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BULLETIN 57

**ICE-PRESSED DRIFT FORMS AND
ASSOCIATED DEPOSITS
IN ALBERTA**

A. MacS. Stalker

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PREFACE

This bulletin describes drift forms that are common features of the prairie regions. Only a few occurrences have been noted elsewhere in Canada, but they undoubtedly are more widespread and numerous than formerly thought.

These forms, here called 'ice-pressed', include a group of dissimilar features that are related by a common method of origin, and are important in deciphering the regional history of deglaciation. Their study has been neglected in the past, and it is hoped that this bulletin will bring them to the attention of more geologists.

The author studied the forms described while mapping surficial deposits in the area, and in this report sets down certain conclusions as to their origin.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, June 11, 1959

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ICE-PRESSED DRIFT FORMS AND ASSOCIATED DEPOSITS IN ALBERTA

Abstract

The various forms of 'ice-pressed' features that occur in the Pleistocene deposits of Alberta are described and a general explanation of their origin is given. The significance of the forms in the history of deglaciation and their relation to the large hummocky moraines of the prairies are also briefly discussed.

These features, which are to be expected in any hummocky moraine in any area where ice stagnation and suitable material occurred, were formed during retreat of the last glacier in broad, marginal belts of the ice-sheet and also where the ice was thin over high land. This indicates that the sub-glacier material probably was not frozen during this stage of deglaciation.

It is concluded that these features were formed by a process of pressing or squeezing of sub-ice material into nearby tunnels, holes and crevasses in the ice-sheet.

Moraines of Alberta may represent changes in rate of, or halts in the lowering of the surface of the ice-sheet and should be correlated by altitude rather than by position.

The various ice-pressed forms are illustrated by a comprehensive selection of air and ground photographs.

Résumé

Cette étude décrit les diverses formes qui sont dues à la pression de la glace et qu'ont empruntées les matériaux des dépôts du Pléistocène de l'Alberta, et donne une explication générale de leur origine. On traite aussi brièvement de l'importance de ces formes dans l'histoire de la déglaciation, ainsi que de leurs relations avec les grandes moraines en bosses et creux des prairies.

Ces formes, qu'on doit s'attendre de trouver dans toute moraine en bosses et creux située dans toute région qui a été le siège de la stagnation de la glace et où se sont déposés des matériaux convenables, se sont formées lors du recul du dernier glacier dans de larges bandes marginales de la calotte de glace, et aussi là où la glace était mince et recouvrait des plateaux. Ceci indique que les matériaux sous-glaciaires n'étaient probablement pas gelés à ce stade de la déglaciation.

On en conclut que ces formes diverses se sont formées par compression ou resserrement des matériaux sous-glaciaires et par leur déposition dans des tunnels, des trous et des crevasses au sein de la calotte de glace elle-même.

Les moraines de l'Alberta peuvent indiquer des changements du rythme, ou des arrêts, de l'affaissement de la surface de la calotte glaciaire. Il faut donc établir la corrélation entre ces moraines d'après l'altitude plutôt que d'après la position.

Les diverses formes résultant de la pression de la glace sont illustrées à l'aide d'un choix étendu de photographies aériennes et terrestres.

INTRODUCTION

General Statement

The forms described as 'ice-pressed' in this bulletin were studied by the writer between 1948 and 1956 while mapping surficial deposits in central and southern Alberta. These forms, which are very common on the western plains of Canada, have not attracted the attention they merit. This is due partly to the general lack of detailed mapping in the region, but chiefly to the earlier lack of airphotos. The peculiar characteristics of many of these forms, and particularly their areal outline, could readily escape attention during ground mapping, and the few that were noticed could easily be ignored as isolated phenomena, or ascribed to various exceptional methods of formation. Other of these forms, such as the till-cored esker ridges, would be recognized as abnormal only if good sections through them were exposed; such sections have not been common in the past. On airphotos, however, these forms stand out remarkably (Plates VIII, IX, X, XI, XIII) and the enormous number present becomes manifest. Recognition of the method of formation of these ice-pressed forms has greatly increased understanding of the methods of deglaciation on the western plains, and of the significance of the large hummocky moraine systems present there. It has also helped explain the small amount of outwash and the few spillways associated with these moraine systems (Johnston and Wickenden, 1931, p. 40; Bretz, 1943, p. 35)¹.

The present paper is an attempt to give a general, unified explanation of the origin of all these forms. Normal glacial, glacial-fluvial and glacial-lacustrine, periglacial, and erosional methods were not adequate to explain origin of all of the forms. Certain of the 'rim ridges' were first thought to have formed through pushing or shoving by active ice, and so to indicate direction of ice movement. This theory was abandoned, however, as the trend of such ridges changed from place to place, and as they commonly completely encircled moraine plateaux. The abandonment of this theory intensified the search for a process that would explain origin of all the forms. The difficulty was increased when parts of one long ridge, apparently an esker ridge (situated mainly in secs. 21, 22, 28, 29, 30, tp. 33, rge. 24, W4th mer.) were found to be composed partly of bedrock. This strictly limited possible methods of origin, had strong influence on subsequent ideas about development of the ice-pressed forms, and forced rejection of previous theories of formation. Much subsequent study was devoted to the numerous

¹Names and dates in parentheses are those of references cited at the end of this report.

rim ridges found in the region. Luckily many good cuts through these were available for study (Warren, 1954, p. 79, figure 1), and much valuable information was obtained which could be extrapolated to other of the features. Good cuts were also available through many of the till-cored esker ridges.

Previous Work

Some types of ice-pressed forms have been studied and described previously. This paper is largely an application to Alberta of the theories of Hoppe (1952) on formation of 'moraine plateaux' with their rim ridges, other moraine ridges found within hummocky moraines (pp. 3 to 9), and terrace ridges (p. 12). In addition to his exhaustive study of these features in Scandinavia, Hoppe reviewed various other theories and possible methods of origin, and previous work.

Madsen (1900) described till-cored esker ridges found in Denmark and explained their origin by methods very similar to those accepted in this report for similar features. Dyson (1952) discussed parallel ridges on ice-ridged moraines (or fluted moraine surfaces), a type of feature related in origin to the forms described herein, and his theory is adapted in this report. In Canada, Erdtman and Lewis (1931, pp. 52 to 55) described features in western Alberta that may be a type of ice-pressed form. Henderson (1952, pp. 50 to 59) described and discussed low till and silt mounds in the Peace River country of Alberta, which are similar to the 'plains plateaux' described in this report. Gravenor (1955) also described and discussed similar mounds in east-central Alberta. Craig (1956, pp. 52 to 56) mapped many moraine plateaux in central Alberta, which he termed 'stagnant ice features'. Christiansen (1956, pp. 9 to 12) described certain of these forms in Saskatchewan.

GENERAL GEOLOGY

Physiography

The glaciated area of southern and central Alberta extends from the flat plains on the east to the Foothills of the Rocky Mountains. Most of the region is rolling, and remnant plateaux, hills and ridges, which represent the more resistant bedrock formations, are common. Rivers that flow eastward from the mountains across the province generally do so in deep, steep-walled valleys, and in the eastern part of the province these valleys are commonly the most striking feature of the topography.

Bedrock

The bedrock of southern and central Alberta is composed of Cretaceous and Tertiary sediments laid down in the Alberta Geosyncline. Clay, silt and sand are the predominant deposits, but there are minor beds and lenses of coal and ironstone. Many of the beds contain much bentonite, and most of them are unconsolidated or only weakly consolidated, both important features in relation to the present study. The beds in much of the region are nearly flat-lying, with local variations, but in the western part of the region, near the axis of the geosyncline and to the west of it, dips are steeper.

Cretaceous rock underlies much of the region, and was mostly laid down in the marginal zone of the Cretaceous (Pierre) Sea. This rock is largely of salt- or brackish-water origin, but in the western parts of the region fluctuations of the sea-margin produced much interfingering with brackish-water and freshwater beds. Tertiary rock, largely of freshwater or brackish-water origin, underlies much of the western part of the region. It was formed from the large quantities of material carried eastward from the rising Rocky Mountains and is, on the whole, coarser grained with a greater proportion of sand than the Cretaceous rock, though it also contains much clay and silt, and locally much bentonite.

Drift

The drift of southern and central Alberta came largely from the underlying bedrock formations, particularly the Cretaceous rock, and its typical characteristics are those derived from the bedrock. It is composed largely of clay, silt and sand, along with a sprinkling of stones brought by glaciers from outside the region. It has an average thickness of about 25 feet, but

is generally thicker in the hummocky moraines and lake basins, and thinner in the ground moraine plains which cover more than half the area. Most of the surface drift is of Wisconsin age.

The chief component of the drift to be considered in studying the ice-pressed forms is the till of the ground moraine plains and the hummocky moraines. Typically this is nearly an ideal till, with significant amounts of each size component, though the clay and silt are in places over represented. It is characteristically compact, hard, massive, brown to blue, and very sticky and plastic when wet, due largely to a high content of bentonite.

ICE-PRESSED FORMS

The term 'ice-pressed forms' is used here as a general name for a number of dissimilar forms believed to have had a similar method of formation. This method is through the pressing or squeezing, by weight of the overlying ice, of sub-ice material into adjoining holes or crevasses in the ice-sheet. This material is generally till. The forms include the following:

- A. Rim ridges and terrace ridges of dead-ice plateaux¹
 - a. of moraine plateaux
 - b. of plains plateaux
- B. Ice-pressed moraine ridges
- C. Ice-pressed plains ridges
- D. Till-cored or completely till esker ridges
- E. Ice-pressed minor moraine ridges (formed between active and dead ice)
- F. Ice-pressed, long drumlinoid ridges.

Hoppe (1952) used the terms rim ridge (p. 5), terrace ridge (p. 12), moraine ridge (p. 5) and moraine plateau (p. 5). The writer accepts and uses these terms but also employs the terms plains plateaux for plateaux on ground moraine plains similar to the moraine plateaux of hummocky moraines, and 'plains ridge' for ridges on ground moraine plains similar to the moraine ridges of hummocky moraines. Dead-ice plateau as used in this paper includes both moraine plateau and plains plateau.

¹Hoppe (1952, p. 5) stated—"It becomes evident that the dead-ice hollows as a rule are surrounded by moraine ridges, which at the same time in most of the cases form turned-up edges around the moraine plateaux. When the moraine ridges assume this appearance, they will in the following be referred to as 'rim ridges'." Hoppe thus classified rim ridges as a type of moraine ridge. Rim ridges, however, also occur outside hummocky moraine areas, i.e., around plains plateaux, and hence the name 'rim ridge' should not carry the connotation of 'moraine'. In this bulletin, therefore, 'ice-pressed ridge' is used as the overall name, and rim ridges, moraine and plains ridges, and till esker ridges are considered to be varieties of it. 'Moraine ridge' is restricted to ridges in hummocky moraine that do not encircle dead-ice plateaux, but which enclose dead-ice hollows or cross hummocky moraine. 'Plains ridges' are the corresponding ridges on ground moraine plains.

The ice-pressed forms rise above the general level of the surrounding country to various heights, but rarely to more than 80 feet, and they range from only a few feet to several hundred feet in width. They are generally long ridges, in a few instances straight but generally curved or circular ridges (Plates VIII, X) that form the rim ridges of dead-ice plateaux, and moraine ridges around dead-ice hollows. Another type is branching and sinuous, and this consists chiefly of the till or till-cored esker ridges. The circular ridges may also form many of the small knobs or hills in hummocky moraine that have small depressions at their summits (Plates IX, XI) but which have been regarded in the past as normal, morainal knobs.

The ice-pressed forms have these features in common. The till in them is of a basal type, similar everywhere to the other nearby till, described above. They characteristically have pockets, or lenses of sand and gravel within or associated with them, and they have troughs or depressions beside them.

Rim and Terrace Ridges, and Dead-Ice Plateaux

The rim and terrace types of the ice-pressed ridges are always associated with dead-ice plateaux. It is therefore necessary to describe these plateaux, and to discuss these ridges in relation to them. The term 'dead-ice plateau' as used here includes both the moraine plateau of Hoppe (1952) and the plains plateau. The term moraine plateau includes the 'stagnant-ice features' of Craig (1956) and the term plains plateau includes both the till and silt mounds of Henderson (1952) and the prairie mounds of Gravenor (1955). Each of these earlier names is suitable where it has been used but, except for 'stagnant-ice features', these names seem rather limited in application and no one of them is suitable for the overall series of forms. Thus moraine plateau, which was used because the features described were found in hummocky moraine, does not seem suitable for those forms occurring in ground moraine plains. Similarly, 'till and silt mounds' tends to infer that they all are composed of these materials. The name 'prairie mounds' seems to limit these forms to prairie regions whereas their occurrence on the prairies is purely incidental and certain types, such as moraine plateaux, are apt to be more common, other factors being equal, in areas that are not typically prairie. In addition, the broad, flat surfaces of many large plateaux do not give the general impression of the shape normally associated with the word mound. On the other hand 'stagnant-ice features' includes all these forms but it is a general term that can include still other forms besides those described here. 'Dead-ice plateau' is not being used to supersede these other names, but rather as a comprehensive term. Dead-ice plateau is both generic and descriptive. 'Dead ice' emphasizes the

condition of the ice-sheet during its formation, and 'plateau' describes the shape the forms tend to reach under ideal conditions. It is emphasized that a true plateau shape is reached only under these ideal conditions.

The dead-ice plateaux comprise a series of forms, somewhat similar in shape but greatly different in size, that have in common one or more till rim ridges and that tend towards a plateau form. Water-deposited sediments are present in the central parts of most of the plateaux (Plates II, III, XII), and under ideal conditions may constitute the bulk of the plateaux and completely fill these central areas.

The moraine plateaux occur typically in hummocky moraine, and commonly in the highest parts and areas of strongest development of such moraines. In many areas they appear to have started to form on high ground early in the development of such moraine, while melting of nearby ice was still slow. Most of those examined were in the Buffalo Lake moraine system, particularly in that sector of it east of the city of Red Deer where they are very common, but others were studied in the smaller, hummocky moraines that are found southward as far as the United States border; in every locality they display similar features. They are recognized most easily, both on airphotos and on the ground, by presenting the only level tracts in the otherwise rugged knob-and-kettle topography (Plates I, IV, X, XI, XII, XIII). They vary greatly in size, the biggest known (tp. 41, rge. 19, W4th mer., in the Buffalo Lake moraine system) is about 7 miles long and embraces some 12 square miles, but it actually embodies several adjoining plateaux and is most irregular in outline. Several in the Buffalo Lake moraine system are more than 3 miles long (Plate XIII); many are more than a mile long; they range downward in size to those a few hundred feet in diameter. Smaller plateaux undoubtedly are common, but for the most part have not been distinguished within the morainal tracts. The small plateaux tend to be round. In general, the plateaux rise to the height of the highest knobs in the surrounding hummocky moraine (Plates I, XI, XII, XIII), but in a few instances the morainal knobs rise well above them (Plate IV). Most of the plateaux rise 20 to 50 feet above the nearby depressions; a few to about 70 feet; the highest noticed that is considered to be a moraine plateau (Boss Hill, in sec. 2, tp. 41, rge. 20, W4th mer.) towers some 150 feet above the nearby kettles.

The plateaux rise steeply from the adjoining depressions or kettles, commonly at about the angle of repose of the till composing their rims. Along about one quarter of the perimeter of the plateaux, on an average, the margins rise as much as 20 feet above the central parts of the plateaux. This extra rise forms the rim ridge proper. From their summits these ridges slope towards the centres of the plateaux at generally low angles (between about 5 and 15 degrees) and disappear beneath the flat, central

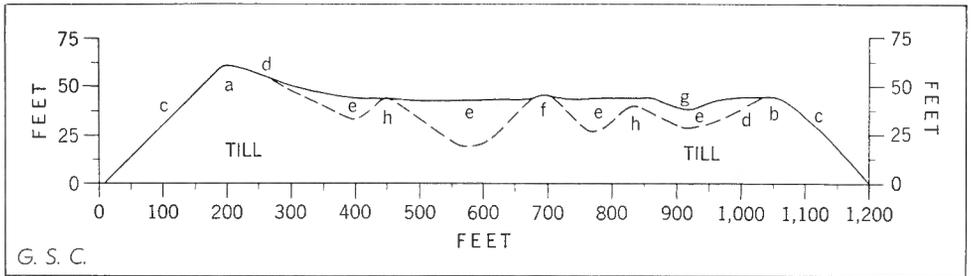


Figure 1. General hypothetical cross-section through a moraine plateau; (a) till rim ridge rising above plateau surface; (b) till rim ridge rising to plateau surface; (c) steep outward slope of rim ridge towards adjoining kettles; (d) gentle inward slope of rim ridge to beneath central sediments; (e) flat central area of water-deposited sediments; (f) till knob rising above plateau surface; (g) shallow kettle-hole; (h) buried till knobs (drawn mostly from examples seen in sec. 32, tp. 35, rge. 20, W.4th mer.).

parts of the plateaux (Plates V, X, XI, XII). The water-deposited sediments of the central parts of these plateaux generally consist of clay, silt, sand and gravel, with included lenses and thin beds of till. Figure 1 shows a general cross-section through a plateau. The continuation of the morainal knobs under the central part of the plateau is purely hypothetical.

The rim ridges are the ice-pressed parts of these plateaux. They normally are composed of a basal till which does not display any marked difference in grain size or other features from the nearby basal till, and which is equally massive. Though they rise above the central fillings only along about one quarter of the perimeters of the plateaux, examination of many plateau margins has shown that the 'rim ridges' are nevertheless commonly present elsewhere but are only observed where there are cuts through the margins of the plateaux. It is, in fact, probable that most of the perimeter of each plateau is marked by such a ridge, though it may

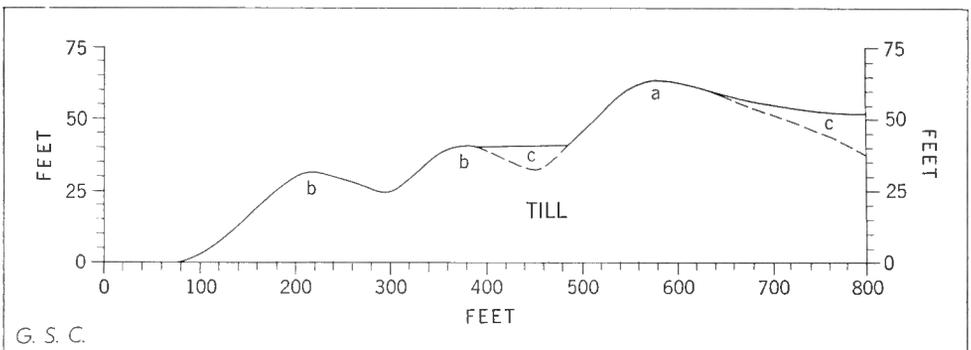
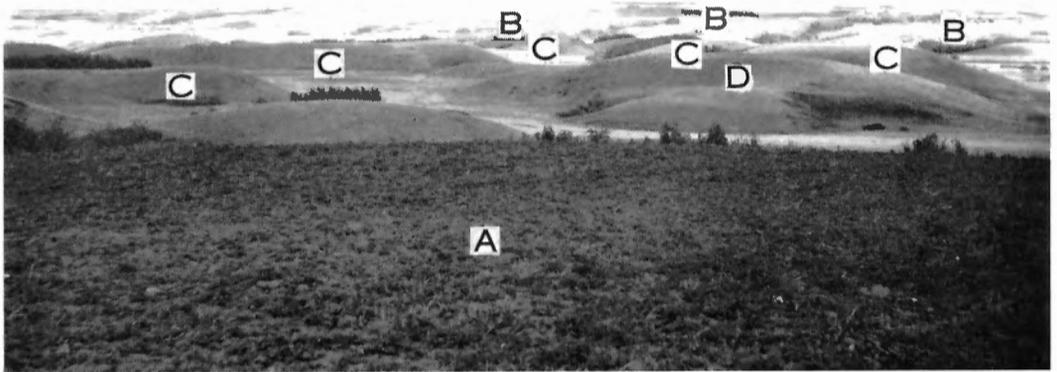


Figure 2. Hypothetical cross-section through margin of a moraine plateau showing three parallel rim ridges (or one rim ridge (a) and two terrace ridges (b)); c, water-deposited sand, silt, and clay.



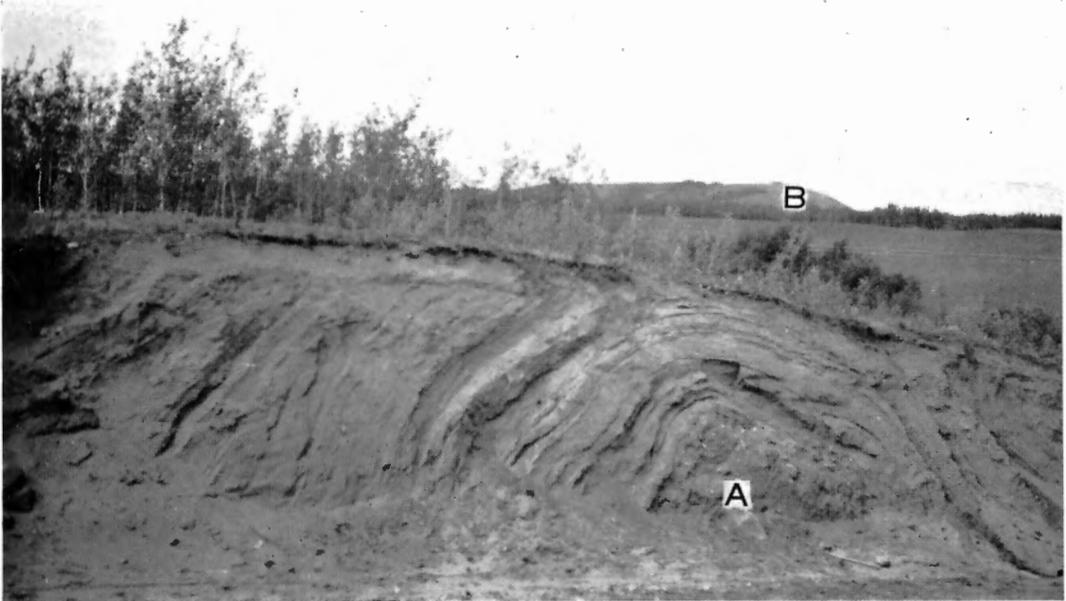
Stalker, 1-2-1952

Plate I. Moraine plateaux. View from surface of a moraine plateau (A) across small plateaux (C) towards large, flat-topped plateau (B). Notice rim ridge encircling small plateau (D). Looking northeastward from the SW $\frac{1}{4}$, sec. 30, tp. 35, rge. 20, W.4th mer.

not rise to the level of the uppermost central sediments. Occasionally a rim ridge may separate from the edge of the plateau; it may then be called a moraine ridge (Plate XII). Sometimes such a moraine ridge connects two plateaux. A plateau may also have two or more parallel rim ridges, the innermost being the highest and the others (terrace ridges) rising to lesser heights outward and away from the centre of the plateau (Figure 2; Plate III).

A rim ridge may be inclined so that its axial plane dips towards the centre of the plateau (Plate III). Where a rim ridge rises above the associated central sedimentary beds of a plateau, these beds may remain horizontal, or else slope upward, to where they are terminated at the ridge. In the latter case they rise with a slope that is less than that of the inward-sloping surface of the rim ridge, and decrease in thickness as they rise. If the ridge does not reach the surface, the overlying sediments generally are folded to correspond to, and to parallel, the buried surface of the ridge. Where examined, these folded beds display little thickening or thinning over the ridges, and appear to have been folded with little internal disturbance of each individual bed (Plates II, III).

The plains plateaux, or dead-ice plateaux occurring beyond hummocky moraine areas and typically on ground moraine plains, are normally smaller than the moraine plateaux but much more numerous. The descriptions by Henderson (1952, pp. 50-59) of his till and silt mounds, and by Gravenor (1955) of his prairie mounds, agree essentially with features of the plains plateaux noted by the writer. The plains plateaux range from less than 50 feet to more than 600 feet in diameter, and from 5 to 30 or more feet in height, but they generally are about 300 feet in diameter and 5 to 15 feet high. Their ideal form is a flat-topped plateau (Plates VI, VII, Figure 3 A), and this type is common. In many instances, however, there is a central depression forming most of the area of the plateau, and generally between 2 and 5 feet deep (Plate VIII, Figures 3 B, 3 C). In extreme cases there is no central filling whatever and the depression may reach the general level of the ground outside the plateau; the form then consists only of a rim ridge. Many of the plains plateaux appear to have a weak trend towards hexagonal outlines. They tend to occur in groups, commonly several hundred being present in a single plateau field; solitary ones are rare. The arrangement of the plateaux in these fields commonly shows a distinct lineation (Plate VIII).



Stalker, 2-3-1950

Plate II. Folded sand and silt beds overlying a rim ridge (A). Notice high moraine plateau (B) in background. SW.¼, sec. 1, tp. 39, rge. 22, W.4th mer.

Ice-Pressed Drift Forms and Associated Deposits in Alberta

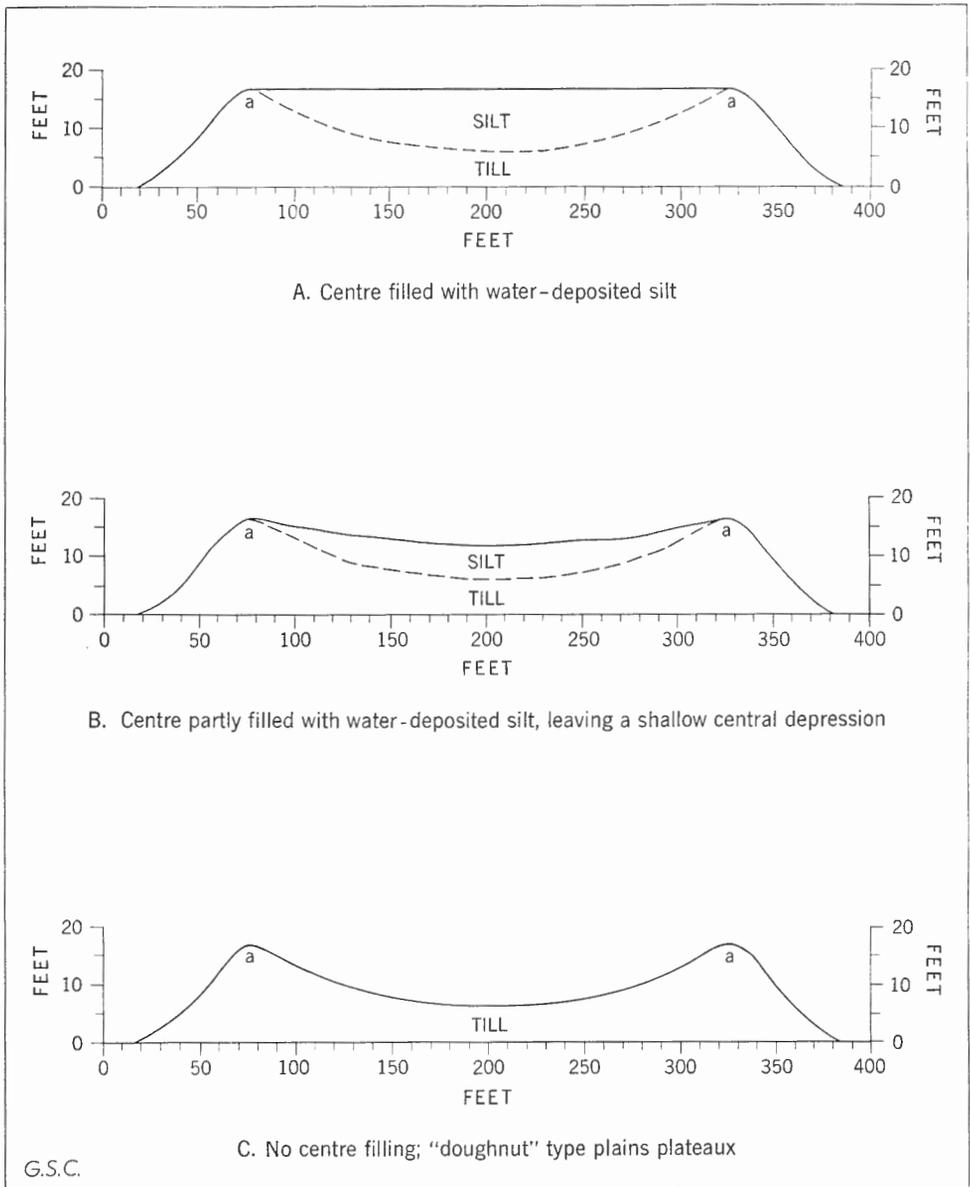


Figure 3. Typical cross-sections through plains plateaux. Note till rim ridges (a).

The composition and structure of the plains plateaux is very similar to that of the moraine plateaux, and is suggested in Figure 3 A, B, C. The important feature, apparently present in and generally completely encircling each unit, is a till rim ridge similar to those enclosing the moraine plateaux.

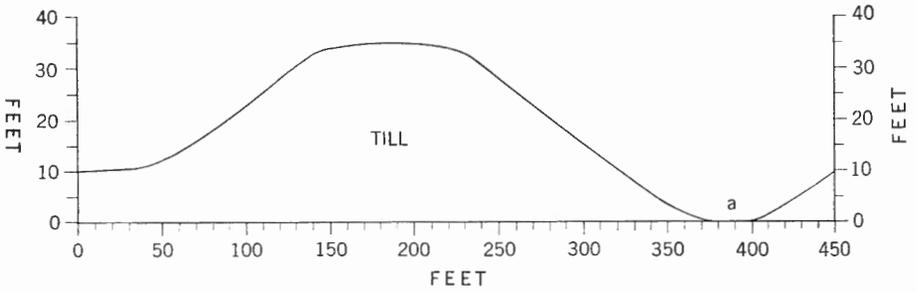


Plate III. Sand, silt and gravel beds folded over two parallel rim ridges (A and B). Notice overturning of upper rim ridge (A). NE. $\frac{1}{4}$, sec. 35, tp. 38, rge. 22, W.4th mer. (Photo courtesy of B. G. Craig.)

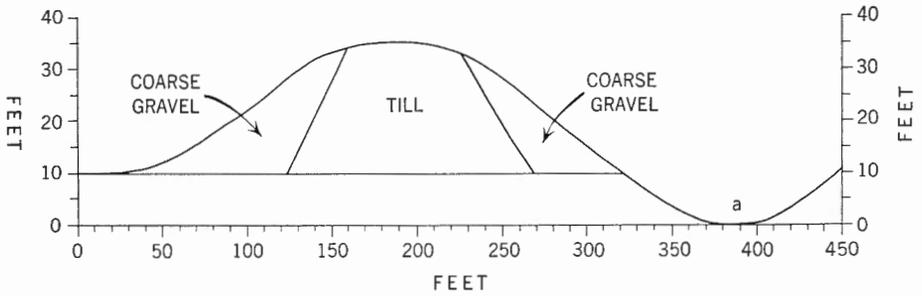
In most of the plateaux examined by the writer the rim ridge is equally high around each plateau; in some of the plateaux in the Peace River country, however, the southeastern sector is higher than the rest of the rim ridge. The outer sides of the rim ridges are steep, and the inner sides dip gently towards the centres of the plateaux, as in the moraine plateaux. The central areas of most of the plains plateaux are partly or completely filled with the associated, water-deposited sediment, mostly silt.

Moraine and Plains Ridges

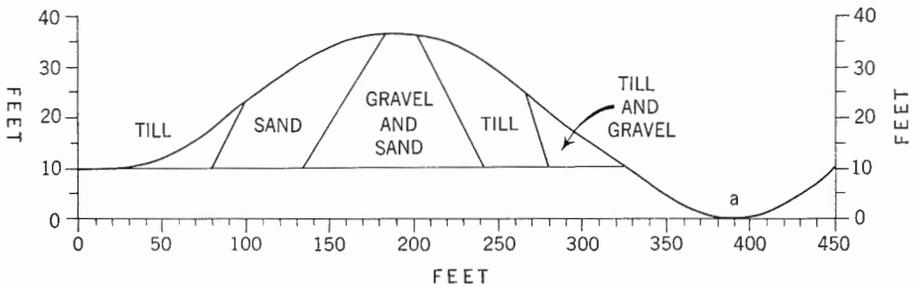
The moraine ridges (footnote, p. 4) are ridges, not necessarily connected with a dead-ice plateau, that encircle and intervene between dead-ice hollows (kettle-holes), or strike through the moraine without any apparent reason for their locations. Plains ridges are the corresponding ridges on ground moraine plains. These ridges are similar to the rim ridges in composition and internal structure, with perhaps the addition of local pockets of sand and gravel. However, both sides of these ridges are steep and near the angle of repose for the till composing them. The moraine ridges, along with the rim ridges of the moraine plateaux, tend to be the highest



A. All till esker ridge (drawn after ridge in section 2, township 31, range 27, west 4th meridian)



B. Till-cored esker ridge (drawn after ridge in north half of section 23, township 32, range 28, west 4th meridian)



C. Esker ridge with partial till cover (drawn after ridge in southeast quarter of section 19, township 32, range 28, west 4th meridian)

G. S. C.

Figure 4. Cross-sections through esker ridges. Note troughs (a).

of the ice-pressed ridges, and some of them approach a height of 80 feet. The plains ridges are generally much lower. Moraine ridges around dead-ice hollows are well described by Hoppe (1952), who strongly emphasizes them in his report.

Till and Till-Cored Esker Ridges

The till and till-cored esker ridges were studied most intensively in tps. 42-46, rges. 15-18; and tps. 31-33, rges. 27-30, all W4th mer. In both these regions several dozen esker-like ridges, ranging between one-half mile and 6 miles in length, are present. The ridges in the first region are mostly simple, and roughly parallel to one another, but those in the latter region have more the appearance of typical esker systems, serpentine, tortuous, and branching and joining. Scattered solitary till and till-cored esker ridges also occur in other regions of southern and central Alberta, but outside these two regions esker ridges of normal composition are thought to be the more common. Madsen (1900) described such till-cored ridges and explained their formation by a process very similar to that set forth below.

The till and till-cored esker ridges are similar to normal esker ridges in outward characteristics, whether studied on the ground or in airphotos. They are equally elongate, equally sinuous, of much the same dimensions as the smaller of the normal esker ridges, and branch or join in much the same manner. Most are between 5 and 50 feet high, with a maximum observed height of about 75 feet, but the height can change markedly along their length. Most are between 50 and 300 feet wide at the base. A few consist of a series of adjoining hills, and in some instances only segments of esker ridge, connected with each other by esker stream channels, are present. Troughs, as much as 20 feet deep and 50 or more feet wide, commonly border both sides of many of the ridges (Figure 4). In the case of the esker ridges to the southeast of Camrose (approximately tp. 44, rges. 17 and 18, W4th mer.) a gully enters the Battle River valley opposite the end of each ridge, although these ridges and the valley are a mile to 5 miles apart. Such features indicate presence of running water during formation of these ridges.

These ridges and normal esker ridges differ chiefly in composition. Typical cross-sections through till-cored or till esker ridges are depicted in Figure 4 A, B, C. A few of the ridges (e.g., an esker ridge in sec. 2, tp. 31, rge. 27, W4th mer.) are composed entirely of a basal type till. The composition ranges from these all-till ridges through ridges with only pockets of sand and gravel, those with till cores of various sizes, to the normal esker ridges that are constructed completely of stream-deposited sediments,



Stalker, 6-1-1953

Plate IV. Nearby morainal knobs rising about 30 feet above the flat surface of a 35-foot-high moraine plateau (foreground). SW $\frac{1}{4}$, sec. 14, tp. 35, rge. 19, W.4th mer.



Stalker, 1-1-1954

Plate V. Till rim ridge (A) sloping steeply towards a deep dead-ice hollow on right (B) and gently towards flat, water-deposited sediments of central part of a moraine plateau (C). NW $\frac{1}{4}$, sec. 28, tp. 35, rge. 20, W.4th mer.



Stalker, 6-5-1955

Plate VI. Plains plateau, about 15 feet high and 300 feet in diameter. Notice person standing on left slope of plateau. SW $\frac{1}{4}$, sec. 5, tp. 18, rge. 27, W.4th mer.



Stalker, 6-8-1955

Plate VII. Part of a "field" of plains plateaux. The two high plateaux (A) are 25 feet high. Notice also lower plateau (B). NW. $\frac{1}{4}$, sec. 31, tp. 18, rge. 26, W.4th mer.



RCAF Photo A11646-138

Plate VIII. Part of a "field" of plains plateaux, consisting of plateaux 100 to 400 feet in diameter and 5 to 15 feet high. The central fillings of most of these plateaux are incomplete, leaving doughnut-shaped rings. Notice southwestward lineation, corresponding to direction of glacier movement. Tp. 21, rges. 24 and 25, W.4th mer.

in this area chiefly silt and sand. The till core may be in the centre or at the edge of the esker ridge, and may either reach the top of the ridge or extend only a short way up (Madsen, 1900; Figures 4, 5, 6; Plate IV).

Minor Moraine Ridges

Certain minor morainal ridges may be a type of ice-pressed form, or at least partly of this origin. These would include the series of long, narrow, parallel, accurate ridges that are common in parts of the prairies. These have not been studied for the purposes of this report, however, and this possible origin is suggested only so that it may be borne in mind during future study of such ridges. Small examples of such ridges, apparently composed of till, occur locally in southwestern Alberta (e.g., 3 to 5 miles southwest of the town of High River, where they are between 3 and 15 feet high and as much as 50 feet wide). Other such moraines on the prairies are described by Lawrence and Elson (1953, pp. 95-104).

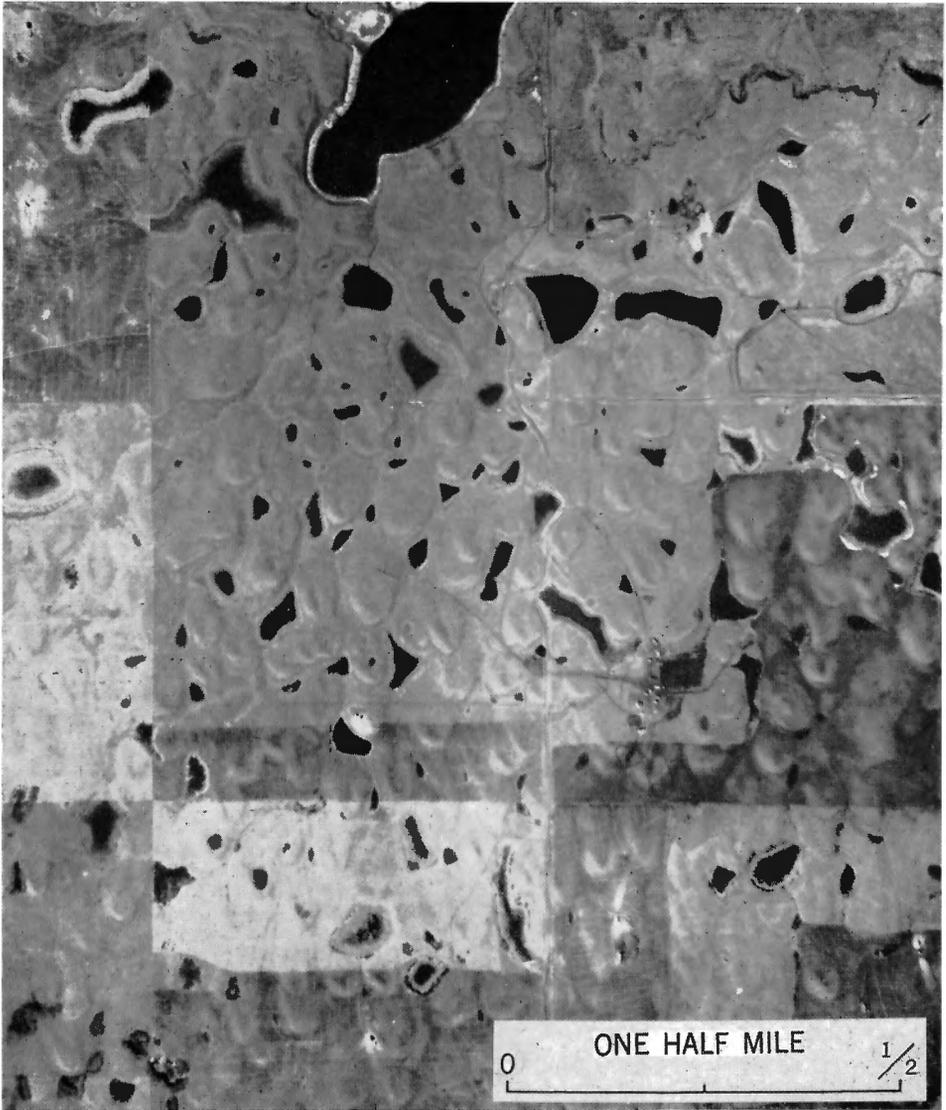
Drumlinoid Ridges

Certain of the long, low, drumlinoid ridges of the prairies may have had an ice-pressed origin. These ridges generally are straight, between 5 and 25 feet high, 50 to 300 feet wide at their base, and may stretch for several miles with little change. Where observed they are composed of compact till. The ridges under discussion include only the constructional type, where new material has been brought in, and not the erosional type, in which pre-existing material, generally in hills, has been remoulded into linear ridges. Such ridges certainly formed near the base of the ice, and although they have not been intensively studied by the writer he considers it unlikely that any other method apart from the ice-pressing process could have supplied the amount of till necessary. 'Dead ice' conditions are not likely to have prevailed during their formation. Such ridges are somewhat similar to, but generally longer than, those described by Dyson (1952) as constructed near the front of valley glaciers by material being forced into subglacial tunnels. Dyson described these ridges as being mostly 2 to 12 feet wide, 1 foot to 3 feet high, with some 500 to 600 feet long. There does not appear to have been any obstruction to ice movement on the proximal end of the present ridges during their formation, such as Dyson considered necessary for their formation.

ORIGIN OF ICE-PRESSED FORMS

An overall theory for formation of the various types of ridge described above must explain the following fundamental features of these ridges:

- (i) That any till present in the ridges is of a basal type, and is completely unsorted;



RCAF photo A7643-97

Plate IX. Unsymmetrical dead-ice plateaux, in an area of hummocky moraine. Notice the high south ends of the plateaux and the elongated central depressions. The strike of the central depressions is approximately the direction of last ice movement. Tp. 35, rge. 21, W.4th mer.

- (ii) That some water-deposited sediment is contained in, or is associated with, most of the ridges, either as centre fillings in the plateaux or as included pockets in the ridges;
- (iii) That dead-ice hollows and marginal troughs lie near, or are associated with, many of the rim ridges of moraine plateaux, the moraine and plains ridges, and till or till-cored esker ridges.

The writer believes that the various forms described earlier had a common method of formation, and that they were constructed through what he calls the 'ice-pressing process'. This process best explains features common to all these forms. The acceptance of this general method does not mean that certain individual examples of each type could not have been built by other means, indeed many examples were probably built by other methods. For instance, rim ridges of certain plains plateaux were undoubtedly built by permafrost action. It rather implies that this is the normal method of construction of the forms, and is the process that should be assumed to have built them if evidence to the contrary is lacking.

The Ice-Pressing Process

Hoppe (1952) gave a detailed account of how the ice-pressing process would produce the moraine and rim ridges; Madsen (1900) similarly described the process for till-cored esker ridges, and Dyson (1952) for a particular type of ice-flow ridge. Hoppe's summary of his conclusions is given in the appendix to this report (p. 37). The present paper is an extension of the ice-pressing theory to account for other drift forms, and a discussion of the theory as it applies to Alberta.

Construction of the various ridges by the ice-pressing process occurred as follows. During deglaciation crevasses and holes of various types were present in the base of the ice. At the same time the sub-ice material, generally till but in places bedrock or other material, was either not frozen or only partly frozen. It also contained much water, commonly being completely saturated, and thus was in a highly plastic or a fluid condition. The weight of ice on this plastic material pressed it towards the crevasses and holes, increasing the amount of material there while decreasing the amount beneath the ice. In the large holes most of the pressed material came to rest around their margins and only a little near the centre. When the ice finally melted the material that had been pressed into the crevasses and holes stood as ridges, whereas the places from which material had been pressed were low and commonly formed troughs and dead-ice hollows alongside the ice-pressed ridges.

There is also the possibility that basal plastic ice was slowly pressed into the crevasses and holes, carrying its contained rock material with it.

Melting of this ice along the edges of the crevasses and holes, perhaps abetted by the water contained therein, would cause this material to be deposited and to appear as ridges upon disappearance of the ice-sheet. Such material would be better sorted than the material in the normal ice-pressed ridges, and might even form ridges composed of coarse material and boulders. This, however, is a separate study and is not discussed further here.

The fact that the till in the ice-pressed ridges is a basal type indicates that it came either from the basal part of the ice-sheet or from beneath it. Till formed from material carried in the higher parts of a glacier tends to be coarse and if it slid down into the crevasses and holes, it would tend to be somewhat sorted. If water was present to wash the material as it fell down the sorting would be even more accentuated, and much of the fine material would be washed out, leaving a coarser till. Further indication that the till was pressed in from beneath the ice comes from studies of the till fabric. The account by Hoppe includes both evidence for movement of the material from beneath the ice into the rim and moraine ridges, and the results of an intensive study of the problem through pebble and cobble orientations on various sectors of rim ridges in several regions of Sweden, in all cases with similar findings. He studied mostly the moraine ridges that surround dead-ice hollows. In all instances the indicated movement of the till is outward from the dead-ice hollows towards the ridges, and generally with marked orientation maxima. This indicates that the ridges were not formed by material falling or sliding into the crevasses or holes, for if that had been so the stones would lie in a helter-skelter manner, rather than in such a regular fashion. Pressing of till into the crevasses and holes is the only process that could form ridges of basal, unsorted till with a regular orientation of stones.

The water-deposited sediment contained in, or associated with, most of the ridges was deposited by water flowing along the crevasses, or by streams pouring into the holes and building deltas at their margins and depositing fine material over the centre of the holes. The first method took place mostly in esker tunnels and long crevasses, and added the sorted material to the till-cored esker ridges, moraine ridges, and plains ridges. The second method was largely responsible for the centre fillings in the moraine and plains plateaux.

The loss of material from beneath the ice to the ice-pressed ridges caused many of the marginal troughs and dead-ice hollows near these ridges.

The water needed to saturate the ground beneath the ice-sheet was available due to the general amelioration of climate which caused the deglaciation. This resulted in large quantities of water being present, both from melting of the ice and from rain falling on the ice-sheet. On the

western prairies, the westward and southward rise of land towards the regions that were ice-free, and the good state of the ice and active condition of the glacier to the north and east, prevented large scale sub-ice seepage or movement through cracks and crevasses. This slowed run-off or seepage of water away from the region, thus raising the water-table in the ground and the water level in the holes and crevasses in the ice. There was thus ample water available to soak into the ground beneath the ice.

The first requisite of the ice-pressing process is that there be holes, tunnels, crevasses, or zones of weakness in the ice, into which the sub-glacier material is pressed or squeezed. Such openings may not be necessary for the long drumlinoid ridges. Esker tunnels are produced by sub-glacier streams but the origin of other openings is uncertain. Indeed no process can be suggested to explain the existence of large holes, a mile or more in diameter, that were necessary for formation of the large moraine plateaux. Meltwater stream moulins and fast melting around nunataks may have formed some of the smaller and medium-sized holes, though nunatak hills are rare near the dead-ice plateaux studied by the writer. Water seepages may have formed crevasses along former joints or strain-planes that had been produced in the glacier while it was yet moving. Most of the small holes necessary for the plains plateaux probably arose from water running down holes formed at intersections of such joints or crevasses.

Once a hole had started to form, calving of adjoining ice probably was a major means of enlarging it. Such calving would result from undermining, through melting of ice near the surface of water contained in the holes. Enlargement of the holes through calving may appear to be at variance with the assumed general stability of the ice-margin around the holes during pressing up of the rim ridges. Calving, however, may have ceased before construction of the rim ridges due to draining from the holes of the water necessary for the process, as the condition of the ice-sheet deteriorated and more drainage channels appeared. Indeed, the inception of growth of the rim ridges along the ice-margin in itself would lessen contact of water contained in the holes with the ice, and thus decrease or end calving. In addition, in a few places, the sub-glacier material may have remained frozen for some time after onset of formation of the holes and not been fluid or plastic enough to flow until calving had largely ceased. Though calving would tend to give the steep ice-walls that are desirable for formation of the ice-pressed forms, and undoubtedly played a role in forming some of the smaller holes, it is not in itself sufficient to explain formation of the large holes.

After the holes had formed their preservation would require that the ice-sheet in the region be largely stagnant, that it be thin enough to inhibit plastic flow of the basal ice, and that the climate had ameliorated enough

to prevent filling of the holes with ice. The minimum thickness of ice necessary to produce plastic flow near its base is, according to Demorest (1938, p. 724), about 150 feet. Dyson (1952, p. 206) mentions cases at Sperry Glacier in which tunnels remained open under ice 240 to 260 feet thick, and the minimum thickness is here assumed to be greater than 200 feet under some conditions. Esker tunnels may possibly be produced under even thicker ice if the water is passing through them under strong pressure.

The ice-pressing process presupposes that the various ridges were constructed through weight of ice pressing underlying plastic material, generally till but in places bedrock or other material, upward and outward into crevasses and the margins of holes in the ice. The till may either be pressed in below the ridge that is being built, raising it bodily, or be squeezed over the surface of the ridge, and so increase its height. The first method, is probably the more common. It was evidently the one that constructed most rim and esker ridges, particularly those rim ridges that were in direct contact with a stable ice-margin and obviously those that shoved up overlying, water-laid sediments as they rose, and probably those ridges with sizable troughs or depressions beside them. The second method, plastering on, probably built those ridges containing numerous pockets of gravel and sand and the ridges without adjoining troughs which were constructed while the ice was slowly receding from them. It may also have produced the long, drumlinoid ridges and some minor moraine and plains ridges.

A ridge would rise until the nearby supply of plastic till was exhausted, the ice-margin had melted back from the ridge, or the ridge had reached a height which approximately balanced the pressure exerted from beneath by the ice. Exhaustion of the supply of plastic till was probably common, particularly if part of the sub-ice material was still frozen. If construction of a ridge ceased due to a receding ice-margin, formation of a new, generally a lower, ridge would commonly ensue at the new ice-margin. This would give rise to the two or more parallel rim ridges, or terrace ridges, found around many moraine plateaux.

Under favourable conditions with ice 200 feet thick, assuming an ice density of 0.8 and a till density of 2.0, a ridge about 80 feet high could be constructed. This agrees roughly with observed heights of the ridges, which reach a maximum of about 70 feet. Higher ridges could form under special circumstances, particularly if the ice contained, or was overlaid by, enough drift to add substantially to the pressure it could exert at its base. Such ridges, however, would be flanked by this drift, and the total height of a ridge of this type should be measured from its summit to the bottoms of troughs or kettles that occur some distance away. A process similar to this may partly explain the height of Boss Hill (p. 6), which apparently consists

of a central ridge flanked on both sides by stratified sediments. Most of the ridges, however, and particularly those associated with plains plateaux, are much lower than 70 feet. The chief cause of this undoubtedly is that the ice was much less than 200 feet thick during formation of the ridges.

The loss of till from beneath the adjoining ice into the ridges would tend to create kettles or troughs near the ridges, and this factor also tends to accentuate the height of the ridges. As much as one third of the apparent height of many of the ridges is due to these adjoining depressions rather than to real or positive height of the ridges themselves. With many of the ridges, such as certain of the long, drumlinoid ridges, these bordering depressions are not evident. In such a case a very plastic till may have been moved towards the ridge, under pressure of overlying ice, from over a broad area rather than from only near the ridge. In addition, the ice probably was relatively much thicker during formation of such 'troughless' ridges than during construction of many of those with troughs, and thus able to exert more pressure.

A side of an ice-pressed ridge next to the ice would, upon withdrawal of the ice, seek an angle of repose dependent upon the grain size and water content of the material. The iceward slopes of the Alberta ridges are generally 12 to 25 degrees; this generally is less steep than the angle of repose for these typically clayey tills when dry, and steeper than for these materials when wet. The till evidently had dried somewhat before or during retreat of the ice. Where ice was present on one side only of an ice-pressed ridge, the slope of the distal side is less steep than that of the proximal, or iceward, side. While rising, apparently the ridge contained much water, which aided flowage and slumping of the till during its construction. This gave a gentle slope to the distal side where ice was not present to support the rising ridge. Water slowly drained from the ridge as time passed, and, when retreat of the ice from the proximal side allowed slumping to take place there, the material was fairly dry. The resulting steeper angle of repose of the material gave a steep slope to the proximal side of the ridge. Also, in the dead-ice plateaux, water in contact with the inner slope of the rim ridges would have aided slumping during construction of these ridges.

Other Processes

Possible methods of formation of the forms under discussion fall into two main categories: those requiring presence of glacier ice and those in which presence of such ice is not necessary. These categories can be subdivided as follows.

1. Glacier ice present
 - a. erosional processes
 - (i) glacier erosion
 - (ii) meltwater erosion

- b. depositional processes
 - (i) from ice surface
 - (ii) from within ice
 - (iii) from beneath ice
- 2. Glacier ice not present
 - a. in pre-glacial time
 - b. in post-glacial time
 - (i) depositional processes
 - (ii) erosional processes
 - (iii) constructional processes
 - (iv) periglacial processes.

Formation through deposition from beneath glacier ice is the ice-pressing process (1b, iii) discussed above.

Erosion of pre-existing material by a glacier (1a, i) or its meltwater (1a, ii) could not produce the observed forms or patterns of the various plateaux and esker ridges, nor has it previously been suggested as a possible method; hence it is not discussed further.

The depositional methods with presence of glacier ice afford more scope for theories to explain the observed features. With such methods, deposition of material from the ice surface (1b, i) or from within the ice (1b, ii) apparently would require holes and crevasses in the ice that reach the ice surface, though not necessarily its base, whereas deposition from below the ice (1b, iii) could take place with openings in the base of the ice that either do or do not reach the surface. Deposition of material from at or near the surface of the ice-sheet is the method suggested by Gravenor (1955, pp. 476 to 478).

Hoppe (1952, pp. 5 to 8) discussed these various possible methods of formation in relation to rim ridges of moraine plateaux and to other moraine ridges, and discarded the first two methods as not able to explain the features he had observed. His summary of his arguments is given in the appendix (p. 37). The third method is the ice-pressing process. The till of the ridges in Alberta appears to contain more clay than does the till of similar ridges described by Hoppe.

Formation of the ridges without presence of glacier ice (2) must be post-glacial as subsequent glaciers undoubtedly would have destroyed any such features produced in pre-glacial time. Of the possible post-glacial processes (2b), deposition by wind or water could not have produced the observed pattern, composition, and form of the various ridges. Again, as Henderson shows, erosional processes can not be accepted. Henderson

(1952), the chief advocate of the two remaining possible processes, constructional (2b, iii) and periglacial (2b, iv), for building of the plains plateaux, states:

Of the several theories which have been proposed to account for such mounds only two are considered as capable of explaining those in the Watino area. The mounds seem too symmetrical to be interpreted as erosion remnants. They can hardly be considered as products of glacial deposition since other expectable associated features are lacking and it is difficult to conceive the mechanism by which they might have been built. The two processes which seem to explain them most adequately are: (1) local upheaval of fluid material induced by freezing of a thawed layer over a frozen substratum and (2) formation of a polygonal system of vertical ice wedges which grew in place.

Henderson apparently did not consider the possibility of material being pressed up from beneath adjoining glacier ice rather than being deposited from the ice itself, which method could explain the lack of "other expectable associated features" of glacial deposition. He discussed the process of local upheaval of fluid material which produces forms such as 'mud volcanos' and 'pingos' and concluded that it is not adequate in itself to explain the pattern and shape of the mounds in the Watino area. He favours the second or periglacial origin by ice wedging, combined with some local upheaval of plastic till, and described the process as follows:

Polygonal ground originates when frozen sediments contract and rupture under tension. Water enters the cracks thus formed, freezes and forces the walls of the cracks apart. Later further shrinkage reopens the cracks and the process is repeated. Water migrates to the growing ice-wedges through silts or clays (fine-grained sediments favor their growth) by capillary action. The wedges exert considerable lateral pressure and frequently cause pronounced bulging and raising of the material within the polygon. Though this seems to be a major mechanism involved in building the mounds, some local upheaval of plastic till probably took place to increase their bulk. This local upheaval would take place where bulging had established areas of weakness about the polygon centers. Freezing of thawed material lying over permafrost would generate pressure to cause this movement. An area of negative pressure, such as tends to form under arched materials, creates a favorable place for growth of an ice lens. Subsequent melting of this lens would leave on top of the mound a central depression.

Henderson also pointed out that the melting of the large ice-wedges would considerably accentuate the relief of the mounds, a very important factor. The writer believes that such ice wedging even by itself, without local upheaval of fluid material, could produce many of the smaller mounds. This is certainly a possible process of formation of the mounds described by Henderson, and would explain the apparent hexagonal outline of many of the plains plateaux. In particular the writer has examined one markedly hexagonal feature (SE $\frac{1}{4}$, sec. 8, tp. 18, rge. 27, W4th mer.) that has a total diameter of 650 feet, a height of 4 feet, and a central depression some 550 feet in diameter, and considers that it formed by a process similar to that described by Henderson. This process cannot, however, explain suitably the formation of large moraine plateaux, with their rim ridges, or

the till-cored esker ridges. The similarities of the plains plateaux and moraine plateaux suggest that both types formed in much the same manner.

Altogether, processes without presence of glacier ice are inadequate to explain formation of all the various forms described in the foregoing. It also appears that, of the processes of formation requiring presence of glacier ice, pressing of material from beneath ice into contiguous holes or crevasses is the only process that adequately explains the origin of many of the large forms (Appendix, p. 37).

APPLICATIONS OF THE ICE-PRESSING THEORY

Rim, Moraine, and Plains Ridges

Rim ridges of the plains plateaux are generally lower than the corresponding ridges of the moraine plateaux. This probably is a result either of the ice being thin near these plateaux during their formation, or of the sub-ice material being largely frozen at the time, as there is generally a good supply of plastic till near these plateaux. Ice not more than 100 feet thick would have sufficed to raise these ridges to their present heights. The ice was probably thin during formation of the plains plateaux due to the glacier's remaining active and retaining movement until relatively thin over the fairly flat, unobstructed regions where ground moraine plains were laid down. Thicker ice was probably needed to give equivalent activity in the rough, hilly bedrock terrain where the hummocky moraine normally was deposited and moraine plateaux built. This continued activity of the ice delayed opening, on ground moraine plains, of the holes and crevasses necessary for formation of the ice-pressed ridges until late in the deglaciation. Depressions between or bordering the plains plateaux are less noticeable than with the moraine plateaux. This is due not only to the rather small amounts of till that were moved, but also probably to a fairly uniform settling of the ice in the areas between the plateaux, which squeezed till towards the rim ridges from beneath broad expanses of ice and over relatively long distances.

The low point on the surface of the till in the central depression of a plains-type plateau normally is about half as high, above the general level of the ground moraine, as is the rim ridge (Figure 3). In many of the till plains this low point may represent the original height of the plain before the rim ridges were pressed up. In most cases, however, if the original till plain had been this high, more till would have had to be pressed from the inter-plateaux areas, to lower them to their present levels, than is in the rim ridges. It is probable that much of the till in the central depression flowed or slumped into it from the rim ridges, and that the low point on the till surface is above the earlier general level of the till plain.

The plains plateaux occur typically in large groups or fields (Plate VIII), and each individual plateau commonly has a faint hexagonal outline. Evidently where conditions were right for formation of a single such plateau, similar conditions tended to exist over a broad area and encouraged construction of many such plateaux. If the holes in which the plains plateaux were constructed began as intersections of crevasses or joints, which represented fractures or strains that occurred while the ice was yet moving, this would largely explain the remarkable linear arrangement of many of the plateaux in certain fields. In addition, if there were three suitably arranged intersecting sets of fractures, the holes would tend to receive a hexagonal outline as enlargement by calving or other processes proceeded, which would give a hexagonal outline to the plateaux formed in such holes.

The construction of the plains and moraine ridges took place in a similar manner to the construction of the rim ridges, but in long crevasses or tunnels in the ice, rather than in holes. Most of these ridges, particularly the moraine ridges, probably formed in open air crevasses but some may have formed in tunnels at the base of the ice.

Till and Till-Cored Esker Ridges

The till and till-cored esker ridges were constructed by a process similar to that which built the moraine ridges, except that most of them formed in tunnels at the base of the ice rather than in open air crevasses, and most of them were strongly affected by flowing water. In addition, their generally greater length permitted more longitudinal change in conditions during their formation. These factors resulted in more variation along their length in height, width and composition than is shown by the other ice-pressed ridges. Thus such a ridge may consist entirely of till where esker stream erosion was too weak to rework the till being squeezed into the tunnel, but consist entirely of silt, sand and gravel where stream erosion was strong enough to rework all the till, or where no till was being squeezed into the tunnel. All variations between these extremes are found. This removal of till from beneath the ice adjoining the tunnels would account for the conspicuous troughs that flank one side or both of many of the esker ridges. The height of some of these ridges is more than 70 feet. The thickness of ice that is needed to construct such a ridge by the ice-pressing process would normally cause ice flow near the base of the ice-sheet. This may indicate that a strong esker stream can keep open a tunnel in the base of ice that is thick enough to prevent the opening of crevasses from the surface to the base of the ice, or to close them if they should open.

Minor Moraine Ridges

The ice-pressing process could form minor moraine ridges in crevasses lying between active and dead ice along the glacier margin or around nunataks, or between belts of stagnant ice that run parallel to the glacier margin and which mark former active ice-stagnant ice contacts. For these ridges material would be pressed in from both sides of a crevasse, and such ridges would be built in the same manner as the other ice-pressed till ridges. Such small moraines have not been studied in detail.

Drumlinoid Ridges

Most of the drumlins, and other ice-flow or long drumlinoid ridges, on the prairies appear to have formed through the destructional or erosional process of glacier remoulding of earlier deposits, particularly morainal knobs (Gravenor, 1953). However, it appears that some of the long, low, drumlinoid ridges on the prairies were built by a type of ice-pressing process. A somewhat similar method was suggested by Dyson (1952) for fluted moraine surfaces formed near the terminal parts of valley glaciers. Dyson (p. 208) summarized the process as follows:

If unfrozen drift underneath terminal portions of temperate glaciers is saturated with water which descends from the surface or forms by pressure-melting at that depth. Under wet conditions the debris possesses a plasticity which presumably would enable it to conform, under the weight of overlying ice, to irregularities in the undersurface of the glacier.

He pointed out (p. 209):

In Glacier National Park the largest and most pronounced ridges occur on moraine which contains a relatively high proportion of rock flour, although ridges are present in all types of morainic material.

He further remarked on the absence of such ridges on bedrock surfaces, where they would be expected if deposited directly from the ice, and he concluded (p. 210): "It is possible that the ridges owe their origin to more than one of the foregoing processes [direct deposition from the ice, erosion of moraine surface, and squeezing debris into tunnel] although it would appear that squeezing of material into the tunnel by weight of the ice is most important." The ice-pressing process is not unlike the commonly suggested plastering-on (constructional or depositional) method of drumlinoid ridge formation. However, in this plastering-on process it has generally been accepted that the material in the ridge was added directly from the overriding ice, rather than from just beneath it as is assumed for the ice-pressing process. A rather large amount of till is present in these ridges. That this till did not come only from the ice that passed directly over the ridge is shown by the general lack of depressions along the strike of the ridges, beyond their either stoss or lee ends. Thus the material in a ridge

must have come not only from along its strike but also have moved towards it from its sides. Actively flowing ice could not have deposited material into the ridges from any part of the glacier other than that directly over-riding the ridge. The only process that could have moved the necessary till towards these ridges from their sides is the ice-pressing process. Under this process till would be squeezed from all directions towards the rising ridge, fairly uniformly from beneath a broad expanse of the ice. The ice responsible for building these ridges undoubtedly was still actively moving at the time (Dyson, 1952, p. 210). This may indicate that, under exceptional circumstances, other types of ice-pressed ridge can also be built with active, rather than dead, ice.

CENTRAL AREAS OF DEAD-ICE PLATEAUX

The normal dead-ice plateau consists mostly of a flat-topped, central filling (Figures 1, 3, 5), composed chiefly of silt with some clay and sand, and characteristically free of stones. The central fillings are associated with the rim ridges of the dead-ice plateaux, but are distinct in composition and method of formation. As Hoppe stated (1952, p. 8):

Studies of the ground indicate that the moraine plateaus form an element distinctly separate from that of the rim ridges. This often becomes evident, as there exists a well developed angle between the rim ridges and the plateaus. Considerable differences may be found in the consistency of the till.

If there is no central filling of water-deposited sediments a 'plateau' consists only of a circular rim ridge and looks like a doughnut (Plates VIII, X). Often the filling reaches the crest of the rim ridge and a true flat-surfaced plateau is the result (Figure 3 A), but more commonly the filling is incomplete and there is a broad depression a foot or two feet deep (Figure 3 B). The beds of silt or other materials tend to be horizontal except where they overlap and rise gently upon the inner slopes of the rim ridges.

The central filling is typically more complex in a moraine plateau (Figure 1) than in a plains plateau, probably due to greater variation in environment during its deposition. The water-deposited sediments consist of gravel, sand, silt and clay, any or all of which may be present several times, though in no set order. Here and there the stratified material includes beds or lenses of till. Both silt and clay, which in some plateaux are varved, are more common than sand, which in turn is more common than gravel. Clay is the most common surface material of the plateaux. Typically the deposits are of quiet water types, and ice-rafted stones are rare. The beds away from the margins of the plateaux were little deformed either during or subsequent to deposition.

Knobs and kettles of ordinary hummocky moraine, similar to those outside the plateaux, are thought to continue under the central parts of the moraine plateaux; in some places these till hills reach the surface or even rise above it. Occasionally they form much of the surface. This last condition appears to be common with the plateaux described by Hoppe (1952). The central deposits may similarly bury moraine and rim ridges.

The central area of a moraine plateau is flat and resembles a small lake plain where the surface material is sand, silt or clay; but it is gently rolling or undulating where the surface is till. Shallow kettles, produced by melting of ice-blocks that were buried in the till or lake deposits, can occur in any of the plateaux.

The relative time of construction of the rim ridges and deposition of the water-laid sediments is not known. As the central fillings overlap on the low, inward slopes of the rim ridges it would appear that the ridges formed

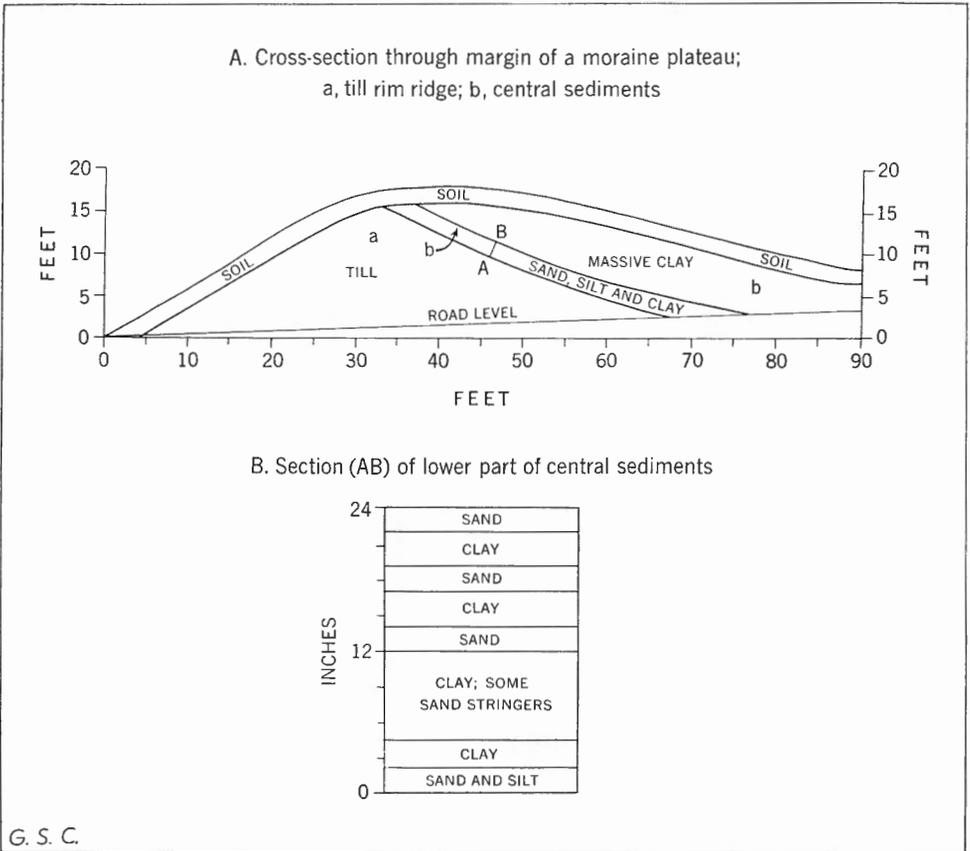


Figure 5. Sections through edge of a moraine plateau (drawn after road-cut in N. $\frac{1}{2}$, sec. 36, tp. 35, rge. 21, W.4th mer.).

first. The fact that these till ridges would also make good, impermeable shores for the water ponded in the holes would seem to strengthen this view. The slight rise (Figure 5) of the beds near the rim ridges may be original with their deposition, or it may represent minor, late rising of the ridges after deposition. If deposition of the sediments and rise of the ridges occurred simultaneously there should be more mixing, along the contacts, of the water-laid sediments and inner parts of the ridges, rather than the sharp breaks that are normally present. In addition the inner slopes of the rim ridges might be steeper as the central sediments would tend to hold up the margins of the ridges. In some places, however, the sediments were deposited before the rim ridges were fully raised, as is shown by some ridges (Plates II, III) that pressed upwards into the sediments and folded them strongly to correspond with the shapes of the ridges.

Stream-flow over, or perhaps beneath, the ice and probably from a long distance, carried most of the sediments into the central parts of the moraine plateaux. The sediments in the plains plateaux probably had a more local origin. The gravel beds that are here and there present represent either deltas of these streams or deposits of the many rivulets issuing from the immediately adjoining ice at periods of maximum melting. In the latter case the gravel beds could be extensive. Slow slumping from the surface of the nearby ice or local ice advances may have formed many of the till beds and lenses.¹ Another possible origin of such local till lenses is grounding and subsequent melting of icebergs, but the rarity of ice-rafted stones in the fine sediment would not seem to denote large-scale calving of such icebergs into the ponds. In addition the sediments below these till lenses generally are little deformed. In general, the sediments were deposited slowly, there was little current or wave action in the ponds, and the nearby ice was melting slowly.

The varved silt and clay give some indication of the rate at which the sediments of the central filling of a moraine plateau were deposited. As many as 20 varves were observed in one place, the individual varves were up to 5 inches thick, and there is no reason to assume that the varves are anything else but annual. When the other sediments are included, the time for building of a central part of a moraine plateau can be measured in tens of years and may have extended for several hundred years in some instances. Relatively long times for their construction are also indicated by quiet-water types of sediments commonly present, which would typically be deposited slowly. The time required for deposition of the central fillings of the plains plateaux was undoubtedly much less, perhaps being only a few years or even only part of a year.

¹Hartshorn (1958) describes in detail a process somewhat similar to this slumping for formation of till lenses in stratified material in Massachusetts. He terms the till deposited in this manner as 'flowtill'.

SIGNIFICANCE OF THE ICE-PRESSED FORMS

The ice-pressed forms indicate the importance of ice stagnation during the last deglaciation of southern and central Alberta. Such stagnation might have been expected to some extent, as the ice-sheet in the region was enclosed on the west by the Rocky Mountains and Foothills, on the south by the Milk River Ridge and other high land, and on the east and north by the main mass of the glacier. Thus except for some loss of ice to the southeast during late phases of the deglaciation, the chief factor in dissipation of the ice was melting in place and only little glacier movement was possible.

In addition the ice-pressed forms tell much about formation of the large hummocky moraines on the prairies. The numerous ice-pressed forms present in most of the moraines indicate that these are largely dead-ice moraines. They display the characteristic features of such moraines, such as irregular topography devoid of lineation or orientation. They consist mostly of thousands of irregularly scattered, small, round hills, interspersed with numerous kettles and other undrained depressions, which commonly contain ponds or swamps. Scattered among these round hills are examples of certain of the ice-pressed forms described in the foregoing.

The large hummocky moraines in southern and central Alberta, with their numerous ice-pressed forms, are largely dead-ice moraines. The locations of such moraines were generally not determined by equilibrium between advance and melting of the glacier, but by pre-existing topography. Typically they are found on high land, where resistant bedrock has remained above the general level of the surrounding country, but a hummocky moraine commonly has a wide range of elevation. A large moraine, such as the Buffalo Lake moraine system, commonly connects and includes several of these high areas. In addition there generally are few spillways, and little outwash or other stratified material associated with such moraines (Johnston and Wickenden, 1931, p. 40; Bretz, 1943, p. 35), excluding the stratified material contained within the ice-pressed forms themselves. This is contrary to what would be expected if readvance of the ice-sheet, or a state of equilibrium between advance and melting, had formed the moraines. The absence of outwash is particularly noteworthy in dead-ice moraine, a type of moraine that might be expected to be composed largely of stratified material.

The simplest explanation for these features is that the moraines started to form in areas well back from the margin of the ice, in places where the ice-sheet had become stagnant over high ground. Continued dissipation of the stagnant ice through melting induced nearby active ice towards the stagnant-ice-active-ice contact, thus bringing in fresh material. As the ice-surface lowered the moraines continued to grow, but on lower ground,

and thus became more extensive. The high, earlier parts of the moraines in time became ice-free. This is one process by which the till necessary for the morainal knobs could be brought into the area.

Escaping meltwater would either flow over the glacier surface or, more likely, flow or seep beneath the surrounding active ice. If it carved subglacial channels these could later become filled with drift as water-flow lessened or ceased, as the ice became stagnant, or as conditions under the active ice changed. This would produce mainly knob-and-kettle moraine. If the escaping water had formed open air channels, perhaps even cutting into the bedrock, such channels would be reinvaded by the nearby active ice once stream-flow had ceased or lessened, and drift would be deposited in the channels. Such channels, carved into bedrock and drift but now largely covered with the knobs and kettles of hummocky moraine, are found in the Buffalo Lake moraine system and other hummocky moraines in Alberta. They may be a mile wide and many miles long in extreme cases, and the morainal knobs in them may be 50 to 100 feet high, but most of the channels are much smaller. They commonly are marked by strings of lakes that are generally larger than the ordinary kettle lakes of hummocky moraine. Cutting of many of these valleys was associated with construction of these hummocky moraines. The valleys carried meltwater from the moraine areas to the margin of the ice-sheet. Some of the large channels, however, were carved by major rivers, such as the Red Deer in Alberta, pouring onto the stagnant or sluggishly moving ice-sheet to flow away beneath or through the ice. These various valleys include channels somewhat similar to the stream trench systems described by Gravenor and Bayrock (1956).

Where hummocky moraines formed some distance within the ice-sheet, melting undoubtedly was slow and the amount of meltwater present at any time was small. Only slow run-off and seepage, perhaps aided by evaporation, were required to remove this meltwater. It thus was not able to wash and sort the material of the moraines to any marked degree. This and the fact that most of the material in the moraines came from near the base of the ice and was a clayey till explain the general lack of stratified material in the drift of the moraines.

Much of the till of the moraines may have been squeezed into its final position by being pressed upward by weight of ice into numerous adjoining holes and crevasses as the stagnant ice became rotten. If so, many of the small, round mounds in these moraines (Plates I, IX, XI, XII, XIII) are ice-pressed forms, and are composed of basal till rather than drift carried in or on the glacier. Certain rare bedrock knobs with a thin till cover may have formed in a somewhat similar manner. Moraines built in this way would not necessarily require till to be brought in from outside the

moraine area, or necessarily represent a thickening of drift over that found in adjacent ground moraine plains. For instance, a moraine consisting of knobs 50 feet high may have formed from a till layer perhaps 20 feet thick, and the knobs would only rise some 30 or 35 feet above the 'original' surface. By such a method a rugged moraine could be formed entirely within dead ice.

The large moraines of central and southern Alberta that were thus built within stagnant ice and generally on high ground, do not necessarily represent former margins of the ice-sheet, though they could have formed in marginal positions. They may have been constructed during halts in the downmelting, during rejuvenation and subsequent thickenings of the ice-sheet, or even during normal lowering of the ice-surface. Thus for example, a Cary readvance of the Wisconsin stage may be represented in these moraines by hummocky moraine at a certain elevation, rather than by a moraine marking the ice-margin of the maximum of this readvance. If this is so, correlation between such moraines in any broad region should not be made solely by locations of the moraines but chiefly by altitudes. Thus a certain sub-stage of glacier advance or retreat would be represented by moraines at a certain altitude. A moraine lying a short distance to the southwest of another on the prairies and in the direction from which the ice retreated, but at a lower altitude, may be younger than the other. As most of the large hummocky moraine systems have a wide range in altitude, and as their construction generally took a long time, it is not only possible but very likely that construction of two, three, or even four, roughly parallel, large moraines would overlap in time. Relative times of formation of sectors of dead-ice moraines built in this manner or even of various parts of the same moraine can thus be roughly estimated by their elevations.

CONCLUSIONS

The various ridges described in this report were formed through pressing or squeezing of sub-ice material into nearby tunnels, holes and crevasses in the ice-sheet.

Ice stagnation was widespread during retreat of the last glacier from southern and central Alberta. This stagnation took place largely in broad, marginal belts of the ice-sheet, and also where the ice was thin over high land. The large amount of stagnation in the ice-sheet at that time has not received general recognition.

The ice-pressing process of formation for the various forms indicates that much of the sub-glacier material was not frozen during the end stages of deglaciation. This may have been due partly to the ice-sheet having melted largely in place due to warming climate rather than having dissipated through flow to other regions.

Ice-Pressed Drift Forms and Associated Deposits in Alberta

The ice-pressed forms are common and significant drift features in Alberta, whose importance generally has not been recognized. They are good indicators of conditions during deglaciation. They are to be expected in any hummocky moraine on the prairies, or in any area where there was ice stagnation plus drift or bedrock of a type that could have been squeezed into nearby holes and crevasses in the ice by weight of overlying ice.

The moraines of southern and central Alberta do not necessarily represent former ice-sheet margins, but may rather represent changes in the rate of, or even halts in, the lowering of the surface of the ice-sheet. Many of these moraines should be correlated by altitude rather than by position.

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APPENDIX

(Quotation from Hoppe, 1952, pp. 5-6)

“Already a study of the anaglyph should make it clear that the rim ridges as well as other moraine ridges—ridges may also lie between dead-ice hollows on both sides—must have been formed by a transportation of debris outward from the dead-ice hollows or from the ice that was originally deposited in them. The question then arises how the transportation occurred? Three alternatives seem plausible:

1. the till has fallen down from or slid off the surfaces of ice blocks remaining in the depressions,
2. the bottom layers of these ice blocks contained moraine which during the melting process was deposited along the edges of the blocks,
3. the till below (not as in 2. within) the ice blocks has because of the weight or movement of these been pressed towards the sides.

“Alternative No. 2 seems to be the least probable solution to the problem. If moraine ridges surround dead-ice hollows of, say, a depth of 15 m, this alternative would mean that the ice at least up to this level once contained thick till beds. Then there would, however, be reason to expect a relatively thick till layer to cover also the bottom of the dead-ice hollow as well, but there are dead-ice depressions which are surrounded even by moraine ridges, though the bottom consists to a great extent of bedrock. Alternative No. 2 would then have to be supplemented with the assumption that the till-containing bottom layer of the ice had been pressed to the sides and upwards by the above-lying ice. This explanation, however, postulates a far greater plasticity of the ice than is compatible with reality.

“Alternatives 1 and 3, the No. 1 alternative corresponding most closely to the general interpretation of the formation of the hummocky moraine terrain, require, in order to be more closely discussed, a thorough investigation of the moraine ridge. Diggings made have proven that the till may vary considerably. On fairly rare occasions—and then only on the side facing the moraine plateaus—it consists almost exclusively of boulders. However, as a rule the finer grain sizes are well represented. The till would then most adequately be classified as sandy with a normal amount of boulders. In other words, the till has not been washed, as is at least quite often the case with the superglacial moraine. This provides an argument against alternative No. 1, even if it is not binding. Furthermore, the till is often quite solidly packed, thus corresponding more closely to what

is generally termed basal till. Therefore the theory cannot be maintained that the moraine ridges may have been caused by the falling of superglacial moraine into crevasses. If such were the case, the consistency of the moraine ridges would be loose. The suggestion may possibly be made that the superglacial moraine instead has been carried from the ice down toward the moraine plateaus by means of some slow movement. In that case no ridges would have resulted but rather flat formations. Against this latter alternative we also have the circumstance that the dead-ice hollows on all sides are surrounded by often quite evenly protruding ridges. The surface of disintegrating ice should more or less preserve the original inclination of the glacier. The transportation of the till would then have become concentrated to the distal, i.e. the lowest part of the ice block.

“A study of the orientation of pebbles and cobbles in the moraine ridges furnished more arguments against their being interpreted as falling-in phenomena. In this connection it should be pointed out first of all that in the majority of soils (sediments in a restricted sense, tills, flow earth) well developed maxima for certain defined positions are found, namely parallel to and at right angles to the main motional direction at the time of the deposition of the soils. Two determinations in rim ridges within the Veiki area gave as a result that the pebbles and cobbles showed a marked orientation maximum at right angles to the ridges. This orientation cannot, however, considering the fact that the moraine ridges may form a continuous circle around a moraine plateau, be regarded as assuming a position transversal to the movement that has formed the ridges. It must be characterized as a parallel position. The movement must, in other words, have emanated from the dead-ice hollows. The possibility that it started from the moraine plateaus may be eliminated for the reason that the ridges are sometimes surrounded by dead-ice hollows on all sides. If the ridges were caused by the falling-in of moraine, such an orientation would hardly have been expected. A more or less total absence of orientation would then have been most likely.

“The above discussion has eliminated alternatives 1 and 2 as less probable explanations of the formation of the moraine ridges, leaving only alternative 3 for the interpretation of their formation. The ridges should thus have been formed, because the till below the ice blocks from the weight of these or due to their movement was pressed toward the sides.”

