thank Jack K. Stathers for his assistance in 1955 and Professors W. H. Mathews (Department of Geology) and R. A. Spence (Department of Civil Engineering) of the University of British Columbia for helpful advice and discussion on various problems.

Nicholson Peninsula (Fig. 2) is about 8 miles long and from 2 to 4 miles wide. The northern half is hilly, the southern half is flat and low. Altitudes in the northern half of the peninsula attain 200 to 300 feet above sea level in the higher western portion, whereas those in the southern half rarely exceed 30 feet above sea level. The greater altitudes of the northern half are believed to have been caused by pushing induced by moving glacier-ice. The portion affected by ice push is at least 5 miles long and in places up to 4 miles wide. Since cliff recession is rapid along the coast, especially on the exposed northwest side, the deformed zone was formerly larger. The hills of the northern half of Nicholson Peninsula rise considerably higher than adjacent mainland areas with similar formations, such as those south of Cape Bathurst and north and south of the Eskimo Lakes. The conical ice-cored hills, called pingos, that are very numerous east of the Mackenzie Delta (Mackay, 1956; Porsild,

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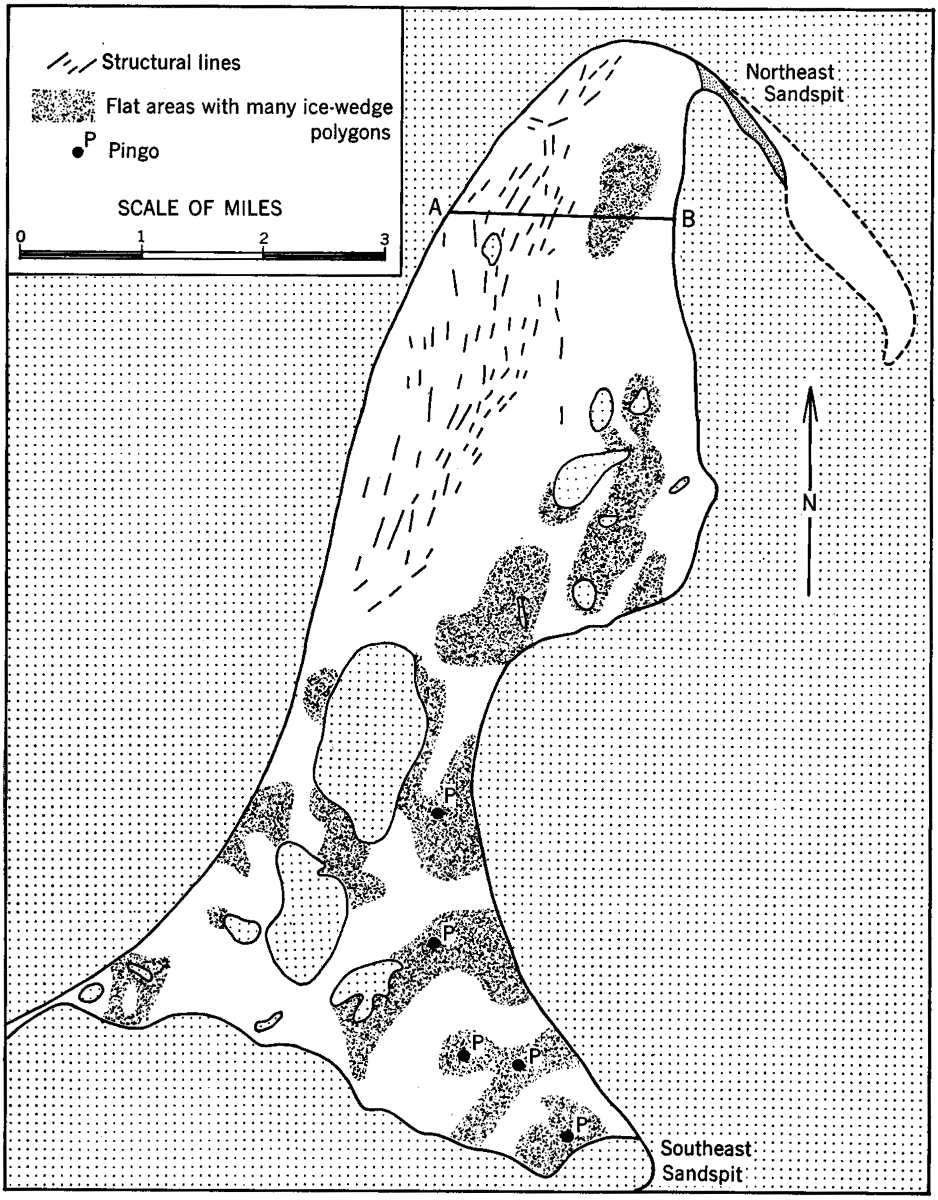

Fig. 2. Nicholson Peninsula, showing structural lines, major areas with ice-wedge polygons, and pingos. The section along A-B is shown in Fig. 4. This map has been drawn from uncontrolled air photographs and is subject to slight errors in scale.

1938; Stager, 1956) are absent in the northern half, but occur in the southern half of the peninsula. The five pingos in the southern half rise 20 to 40 feet above the polygonal ground of old lake bottoms, from which they have bulged up and grown like huge blisters. The absence of pingos in the northern half would seem to indicate conditions unfavourable for pingo formation.

Material

Nicholson Peninsula is composed of sands, silts, and clays, with ground-ice segregations in the form of tabular sheets, wedges, veinlets, etc. The sediments are probably Pleistocene in age and largely of marine origin. A small pelecypod, *Yoldia arctica,* (Wagner, 1956) occurs abundantly in the clay. Water-worn twigs, branches, and logs are also fairly common. Some of the plant remains look as fresh as modern driftwood, whereas others are carbonized and resemble charcoal; a few fragments are strongly iron-stained. Similar material occurs in the region of the Eskimo Lakes and Cape Bathurst.

The clay beds are 5 to 20 feet thick and without visible stratification. Gravel lenses occur in some clay members. The clay breaks readily into blocky fragments. The sandy beds are up to 60 feet in thickness; some are without visible stratification, others cross-bedded, and a few are finely laminated. Tabular sheets of ground ice have grown in situ in many parts of the peninsula, although the exposures are naturally best displayed along the coast. The ice sheets are 5 to 10 feet or more in thickness and are cut in places by vertical ice wedges that underlie the fissures of large polygons. Several ice sheets lie buried beneath a discontinuous bed of windblown silt up to 40 feet thick. Although the growth of ice segregations has undoubtedly contributed a share to the disturbance of the overlying and adjacent deposits, this mechanism is quite incompetent to produce the extensive deformation present in the northern half of the peninsula, because of the structure of the beds and the small amount of ice involved. In addition, it seems pertinent to stress the fact that ice segregations are more abundant in the southern half of the peninsula than in the northern half.

Structure

The general structural lines of Nicholson Peninsula (Fig. 2) are displayed with remarkable clarity on air photographs (Fig. 3). The fine details are not obscured by trees or bushes because the area lies within the tundra and most of the vegetation is only a few inches high. The air photographs show a ridged pattern suggestive of bedrock outcrops striking parallel to the west coast. However, the smooth contours, lack of angularity, and numerous gullies indicate unconsolidated material and not bedrock. The structural lines which are so clearly delineated on air photographs cannot be easily discerned on the ground, because the field of view is too limited to encompass a repeating pattern.

A none too successful attempt was made to map the material exposed in the ridges and depressions. Six exposures were examined on ridge crests; all were of sands and silts and none of clays. Solifluction, slope wash, and vegetation have obscured the sequence in the depressions (Fig. 4).

Structural features are best exposed along the bare sea cliffs. At the northern tip of the peninsula the commonest sequence is clay over sand. The cliffs are 80 to 100 feet high but the lower slopes are so covered with slumped material that the sequence there is difficult to determine. The strata have a general westerly dip of 15 to 20 degrees. The beds are locally deformed and contorted. Small folds, drag folds, and other features indicate thrust acting from the west. The amplitudes of the individual folds are small, usually of the order of 5 to 10 feet. Folding is greatest in interlaminated beds of sand and clay, where each layer is only a few inches thick.

The bluffs of the western side of the peninsula differ from those of the northern side in being lower, covered with vegetation, and consisting of sands and silts without clay members.

The bluffs of the east side of the northern half of the peninsula are from 10 to 40 feet high. They are cut into sands, silts, and clays, with silts being the most abundant. On the east coast, one mile south of the base of the long "northeast" sandspit, a cutbank exposes a section with fault planes so closely spaced—often at intervals of only one inch—that they give the appearance of bedding planes, although no bedding is visible. Some fault planes are horizontal, whereas others are curved, both upward and downward. The shear surfaces are smooth to the touch, slickensided, and streaked with crushed fragments of clam shells (*Yoldia arctica*). The slickensides trend approximately east-west. The shear planes can be followed back into the bluff by detaching blocks of clay.

Ice push

The structural features of Nicholson Peninsula could have been produced only by the pressure of glacier-ice or by earth movements. The localization of the structural features in Nicholson Peninsula rules out earth movements, as has been argued by other writers for similarly disturbed areas (e.g. Slater, 1926-27a, pp. 298-302; 1926-27b, pp. 303-15). No tectonic movements involving Pleistocene deposits are known in the area. Slumping could not explain the disturbance, because there is no higher land nearby.

In the literature of ice pushing several different mechanisms for producing deformation have been described. These mechanisms are not always distinct, for they may occur singly or in combination, depending on such varying conditions as advance or retreat of the ice, encumbent load, nature of the subjacent material, and type of topography encountered by the ice. The different mechanisms of deformation may be grouped into three categories.

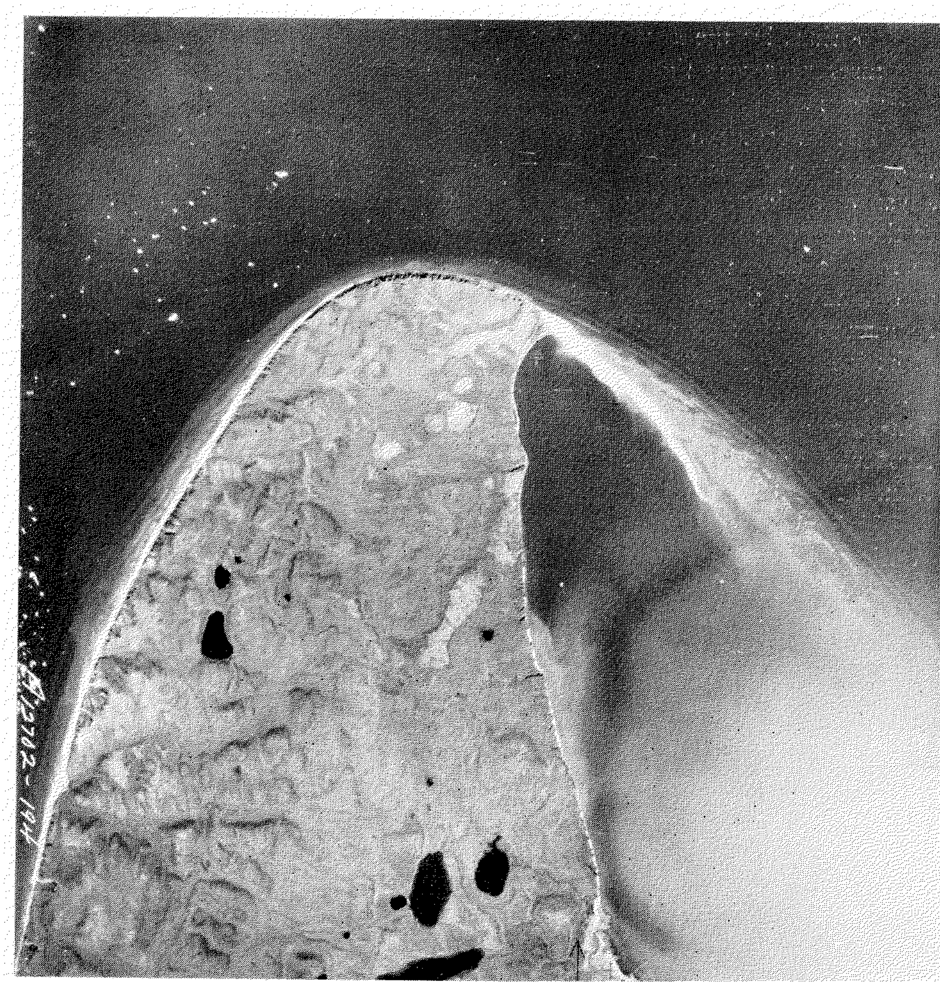

Fig. 3. Air photograph of the northern portion of Nicholson Peninsula showing the structure of the deformed beds along the west side of the peninsula. North is at the top. Note the northeast sandspit and the wave-cut cliffs. Royal Canadian Air Force photograph.

1. The pressure of glacier-ice as it advances against and possibly over a topographic obstruction causes deformation (Fuller, 1914, pp. 201-7; Hopkins, 1923).

2. The drag effect of ice moving over weak strata produces deformation (Slater, 1926).

3. The advancing ice incorporates as englacial material the subjacent beds, which are later preserved in their deformed shapes by the melting of interstitial ice (Woodward, 1903; Slater, 1926-7a, pp. 289-302; 1926-7b, pp. 303-315). The deformed beds are envisaged as retaining their relative

positions by the slow melting of interstitial ice so that the present structures represent those of a fossil glacier whose "hard parts" have been preserved (Slater, 1926, p. 396).

The structure of Nicholson Peninsula seems best explained by the first two mechanisms, whether operating singly or in combination. If the ice advanced against a topographic obstruction, such as a valley running transverse to the direction of ice movement, it may have shoved and faulted the material to form a large push moraine. This is the type of structure that has been recognized in the Long Island deposits of New York, where the glacier-ice found opposed to its advance the thick series of gravels previously deposited at its front (Fuller, 1914, pp. 206-7). The drag effect of ice moving over a continuous sheet of weak sediments may also have produced deformation. The sections exposed along the cliffs of Nicholson Peninsula resemble in many respects those beds with a uniform direction of dip that have been reported from the ice thrust beds of Møens Klint, Denmark (Slater, 1926-7a, pp. 209-302).

If the strata had been removed from a horizontal surface, then the original position would now be marked by a depression. Unfortunately, there are too few soundings west of Nicholson Peninsula to test the theory, although it may be pointed out that the greatest known depths (8 to 11 fathoms) within at least 20 miles of the peninsula are those within 2 to 3 miles of the west coast. However, it is interesting that there is an isolated depression with depths exceeding 200 feet in the direction and position from where the deformed sediments of Herschel Island could have been shoved into position by ice moving northwest along the arctic coast.

There is little evidence to support the third or englacial mechanism of deformation. According to this theory, which has been expounded most vigorously by Slater, material that was once horizontal was incorporated as sheets into the ice and subsequently split up by numerous thrust planes near the terminus of an overloaded stagnant glacier front. A major objection to the englacial theory is that it provides no means for lifting thick sheets of sediments off the ground prior to their incorporation as englacial material in the ice. It seems difficult to conceive of any way whereby thick beds could have been incorporated into the ice except through an initial stage of folding or thrust faulting. However, if the possibility is granted that thick sheets could be incorporated as englacial material, shearing in the ice would gradually slice up the thick sheets into thinner and smaller ones. But sheets at least 60 feet in thickness occur at Nicholson Peninsula and the major structural lines can be followed almost without a break for at least 5 miles. Therefore, it seems doubtful that such a perfection in structure could have survived the disturbance that englacial material would have undergone during incorporation, transportation, shearing, and final deposition by melting of interstitial ice.

The overturned folds in the strata suggest ice push from the west. It should be emphasized that the time of deformation is unknown. It could have been during the last advance of the ice or earlier. If the disturbance had resulted from two periods of ice advance, the structure would probably be

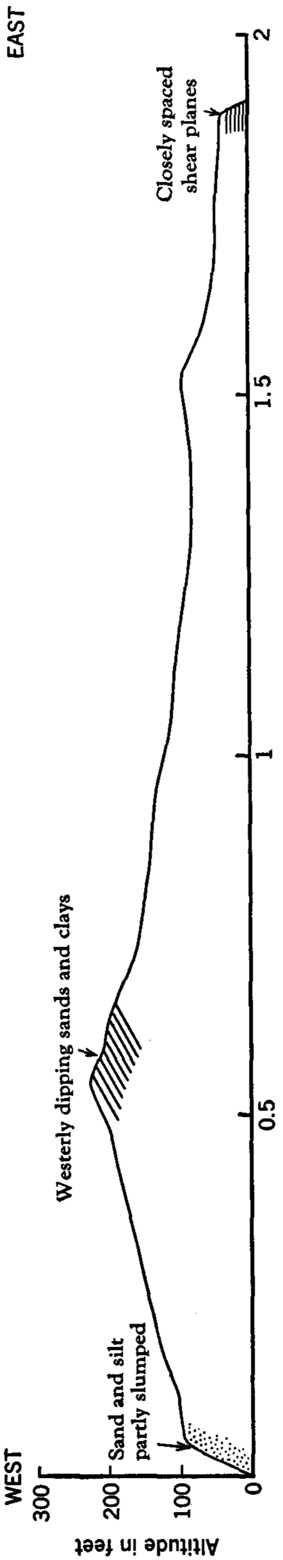

Fig. 4. Profile along the line A-B in Fig. 2. Note the higher western side of the peninsula. The dip of the strata on the ridge crest was not measured at the exact location of the profile, because no good sections were available, but was measured farther north in gullies and along the coast. The profile may be considered to be a general one for the northern part of the peninsula. Altitudes were obtained from two altimeters and distances from uncontrolled air photographs.

more complex than it is, because it is unlikely that the directions of two different movements would coincide to give the simple pattern that is present. The last movement of ice in the region of Nicholson Peninsula was affected by at least two major factors: the area was near the limit of the advance of the ice and the obstacle of the Richardson Mountains profoundly influenced the movement of the ice as far east as the Anderson River. In addition, the movement of the ice east of the Anderson River may have been affected by the ice lobe that moved across Parry Peninsula west to the Smoking Mountains. The obstacle of the Richardson Mountains caused the ice moving northward near the apex of the Mackenzie Delta to spread like a fan, with ice pushing northwest along the arctic coastal plain toward Herschel Island and northeast along the general trend of the Campbell-Sitidgi-Eskimo lakes system toward Nicholson Peninsula. It has been suggested that the area north of the Eskimo Lakes is a gigantic end moraine, formed by ice moving in a northerly direction (Downie, Evans, and Wilson, 1953), but this is debatable, because most of the area is composed of water-laid estuarine or marine sands, silts, and clays, with only a patchy distribution of morainic material. The deflection of the ice by the Richardson Mountains can also be recognized by the rapid change in direction of glacial fluting in the area west of the Anderson River and south of Nicholson Peninsula. At 68°N and 129°W, that is, at a position some 130 miles due south of Nicholson Peninsula, glacial fluting trends southeast-northwest; at 68°55′N and 130°W the trend is south-north; at 60°25′N and 129°30′W the trend is southwest-northeast. Thus in a south-north distance of about 100 miles the orientation of glacial fluting has undergone a shift of about 90 degrees or about 1 degree per mile. Although the direction of the last ice movement across Nicholson Peninsula is unknown, a projection of the nearby trends would indicate a direction somewhere between southwest-northeast and west-east.

There is not enough information available to indicate whether the sediments were frozen or unfrozen at the time of deformation. At the present time the area is underlain by permafrost with the active layer usually less than 3 feet thick. Material on the sea floor remains unfrozen to an unknown depth. Frozen sediments have mechanical properties approaching those of ice so that they yield to shearing stresses much as ice does near the terminus of a glacier. Whether shearing in frozen ground could have produced the smooth polish present on the shear planes in the clays of Nicholson Peninsula is uncertain. However, shearing in unfrozen clay can give a high degree of polish by remoulding of the clay as seen here. Since clay may remain unfrozen at below freezing temperatures, this factor must be taken into consideration in attempts to determine whether the ground was frozen or not during deformation.

If the sediments of Nicholson Peninsula were unfrozen when deformed, as seems possible, then they probably remained unfrozen because they were submerged beneath the sea or a lake. Further study of the strata of Nicholson Peninsula may reveal whether they were frozen at the time of deformation, and in this way information may be obtained on the level of the sea at the time of the advance of the ice. In the case of the sediments of Long Island, New York, they "were unquestionably saturated with water" when the ice passed over the area (Fuller, 1914, p. 203). At Spitsbergen, where the ground is frozen to a depth of about 320 metres, calculations and observations have shown that frozen ground extends for about 100 metres along the sea floor from the coast (Werenskiold, 1953). Beyond about 100 metres, the sea floor is not frozen. Even if climatic conditions at Nicholson Peninsula during the time of the last advance of the ice were much more severe than those of Spitsbergen at the present time, calculations based upon the theory of Werenskiold indicate that unfrozen ground would have been found on the sea floor at less than a mile from the coast; these calculations are subject to a considerable margin of error.

It may be pertinent to point out that deformed sediments occur in other areas of the Western Arctic. Herschel Island is in many ways a replica of Nicholson Peninsula, for it too is an anomaly. The island rises several hundred feet above adjacent areas of similar sediments; structural features show up clearly on air photographs; and deformation of the Pleistocene strata are observable on the ground (see, for example, O'Neill, 1924, plate V, p. 77A). Leffingwell (1919, p. 169) has stated that Barter Island, Alaska, and Herschel Island are domes of deformed Pleistocene formations, but he has not discussed the mechanism of deformation. The unusual interdigitate peninsulas or "fingers" of the Eskimo Lakes may have resulted, in part at least, from deformation by glacier-ice. The arcuated "fingers", their orientation transverse to the last ice movement, and the occurrence of tilted beds in at least one place all suggest the possibility of deformation. Tilted beds of sand and gravel occur along the coast between Tuktoyaktuk and Topkak Point in a form that suggests overriding by glacier-ice more than disturbance resulting from the growth of ground ice.

Conclusions

The hills of the western side of Nicholson Peninsula have been formed by the action of glacier-ice. The ice may have moved against a topographic obstruction to construct a large push moraine, or the drag effect of ice moving over weak strata may have produced the deformation. The time of deformation is unknown; it could have been during the last ice advance or at an earlier period. Although deformation may have taken place at different times, the evidence favours a single period. There is insufficient evidence to indicate whether the ground was frozen or not at the time of deformation. The theory of deformation by glacier-ice explains why the deformed strata of Nicholson Peninsula, and also of Herschel Island, rise considerably higher than adjacent areas of similar, but undisturbed material.

References

Downie, M. J., A. G. Evans, and J. T. Wilson. 1953. "Glacial features between the Mackenzie River and Hudson Bay plotted from air photographs" (abstract). *Bull. Geol. Soc. Am.*, Vol. 64, pp. 1413–14.

Fuller, M. L. 1914. 'The geology of Long Island, New York'. *U.S. Geol. Surv. Prof. Paper*, No. 82, 231 pp.

Hopkins, O. B. 1923. "Some structural features of the plains area of Alberta caused by Pleistocene glaciation". *Bull. Geol. Soc. Am.*, Vol. 34, pp. 419–30.

Leffingwell, E. de K. 1919. 'The Canning River region, northern Alaska'. *U.S. Geol. Surv. Prof. Paper*, No. 109, pp. 1–251.

Mackay, J. Ross. 1956. "Mackenzie Deltas–a progress report". *The Canadian Geographer*, No. 7, pp. 1–12.

O'Neill, J. J. 1924. 'The geology of the arctic coast of Canada, west of the Kent Peninsula'. *Rep. Can. Arct. Exped. 1913-18*, Vol. XI, Part A, Ottawa: pp. 1A–107A.

Porsild, A. E. 1938. "Earth mounds in unglaciated arctic northwestern America". *Geog. Rev.*, Vol. 28, pp. 46–58.

Slater, George. 1926. "Glacial tectonics as reflected in disturbed drift deposits". *Geol. Ass. Proc.*, Vol. 37, pp. 392–400.

——— 1926-7a. "The structure of the disturbed deposits of Møens Klint, Denmark". *Roy. Soc. Edinb. Trans.*, Vol. 55, Pt. 2, pp. 289–302.

——— 1926-7b. "The disturbed glacial deposits in the neighbourhood of Lønstrup, near Hjørring, north Denmark". *ibid.*, pp. 303–15.

Stager, John K. 1956. "Progress report on the analysis of the characteristics and distribution of pingos east of the Mackenzie Delta". *The Canadian Geographer*, No. 7, pp. 13–20.

Wagner, F. J. E. 1956. 'Report on shells from Nicholson Island, Liverpool Bay, N.W.T., submitted by J. R. Mackay, 1956'. *Report No. P1-3-56/57 of Sect. of Stratigr. Paleontol., Geol. Surv.* Ottawa: 1 p. Manuscript.

Werenskiold, W. 1953. "The extent of frozen ground under the sea bottom and glacier beds". *J. Glaciol.*, Vol. 2, pp. 197–200.

Woodward, H. B. 1903. "On some disturbances in the Chalk near Royston (Hertfordshire)". *Quart. J. Geol. Soc.*, Vol. 59, Pt. 3, pp. 362–74.