M. J. J. Bik *
Ottawa

THE ORIGIN AND AGE OF THE PRAIRIE MOUNDS OF SOUTHERN ALBERTA, CANADA

Abstract

The distribution of prairie mounds in the Foremost-Cypress Hills area in particular and in the area between the Cypress Hills and Edmonton in general, is described and analyzed. Earlier hypotheses of super- or subglacial origin of the prairie mounds do not account for the breaches of the mound rim and cannot explain their occurrence on both glacial and proglacial deposits. A periglacial mechanism of formation is more likely.

In aspect of form the prairie mounds are similar to, but not identical with the collapsed pingos of western Europe. However, there is an excess of material in the former. The low Atterberg limits of the till of the mounds of the Foremost-Cypress Hills area, and the high content in montmorillonite of the clay fraction suggest that subsurface displacement of this material under supersaturated conditions is probable.

The frost-heave potential of the till of the mounds is substantial and ice-lenses of considerable thickness could have formed in it. The parent relief of the mound fields was probably a rolling till plain or lacustrine plain with low internal relief. Under periglacial climatic conditions, ice segregation would start earlier and continue longer below the depressions than beneath the convexities of such a relief, if the till is saturated with water. Below the downwards advancing freezing front supersaturation occurs only when ice segregation has ceased; it ensues earlier under the convexities than beneath the depressions of the parent relief. The „eruption'' and subsurface movement of deposits towards the mound sites is explained from the formation of „closed systems'' of supersaturated till between an arched permafrost front above and a remnant permafrost layer or a hardrock surface below.

The majority of prairie mounds occurs in belts that regionally run parallel to proglacial lacustrine deposits; these belts appear to be located in the shore-zones of former proglacial lakes. In the Foremost-Cypress Hills area the deposits of a proglacial lake along the margin of which mound fields formed, are less than 20,600 years old. The minimal age of the prairie mounds was determined to be 12,500 years.

INTRODUCTION

The prairie mound (Gravenor, 1955) — a low, shield-like mound with a central depression — is a common landform in the glacial landscapes of Alberta and Saskatchewan. Several hypotheses have been advanced to explain its origin. Henderson (1952, 1959) concluded on a periglacial mode of genesis; the central de-

* Department of Energy, Mines and Resources, Geological Survey of Canada, Ottawa.

pression of the mound would result from the melting of an ice core, the mound itself from lateral squeeze within giant ice-wedge polygons. Gravenor (1955) proposed a superglacial origin; the mounds would result from the accumulation of debris in pits in the surface of a stagnant ice-body, the central depression from the trapping of an ice-core below the debris and from relief inversion during continued melting of the ice between the pits. Stalker (1960a) assumed a subglacial origin; the mounds would result from the squeezing of till into basal cavities of a stagnant ice mass. Mathews (1963) suggested an origin in the nature of the modern arctic pingos; however, the mounds would result from a combination of subsurficial movement of sediment and the segregation of an ice-core. Clayton (1964, 1967) produced evidence from the stagnant zone of present-day glaciers to support the hypothesis of superglacial origin. Bik (1967) concluded that certain physical properties of the till, on which prairie mounds occur in southern Alberta, do not exclude the subsurficial movement of this material below permafrost.

Detailed stratigraphic observations were made of the deposits in the central depressions and on the outer slopes of some prairie mounds in southern Alberta; the prior form of the prairie mounds was reconstructed (Bik, 1968).

This paper intends to discuss the regional distribution of the prairie mounds, and to review critically earlier hypotheses of origin. Evidence that supports the mode or origin suggested by Mathews (1963) is presented and the age of the prairie mounds of southern Alberta is discussed.

The field evidence was collected during the summers of 1965 and 1966, mainly in the Foremost-Cypress Hills area of southern Alberta; more general statements on the distribution of prairie mounds are based on field survey and air photo mapping of mounds between the Cypress Hills in the south and Edmonton in the north.

DISTRIBUTION OF THE MOUNDS IN THE FOREMOST-CYPRESS HILLS AREA

DEFINITION OF THE FORM

Not withstanding the regularity of its external form, the prairie mound has previously been described as a part of the often chaotic irregularity of landforms ascribed to the desintegration of stagnant ice. The mounds have been described with terms such as *rimmed kettles, rim-ridges, circular disintegration ridges, doughnuts, closed ridges, humpies* and *ice- block ridges* (Gravenor and Kupsch, 1959). Confusion easily results from the grouping of prairie mounds under any of these terms, which have been applied to a broader group of landforms. A stricter definition of the *prairie mound* is, therefore, proposed.

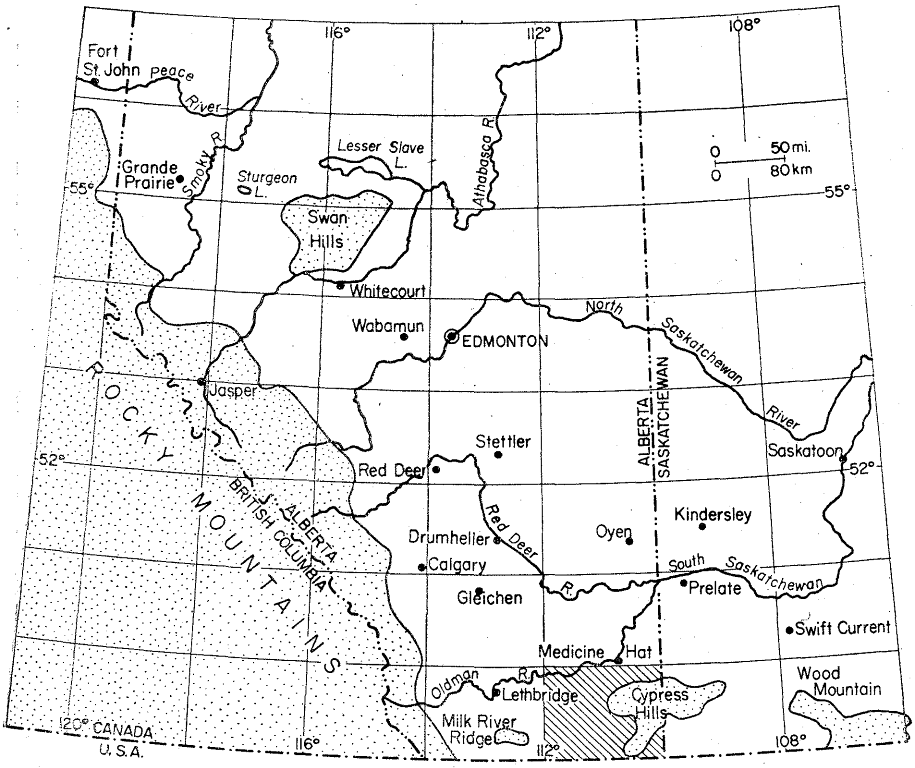


Fig. 1. Locations mentioned in the text. The hachured area coresponds with Fig. 3

The *prairie mound* is oval or round in plan, usually less than 600 feet (183 m) in diameter, and less than 30 feet (9 m) high. The center of the mound contains always one and infrequently several depressions. The floor of this depression may extend down to the level of the terrain adjoining the mound, but the relief difference between the highest point on the mound and the level of the depression floor commonly does not exceed 10 feet (3 m). The highest part of the mound is a ring wall or rim around the central depression. Both the external and internal slopes of the rim continue smoothly to the foot slopes and the depression floor. The mound-rim is breached, always at one and commonly at several places; the central depression of the mound may or may not be enclosed. Of the several breaches, commonly one, and rarely two, considerably exceed in size the remaining gaps of the rim. With exception of the area of the major breach in the rim, the external slopes of the prairie mound are convex. The perimeter of

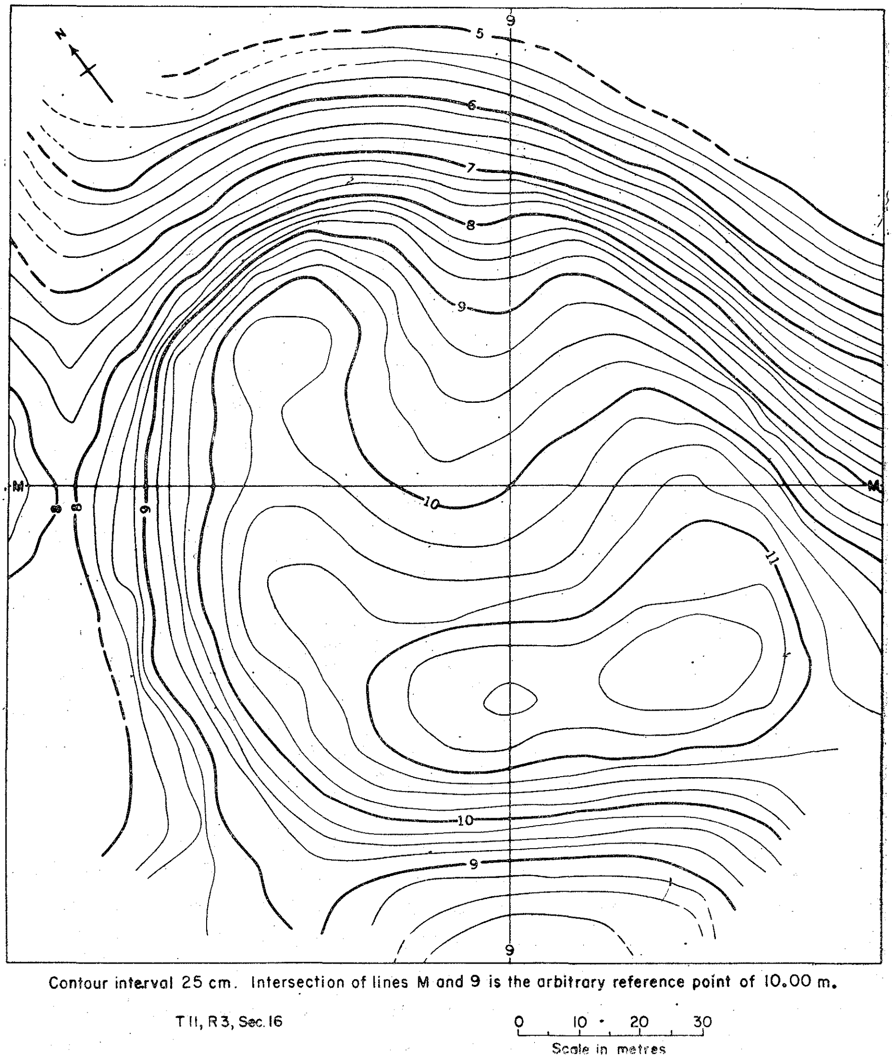


Fig. 2. Contour map of a prairie mound located approximately 5 miles south-southwest of Irvine, Alberta

elevation of the terrain seems to control the distribution of the fields, the mound-field belts are not contour belts in the strict sense, but cross these with a slight angle. The fields are associated with smooth, accumulative glacial and proglacial topography with little relief and gentle angle of regional slope, such as ground moraine plains, lacustrine plains, broad ridges, and broad valley floors.

(B) Small groups of mounds occur in the re-entrants of hilly topography of the Sweet Grass Hills and the Cypress Hills, and in poorly drained areas such as stream valleys, small lacustrine plains and other depresssions of irregular shape within hummocky moraine topography.

In altitude the occurrences of prairie mounds of the second group range from 2,900 feet (885 m) along Gros Ventre Creek to 3,900 feet (1,190 m) to the southwest of Eagle Butte. In contrast with the mound occurrences of group A, elevation does not seem to control the regional distribution of the scattered groups.

The elevation of the topographically upper margin of the main belt of mound fields is approximately 2,800 feet (854 m) in the east; it rises to 3,100 feet (945 m) southwest of the Peace Butte, and falls to 2,850 feet (869 m) near Pakowki. Westwards from here it rises gradually to 3,100 feet (945 m) near Conrad.

To the south and north of this main mound-field-zone, less clear belts occur (Fig. 3). Though located at higher and lower elevations than the main belt, they accord with it in the ascending or descending elevation trends.

CHARACTERISTICS OF THE MOUND FIELDS

The geomorphological setting of the mound fields of southern Alberta does not differ from other areas for which mound occurrences were described. The regional angle of slope of the terrain adjoining the mound fields commonly does not exceed 4° in southern Alberta.

Though mounds of similar size make up the individual fields, and there is a distinct difference of mound size between fields rather than between individual mounds of a particular field, their density does not vary between fields with mounds of differing size. Density ranges from 100—160 per square mile (40—62 per km^2) in fields of large mounds to 100—180 per square mile (40—70 per km^2) in fields with medium-sized or small mounds. With-

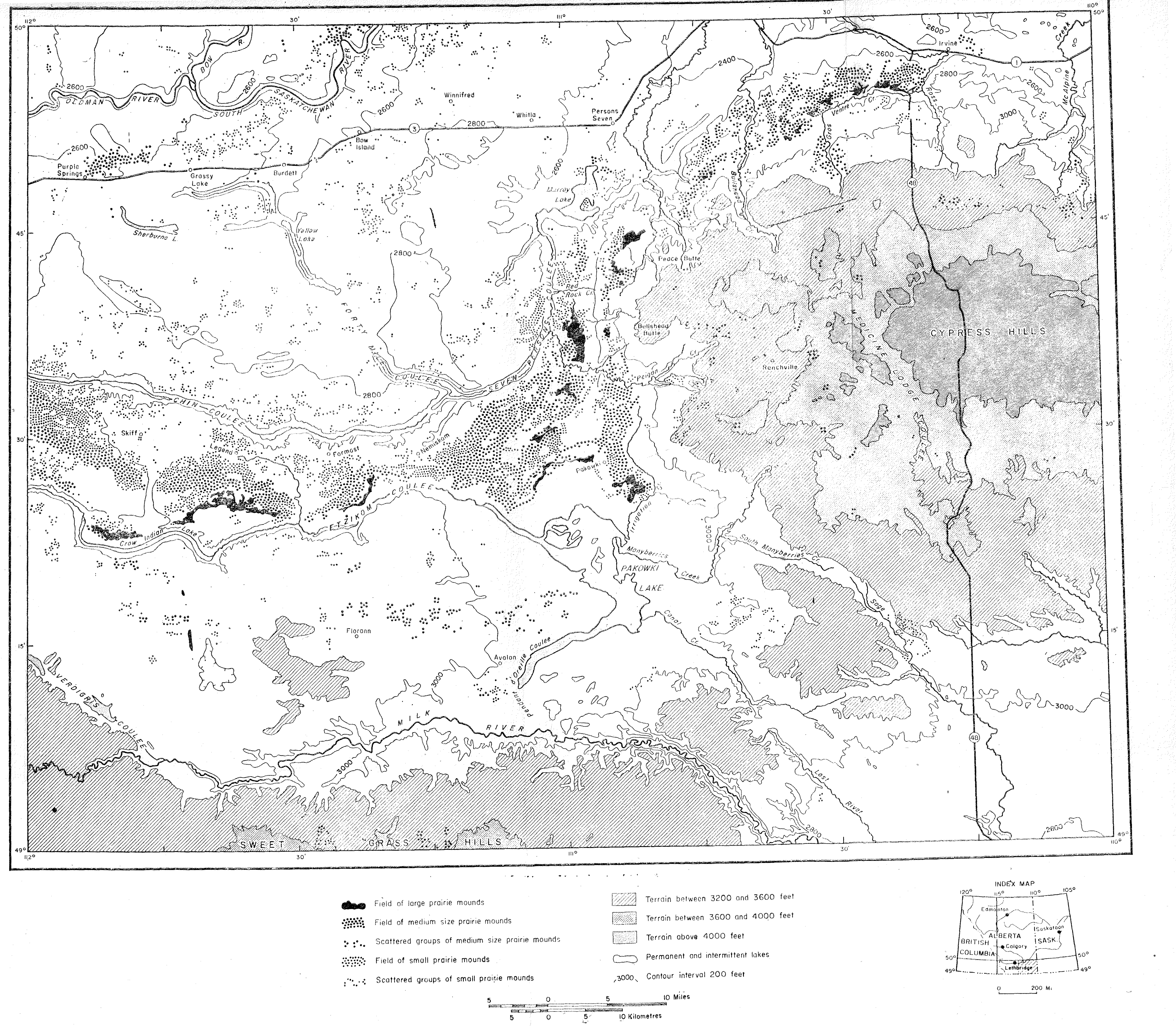


Fig. 3. Distribution of prairie mounds in the Foremost-Cypress Hills area

the mound is convex in plan; a crenulated perimeter is very uncommon. Prairie mounds occur commonly in fields, less commonly in groups of two to five and rarely single.

The prairie mound, thus defined, comprises all occurrences mentioned by Henderson (1952), Gravenor (1955), Stalker (1960a) and Bik (1968). Excepting a group of exceptionally large mounds (up to 1,500 feet, 460 m, in diameter, up to 40 feet, 12.2 m, in height) reported by Mathews (1963) from the Fort St. John area, British Columbia, the many thousands of smaller mounds of that area fit the definition. Next to the descriptive name of *prairie mound*, the mounds were also named *till* and *silt mounds* and *plains plateaux*. Plate 1 portrays a typical prairie mound, figure 2 the contours of a mound in southern Alberta.

MAPPING OF MOUND DISTRIBUTION

In an earlier paper (Bik, 1968) it was stated that the principal occurrence of prairie mounds in the Foremost-Cypress Hills area is in a belt composed of fields of prairie mounds. This belt has been traced via Lethbridge to the vicinity of Edmonton (Bik, 1967) and seems to continue even further to the northwest.

For the Foremost-Cypress Hills area all occurrences of prairie mounds that could be recognized on aerial photographs were mapped (Fig. 3). The mounds were subjectively subdivided according to size: large mounds, 500—600 feet (153—183 m) in diameter; medium size mounds 300—500 feet (92—153 m); small mounds up to 300 feet (92 m). Further criteria used in mapping were that for large mounds the central depression could be observed stereoscopically on air photos of 1 : 45,000 approximate scale; that for medium sized mounds the central depression could be recognized because of textural differences; that the outline of small mounds could be recognized from textural differences rather than in stereoscopic relief. Plate 2, 3 and 4 present low oblique aerial views of the three mapping units.

CHARACTERISTICS OF DISTRIBUTION

In the Foremost-Cypress Hills area the prairie mounds occur in two distribution patterns:

(A) Fields that contain almost exclusively prairie mounds. The fields form belts which are of limited vertical extent. Though in their fields the prairie mounds are randomly distributed rather than equidistant. Alignment occurs in some areas but this is not common.

The intermound depressions have a haphazard form, owed to the location and shape of the mounds within the fields. The drainage from these depressions may or may not integrate into small endoreic systems. Particularly in fields of large or of medium size mounds the drainage is not intergrated with present-day stream channels. Excess precipitation is removed by infiltration or evaporation in this semi-arid environment. Many intermittent and some permanent ponds occupy the intermound spaces. The water of the ponds and the soils of the depression floors are alkaline. Average precipitation amounts to 13 inches (330 mm) yearly on the plains surrounding the Cypress Hills; the latter receive approximately 18 inches (460 mm) yearly. Fields of small mounds generally drain into present-day exoreic and endoreic systems and intermound ponds are rare in those fields. The internal relief of the mound fields varies from up to 30 feet (9 m) for large mounds, to 5 feet (1.5 m) in fields of small mounds.

Occasionally, kettles and ponds and ice-marginal channels occur in the mound fields. The ponds and depressions are not of the rimmed type, the margins are commonly gently curved, contrasting with the irregular shape of the intermound depressions. These channels and depressions belong to the „normal" till plain morphology.

Fields of large and medium-sized mounds are commonly separated from the adjoining till and lacustrine plains by a narrow, marginal depression; the level of its floor accords to the average level of the intermound spaces. This marginal vale is well developed at the topographically upper margin of the mound fields; on aerial photographs it often clearly delineates this side. The outer margin of the vale is smooth and gently curved, the inner is as irregular as is common for the intermound depressions. Like these, the marginal vale has an undulating floor, broken by slope salients extending from the mound field. It frequently contains intermittent ponds and swampy vegetation. Finally, as is apparent from Figure 3, mounds of large size occur only in the principal mound-field-belt that traverses the Foremost-Cypress Hills area from east to west. Within this belt, the fields of large mounds are located near the topographically upper, or southern margin. To the north of Lake Pakowki the largest mounds mainly occur centrally in the area where three distinct zones together make up the mound-field-belt. Yet also here, the largest mounds occupy the highest terrain within the belt.

GEOMORPHOLOGICAL SETTING

Westgate (1964) described and mapped the surficial geology of the Foremost-Cypress Hills area. According to that author, the whole area, with exception of the summit surface of the Cypress Hills was glaciated during the Wisconsin Period. Westgate distinguishes five major stages in the deglaciation of the area; the oldest, greater than 54,000 radiocarbon years in age, during which the Cypress Hills rose as a nunatak above the ice; the youngest not less than 13,000 radiocarbon years old, during which a small area in the northwest quadrant of Figure 3 still retained a glacial cover, the southern limit coinciding with the northernmost prairie mound belt.

From the Cypress Hills in the east and the Sweet Grass Hills in the south the terrain descends gently towards the valley of the South Saskatchewan River in the north. The local relief on glacial accumulative and proglacial topography seldomly attains 50 feet (15 m). The monotony of this relief, however, is broken by „coulées", which are steepsided, flat bottomed valleys, up to a mile wide (1.6 km) and up to 200 feet deep (61 m) which traverse the area in easterly direction. West of the Cypress Hills, these valleys curve partly to the north, partly to the south. The valley floors are occupied by underfit streams and natural or man-made lakes. Westgate interpreted these valleys as glacial meltwater channels that carried glacial drainage towards the southeast and later to the northeast, when continental ice covered part of this area.

EARLIER INTERPRETATIONS OF THE MOUND-FIELD-BELTS

PREVIOUS INTERPRETATIONS

The main mound-field-belt of the Foremost-Cypress Hills area coincides with the belt of Etzikom End and Recessional moraines, as named by Westgate (1964, 1965). The location of this moraine is portrayed in Figure 4. The youngest end and recessional moraine, the Oldman System, also coincides with a belt of prairie mounds. Other belts of Figure 3, however, are not located over the outer limits of glacial advances distinguished by W e s t g a t e.

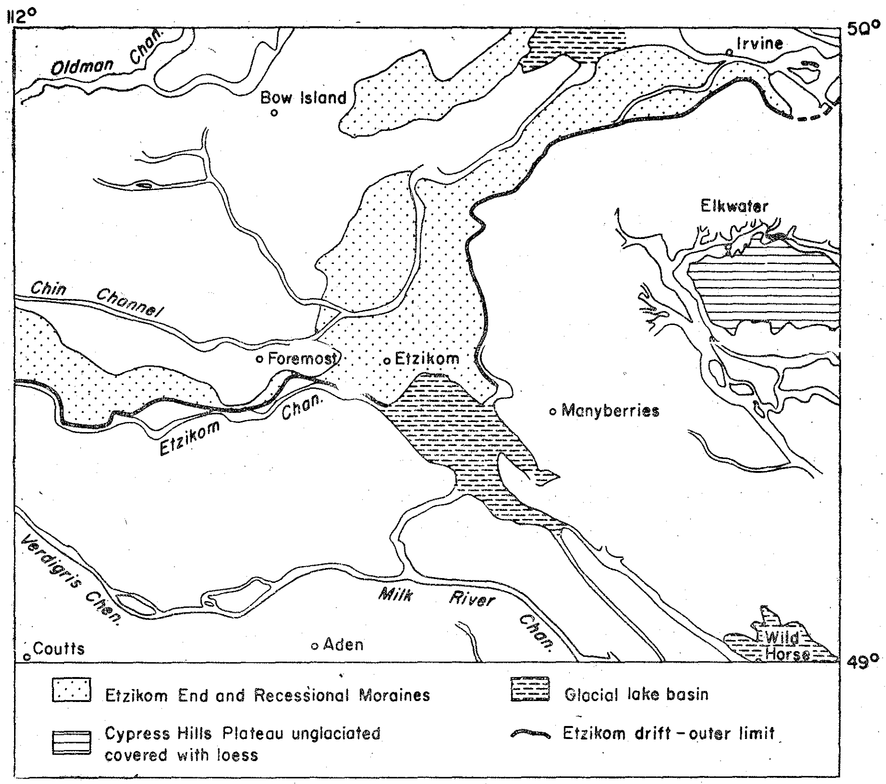


Fig. 4. Location of the Etzikom end- and recessional moraines (from W e s t g a t e, 1965)

The areas where fields of mounds of various size, as well as small groups of mounds that form belts occur, coincide or overlap with a variety of the mapping units of accumulative glacial and proglacial terrain that were defined by W e s t g a t e (1964). Though the area of Etzikom End and Recessional moraines to the south of the Chin Coulee and to the east of the Sevenpersons Coulee consists almost exclusively of prairie mound fields of varying size and a minor admixture of till plain and lacustrine plain, the mound fields themselves were mapped as: *ground moraine, hummocky* and *ridged end moraine, washboard moraine,* or *lacustrine sediments.*

The westward continuation of the main mound-field-belt (Bik, 1968) was mapped by Stalker (1962) as *hummocky moraine* for fields of large and medium size mounds and as *ground moraine* for fields of small prairie mounds.

The main mound-field-belt of Figure 3, an end moraine according to Westgate, is the same feature described as the Lethbridge End Moraine by Horberg (1952), which „marks a point of distinct readvance rather than a recessional halt. This relation between the drift sheets east and west of the Lethbridge Moraine is not apparent from area maps, but can be established from the stratigraphic evidence" (Horberg, p. 308). Westgate describes this feature in the Foremost-Cypress Hills area as a „broad, well-developed end moraine, at about 3,000 feet above sea-level, which marks the outer limit of the Etzikom Drift" (1965, p. 97). Located between two „coulées" that are up to a mile wide and average 200 feet in depth below the adjacent plains and which run parallel at approximately 6 miles (9.6 km) from each other, this „end moraine" seems more a „normal" interfluve. The plateau between the two „coulées" is not markedly higher than the elevation of the plateau to the south of Etzikom Coulee or the north of Chin Coulee.

Though the interpretation of the mound-field-belt as the Lethbridge moraine east of Lethbridge and Etzikom moraine in the Foremost-Cypress Hills area lacks morphographic evidence (as pointed out by Horberg, 1952) stratigraphic evidence gathered by Westgate (1965) confirmed the existence of at least two petrographically distinct till sheets, the younger one of which is thought to extend to the Etzikom Coulee.

The main mound-field-belt (Fig. 3) has also been interpreted as marking a retreat stage by Johnston and Wickenden (1931) and Bretz (1943).

USE OF THE END-MORAINE FOR THE GLACIAL LANSCAPES OF ALBERTA AND SASKATCHEWAN

Westgate's (1964) interpretation of the mound fields of the Foremost-Cypress Hills area as end moraine is not unusual when taken in the context of the earlier surficial geological literature for the Canadian Prairies. That author defined two types of end moraines, one in accordance with Flint's (1957, p. 131) definition, the other described as the „major end moraines (especially hummocky end moraine) formed along a wide marginal zone of the glacier, chiefly by stagnation of fractured, debris-clogged ice" (1964, p. 20). This obvious change in the meaning of the term *end moraine* as defined by Klebelsberg (1948), Woldstedt (1954), and Flint (1957) is foreshadowed in ealier interpretations of the glacial topography of the Canadian Prairies (Johnston and Wickenden, 1931; Bretz, 1943; Johnston *et al.*, 1948; Horberg. 1952).

Craig (1956, p. 47, 48), discussing belts of end moraine in the Drumheller area, Alberta, stated „that the deposition of this end moraine must be different than that generally ascribed to end and terminal moraines". „The width of the morainal masses and the monotonous similarity in appearance across them indicate that deposition was taking place over considerable areas at the same time, not at successive halts of a retreating ice-front." Similar views are expressed by Stalker (1960a, p. 34; 1960b p. 20—31), Christiansen (1956, p. 9—12), and Gravenor and Ellwood (1957, p. 12—17).

Gravenor and Kupsch (1959) also questioned earlier interpretations of „end-moraine" topography and indicated that much of the alignment of disintegration forms may actually be inherited from „live-ice" forms that underlie areas of disintegration — moraine topography.

The interpretation of the main prairie mound-field-belt in the Foremost-Cypress Hills area as *end moraine* is thus rather doubtful in the context of many recent publications on the origin of the broad tracts of hummocky moraine on the Canadian Prairies. Furthermore, whereas the prairie mound was frequently observed in other areas to occur among other landforms that together have been described as *hummocky moraine*, it occurs virtually exclusively as mound fields between Irvine and Lethbridge (Bik, 1967b), without the association of the usual other landforms such as moraine-plateaux, moraine ridges, knobs and kettles, and stream trenches, which landform association was described as *dead-ice, stagnant ice,* or *ice-disintegration* features by Craig (1956), Christiansen (1956), Bayrock (1957), Gravenor and Kupsch (1959), and Stalker (1960a, b). The interpretation of the mound belt as a *dead-ice* landform association is equally doubtful as forms other than prairie mounds do virtually not occur within the mound fields (See Plates 2, 3 and 4). Appreciation of the geomorphological significance of the mound-field-belts would follow from further research on the origin of the prairie mounds.

DISCUSSION OF HYPOTHESES FOR THE ORIGIN OF THE PRAIRIE MOUNDS

To date four hypotheses have been proposed for the origin of prairie mounds. Two of these require the presence of a stagnating ice mass over the present locations of the mounds (Gravenor, 1955; Stalker, 1960a). Clayton (1962, 1964, 1967) advanced further evidence in support of a glaciogenetic origin. Two hypotheses (Henderson, 1952, 1959; Mathews, 1963) propose an origin under periglacial climatic conditions.

GLACIOGENETIC HYPOTHESES OF ORIGIN

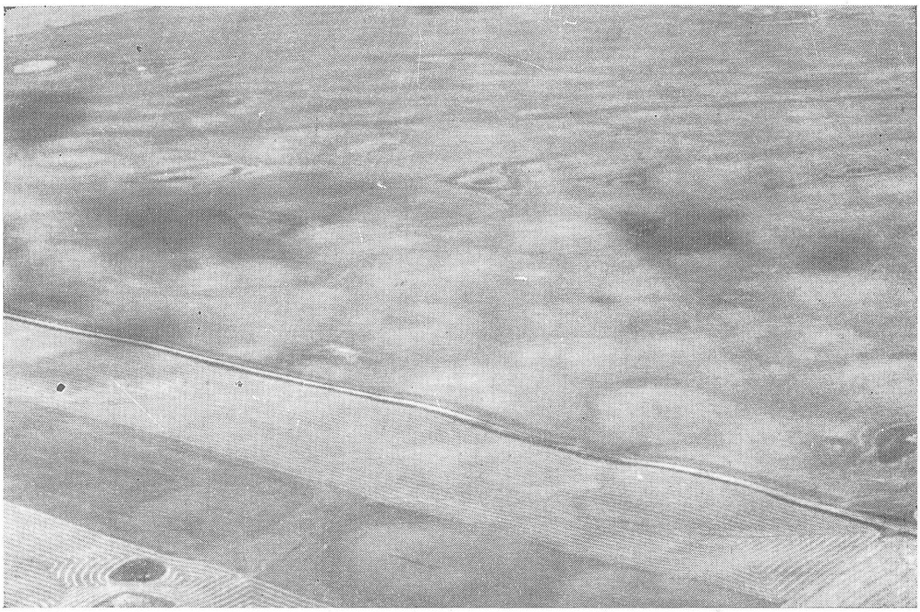
Superglacial origin

Gravenor (1955) proposed the trapping of surface debris in pits on the surface of a stagnating ice-mass, relief inversion through differential melting, and ultimate melting of an ice-core trapped beneath the debris as the origin of prairie mounds. This hypothesis was supported with descriptions by Russell (1904, p. 109—130) and Tarr and Martin (1914, ch. XI) of some Alaskan glaciers. According to the latter authors the debris cover of the tongue area is derived from the valley walls that contain the glacier. Larger glaciers would be less liable to the moraine-covered condition as the valley walls would shed relatively less material per unit area of glacier surface. Though this observation would make the presence of a substantial debris cover on the continental ice unlikely, Clayton (1967) stated that, though much surface debris on the piedmont glaciers of Alaska does originate from mountain slopes and occurs as medial moraines and landslide debris on the Martin River, Bering and Malaspina Glaciers, superglacial drift of this origin forms only a „very discontinuous cover". The stagnant terminal zones, a few miles wide, are covered with a thick continuous blanket of finer superglacial drift at least several feet thick. This material was dragged up from the glacier base along thrust

Pl. 1. Prairie mound, located approximately ten miles south-southeast of Medicine Hat, Alberta

Pl. 2. Oblique aerial view of a field of large prairie mounds, Foremost area, Alberta

Pl. 3. Oblique aerial view of a field medium-sized prairie mounds, Foremost area, Alberta



Pl. 4. Oblique aerial view of a field of small prairie mounds, Foremost area, Alberta

Pl. 5. Oblique aerial view of an arctic pingo, in Randböldalen, Cape Franklin area, central-east Greenland
(taken by E. Hofer, reproduced by courtesy of Dr. F. Müller, McGill University)

planes; such was observed in sink-holes in the stagnant part of the Martin River Glacier.

Though the presence of a debris cover on stagnating continental ice thus appears probable, Gravenor's hypothesis itself is improbable for several reasons:

(A) Unless a specific set of climatic conditions, of critical thickness and albedo of the debris cover, and of ice-thickness in relation to both the former factors did occur, relief inversion would either not take place, or happen more than once. If the former, a mound without central depression would result (Gravenor, 1955); if the latter, a dirt cone would result from the first inversion, debris would accumulate around the cone in a ring shape, repetition of the inversion would distribute the debris of the ring wall partly inside, partly outside it. Repetition of this process would distribute rather than concentrate the debris at the site of the mound[1].

(B) The majority of the mounds have been reported to consist of till. The till of these mounds is similar in texture to the till occuring below the intermound depressions (Gravenor, 1955; Bik, 1967, 1968) or was described as „basal" till (Henderson, 1952; Stalker, 1960a; Bik, 1968). If the mounds originated in the way proposed by Gravenor (1955) one would expect them to consist of „ablation" till.

According to Clayton (1967), the „ablation till" of dead-ice moraine is not noticeably different in grain-size composition or compaction from associated subglacial or „lodgement till". This seems surprising as the mechanics of deposition of the two sediments appear rather different. Furthermore, study of the textural composition of either for alpine glacial deposits revealed an appreciable difference in the grain-size distribution between the two modes of deposition (Portmann, 1956; Bik, 1960).

Finally, prairie mounds have also been formed of lacustrine silts (Henderson, 1952; Mathews, 1963; this paper; but also Gravenor, 1955).

[1] According to Clayton (written communication 1966) „strongly aligned ridges of ablation moraines are very common at the up-glacier margin (or most recently formed edge) of the stagnant, drift-covered terminal belts of the Malaspina and Bering glaciers. But, repeated relief inversions quickly destroy this lineation, so that most of the stagnant ice belt is nearly free of lineation". This would indicate a spreading of the debris load rather than permanent concentration in depressions.

(C) If the prairie mound fields of the Foremost-Cypress Hills area were circular or oval pit fillings, one would expect those to occur in close association with other stagnant-ice forms, as pointed out above. In other areas prairie mounds have been observed in association with stagnant-ice morphology. Their occurence in southern Alberta as large fields that contain almost exclusively prairie mounds, would indicate that the reported local association with dead-ice forms does not necessarily imply a genetic association; the mounds could have formed after construction of the dead-ice topography.

(D) Gravenor's hypothesis fails to account for the breach(es) of the mound rim, which are a characteristic of all prairie mounds (Bik, 1967b) of southern Alberta.

Clayton's description (1964, 1967) of surficial glacier-karst features of several Alaskan glaciers lends support only to the superglacial origin of mounds without central depressions, as proposed by Gravenor (1955). The absence of water-sorted deposits of glacial origin in association with the prairie mounds of the Foremost-Cypres Hills area, makes the „glacier-karst" hypothesis improbable here.

Clayton (1967) explained the breaches of the rim of „doughnuts" of the Missouri Coteau, some of which resemble the prairie mounds, by assuming the presence of a „disintegration trench". The „disintegration trench" is thought to result from the trapping of an elongate ice core below a crevasse filling and subsequent relief inversion, similar to Gravenor's hypothesis of origin of prairie mounds.

The Missouri Coteau „doughnuts" are „commonly doubly breached on opposite sides of the ring. Commonly several breached „doughnuts" are aligned in a row like a chain" (p. 32). According to Clayton ice-sinkholes are initiated along a crevasses, and a „chain" of breached „doughnuts" occurs where several ice-sinkholes are formed along a single crevasse. However, for the prairie mounds of southern Alberta it was observed that alignment is uncommon, that several breaches of the rim commonly occur, that always one, and rarely two of these breaches considerably exceed the remainder in size, and that the location of the principal breach appears related to the direction of regional slope of the mound field (Bik, 1968). Though alignment of prairie mounds has been observed in other Canadian mound fields (Gravenor and

Kupsch, 1959; Stalker 1960a), it is by no means a dominant characteristic (Henderson, 1952; Stalker, 1960a; Mathews 1963). It may be concluded that there is no apparent genetic relation between the locally occuring alignment of mounds and the fact that the rims are generally breached in one or more places.

Subglacial origin

The subglacial hypothesis of origin of the prairie mounds, proposed by Stalker (1960a), according to which the mounds would result from intrusion of plastic till into basal cavities of a stagnant ice mass, also has disadvantages:

(A) It explains neither the breaching of the rim nor the central depression of the mounds, both of which were found to be a part of the parent form of the present-day mounds, that has been modified by exogenic processes during the last 10,000 years or so (Bik, 1968).

(B) The prairie mounds of the Foremost-Cypress Hills area are not associated with other ice-pressed drift forms. If formed by ice-pressing only, cavities that were circular or oval in plan would have occurred at the base of the stagnating ice-mass. The absence of elongate ice-pressed forms such as crevasse-castings makes the proposed subglacial origin unlikely.

(C) In Stalker's opinion (1960a) prairie mounds or „plains plateaux" are related in origin to moraine plateaux (Hoppe, 1952). The till ridge that commonly borders the moraine plateau would originate from subglacial squeezing, as does the much smaller rim of the plains plateaux. The central fill of both, which gives the center of the moraine plateau the appearance of a (sometimes perched) lake plain, is also considered to be of glacial origin (Stalker, 1960a, p. 30). However, for two mounds of the Foremost-Cypress Hills area, it was shown that the central fill was deposited long after the ice had disappeared from their locations (Bik, 1968).

Furthermore, the rim of the moraine plateaux, explained from basal squeezing by Hoppe (1952) and Stalker (1960a), has recently been explained from sliding of thick superglacial till into holes in the surface of a stagnant ice mass by Clayton and Cherry (1967), who discussed the perched plains of ice-walled lakes of the Missouri Coteau in North Dakota. These perched lake plains are in form, size and constituting deposits identical with the moraine plateaux described by Stalker (1960a). It is thus doubtful whether the ice-pressing theory may be applied to these forms.

(D) Finally, the ice-pressing theory cannot by applied to prairie mounds consisting of proglacial deposits which were formed after the disappearance of the ice from their locations (Henderson, 1952; Mathews, 1963).

In summary, both the glaciogenetic hypotheses of origin appear improbable as they do not account for all the prairie mound occurences described to date; neither do they satisfactorily explain the various characteristics of the form.

Periglacial hypotheses of origin

Henderson (1952) concluded on a periglacial origin of the prairie mounds of the Sturgeon Lake area. He proposed a mechanism in which the centers of giant soil polygons would be raised by the growth of polygonally patterned ice wedges; an ice-core would subsequently be segregated beneath the surface of the central part of the polygons. The central depression would result from ultimate melting of this core, the breach in the rim initially from drainage of the mound during melting of the core.

This hypothesis was rejected by Gravenor (1955); most of his arguments, however, appear to be invalid as the result of more recent work. Yet, as pointed out by Gravenor, the mere size of the required wedges makes the mechanism proposed by Henderson rather improbable, and the fillings of the assumed giant ice-wedges were to date not observed in the field.

The pattern of ice wedges, required to form the mounds, and which is that „commonly found for frost polygons" (Henderson, 1952, p. 54), does not fit well with the actual distribution of the mounds within their fields. In the Foremost-Cypress Hills area this distribution is of rather even density, and commonly random, not approximately equidistant; furthermore, it fails to explain the occurrence of isolated mounds (as pointed out by Mathews, 1963). As noted earlier, the form of the intermound depressions apparently depends on the location of the mounds within their fields. Depression margins are a composition of intersecting mound-foot-slope segments. The width of the intermound spaces varies from almost nil to 1,000 feet (300 m) and more. Mounds may adjoin so closely that the intermound saddle is sometimes reduced to a depression between two rims, hardly more than one foot (30,5 cm) below their levels. Clearly, this cannot be explained with an ice wedge pattern, since such an assumption implies a greater measure of regularity of the form of the intermound depressions. Composite patterns, in which smaller mounds are located on the outer slopes of a larger individual, cannot be explained with Henderson's hypothesis either.

Finally, the contraction theory of origin of ice wedge polygons (Lachenbruch, 1963), which explains the formation of cracks in frozen soil from thermal contraction, rather than from expansion of freezing water within the wedges, appears in conflict with Henderson's proposed mechanism of formation of the mounds.

Mathews (1963) proposed a mechanism of the nature of pingo formation for mounds of the Fort St. John area, which characteristically occur where lacustrine sediments of Glacial Lake Peace form a continuous mantle over ten feet (3 m) thick. The development of the mounds „possibly involved displacement of water saturated soil, rather than water alone, during the development of permafrost, and that this soil moved at depth towards points of potential rupture, where permafrost was thinnest, as for example beneath the center of shallow ponds" (Mathews, 1963, p. 18).

Though the actual mechanism proposed by Henderson appears less suited, an origin under periglacial climatic conditions would permit an explanation of the formation of the mounds on a range of parent materials, rather than restrict the applicability of the mode of origin to prairie mounds occuring on till.

Mathew's proposal of a mechanism in the nature of pingo formation permits to explain the central depression from the melting of an ice core and also of the breach(es) in the rim, which are a common form characteristic of the active pingos, as well as of the collapsed pingos of western Europe. The mechanism of the mounding, as well as the segregation of a discreet ice core remains to be explored. Furthermore, such a mechanism should not only account for the mounding phenomenon in a variety of parent materials, but also explain the characteristics of distribution within one field as well as the apparent elevation control of the distribution of the fields themselves.

THE ORIGIN OF PRAIRIE MOUNDS

COLLAPSED PINGOS (?)

In an earlier paper (Bik, 1968) it was shown that the parent form of two mounds prior to modification by exogenetic processes descriptively compares with a ringwall and crater, that the breaches and saddles of the rim are present in this parent form, and that modification of the form resulted from mass wastage of the rim and niveo-aeolian deposition.

The occurrence of prairie mounds consisting wholly (Sturgeon Lake area, Fort St. John area) or partly of lacustrine deposits (southeast of Edmonton), next to forms that are made up of till, would indicate that, inasmuch as the prairie mounds occurring on till are indentical in size and shape to those occurring on proglacial lacustrine deposits, the landform cannot have a subglacial or superglacial genesis, but is either of subaquatic or subaerial origin. Furthermore, as the parent form of many mounds consists of basal till, the genesis of the form is most probably the result of deformation of an already existing deposit, rather than of concurrence of deposition and deformation.

Maarleveld and van den Toorn (1956) recognized the existence of pingo ruins in western Europe as a result of palynological and sedimentological studies in depressions in the Riss ground moraine landscape of the northern Netherlands. Pingo ruins, dating from the Würm Period, could be distinguished from dead-ice hollows or kettles through the absence of late-glacial cover sands from the former, whereas these are present in the older depressions. Stoltenberg (1935) and Troll (1944) also commented on the similarity between kettles of the young moraine landscapes in north-western Europe and pingo ruins. The forms described by Maarleveld and van den Toorn are depressions in the ground moraine plain, up to 20 feet (6 m) deep, and surrounded by closely adjoining ring walls, attaining elevations of up to 7 feet (2 m) above the level of surrounding plain segments. The ring walls are breached, their crest lines undulated; in one particular case an erosion gully was found, leading away from such a rimmed depression.

Pissart describes pingo ruins found in the Ardennes, Belgium (1956); similar forms for the Paris Basin (1958); collapsed pingos that were discovered in Wales (1963). The depressions may attain depths of up to 26 feet (8 m) and are frequently filled with peat. Structures examined in the rims (ramparts) suggest that these result from thrusting related to the growth of the central ice-wedge. Internal diameters may attain 390 feet (120 m).

In the Ardennes, densities comparable to those noted for the Foremost-Cypress Hills area were found as: „nonante cinq pour cent des formes observées sont situées sur le plateau des Hautes Fagnes, qui s'étend du SW au NE sur 35 km, depuis la crête de Malchamps (5 km au sud du Spa), jusqu'en Allemagne à proximité de Montjoie. Il existe là, plus d'un millier de dépressions qui occupent d'une maniére quasi continue quelques régions bien determinée dont la superficie totals est de l'ordre de 2500 ha" (Pissart, 1963, p. 154).

Rapp and Rudberg (1960) observed „a special type of small, circular or elliptical lakes, only 32 to 65 feet (10—20 m) wide, surrounded by ridges of pressed soil with tangentially oriented boulders and with cracks. The whole feature looks like the remains of small pingos, described from Greenland...". The forms occur on swampy flat valley bottoms and „mountain plains" in the Abisko area, northern Sweden.

Svensson (1963) described pingo ruins from northern Norway. The form here sometimes takes the shape of a hummock with a crater-like depression, sometimes of a circular rampart. A diameter of more than 325 feet (100 m) and a height of 26 feet (8 m) was observed; most individuals have smaller dimensions. The crest-line of the rim ridge is not always horizontal; it is not as commonly breached as is found in the Foremost-Cypress Hills area either. The forms occur on slightly sloping ground on the upper part of mountain slopes.

The above mentioned occurrences of pingo ruins are on till (Netherlands, Norway, Sweden), valley alluvium (Wales), and on surficial loams (Ardennes); Wiegand (1965) describes occurrences on many types of consolidated rock as well.

An origin of the prairie mounds by means of processes similar to pingo formation is likely since:

(A) The parent form, and to a lesser extent the present-day prairie mound has many of the form characteristics of the collapsed pingos described from western Europe. But, inasmuch as augering in two of the mounds of the Foremost-Cypress Hills area could show (Bik, 1968), the prairie mound is a positive landform, in which the central depression does not extend below the average level of the terrain outside the mounds, if the layer of superficial deposits of the intermound depressions, which are younger than both the till and the mounds, is not taken into account. The European collapsed pingo consists of a breached ring wall, surrounding a depression that extends beneath the level of the surrounding terrain, if the layer of post-collapse fill is not taken into account. In aspects of the form the prairie mound is thus similar to, but not identical with the collapsed pingos of western Europe.

(B) Prairie mound fields in the Red Deer and Wabamun areas of Alberta and the Kindersley area of Saskatchewan contain a minority of forms that are identical with the European collapsed pingos. The same was observed in the Whitecourt area Alberta [2]. In the area to the southeast of Edmonton, prairie mounds are generally less strongly „mounded" than found to the west of the Cypress Hills. Thus, within this landform group as well as within the prairie mound belts as landform-association there is a variation of the form that ranges from replicas of the generally acknowledged collapsed pingo of western Europe to a kind of „mounded pingo" or prairie mound.

An explanation of the origin of the prairie mound as resulting from some kind of pingo formation, however, raises the following questions:

(1) Can till be displaced below the surface under an aggrading permafrost layer, as suggested by Mathews (1963) for lacustrine deposits?

(2) Can discreet ice cores be segregated in till?

(3) What controls the distribution of prairie mound fields, which appear to be of limited vertical and rather unlimited lateral extent?

SOME PROPERTIES OF THE TILL

The liquid limit of the till of two of the mounds that were studied in detail (Foremost-Cypress Hill area, Bik, 1968) is low the plasticity index is also low (Table I).

These values are lower than those reported for the tills of southern Saskatchewan (Christiansen, 1959, 1960; Parizek,

[2] Dr. D. A. St. Onge, Geological Survey of Canada; Personal communication (1966).

Table I

Liquid limits and plasticity indices of till

Sample number	Liquid limit	Plasticity index
GBL 50	26.4%	10.7%
103	32.3	15.6
233	27.2	13.7
656	24.2	5.5

1964). The low Atterberg limits reflect the presence of montmorillonite in the clay fraction of the till. This clay mineral swells substantially of the presence of water, which changes the textural properties of the till in which it occurs. Absorbed water furthermore, makes the clay mineral act as a lubricant between the larger grains of the sediment.

Montmorillonite is the most abundant mineral in the clay fraction of the tills of southern Alberta and southern Saskatchewan (Christiansen, 1959, 1960, 1961; Greer and Christiansen, 1963; Gardiner, 1965). This is ascribed to high percentages of montmorillonite that are found in the largely argillaceous upper Cretaceous rocks that underlie the glacial drift and which appear to have provided a substantial part of the matrix of the till (Christiansen, 1959: Bearpaw Formation; 1960: Marine Shales; 1961: Bearpaw Formation, Marine Shales; 1965a: Oldman, and Bearpaw Formation; Greer and Christiansen, 1963: Bearpaw and Marine Shales; Byrne and Farvolden, 1959; Forman and Rice, 1959: Bearpaw Formation; as quoted in Gardiner, 1965).

In the literature subsurface displacement of material has not been suggested in connection with pingo formation, except for (Mathews, 1963). But, subsurficial movement of material under periglacial climatic conditions was proposed to explain "diapyrs" of argillaceous deposites into their overburden by Auber (1951) and Michel (1962). Auber described the injection under periglacial conditions of marls for a quarry near Bonneuil, in the Paris region. Michel described elongate "diapyrs", up to 40 m (130 ft.) long and up to 7 m (23 ft.) high, and consisting of Eocene marls, that were injected into Quaternary alluvium of the Seine and Marne rivers near Paris. "Marl-veins" 6 to 25 cm (2 to 10 in.) thick, were ejected from the convex roof of the "diapyrs". Michel proposed injection of thawed out marls into the overburden as a result of the latter's weight. This occurred during the terminal phase of a glacial period for some forms; injection of a „mollisol" under pressure below the frozen cover of alluvial deposits was proposed for other phenomena.

For the occurrences of pingo ruins in western Europe reviewed above, there seems to be no excess of material, when the volume of the material of the wall is compared with the volume of the depressions, horizontally bedded organic and inorganic deposits constituting the post-collapse fill excluded. Taken in this sense, the (presumed) pingo ruins of the Foremost-Cypress Hills area generally show excess of material and following Mathews (1963) it is assumed that "eruption" did not so much involve only expelled porewater but rather a plastic mass of glacial deposits, saturated beyond flow limits, as well.

It is the apparent excess of material in the mounds, the commonly occurring marginal vale, and the fact that mound tops surmount and intermound depression floors lie below the level of the terrain adjoining the mound fields that need to be explained; in other words the mound fields with their various characteristics as form association rather than the individual mounds, which are only a part of the genetic system. Mound fields could be viewed as a "disturbance" of the adjoining, smooth topography, where internal relief usually does not exceed 5 to 10 feet (1.5—3 m). The excess of material within the mounds could have been derived from the adjoining intermound depressions; the marginal vale could mark the outer limit of "disturbance" of the topography.

IMPLICATIONS OF THE ASSUMPTION OF SUBSURFICIAL MOVEMENT

The distribution of prairie mounds within the mound fields and their round or oval plan indicates that, if owing their positive relief partly to subsurface displacement of mobile till, this displacement was directed to points rather than to lines of weakness in the frozen layer below which displacement occurred. This would suggest that the mounds are located either over the initial depressions or over the initial convexities of rolling surfaces, presumably similar to the landforms that now adjoin the mound fields.

Location over initially high areas seems unlikely, as permafrost establishment is thought to proceed more rapidly below these; moisture content of the upper horizons below such areas may be expected to be lower than in the depressions. However, as the total mass of material in the parent form of the prairie mound (i.e. the mass of the rim less the volume of the depression) rises above the surface of the surrounding terrain, inversion of the initial relief seems to have occurred, when the mounds are indeed located over the initial depressions.

Perhaps not initially, but certainly in the later stages of the development of the mounds, the forces that formed the protrusion must have been derived from the process of permafrost aggradation itself. For the less likely case of mound formation over the existing convexities of the terrain, this also applies to the initiation of the process.

Finally, the assumption of the growth of a discreet ice core within an existing high area of a till plain cannot explain the relief of all prairie mounds. The mounds on thick lacustrine silts, described by Mathews, cannot be explained in this way; it is unlikely that relief differences of the surface on which the lacustrine deposits rest would have been sufficiently maintained during the deposition of up to 100 feet of lacustrine deposits.

For the more probable case, mounds over previous depressions of the terrain, the greater thickness of frozen overburden below the topographic highs results in greater pressure being exerted on the unfrozen layer below it, relative to the depressions. But, the low relief of the undulating forms that are laterally associated with the prairie mound belts of the Foremost-Cypres Hills area (till plains, lacustrine plaine) would suggest that pressure differences could not have been large, perhaps in the order of 0.5 kg/cm^2, as relief is only 5 to 10 feet (1.5—3 m) usually. The continuous strenght of frozen soil is from 5 to 15 times smaller than the momentary one (Vyalov, 1963). Values for the continuous shear strength of soils with a grain-size distribution comparable to the till of the mounds are, however, somewhat higher than 0.5 kg/cm^2 (Vyalov, 1963; continuous shear strength at —0.3°C for light clayey loam: 0.7 kg/cm^2). Unusually low values for the continuous shear strength of the till under discussion may be expected in view of its high content of montmorillonite.

Although initial subsurface displacement can perhaps be explained from subsidence of the convexities of the initial relief, beneath which permafrost is thicker, the continued growth of the prairie mounds can only be imagined by assuming that the volume expansion resulting from downward progress of the freezing front is contained in some kind of "closed system" (Müller, 1959). This would direct "eruption" towards the weakest area of the enclosing medium, i.e. upwards towards the thinnest part of the covering permafrost.

SEGREGATION OF THE ICE CORE

Could the lower segment of the mound perhaps be explained from subsurface movement under pressure towards areas of "eruption", (see also below), the upper segment appears to have resulted from the growth of an ice-core below the surface of the soil, which on melting left the central depression. The breaches of the rim would result from radial cracks in the updomed overburden, caused by growth of the ice-core beneath it (compare Plate 5).

To date three mechanisms were proposed for the formation of the present-day arctic pingos:

(1) East-Greenland type (Müller, 1959, p. 70—71). Assumed is the ascent of intra- and sub-permafrost water and gas under hydrostatic pressure. Variation of conditions of volume and temperature is so small that no revolutionary disruption of the permafrost results. Within the permafrost a hydrolaccolith in the true sense is formed, out of which an ice body develops. Pressures generated by crystallization of ice result in arching of the overburden. The volcano-like form is atributed to the circumstance that thermal and mechanical forces, of necessity close to labile equilibrium, are thought to operate from a point rather than an axis or a plane. Deviations from the circular plan are ascribed to the interruption of the continuity of the beds of consolidated or unconsolidated rock in which the pingo develops, such as dykes and faults. This mechanism has become known as the „open system".

(2) Mackenzie Delta type (Müller, 1959, p. 102—103). Progressive penetration of permafrost in the sediments of former lake-basins results in the increase of hydrostatic pressure in the talik-zone to such an extent that „eruption" takes place, when the permafrost front advancing both downwards as well as from the lake basin margin reduces the „open area" to below a critical diameter. This mechanism has become known as the „closed system".

(3) Spitsbergen type (Wirthmann, 1964, p. 41). Progressive establishment of permafrost in unconsolitated deposits overlying impermeable hardrock, possibly or preferably over depressions in the hardrock surface, will increase the hydrostatic pressure in the resulting enclosed ground water lens; „eruption" may follow.

For the Hautes Fagnes pingo ruins Pissart (1963) accepts the mode of origin proposed by Mückenhausen (1960). The moisture required to build the ice-lens, is thought to have been derived from upslope of the pingo ruins. The form of the ice-lens is wedge-shaped in plan and is explained with growth on its upslope side: the feeding water could be contained in colluvial deposits resting on impermeable hardrock.

The various mechanism of formation of the ice core do not apply to the prairie mounds of the Foremost-Cypress Hills area of Alberta, since neither the possibility for the trapping of a ground water lens, nor sufficient hydraulic head appears to exist for the sites where the majority occurs.

Whereas known occurrences in Canada of active pingos are generally found on thick alluvial, deltaic or fluvioglacial sands, and numerically are mostly of the "closed system" type (Mackay, 1963), the pingos of the interior of Alaska are found in „areas underlain by complex and deformed Paleozoic and Mesozoic rocks, by the Precambrian Birch Creek Schist, by Mesozoic granitic rocks and by Mesozoic or Tertiary volcanic rocks. They exist (also) on valley slopes and floors covered with Pleistocene and Recent unconsolidated deposits (ranging in grain-size from silt to gravel), alluvial fan deposits, loess, organic silt, and weathered rock. Although no pingos were observed in areas of glacial till or outwash, they might be found in areas of glacial drift" (Holmes, Forster and Hopkins, 1963, p. 92). The occurrences of active pingos are thus not restricted to a particular parent rock (see also Müller, 1959).

Collapsed pingos also have been reported as occurring on a wide variety of deposits, including till (Maarleveld and van den Toorn, 1965; Pissart, 1956, 1958, 1963; Svensson, 1964; Wiegand, 1965).

Though the granulometry of the till of the two mounds of the Foremost-Cypress Hills area, that were analyzed in detail (Bik, 1968), would suggest a low measure of permeability, the hydraulic conductivity of 0.54—0.006 inches/hr., reported for till beneath a "willow ring" in south-central Saskatchewan does not preclude some measure of water movement through it (M e y b o o m, 1966).

In summary, though permeability of the till on which the mounds formed is undoubtedly low, this does not in itself exclude an explanation of the prairie mounds as resulting from some form of pingo-formation, as both active and collapsed pingos have been reported to occur on a wide variety of parent formations, including those with low permeability.

AIR INTRUSION VALUES AS A MEASURE OF FROST HEAVE POTENTIAL

Provided the till is saturated with moisture substantial frost heaving may occur in it. Frost heaving in soils is the result of an increase in moisture content at the freezing front, resulting from the migration of water to the freezing layer (W i l l i a m s, 1966) [3].

Frost-heave, defined as the volumetric increase of the soil which occurs as the result of the uptake of water by the freezing soil (generally resulting in the formation of ice lenses) can be predicted from the pressure at which air will enter and spread through the pores of the soil, displacing water from it. This pressure is the „air intrusion value" of a soil. It is probable that the air intrusion value depends on the radius of the largest continuous openings of the soil pore structure, and that it is this size which determines pore pressure at a penetrating freezing front in a given soil. The air intrusion values of four till samples are given in table II. The values are quite high. By comparison silty soils may show about 0.5 kg/cm^2 and rather pure clay soils 2—3 kg/cm^2 (W i l l i a m s, 1966).

For what follows it is assumed that the parent form of the mound fields prior to formation of the mounds is a till plain with relief of 3 m (10 feet). Before freezing there is a free water table at 2.5 m (8.2 feet) below the convexities and at 1.0 m (3.3 feet) below the center of the depressions of the parent form. The bulk density of frozen till is assumed to be 0.002 kg/cm^3. Capillary ascent of water above the free water table is disregarded; it is assu-

[3] The author is indebted to P. J. W i l l i a m s, National Research Council, Division of Building Research, for the use of a completed manuscript: „Properties and behaviour of freezing soils", as well as for the determination of the air intrusion values given in Table II.

Table II

Air intrusion values of till

Sample Number	Air intrusion value	% Sand 2000—53 μ	% Silt 53—2 μ	% Clay < 2 μ
GBL 50	1.5 kg/cm²	41.0	34.6	24.4
103	2.2	40.1	31.8	28.1
233	2.2	41.4	32.8	25.8
656	1.5	46.9	30.1	23.0

med that losses of water from below the level of the ground water table are replaced by ground water flow.

Local ice segregation would have a tendency towards warping the freezing front into a dome at the site of the segregation (see M a c k a y, 1962). The latent heat of fusion of ice is about 400 times as large as the heat capacity of soil particles. The heat capacity of ice is about 2.5 times the heat capacity of soil particles. Both in the establishment of permafrost and in the further cooling of the frozen layer more heat has to be disposed of for areas where ice-segregation occurs. It is further assumed that the downward advance of the freezing front occurs twice as fast above the water table as below it, as long as ice-lens segregation occurs.

On the basis of the average of four air intrusion values of 1.85 kg/cm², the pore pressures at the freezing front were calculated following W i l l i a m s (1966). The figures are recorded in Table III, and schematically portrayed in Figure 5. According to W i l l i a m s (1966) ice segregation will occur when the pore water pressure (u_x) at depth x prior to freezing is higher than the pore pressure at the penetrating frost line (u_{ix}) at this depth, or $u_x >$ u_{ix}. Table III shows that ice-segregation will persist longer below the depressions than beneath the convexities of the initial relief; also that segregation starts earlier below the depressions. Yet, the relief inversion suggested by Figure 5 is only apparent since it results from ice segregation alone.

As the air intrusion value of the till is high, and consequently the pressure gradient towards the penetrating frost line is equally high, ice segregation may be expected to actually occur above the free water-table due to capillary ascent of ground water prior to freezing. However, since the pore necks are obviously very small, it is likely that the freezing front will penetrate rather rapidly to the ground water table, as replacement of moisture stored in ice lenses when the freezing front advances, probably occurs at

Table III

Pore water pressure, presure on the ice phase at the freezing front and pore pressure at the penetrating frost line at various depths and for consecutive points in time, below a depression and a convexity of a roling till plain with 3 m relief and a free water table at 2.5 m below the convexity and 1 m below the concavity

	Below the convexity					Below the depression				
Time phase	Depth* m	P_i kg/cm²	u_x kg/cm²	u_{ix} kg/cm²	$u_{ix}-u_x$ kg/cm²	Depth* m	P_i kg/cm²	u_x kg/cm²	u_{ix} kg/cm²	$u_{ix}-u_x$ kg/cm²
I	1.0	0.20	—0.15	—0.58	—0.43	1.0	0.20	0.0	—0.58	—0.58
II	2.5	0.50	0.0	—0.28	—0.28	1.75	0.27	0.0	—0.51	—0.51
III	5.58	0.78	0.0	0.0	0.0	4.85	0.54	0.0	—0.23	—0.23
IV	10.76	1.81	0.52	1.04	0.52	7.42	0.78	0.0	0.0	0.0

* — The depth of penetration of the freezing front below the surface; includes the thickness of the ice segregations formed

P_i — Pressure on the ice phase (is overburden pressure at the freezing front, air pressure 0.0 kg/cm²)

u_x — Pore water pressure

u_{ix} — Pore pressure at the penetrating frost line (or freezing front) a low rate in the zone of capillary rise. At the level of the ground water table the pressure gradient towards the ice is less easily overcome, since replacement of water stored in the ice lenses, which would lower the ground water table, will be more rapid. It thus seems that the greatest thickness of ice will, therefore, be segregated at the level of the ground water-table, and that the assumptions made above are sufficiently valid.

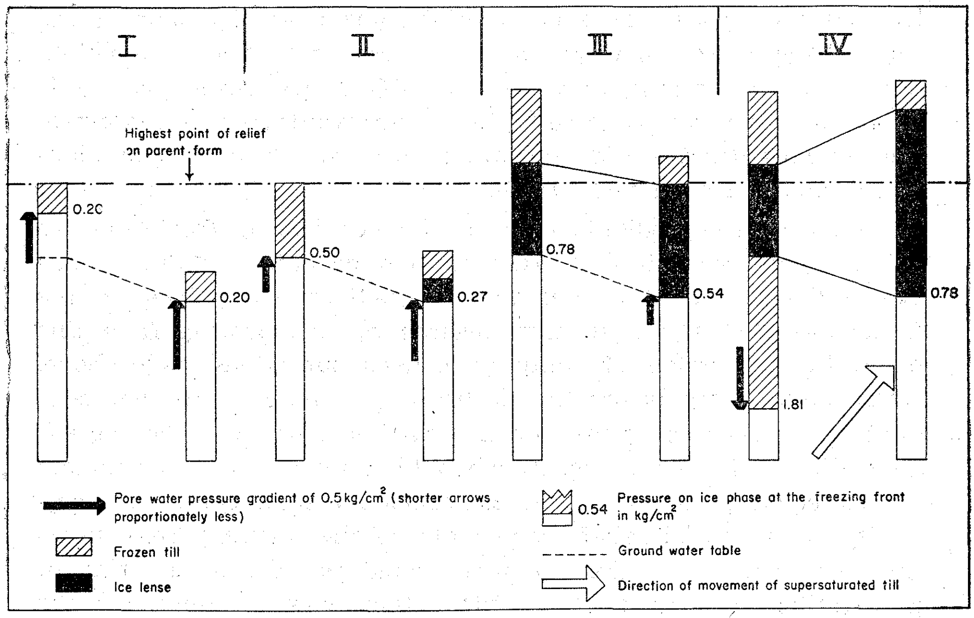


Fig. 5. Segregation of ice in an aggrading permafrost layer below a till plain with initial relief of 3 m

The figure is a schematic presentation of the data of Table III. The left column of each pair represents the convexity, the right column the concavity

Ice segregation ceases when $u_x = u_{ix}$. On further penetration of the freezing front, the pressure at the penetrating frost line will exceed the pore water pressure, and pore water will in part be expelled. Supersaturation results, initially under the convexities of the relief, later also under the depressions. The till will then behave as a sludge and an upwards directed force is exerted below the site of the initial depression of the parent form. For the theoretical example given in Table III the magnitude of that force is in the order of 1.0 kg/cm², the difference in overburden pressure at the penetrating frost line below the convexity and the overburden pressure at the penetrating frost line beneath the depression. The continuous strength of frozen soil is the greater the lower its temperature (V y a l o v, 1963). It thus seems that, although conditions of supersaturation are most likely the result of permafrost aggradation during the winter season, subsurface displacement of material towards areas of weakness in the frozen overburden most likely occurs during the subsequent warmer summer months. Even if the upper frozen layer of till above the ice lens of the original depression (now protrusion) were not to thaw completely but to attain a temperature close to 0°C in its frozen part, it is likely that an upwards force of 1.0 kg/cm^2 would not be contained. The ice-lens itself would deform at lower stress levels (B u t k o v i c h and L a n d a u e r, 1960).

The pressure gradients towards the penetrating frost line are larger below the initial depression than beneath the initial convexity (Table III). There is thus a gradient from beneath the frozen layer of the convexity towards the penetrating frost line below the depression. If, contrary to the assumptions made above, water losses from below the penetrating frost line are not adequately replaced to permit the full thickness of ice to be segregated, (Table III), ice segregation would more closely approximate the expected thickness below the concavity than below the convexity of the initial relief. Penetration of the freezing front below the convexity would then be more rapid relative to the rate of penetration beneath the concavity, than was assumed for the construction of Table III and Figure 5.

In summary it may be concluded that subsurficial displacement of till towards the initial depressions in the parent form of the present-day prairie mound fields is not incompatible with a greater measure of ice-segregation beneath the initial depressions. At least qualitatively, the characteristics of the till do not exclude an origin of the prairie mounds in the nature of pingo formation as suggested by M a t h e w s (1963).

FORMATION OF A »CLOSED SYSTEM«

The subsurficial movement, discussed above, would only continue until the hydrostatic pressure differences in the supersaturated till would have been equalized. Subsequent melting of the ice-cores would then leave the acknowledged type of collapsed pingo described from western Europe (see above). Could this explain the accessory occurrence of this type in the pattern of the mounds within their fields, the prairie mound or "mounded collapsed pingo", then appears to have resulted from continuation of the subsurficial supply of material. This could only occur when the forces derived from permafrost aggradation would work within a „closed system"; if no separate cells of supersaturated material were formed, volume expansion would lead to heave of the mound field as a whole.

Two situations in the subsurface could bring about the creation of closed pockets of supersaturated till on penetration of a freezing front:

(A) The presence of a solid bedrock surface that would be attained by the penetrating freezing front, initially below the convexities of the terrain. Two gaps in the main prairie mound belt, near Skiff and near Foremost (Fig. 3) are located over N—S trending linear lows in the bedrock surface below the drift, as mapped by Westgate (1964). Prairie mound fields occur in areas where drift is less than 50 feet (15 m) thick as well as where drift attains over 200 feet (61 m) in thickness. The pattern of the mound-field-belts does not accord at all to the variation of drift thickness in the Foremost-Cypress Hills area. Finally, the two gaps in the main prairie mound belt occur where the topography is 100 feet (30 m) or more lower than the plateau surface on either side; taken together with the limited vertical extent of the mound-field-belts, it indicates that the absence of mound fields over the two bedrock valleys is related to the configuration of the surface rather than to the bedrock topography.

Though the assumption of the formation of cells enclosed by hardrock below and an arched freezing front above is unlikely for the mound-field-belts, it could apply to the occurrences of scattered groups of mounds in the re-entrants of hilly topography, where the drift cover is generally thin (less than 50 feet, 15 m).

(B) The presence of fossil permafrost in the subsurface, which would form cells of supersaturated till above it when salients of an arched freezing front would attain it.

With regard to the probable time of deglaciation of the Foremost-Cypress Hills area (see below) it is not unlikely that permafrost was established during subsequent cold periods, which were recorded as glacial advances both to the north and in the Rocky Mountains. The presence of permafrost in the subsurface at the time of formation of the mounds is also likely; it is discused below.

THE DISTRIBUTION OF PRAIRIE MOUND FIELDS IN RELATION TO A PERIGLACIAL ORIGIN

Though the „mounded" aspect of the prairie mounds does exclude an explanation of the origin following either Müller (1959), Muckenhausen (1960) or Wirthmann (1964), the occurrence of scattered groups of prairie mounds in the re-entrants of hilly topography and in depressions of hummocky moraine areas is not unusual if the mounds are indeed a kind of hydrolaccolith. The location of the mound field belts, however, seems in no way to relate to the present-day topography and expected ground water flow, to the stratigraphy or the thickness of the glacial drift, or to the lithology and topography of the bedrock surface.

The rather constant density of the mounds in their fields, the frequent occurrence of the marginal vale, and the little variation in size of the mounds of one field, would suggest that the growth of the mounds of a field may have started at the same point in time and continued for the same length of time for all mounds of the field.

Mound fields occur as strictly elevation controlled phenomena in southern and central Alberta and southern Saskatchewan (Bik, 1967a). Though this seems to be the only apparent rule in the present-day distribution of this fossil landform, the availability of moisture must have been the genetic control during its formation under periglacial climatic conditions.

The till of the mounds, which has such unusually high air-intrusion values, differs neither in texture nor in clay-mineralogy from the till of the ground moraine plains adjacent to the mound fields. Mounds were not formed on the latter. Moisture required for the construction of the mounds, discussed in a preceding section, would thus seem to have been available in near-horizontal belts in the terrain.

Finally, if the development of a „closed system", as inferred in an earlier section, rather than moisture distribution is the most critical factor in the formation of the mounds, then near-horizontal belts in which permafrost establishment progressed towards an (assumed) permafrost remnant in the subsurface must have been present during the time that the prairie mounds were formed.

A survey of the distribution of prairie mounds, detailed for the Foremost-Cypress Hills area and more general for approximately 50,000 square miles (128,000 km²) of Alberta and Saskatchewan indicates that the mounds occur generally in clearly defined belts that bend upstream into major river valleys and sometimes encircle higher tracts of terrain (Bik, 1968).

An explanation of the distribution of the prairie mound belts, of the apparent near-simultaneous initiation of mound-growth within a field, as well as of the inferred requirements of moisture distribution and partial thawing of permafrost in belts of limited vertical extent, can be found in the assumption that the prairie mound belts may mark the former extent of proglacial lakes. Considering the aspects of distribution and of constituting deposits no alternate assumptions appear feasible.

Though surficial geological information is available for much of the area for which the distribution of prairie mounds was surveyed, detailed comparison between the location of prairie mound fields and mapped occurrences of proglacial lacustrine deposits cannot be made as most published information was gathered with reconnaissance methods. Yet, notwithstanding this limitation there is generally a good accordance between the patterns of distribution of both.

A substantial belt of prairie mounds, occurring to the east and southeast of Edmonton parallels and partly straddles the southeastern shore zone of Glacial Lake Edmonton (Bayrock and Hughes, 1963)[4]. Near Campbellton, prairie mounds developed on „heterogeneous sediments"[5] resting on till, as well as on till alone; the mound field here straddles the shore zone which slopes to the west.

In the Red Deer-Stettler, Drumheller, Gleichen and Lethbridge areas the regional distribution of prairie mounds delimits the topographically upper margin of lacustrine deposits as mapped by Craig (1956) and Stalker (1955, 1957, 1960b, 1962, 1965).

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[4] Dr. L. A. Bayrock, Research Council of Alberta, kindly provided the author with a completed manuscript „Recent orogenic uplift in western Canada, indicated by tilted Glacial Lake Edmonton".

[5] „Heterogeneous sediment": lacustrine deposits contorted by the grounding of ice rafts on the shore (Dr. Bayrock, personal communication, 1966).

In the Medicine Hat area the vertical limits of distribution of prairie mound belts accord with the level to which the terrain was proglacially inundated inasmuch as reconnaissance data available to date permit a comparison [6].

With the exception of the lake Pakowki depression, all lacustrine deposits described by Westgate (1964) for the Foremost-Cypres Hills area occur topographically below and to the north of the main mound-field-belt. The lacustrine deposits, occurring in the vicinity of Lake Pakowki were mapped as proglacial sediments (Westgate, 1964). Part of these could have been deposited relatively recently as a higher water level in this endoreic basin would inundate substantial tracts of land, particularly to the east of the present lake if climatic conditions were wetter in the past. Present level is 2,806 feet above sea level (855.8 m) the present day outlet level is 2,835 feet (864.7 m). An area about 3 times the size of the present lake would be flooded prior to initiation of discharge through the outlet of Pendant d'Oreille Coulée.

The mound field belts of the Kindersley area, Saskatchewan, accord to the distribution of lacustrine deposits as mapped by Christiansen (1965a).

In southern and central Alberta and southern Saskatchewan the majority of the mound-field-belts were developed on till. Wherever mounds developed on lacustrine deposits they occur topographically below mound fields on till. Since the control on the distribution clearly operated on different parent materials, it seems that a further assumption of staged lowering of lake levels would explain the parallel occurrences of prairie mound belts on till and lacustrine deposits.

Permafrost probably was established prior to the formation of proglacial lakes. Its formation would be a direct reaction to the cooling of the climate, whereas a glacier advance resulting in the damming of proglacial lakes would occur as a delayed reaction. Progressive damming of proglacial lakes would inundate areas where permafrost was previously established. The inundated permafrost would melt, most rapidly from the top downwards. In areas where it would not melt completely the conditions for the formation of prairie mound fields, as inferred above, would exist if the water level would be lowered and shore-zones exposed to the re-esta-

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[6] Dr. T. Berg, Research Council of Alberta, personal communication, 1966.

blishment of permafrost. Proglacial lakes would also form during a north-eastward retreat of the continental glacier from this part of the Great Plains. In a subsequent section evidence will be discussed which indicates that the last advance of the Wisconsinan ice-sheet, manifested itself in the waxing and waning of proglacial lakes of the Foremost-Cypress Hills area. It appears likely that the inundation by proglacial lakes of the terrain now occupied by prairie mound fields occurred after cooling of the climate, and that, at least during the initial staged lowering of the lake-levels periglacial conditions also prevailed.

Finally, the earlier an area is drained, the more time would be available for prairie mound formation. Pingo formation may take several hundred years if not more (Müller, 1959, 1962; Mackay, 1962, 1963; Maarleveld, 1965). The zonality of prairie mound occurrences (Fig. 3), could have resulted from staged rather than gradual lowering of the water level. The difference in size of the mounds across the mound field belts, however, more probably resulted from longer duration of mound formation in the parts of the shore-zone that emerged earliest.

AGE OF THE PRAIRIE MOUNDS

MINIMUM AGE

A sample of shell fragments taken from the central fill of one of the mounds was dated at 10,550±350 radiocarbon years (I 1877). The shell fragments occur in the upper horizon of a niveo-aeolian deposit. It forms the base of the fill of the intramound depressions. Horizontally bedded gypsum laminae are sometimes intercalated in this upper segment of the niveo-aeolian deposit. It is covered by a slightly coarser niveo-aeolian sediment which is not bedded in contrast to the former (Bik, 1968). The date obtained on the shell fragments as well as the interruption of aeolian sedimentation reflect the oscillation of climatic conditions found by Ritchie and de Vries (1964) in the pollen diagram of a late-glacial deposit at the Hafichuck site on the Missouri Coteau, Saskatchewan. This oscillation correlates chronologically and ecologically with the Dryas—Allerød—Dryas oscillation of western Europe (p. 691). The fill of the intramound depressions in southern Alberta suggests an oscillation from periglacial to warmer and dryer conditions and a return to a periglacial climate. At the Hafichuck site the lower and middle pollen assemblages of aquatic plants closely resemble „the differences between contemporary floras of stable kettle lakes of boreal and temperate regions of west-central Canada" (Ritchie and de Vries, 1964, p. 690). A radiocarbon date of 10,630±150 years B.P. was obtained for the top of the organic sediments that contained the lower, boreal, pollen assemblage (S-189). It correlates with the date obtained for shell fragments of a mound in southern Alberta and there is accordance of palynological and sedimentological events. When indeed Allerød oscillation, it is approximately 500 radiocarbon years younger than in western Europe (Tauber, 1960, 1962; v.d. Hammen and Vogel, 1966). The proposed correlation of the Two Creeks forest bed with the Bølling oscilation (Broecker and Farrand, 1963), would also indicate a discrepancy of similar order, compared with western Europe.

If the shell fragments are interpreted as Allerød, the preceding niveo-aeolian phase could possibly represent the Earlier Dryas Period (in the sense of v.d. Hammen and Vogel, 1966). The Bølling oscillation (or Two Creeks) could then be the minimum age for the melting of the ice cores, and of the formation of the intramound depression. A minimum age for the growth of prairie mounds would then be Earliest Dryas (Mankato) which terminated approximately 12,500 radiocarbon years ago (v.d. Hammen and Vogel, 1966).

MAXIMAL AGE

The maximum age of the prairie mounds is inferred from the age of the drift sheets on which they occur. Though there are no apparent differences in external form or measure of destruction of mounds occurring on different drift sheets and it is likely that all mounds of the Foremost-Cypress Hills area are approximately of the same age, this cannot be established on the basis of stratigraphic evidence. The principal occurrence of the mounds is on Etzikom Drift (Westgate, 1964, 1965), a less important occurrence on the younger Oldman Drift.

According to Westgate (1965), five drift sheets are exposed on the surface in the Foremost-Cypress Hills area. The oldest, the Elkwater drift was correlated with Advance 1 in Montana (Lemke, *et al.*, 1965), which was correlated with the Altonian substage of Frye and Willman (1960). The four younger sheets, Wildhorse, Pakowki, Etzikom and Oldman are all younger than 24,000 years according to Westgate (1965), who places all four in the Woodfordian substage of the Wisconsin, as defined by Frye and Willman (1963).

Westgate assigned these four sheets an age on the basis of two radiocarbon dates on till-buried soils in southwestern Saskatchewan (Prelate Ferry Paleosol, 20,000 ± 850, S-176; Marsden, 21,000 ± 800, S-228; Christiansen, 1965) and on wood buried by three till sheets at Medicine Hat, Alberta (24,490 ± 200, GSC-205; Dyck, Fyles and Blake, 1965).

However, two radiocarbon dates providing minimum ages for the topmost till deposits outside the limit of distribution of the Etzikom till (refer to Fig. 4) indicate that the Pakowki and Wildhorse till are older than concluded by Westgate.

A radiocarbon age of 34,900 ± 3,000-2200 years was obtained on a sample of charcoal fragments, collected from the top of a colluvial layer resting on till, 4 miles south of Irvine at 2,900 feet (885 m) above sea level. The till resembles the Pakowki till in erratica composition and in its colour (I 1878).

Vegetation debris and charcoal fragments are included in the basal current-bedded sands of a terrace deposit that rests on till, exposed in the valley of Manyberries Creek, 7 miles (11 km) northeast of Manyberries. No drift was deposited on the terrace sands and silts. The till underlying the deposit resembles the Pakowki till in colour and in erratica content. The radiocarbon age of the basal part of the terrace deposits is 20,600 ± 410 (I 2607). It is concluded that both locations were free of ice at the time that soils could be formed further north approximately 20,000—24,000 radiocarbon years ago, and have not been covered since. The older drift sheets, Elkwater, Wildhorse and Pakowki are either of earlier Wisconsinan vintage or older.

The Etzikom and Oldman drift sheets are petrographically different from earlier drifts. The erratics and fabric of the former indicate a northeasterly provenance, in the latter a northearly direction of flow of the depositing ice (Westgate, 1965). If the Etzikom till is indeed a correlative of the drift that covers the earlier mentioned radiocarbon sites in Saskatchewan and near Medicine Hat it would be younger than approximately 24,000 radiocarbon years. The same applies to the prairie mounds occurring on this drift. The age span of 12,500—24,000 radiocarbon years approximately straddles the Woodfordian substage of Frye and Willman (1960) in Illinois, the Pinedale glaciation in the Rocky Mountains (Richmond, 1965), and the Upper Pleniglacial in West Europe (van der Hammen, *et al.*, 1967). The establishment of permafrost in proglacial areas during this period is thus probable.

RIVER TERRACES AND LACUSTRINE DEPOSITS

Three terraces occur along the Manyberries, Peigan, Bullshead and Gros Ventre Creeks, which drain westwards and northwards from the Cypress Hills. The highest of these (I) is developed on Etzikom Drift along the lower courses of Bullshead, Gros Ventre and Peigan Creeks. Further upstream the terrace is developed on older drift deposits. No till has been observed to overlie the deposits of terrace I.

Terrace I occurs commonly between 20 and 50 feet (6 and 15 m) above present-day stream level. Its base is cut into till which is covered with a lag gravel and up to 10 feet (3 m) of sandy deposits. For Manyberries Creek the base of these deposits was dated at 20,600 ± 410 radiocarbon years (see above).

Along Peigan and Bullshead Creek it was observed that the lag gravel and the terrace deposits are covered by fan, delta or lacustrine sediments 1 to 4 miles (1.6—6.4 km) upstream from the main prairie mound belt; the latter is located on Etzikom Drift (above). As the till on which the terrace developed along the lower course of Peigan Creek is of Etzikom age (Westgate, 1965), this drift is older than 20,600 (I 2607, above).

The lacustrine deposits that transgress eastward and southward over the deposits of Terrace I are younger than Etzikom and younger than Terrace I. This would suggest that the situation, inferred from the hypothesis of origin of the prairie mounds above) i.e. proglacial inundation of the localities of mound fields on the Etzikom Drift, clearly younger than the drift (formation of terrace I), did indeed occur. Presently available data do not permit to arrive at a *post quem* date for the proglacial lake, other than the age of Terrace I along Manyberries Creak.

The two lower terraces (II and III) were formed after incision into Terrace I which attained, or extended beneath, present-day stream levels. Both terraces were accumulated after cutting down to present-day levels. Buried soils suggest ages of 3,000—4,000 radiocarbon years for II and 1,000—1,500 years for III (P. D. Jungerius, personal communication).

CONCLUSIONS

(1) As prairie mounds have been formed from till as well as proglacial lacustrine deposits this landform cannot be explained from sub-or superglacial processes, but must be of subquatic or subaerial origin. The association of the prairie mounds with a variety of sub-and superglacial landforms in the present-day landscape does not imply a genetic association, suggested by some previous studies of prairie mounds.

(2) The analogy in form with the collapsed pingos of western Europe as well as the variety of deposits that may constitute the mounds, makes a periglacial origin probable. The minimum and maximum age of respectively 12,500 and 24,000 radiocarbon years for the main mound occurrences in southern Alberta, a period of glacial advance in other areas, suggests that the mounds formed under cold climatic conditions in the Foremost-Cypress Hills area. Early during this period the Etzikom drift sheet was deposited in its northern part.

(3) In external form prairie mounds are similar to but not identical with the pingo ruins of western Europe. In comparison with the latter, prairie mounds have an excess of material in their ringwall and base. The stratigraphy and thickness of the drift, the lithology and topography of the bedrock under it, as well as the topography of the sites on which the majority of the prairie mounds of southern Alberta are located, indicate that earlier theories of pingo formation do not directly apply to the mounds (Müller, 1959; Mückenhausen, 1960; Wirthmann, 1964).

(4) The till from which mounds in southern Alberta are made would be highly mobile under supersaturated conditions, which are attained at relatively low moisture content. Its Atterberg limits are low, its content in montmorillonite high. With regard to these properties, the mode of origin of prairie mounds proposed by Mathews (1963), pingo formation combined with flow of material below a frozen overburden, is probable.

(5) The unusually high air intrusion values of the till indicate a substantial frost heaving potential when saturated. Below a rolling till plain, the thickest ice-segregations would form beneath the depressions. A penetrating permafrost front would advance more rapidly beneath the convexities of such topography; this front would arch upwards beneath the depressions.

(6) The penetration of the freezing front to depths below the surface at which no further ice-segregation takes place due to the weight of the overburden leads to supersaturation below the permafrost front. This occurs first below the convexities. Hydrostatic pressure differences in the super-saturated layer between areas beneath convexities and below concavities then make subsurficial movement of till possible.

(7) The formation of the positive relief form, the prairie mounds results from the formation of a „closed system"; „eruption" of supersaturated till is maintained by volume expansion at the penetrating permafrost front. Closed systems between an arched permafrost front and a bedrock surface are probable for scattered occurrences of prairie mounds in re-entrants of hilly topography. For the principal occurrences of prairie mounds in southern Alberta, the development of „closed systems" is concluded to have occurred against a fossil permafrost layer, as neither the topography of the bedrock surface nor the thickness of the drift are related to the distribution of prairie mounds.

(8) The alignment of prairie mound fields in belts that encircle higher tracts of land and that bend upstream into major river valleys, the regional association of prairie mound belts and proglacial lacustrine deposits, the approximately equal size of the mounds of a field, which suggest mound formation to have occurred at the same time for all mounds of the field, prompt the conclusion that the distribution of mound field belts is determined by the location of the shore zone(s) of proglacial lakes.

(9) Proglacial flooding occurred after the formation of the highest terrace occurring along several streams that drain northward or westward from the Cypress Hills. The terrace is developed on Etzikom drift, and lacustrine deposits transgress southward and eastward over it; the lakes along which the prairie mound belts were formed result from a glacial advance. This advance is younger than 20,600 radiocarbon years. It is probable that the proglacial lakes inundated terrain below which permafrost was es-

tablished, as glacier advance is a delayed reaction to colder climatic conditions.

(10) Prairie mound belts formed in areas where the permafrost partially thawed below the shore-zones of proglacial lakes prior to a lowering to the water level and subsequent re-establishment of permafrost in the drained zone.

(11) Scattered occurrences of prairie mounds in the re-entrants of hilly topography may be of approximately the same age as the prairie mound belts developed on Etzikom till, as suggested by their state of conservation. However, this conclusion could not be confirmed with stratigraphic evidence; it is tentative only.

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