GIANT GLACIAL GROOVES IN NORTHWEST CANADA

H. T. U. SMITH

ABSTRACT. In the Mackenzie Valley area west of Great Bear Lake, the bedrock on many ridges and mountain slopes is furrowed by glacial grooves of unusually large size. Individual grooves range up to about 100 feet in depth and upwards of one mile in length. The grooves are approximately straight and parallel, and occur closely spaced in zones reflecting the influence both of the erodibility of bedrock and of topographic position. The trend of the grooves in the various zones is indifferent to structural axes and to drainage lines, and conforms to a systematic regional pattern which records the advance of an ice sheet west to and then northwest along the Mackenzie valley.

INTRODUCTION

THE purpose of this paper is to describe an unusual type of large-scale grooving found in the Mackenzie Valley region of the Northwest Territories in Canada. The area described lies in that section of the Mackenzie Valley west of Great Bear Lake, and just south of the Arctic Circle (Text Fig. 1). The paper is based on observations made while

Text Fig. 1. Outline map of Canada showing location of area included in Figure 2.

serving as a geologist on the Canol Project, in the summer of 1943. Ground observations were limited to a few localities, and were purely incidental to studies in petroleum geology. Low-altitude flight provided opportunity for inspecting additional localities. Since leaving the region, detailed examination of aerial photos has provided the basis for a more thorough analysis of the problem of grooving.

Recognition of the grooving and of its glacial origin was not original with the writer, but was a matter of common experience for many geologists working on the Canol Project. The grooving at one locality, in fact, has already been referred to in a published report (Steward, 1945). The writer assumes no credit save that for the time and effort required to place the pertinent facts on record in this paper.

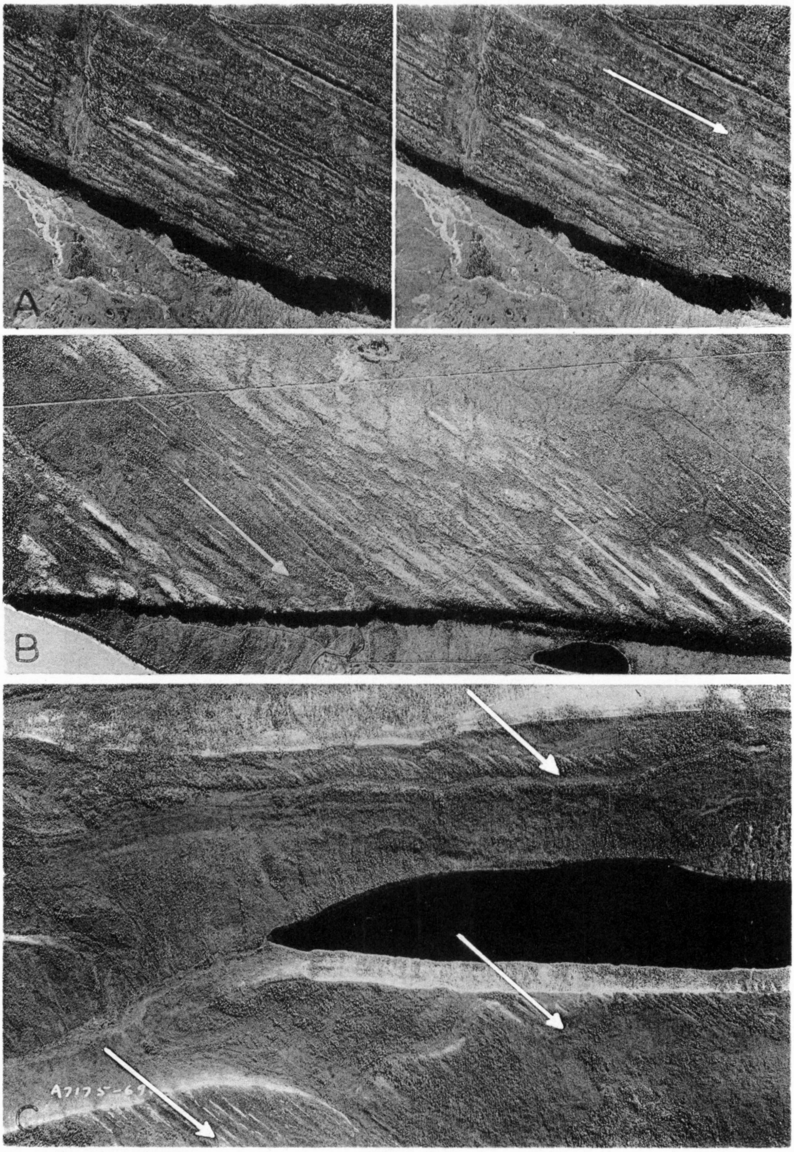
Particular thanks are due to Dr. T. A. Link for the opportunities made available to the writer while serving on the Canol Project. Acknowledgment is due also to the Royal Canadian Air Force, the U. S. Army Air Forces, and the Canadian Pacific Air Lines, Ltd., for supplying aerial photos and for permission to reproduce photos. The maps were drafted by Don Owen. A grant from the Graduate Research Fund of the University of Kansas contributed to the cost of plates.

TOPOGRAPHIC AND GEOLOGIC SETTING

The Mackenzie Valley, in the area described (Text Fig. 2), is a broad though irregular lowland bordered by mountains. To the southwest lies the massive Carcajou Range, which forms a part of the Mackenzie Mountain system, and rises to heights of more than a mile. To the northeast lies the Norman Range, an asymmetric ridge with a pronounced escarpment on the northeast side. It parallels the Mackenzie River for about 60 miles, and rises to a maximum altitude of some 3,000 feet. Structurally it is monoclinal, with moderate dips toward the river. Between the Norman Range and Great Bear Lake to the east, there are other ridges and uplands known collectively as the Franklin Mountains.[1] North and west of the Norman Range are several smaller, detached mountains and ridges of divergent trend. These in general are asymmetric also, with the steeper sides facing here in one direction and there in another. Structurally, these ranges are monoclines and asymmetric anticlines, both complicated by thrust faulting.

Lowland areas between and around the mountains are poorly drained and covered with muskeg. Bogs are common and lakes of all sizes are very numerous.

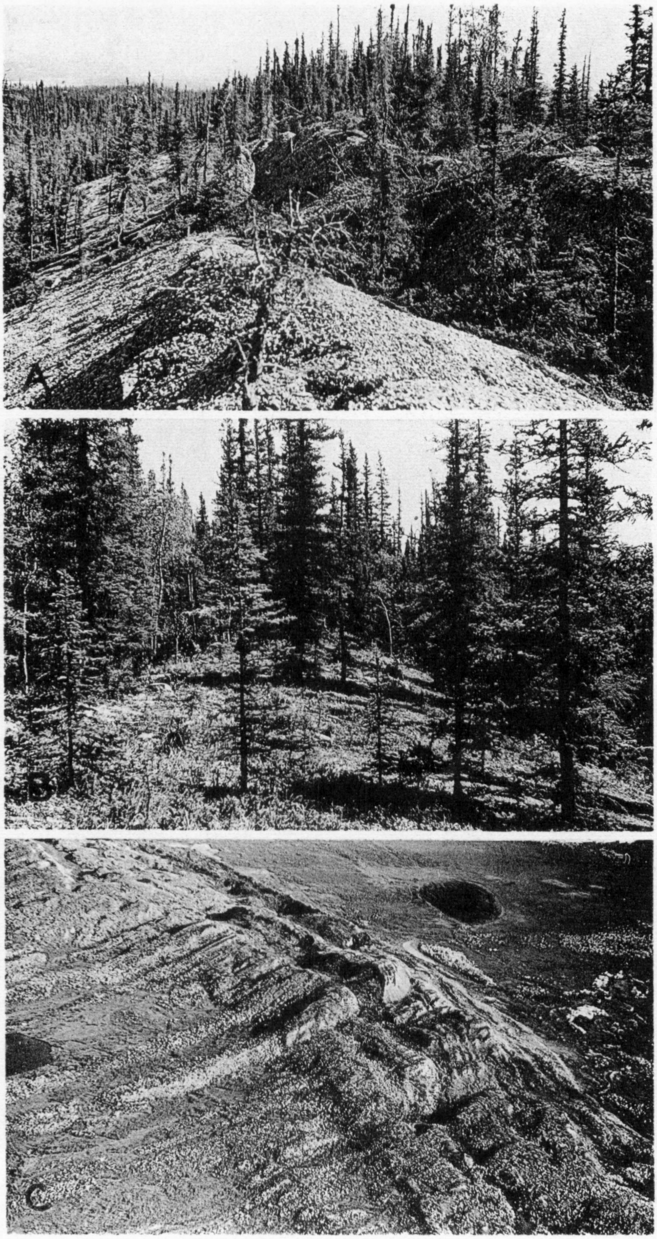
[1] Additional information on the regional topography is given on AAF Aeronautical Chart No. 79 (Great Bear Lake), distributed by the U. S. Coast and Geodetic Survey.



A. Stereogram showing grooving at locality *E* as seen from the air. The grooves cross a dip slope and are essentially parallel to strike. The arrow indicates the direction of ice movement and is approximately 2000 feet long. Local relief is up to 75 feet. RCAF photo.

B. Vertical aerial photo of grooving at locality *G*. The grooves trend diagonally across the gentle flank of an asymmetric anticline. Local relief is estimated to reach 100 feet. Arrows same as above. RCAF photo.

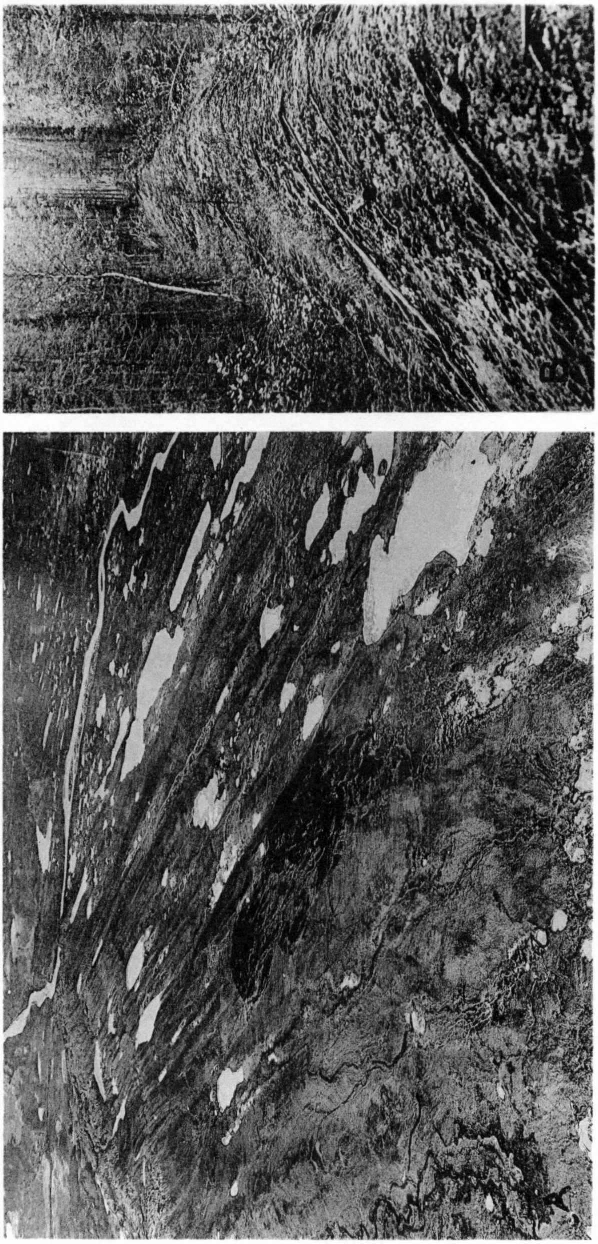
C. Vertical aerial photo of small-scale grooving at locality *I*. Local relief is about 10 feet. Scale same as above. RCAF photo.



A. One of the higher inter-groove ridges at locality *E* (included in area of Pl. 1A), looking northwest. Smaller grooves are superimposed. The rock is a coralline limestone of loose structure.

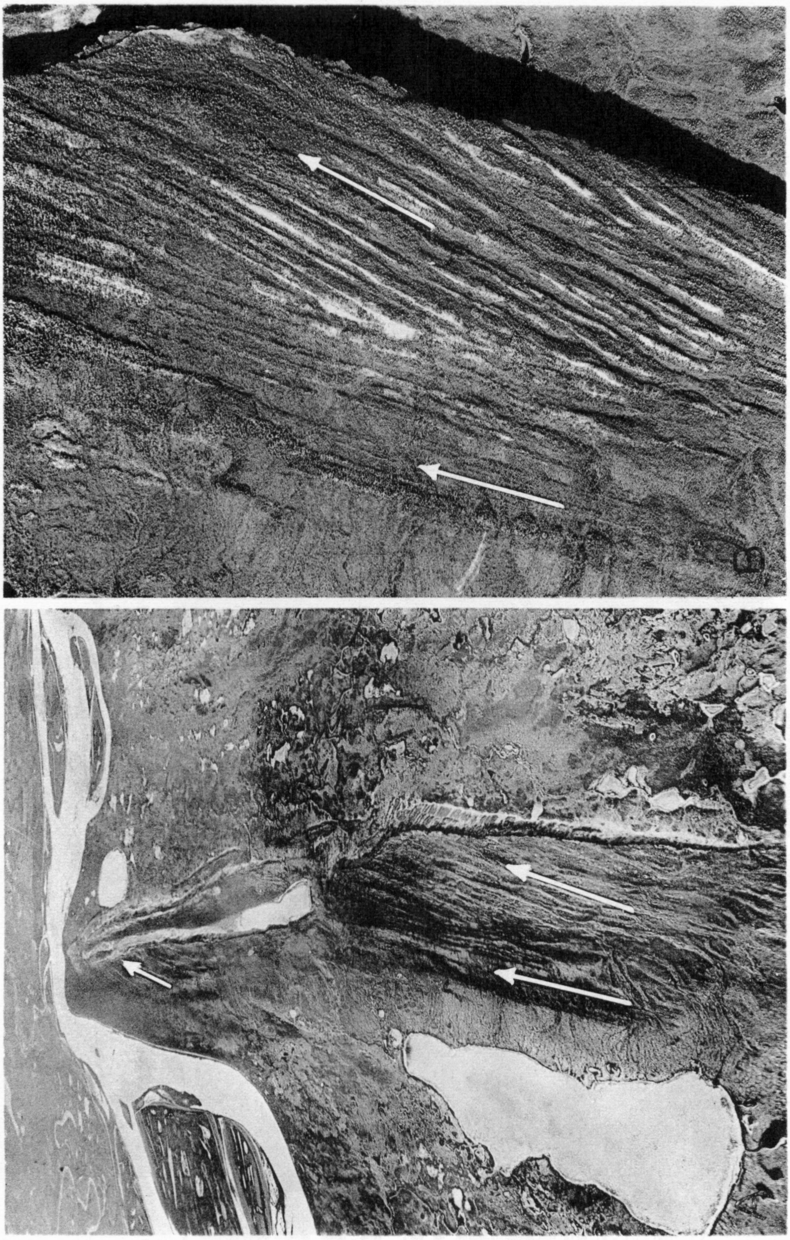
B. One of the lower ridges at locality *E*, looking southeast.

C. Oblique aerial view of locality *A*, looking northeast. The ice moved from right to left.



A. Oblique view of locality *A*, looking southeast. Great Bear River is in the background. The grooves here are estimated to reach a length of 8 miles. USAAF photo.

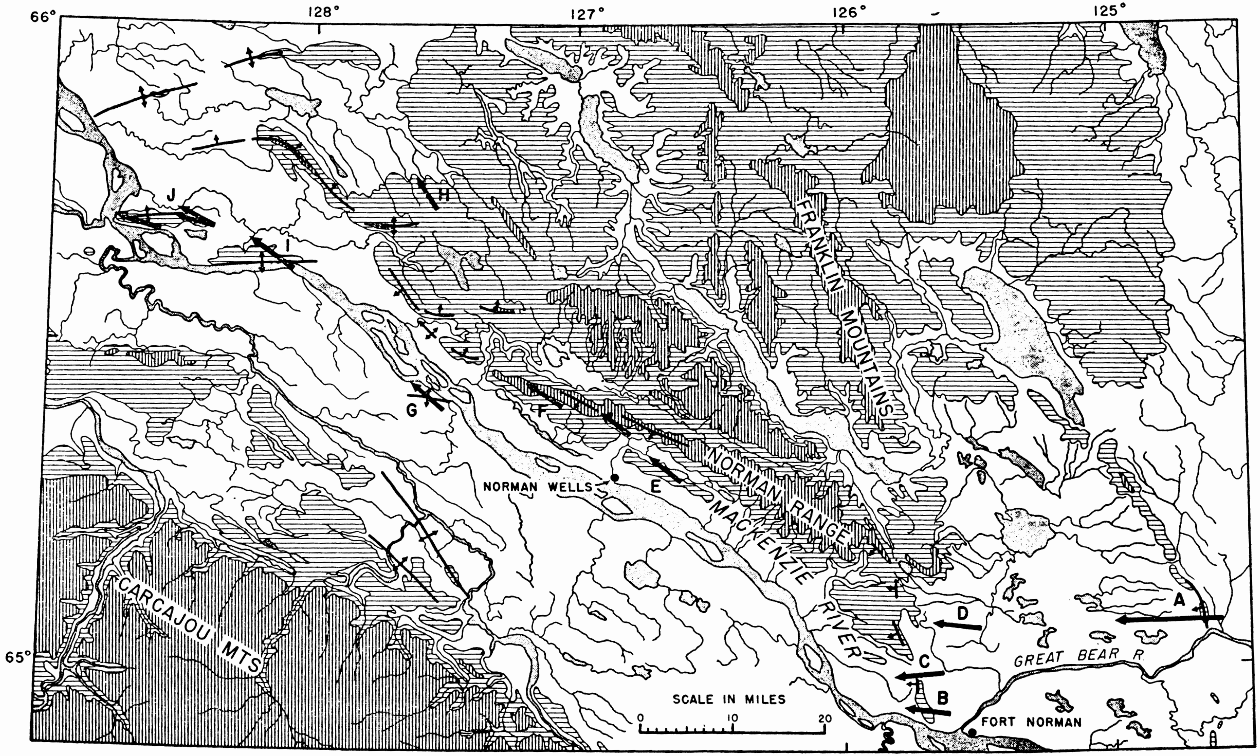
B. Ground view of one of the minor inter-groove ridges at locality *I*, looking northeast; near center arrow in Pl. 1C.



Grooving at locality *J*.

A. High-altitude oblique view, looking northwest. USAAF photo.

B. Vertical view. Note divergence in trend of grooves. The arrows indicate direction of ice movement and are approximately 2000 feet long. RCAF photo.



Text Fig. 2. Relief map of the Mackenzie Valley area, showing location of the main areas of glacial grooving. Blank areas are up to 1,000 feet in elevation. Areas with light horizontal cross-hatching are between 1,000 and 2,000 feet. Areas with heavy vertical cross-hatching are above 2,000 feet. Arrows are centered over grooved localities and show trend of grooves; localities are referred to by letters. Structural trends are represented by symbols for anticlinal axes and for strike and dip. Based on USAAF Aeronautical Chart No. 79. Geological data are from Hume and Link (1945).

The bedrock of the area described is sedimentary, and ranges in age from Silurian to lower Tertiary (Hume and Link, 1945). A thick, massive limestone formation of Silurian age forms the core of the Norman Range, and of certain other outlying mountains. Overlying the massive limestone are several hundred feet of brecciated limestone, together with gypsum and anhydrite, comprising the Bear Rock formation, of Silurian or Devonian age. Next in the succession are the Ramparts formation, consisting of thin-bedded to massive limestones with interbedded shale; the Fort Creek formation consisting mainly of shale with interbedded reef limestone; and the Imperial formation, containing sandstone and shale. These three formations are all of Devonian age, and total upwards of 2,000 feet in thickness; they outcrop on the southwest side of the Norman range, and their limestone members cap certain of the smaller outlying mountains. Next in the regional sequence are Cretaceous and Eocene beds, consisting mainly of poorly-consolidated sandstone and shale, and totalling several thousand feet in thickness. These beds underlie the lowland areas.

The effects of Pleistocene glaciation are seen in the deranged drainage, numerous lakes, occasional erratic boulders, and drift deposits in stream banks. A continental ice sheet is believed to have advanced from the general direction of Hudson Bay, and to have been of sufficient thickness to cover the mountains on the east side of the Mackenzie River. At certain places, ice is believed to have enterd the Mackenzie Valley also from the west (Camsell and Malcolm, 1919), but the writer did not happen to observe any indications of this within the area under consideration. Actually, the published information on glaciation in this region is meager and fragmentary, and little is known beyond the mere fact of glaciation.

DESCRIPTION OF THE GROOVED AREAS

The principal localities at which grooving was studied are indicated on the map, Text Fig. 2, by arrows showing the trend of the grooves. Individual localities range in area from a fraction of a square mile to roughly 20 square miles. The total area grooved is estimated to be about 50 square miles, and the major part of this total is represented by localities

A, B, C, and D. Other localities average between 1 and 2 square miles.

The general character of the grooved areas is best seen from the air (Pl. 1). The impression thus received is that of ground deeply scored by a giant rake. Narrow, closely-spaced ridges and troughs dominate the landscape. After the first heavy frost in fall, many of the grooved areas are accentuated by a color contrast in the vegetation, with golden-yellow on the ridges and green in the grooves. On the ground, the field of view is greatly limited by trees and brush, so that the true nature of the grooves generally is not apparent at any one spot. If a traverse happens to cross the grain of the grooving, however, the unusual repetition of local relief features is unlikely to escape notice, and if one is aware of their significance, interesting details may be observed. The troughs are found to be poorly drained, with thick muskeg to impede progress. Locally there are ponds. Where the sides of the grooves are moderately sloping, a cover of trees and brush is common (Pl. 2B). Where the sides are steeper, however, bare rock is frequently exposed (Pl. 2A), and exhibits a moderate degree of weathering. Scattered about the surface are occasional erratic boulders of crystalline rock.

The size of the grooves is their most notable characteristic. Observed local relief of the grooves ranges from about 6 feet at locality *I* (Pls. 1C and 3B), to 75 feet at locality *E* (Pls. 1A and 2A), and a figure of at least 100 feet is estimated for localities *F* and *G* (Pls. 5C and 1B). The average depth is probably about 50 feet. The width of the grooves, as scaled from aerial photos, ranges from a few tens of feet at locality *I* to more than 150 feet at localities *G* and *J*, and is estimated to reach a maximum of more than 300 feet at locality A. The length of individual grooves ranges from a few hundred feet at locality *I* to about one mile at *E* and *J*, and is estimated to reach as much as 8 miles at locality *A* (Pl. 3A). Within each grooved area, there are numerous local variations in depth, width, and length of the grooves.

In detail, the grooves show considerable variation in form. The transverse profile ranges from V-shaped to U-shaped, the latter being the more typical. The crests of the ridges between grooves vary from flattish through rounded to sharp and irregular. At many places, the ridge crests are essentially accordant, suggesting that they represent the level of the antecedent surface. At some places, however, there are distinct sags in the general accordance, suggesting further that the original surface has been entirely reduced locally by the erosive process, which formed the grooves. Obviously, the form of the ridges is a function of the original spacing of the grooves and of the amount of widening and deepening which they sustained. Where the width of adjoining grooves exceeded the distance of spacing, the ridge between them was lowered, and where the lowering proceeded sufficiently far, the grooves in effect merged together. The cross profile of the grooves thus provides a basis for estimating the amount of surface reduction which accompanied the grooving. Where the grooving is strongly developed, it is inferred that the amount of erosion was equivalent to the removal of a layer of rock having a thickness of from 40 to 80 per cent of the relief of the grooves.

In general, the grooves at any one locality are essentially straight and parallel, but there are many minor deviations from a rectilinear trend, and at a few places the deviations are considerable. At locality *J* (Pl. 4), there is a divergence of several degrees in the trend of the grooves, and east of locality *C* there is a broad curvature in the pattern of poorly developed grooves.

Along with the minor deviations in trend there are variations in the form of the grooves and ridges, particularly the latter. At some places the ridges are continuous for long distances, with minor irregularities only in height and in the width and shape of the crest. At some other places, however, as at locality *B*, the ridges are broken into many short segments (Pl. 5D), presenting a decidedly choppy appearance. Locally, the discontinuous ridges tend to show en echelon offsets (Pl. 1B). At a few of the places where the ridges are discontinuous, there is a suggestion of streamlined form, and at locality *D* there is one well developed drumlinoidal form (Pl. 5A).

In their relations to structural axes the grooves show complete indifference, so far as trend is concerned. At localities *E* (Pl. 1A), and *F* (Pl. 5C), the grooves are essentially parallel to the strike of the bedrock. At all other localities they trend either oblique or transverse to the structural axes.

In localization and in scale, the grooving is strongly influenced by lithology. In the massive Silurian limestones, no grooves were found. In the brecciated and porous to cavernous Bear Rock formation, the grooves attain maximum depth (Pl. 5C). In the poorly indurated reef limestones of the Devonian, the grooves attain large size also. In the harder limestones of the Devonian, however, the scale of the grooving is smaller (Pl. 1C). Where grooving can be recognized in shale and poorly consolidated sandstone formations, as at locality *H*, it is more rounded and subdued in form. Where the grooves cut across structure, an abrupt change in appearance may be observed in passing from one type of rock to another, as at locality *C* (Pl. 5B).

As to the relation of the grooves to topography, it is difficult to generalize. The vertical range is from a few hundred feet above river level to an estimated height of at least 1,500 feet above river level at locality *F*. Grooves of maximum depth occur at both extremes of altitude. In their longitudinal profile, the grooves conform to the topography upon which they are superimposed. At localities *E* and *F* (Pls. 1A and 5C), the grooves are nearly level. At localities *G* and *J* (Pls. 1B and 4), they make a diagonal ascent over dip slopes which faced toward the advancing ice. At *A*, however, the grooves descend a slope that faced away from the ice advance (Pls. 2C and 3A). Other localities show intermediate relations. At a few places, such as locality *C* (Pl. 5B), the grooves continue across an abrupt break in slope with only minor interruptions. In so far as the grooving can be correlated with topographic position, it appears to be associated with the tops or stoss sides of slopes rising more or less above the surrounding surface, but there are several exceptions to this.

At all of the localities studied, the grooves, show essentially the same state of preservation, allowance being made for local differences in the resistance of the rock to erosion and weathering. It is therefore concluded that the grooves throughout the area are contemporaneous.

The trends of the grooves at the various localities fit into an orderly regional pattern. Along the Great Bear River, the trend is westward. On crossing the southern end of the Norman Range, however, the grooves swing around to the northwest, and follow the Mackenzie Valley. Minor deviations from the general trend, as at localities *B* and *C*, appear to represent deflection by local topographic obstacles.

COMPARISON WITH OTHER GROOVED AREAS

The glacial grooves on bedrock previously reported in North America are all on a much smaller scale than the grooves described in this paper. Perhaps the best known locality is on Kelleys Island, near the southwestern shore of Lake Erie, described in turn by Chamberlin (1888), Carney (1910), and Ver Steeg and Yunck (1935). The grooves here range up to several feet in depth and width, are cut on limestone, and show a more or less U-shaped cross profile. Somewhat larger grooves, up to 6 feet deep and 20 feet wide, have been reported by Andrews (1883) in the Laurentian Hills of Ontario. In Finland, Tanner (1938) has described a glacially-eroded ridge terrain somewhat similar to the grooved areas of the Mackenzie Valley area. The ridges are carved on igneous rocks, and are up to one kilometer in length; the height of the ridges is not specified.

On till, grooving more nearly comparable in scale to that discussed in this paper, has been described. Along the lower Liard River, Hage (1945) reported narrow, straight, parallel ridges several miles long, with a local relief of up to 20 feet. In the Carp Lake area of British Columbia, Armstrong, Tipper, and Hoadley (1947) described large areas of grooved and "drumlinized" till with local relief up to 75 feet. A more extended description of the same area was given by Armstrong and Tipper in 1948.

ORIGIN OF THE GROOVES

Development of the grooves by differential glacial erosion is indicated by the following relations: (1) occurrence in a glaciated region, with a pattern corresponding to the known direction of flow of a continental ice sheet; (2) the similarity in form to smaller glacial grooves on bedrock, and to grooves of comparable size on till; and (3) the inability of any other known process to produce grooving of the type described, with discordant relations to structural trends and to topographic and drainage features. Granting glacial origin, however, there remain the problems of localization of the grooves, of the mechanics of the erosive process, and of factors responsible for the unusual size of the grooves.

In general, the localization of the grooved areas is related to lithology and topography. Lithology was a selective factor, making for varying degrees of susceptibility to the erosive process, and thus permitting easy incision at some places while inhibiting effective carving elsewhere. The influence of topography is less definite. Several of the areas of well developed grooving occur on ridges and on slopes which rose in the path of the advancing ice, and thus were in positions that might be expected to have felt the full force of glacial erosion. It might be supposed that upward deflection of the flow lines of the ice was especially favorable for grooving. That such a condition, while perhaps favorable, was not strictly essential, however, is indicated by locality *A*, where most of the grooving is on the leeward side of the ridge, by locality *F*, where the grooved section is not conspicuously above adjacent sections aligned with it, and by locality *H*, where the grooves occur in a relatively low area to the lee of an escarpment. The only conclusion to be drawn is that topographic position, although a factor, was not the dominant factor.

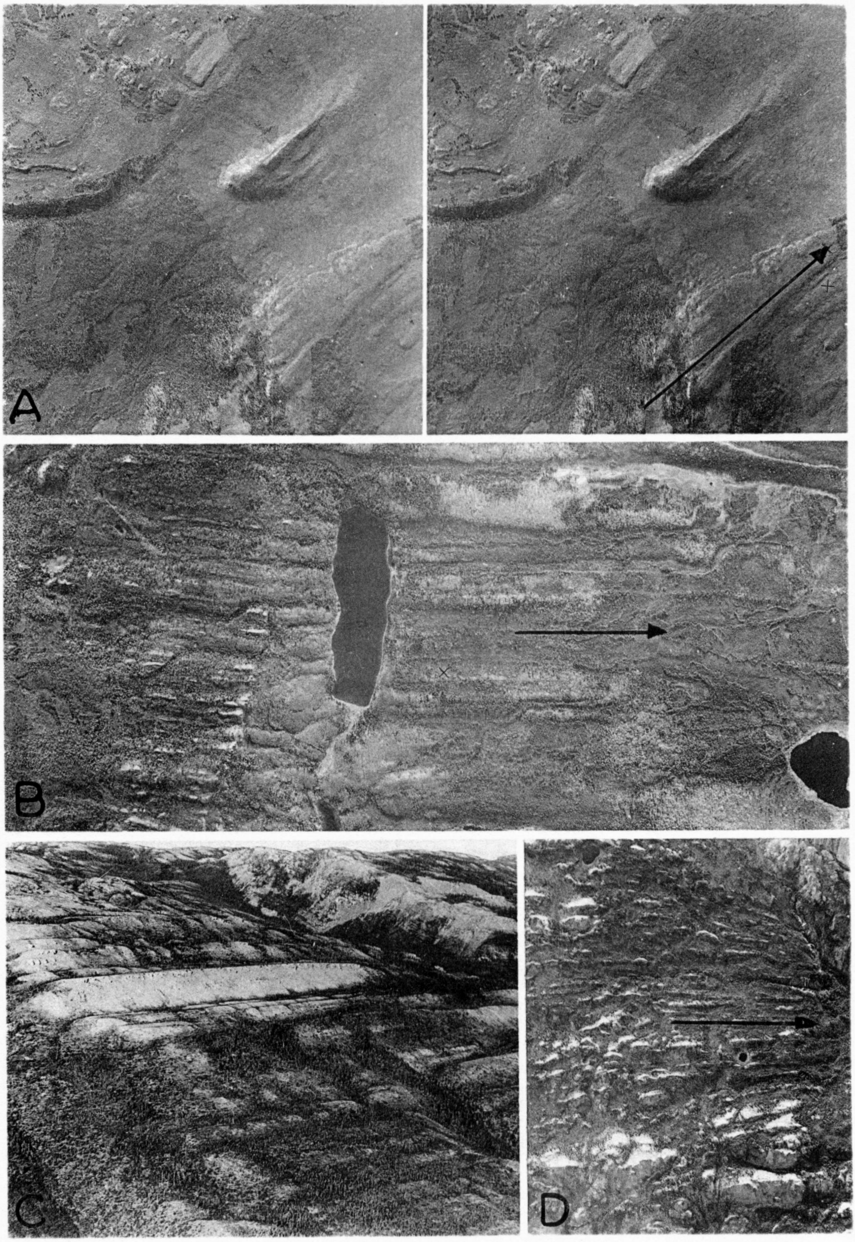
Within the grooved areas, there are no indications that individual grooves were localized either by structure or by antecedent topographic details. The discordance between the trend of the grooving and the trend of the folds and faults which it crosses would leave only joints or fractures as a possible structural influence. No evidence for the existence of the necessary type of fracture pattern has been found, however, either from study of aerial photos or from such field observations as have been made. Indeed, it is extremely improbable that any system of fractures would correspond so closely to the expected lines of ice movement, and yet show such complete indifference to larger structural features.

In general, there is no basis for supposing that antecedent topographic relief features might have localized individual grooves. Where the grooves trend parallel to the strike of the rocks, it might be guessed, at first thought, that outcropping ledges or hogbacks channelized glacial erosion. However, the occurrence of the grooves on what are essentially dip slopes, together with the absence of any surface indications of beds that might have formed the required ledges, leave the above supposition without support. Furthermore, the occurrence of the same type of grooves at other places, oblique or transverse to structure, rules out the likelihood of direct control by any reasonably inferable topographic irregularities. A single exception to this generalization is represented by locality *A* (Pl. 2C), where it is possible that preëxisting notches in the ridge might have conditioned the location of grooves.

Having eliminated the likelihood of structural or topographic control, we are left with the question as to just what did localize the grooves. To this question, no very adequate or positive answer can be given yet. It can be inferred only that whatever factor was at work must have existed within the glacier ice itself. Perhaps, as suggested by Carney (1910), in discussing the much smaller grooves on Kelleys Island, there was "a localization of tools and a constant supply of them in the basal area of the ice." In any event, it may be concluded that the grooves do record the true direction of ice flowage.

Intimately related to the question of localization of the grooves is the problem of the mechanics of groove cutting. In this connection, Carney may be quoted further: "these grooves indicate a concentration of erosive processes within a narrow limit, or, better, a superimposed alignment of striae, causing at first a depression below the general level of the rock surface; . . . the basal ice under pressure moulded itself to the slight depression thus made; in consequence there was further localization of mechanical work . . . the ice continued to fit the grooves as they were deepened." Probably both plucking and abrasion played a part in the enlargement of the grooves. The brecciated character of the Bear Rock formation, and the loose, coralline structure of some of the Devonian reef limestones, suggest particular susceptibility to plucking, and it is on these formations that the grooves attain great depth. On the harder Devonian limestones, however, where the grooves are smaller, plucking may have been less effective and abrasion relatively more important. Possibly, once the grooves became well incised, their subsequent enlargement was analogous to the erosion of valleys by valley glaciers.

The reason for the unusual size of certain of the grooves is not clear. Perhaps it lay partly in the long duration of the erosive process, under conditions particularly favorable in some undetermined way. Perhaps there was some degree of



A. Stereogram of drumlinoidal form between broad grooves at locality *D*. The arrow, here and below, points in the direction of ice movement and is approximately 2000 feet long. Canadian Pacific Air Lines photo.

B. Grooves at locality *C* showing changed appearance on crossing break in slope controlled by structural boundary. Canadian Pacific Air Lines Photo.

C. Low-altitude oblique view of locality *F*, looking east. The maximum depth of grooving is estimated to be about 100 feet, and is on the Bear Rock formation. The ice moved from right to left.

D. Discontinuous grooves at locality *B*. Canadian Pacific Air Lines photo.

integration of many initial small grooves into fewer large resultant grooves, due to the encroachment of certain favored grooves sideward on neighboring grooves that grew more slowly.

Obviously much remains to be learned about the grooving process. Future studies on the physics of ice behavior, and on the details of other grooved areas, particularly if such can be found adjacent to existing glaciers, may be of assistance.

CONCLUSIONS

1. The grooved areas of the Mackenzie Valley region represent a distinctive type of glaciated landscape, formed by processes differing in degree, if not in kind, from those hitherto recognized in North America.
2. The occurrence of the grooving on mountain slopes and ridges adds to the known effects of continental glaciation on mountainous terrain.
3. Transitions from grooves to drumlinoidal forms suggest that the process of grooving is related to the process by which drumlins are formed, and that better understanding of the one may lead to better understanding of the other.
4. The grooving represents a type of glacial erosion having quantitative importance. If it be assumed that the area grooved is 50 square miles, that the average depth of the grooves is 50 feet, and that 50 per cent of the material to that depth was removed, the total volume of rock removed amounts to about a quarter of a cubic mile.
5. The trend of the grooves is uninfluenced by structure or topography, and records the true direction of ice flowage. The large scale of the grooving, and its distinctive appearance from the air, thus provides a new criterion for the rapid determination of the direction of ice movement in areas photographed from the air but difficult of access on the ground.
6. Application of the above criterion provides new data on the direction of ice movement in the Mackenzie Valley area.

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University of Kansas
Lawrence, Kansas