CHAPTER

6

ICE-MARGINAL TERRESTRIAL LANDSYSTEMS: SOUTHERN LAURENTIDE ICE SHEET MARGIN

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6.1 INTRODUCTION

During the late glaciation, the Laurentide Ice Sheet (LIS) created the spectacular glacial landscape of northern North America. This landscape preserves a detailed record of the former ice-sheet size, subglacial bed conditions and ice-sheet behaviour. This chapter discusses the distribution of glacial landsystems that were created along the southern margin of the LIS in the northern USA during the late Wisconsin Glaciation (Fig. 6.1). As we show, landforms and sediments along the southern margin of the LIS are not randomly distributed but are arranged in patterns, which suggest that climate, topography, bed conditions and the resulting ice-sheet dynamics combined to yield distinct landsystems.

A difficulty in interpreting glacial features is the time-transgressive nature of the landscape. Ice-sheet conditions evolved and we must distinguish between landforms developed during cold conditions of ice advance and stability during the Last Glacial Maximum (LGM), and those that formed during deglaciation, when water was abundant and the ice margin was more dynamic. Because of this, our use of the word ‘landsystem’ is different from its use by others in this volume. We define a landsystem as ‘a genetically related set of landforms and sediments within a distinct region’. Others use landsystem as a synonym for ‘depositional environment’. Our definition of landsystem instead contains numerous depositional environments (such as subglacial and ice marginal) that are created by a single ice lobe during a restricted time interval (such as a glacial phase). As genetic processes change with time and environments migrate laterally, one landsystem is superimposed on another. Therefore, to speak of a particular area as containing one specific landsystem is misleading as numerous depositional environments, during multiple phases, produce a suite of landforms and sediments. Commonly, an area is dominated by one landsystem, but includes older (palimpsest) or younger features (superimposed). Our experience and our landsystem maps reflect this, in that we find that two or three landsystems are commonly superimposed even in a small area such as is covered by a 7.5 × 7.5 minute USGS. quadrangle. Nevertheless, the purpose of thematic mapping is to generalize and show patterns within the complexity of nature.

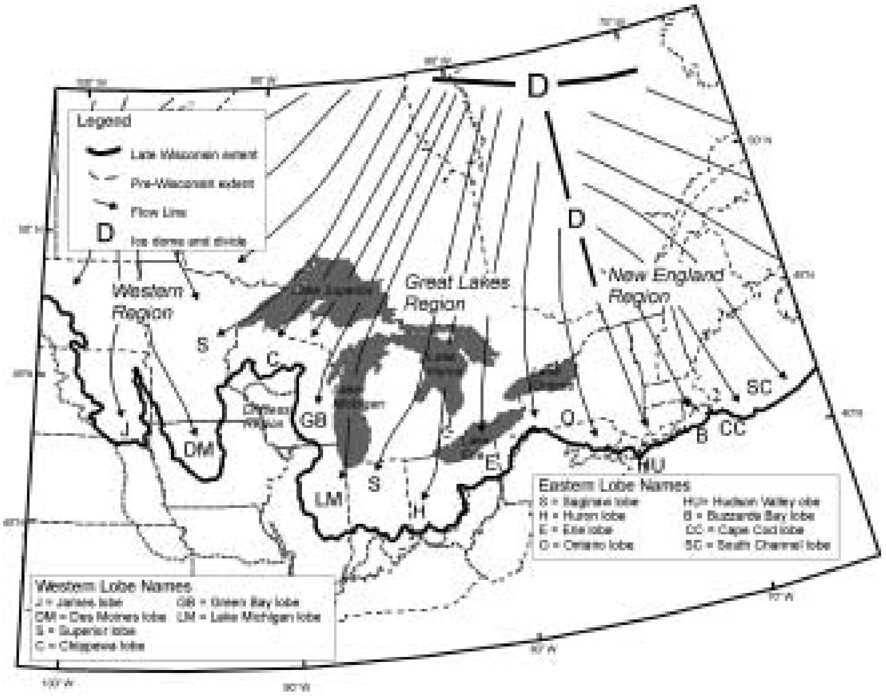


Figure 6.1 The maximum extent of southern margin of the Laurentide Ice Sheet. The Last Glacial Maximum extent was probably never a continuous ice margin because each lobe reached its maximum position at slightly different times and began retreating at different times. For example the Des Moines lobe and other lobes in the western region reached their maximum extent sometime after 14,000 ^{14}C years BP, whereas the most of the lobes in the Great Lakes region reached their maximum positions earlier at about 21,000 ^{14}C years BP. Lobes in New England may have reached their maximum even earlier by about 23,000 ^{14}C years BP. Ice flow directions and ice divides are after Dyke and Prest (1987), and Veillette *et al.* (1999).

We seek to understand the southern LIS by:

1. mapping the distribution of landforms and sediments and classifying them (as landsystems)
2. interpreting conditions of landform-sediment genesis, and
3. deducing characteristics of the ice sheet from those features.

We restrict most of our discussion to landforms created during the maximum extent of the LIS. We also discuss how in many areas, landforms and sediments created during deglaciation changed significantly from those created during advance and while ice was at its maximum position. This indicates that glacier-bed conditions also changed significantly between the LGM and deglaciation.

6.2 PHYSICAL SETTING AND TIMING OF GLACIATION

Ice advanced into northern USA after 26,000 ^{14}C years BP, yet the LGM extent was reached at different times in different places (Mickelson *et al.*, 1983). Lobes in the Great Lakes and New

England regions reached their maximum before 21,000 ^{14}C years BP. Rapid decay of the ice sheet began after 14,500 ^{14}C years BP. Although lobes to the west of the Great Lakes also advanced before 21,000 ^{14}C years BP, they reached their maximum extent at about 14,000 ^{14}C years BP, out of phase with the rest of the ice-sheet margin (Hallberg and Kemmis, 1986). Readvance of lobes, some perhaps as surges, are recorded all along the southern LIS margin at 13,000 ^{14}C years BP, 11,800 ^{14}C years BP and 9,800 ^{14}C years BP. After about 9,800 ^{14}C years BP ice retreated out of northern USA (Mickelson *et al.*, 1983).

The southern margin of the LIS stretched from Montana to Maine (Fig. 6.1). In the west the margin was highly lobate as it enlarged the bedrock-controlled lowlands of preglacial river valleys (Fig. 6.2). The Des Moines and James lobes advanced to 42°N into central Iowa and eastern South Dakota, respectively, after being split by the Prairie Couteau as ice moved south through the Red River lowland. The Superior and Chippewa lobes advanced southwestward out of the Superior lowland. The Green Bay lobe, Wisconsin Valley and Langlade sublobes were fed by ice advancing over the eastern end of the Superior lowland. The Lake Michigan lobe flowed down the axis of Lake Michigan, and into southern Illinois, to nearly 38°N. The Huron

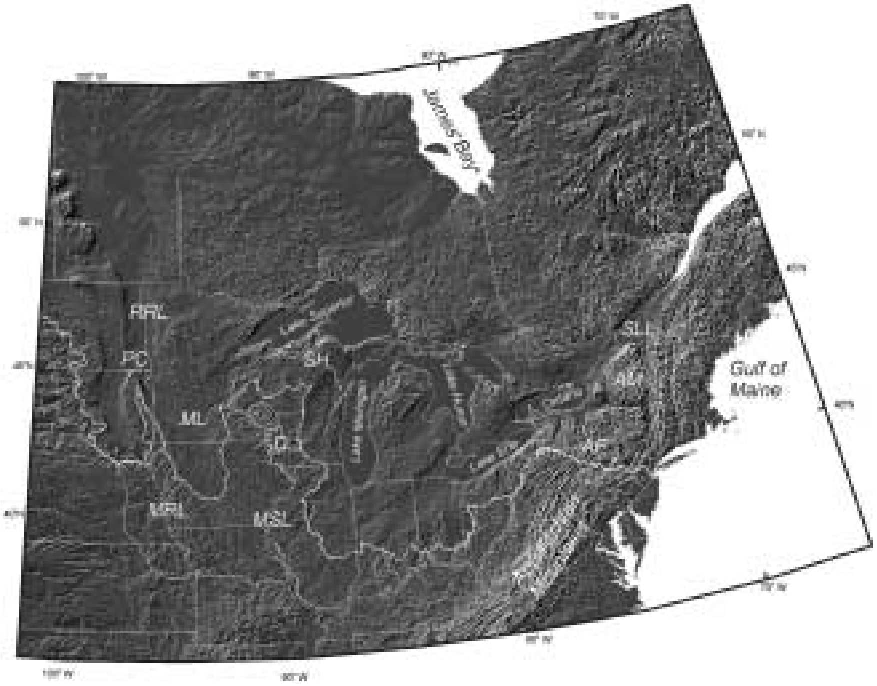


Figure 6.2 Shaded relief image showing the first-order topography the northern USA. The major physiographic features of the study area discussed in the text are labelled. RRL = Red River Lowland, PC = Prairie Couteau, ML = Minnesota Lowland, MRL = Missouri River Lowland, D = Driftless Region, MSL = Mississippi River Lowland, SH = Superior Highlands, AP = Appalachian Plateau, AM = Adirondack Mountains, SLL = Saint Lawrence lowland. The white line indicates the maximum extent of the Late Wisconsin Laurentide Ice Sheet. The grey line shows the maximum extent of pre-Wisconsin advances. (Data are from US Geological Survey ETOPO5 database.)

and Saginaw lobes advanced out of Huron lowland into Michigan and Indiana. In Indiana and Ohio, sublobes of the Huron and the Erie lobes advanced to nearly 39°N. The ice margin in Pennsylvania and New York was less lobate and formed a major re-entrant as it encountered the Appalachian Plateau and the Ridge and Valley Province. Small tongues of ice did project down narrow river valleys, but these were smaller than the lowland lobes to the west. Farther to the east, the ice-sheet margin remained much less lobate with the exception of the Hudson River and the Cape Cod lobes. Ice in eastern New England advanced well into the Gulf of Maine and onto the exposed continental shelf.

6.3 METHODS

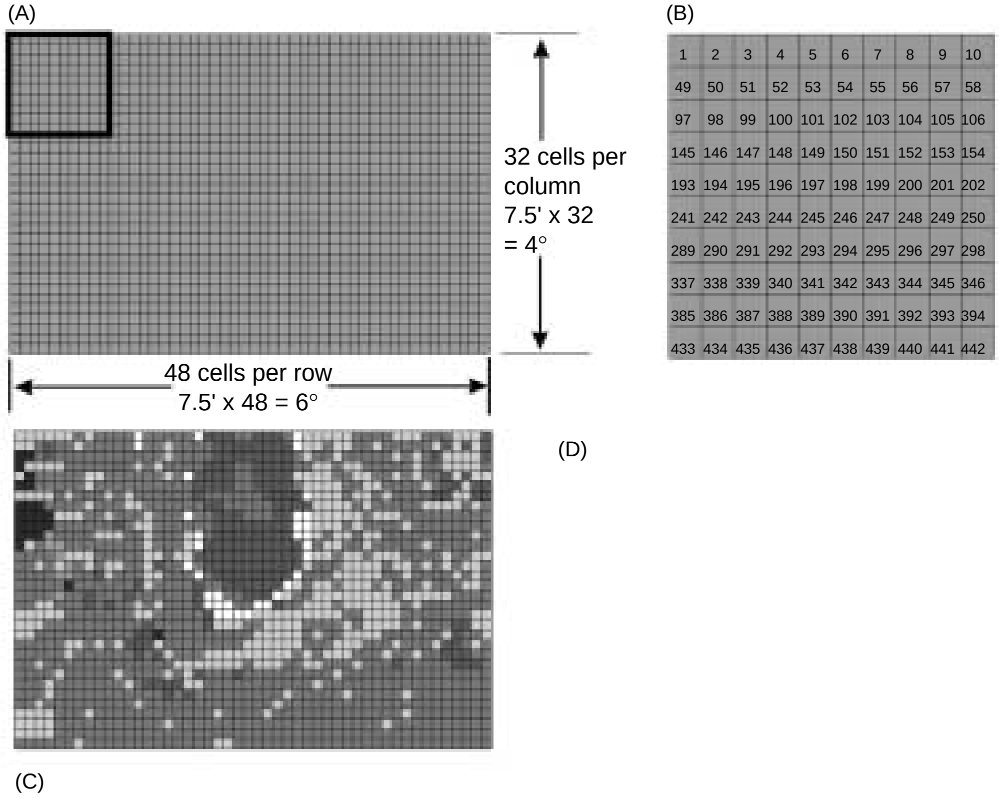
We compile information about the distribution of glacial landforms and sediments in northern USA from North Dakota to Maine. Our compilation aims to minimize interpretations of genesis in the data collection because we do not fully understand the details of the genesis or conditions of formation of all landforms.

Unfortunately, past mapping has been non-standardized in different areas and the comparison of features from published sources is difficult. Ridges called end moraines in one area are not called end moraines in another (e.g. central Iowa). Similarly, different criteria are used to recognize streamlined features. This makes it difficult to compare areas using only existing glacial maps. Because of this, we examined the raw data sources (topographic maps, etc.) from which these maps have been created. We have used published maps and reports for information about sediment types. These are supplemented locally with high-resolution digital elevation models. Thus, we use a combination of published reports and maps and interpretation from topographic maps, digital elevation models and aerial photographs to add to the compilation.

6.4 MAPPING AND CLASSIFICATION OF THE DATA

Our database consists of sedimentologic and geomorphic information. Data are compiled in a pseudo-raster format with each cell dimension consisting of 7.5 minutes of latitude by 7.5 minutes of longitude (Fig. 6.3). The study area is divided into 18 zones (each 4 by 6 degrees). Each zone is represented with a grid of 1536 cells (Fig. 6.3). Some zones contain less than this number of cells because they border Canada or the ocean. In each zone, cells are represented by vector polygons, and each is linked to an attribute table, which lists the features found in that cell. For example if drumlins are present in a given $7.5' \times 7.5'$ area the attribute table notes this with the integer ‘1’ in that attribute column for that cell. If drumlins are not located in this area then a ‘0’ is entered. In other attribute columns the type of sediment that lies at the centre of that cell is recorded by an integer value. By this method the presence or absence of glacial features can be recorded, or the type of sediment, sediment thickness or other attribute of the area can be entered into the database.

To create our current maps we used nine attributes for which we have complete coverage (Fig. 6.4). These nine attributes are used as input to create the landsystem maps. From these nine attributes we defined seven different landsystems. Fig. 6.5 illustrates how the nine attributes were used to create the seven landsystems shown in Fig. 6.6. Some landforms are considered more important than others in this classification scheme. This is the case for features that we



1	2	3	4	5	6	7	8	9	10
49	50	51	52	53	54	55	56	57	58
97	98	99	100	101	102	103	104	105	106
145	146	147	148	149	150	151	152	153	154
193	194	195	196	197	198	199	200	201	202
241	242	243	244	245	246	247	248	249	250
289	290	291	292	293	294	295	296	297	298
337	338	339	340	341	342	343	344	345	346
385	386	387	388	389	390	391	392	393	394
433	434	435	436	437	438	439	440	441	442

Figure 6.3 The structure of our geologic database. A) Grid of 1536 cells. We used part of 18 of these grids to cover the study area. B) A close-up of the numbering of the cells that are highlighted in black in A. Each cell is numbered and linked to a database table shown in D. C) An example of a map showing the distribution of sediment types in each cell. D) An attribute table showing the feature attributes for each cell. Though we only show seven attributes here, the database contains more than two dozen attributes for each cell area.

believe are the defining characteristic of a landsystem such as drumlins, till plains with thick glacial sediment, and low-relief hummocky plains. For example, any cell in which drumlins occur is classified as landsystem B (see Fig. 6.6a). Many cells contain landforms and sediments of more than one landsystem because landsystems created during deglaciation were superimposed upon LGM landsystems or because the size of each cell encompasses two or more distinct areas. Nevertheless, our maps show the regional-scale distribution of the dominant landsystems.

6.5 LANDSYSTEMS OF THE SOUTHERN LAURENTIDE ICE SHEET

Our maps show seven different landsystems (Fig. 6.6). We restrict our discussion here to the four landsystems that we believe are linked to bed conditions and glacier dynamics during the LGM:

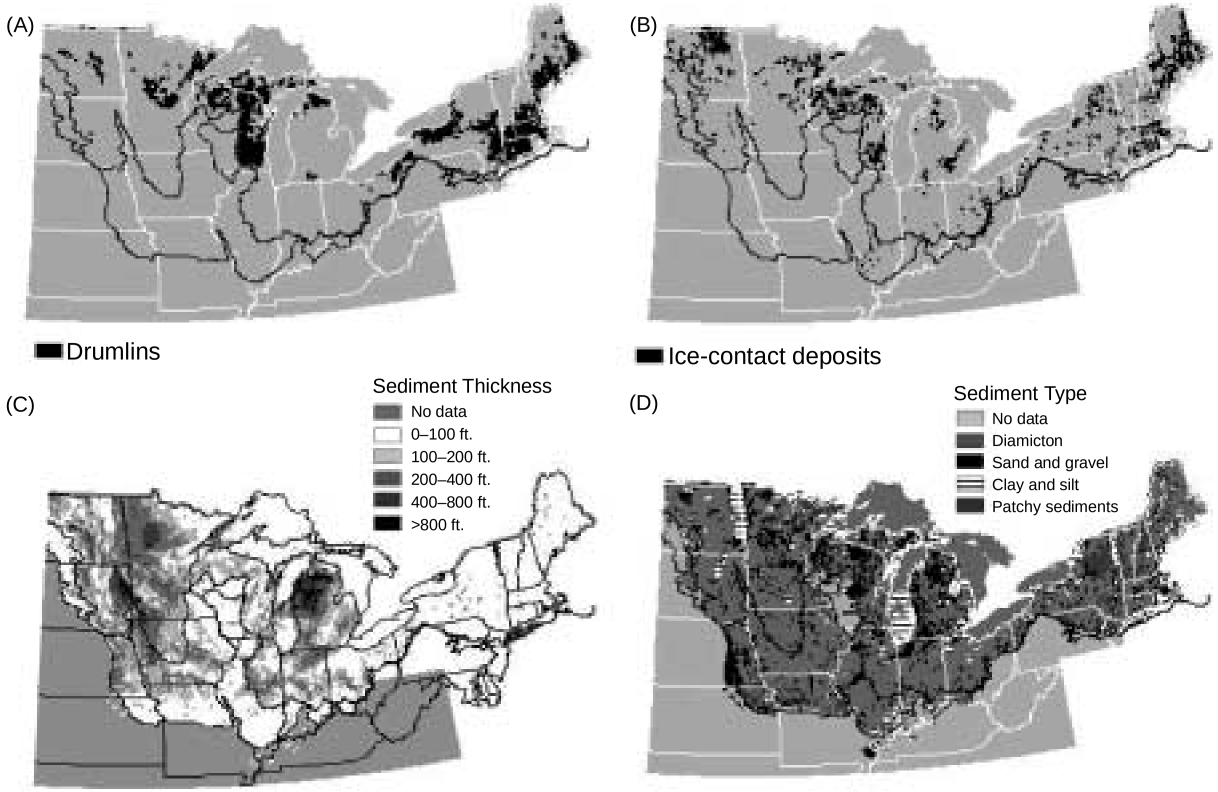


Figure 6.4 Four of the nine input data themes used in creating the landsystem maps. A) Distribution of drumlins. B) Eskers and other ice-contact deposits. C) Glacial sediment thickness from Soller and Packard (1998). D) Surficial sediment cover, also from Soller and Packard (1998).

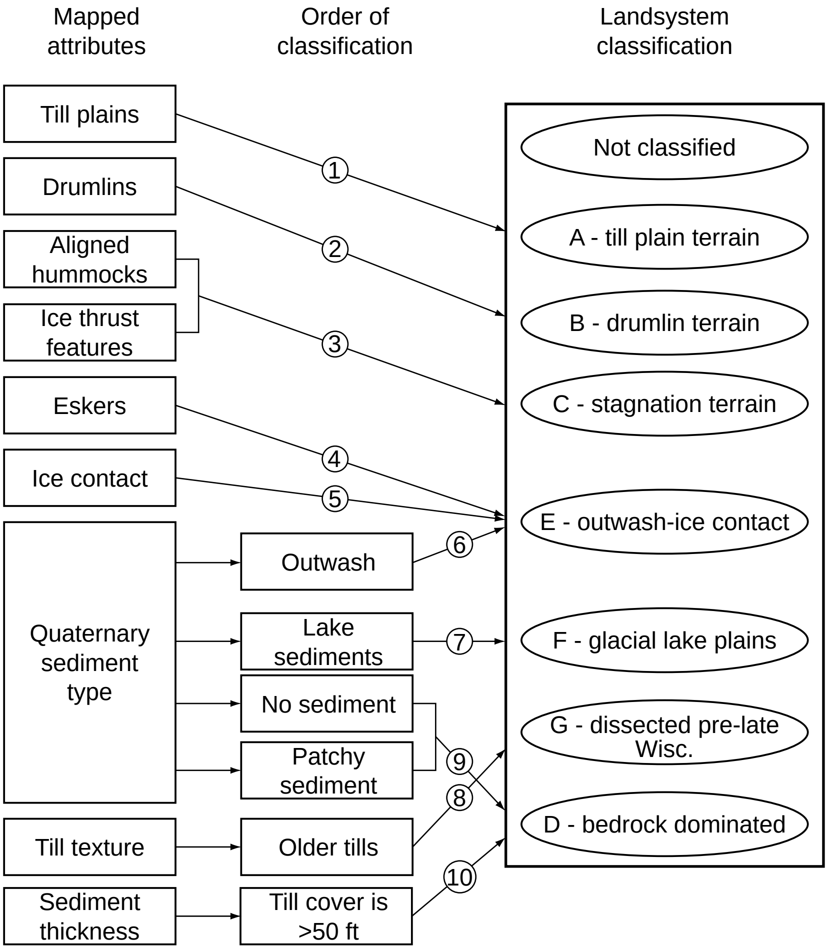
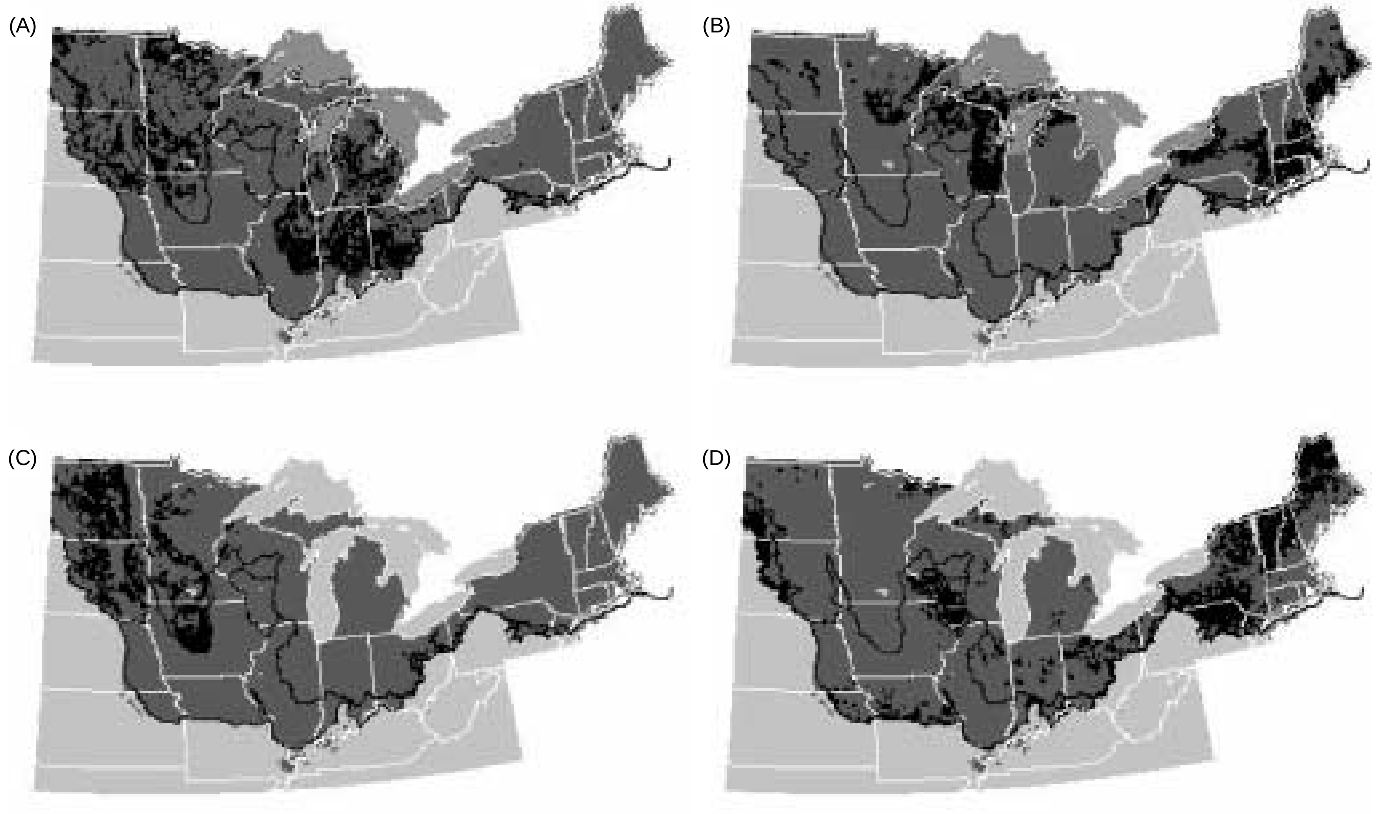


Figure 6.5 Flow-chart showing the classification methods used to create the landsystem maps (see Fig. 6.6). Input layers on the left were classified into the seven landsystems shown on the right. The order and type of classification are shown in the middle. The numbers show the order in which the classification was carried out. Classification was done by using a series of structured-query-language commands on the database tables.

1. low-relief till-plains (landsystem A)
2. drumlins and high-relief moraines (landsystem B)
3. low-relief hummocks and ice-thrust terrains (landsystem C)
4. bedrock-dominated glacial landscapes (landsystem D).

Glacifluvial (landsystem E) and glacilacustrine features (landsystem F) dominate two additional landsystems. Landsystems D and G were primarily created before the LGM, although there has clearly been continuing evolution of the landscape up to the present.


(A)
(B)
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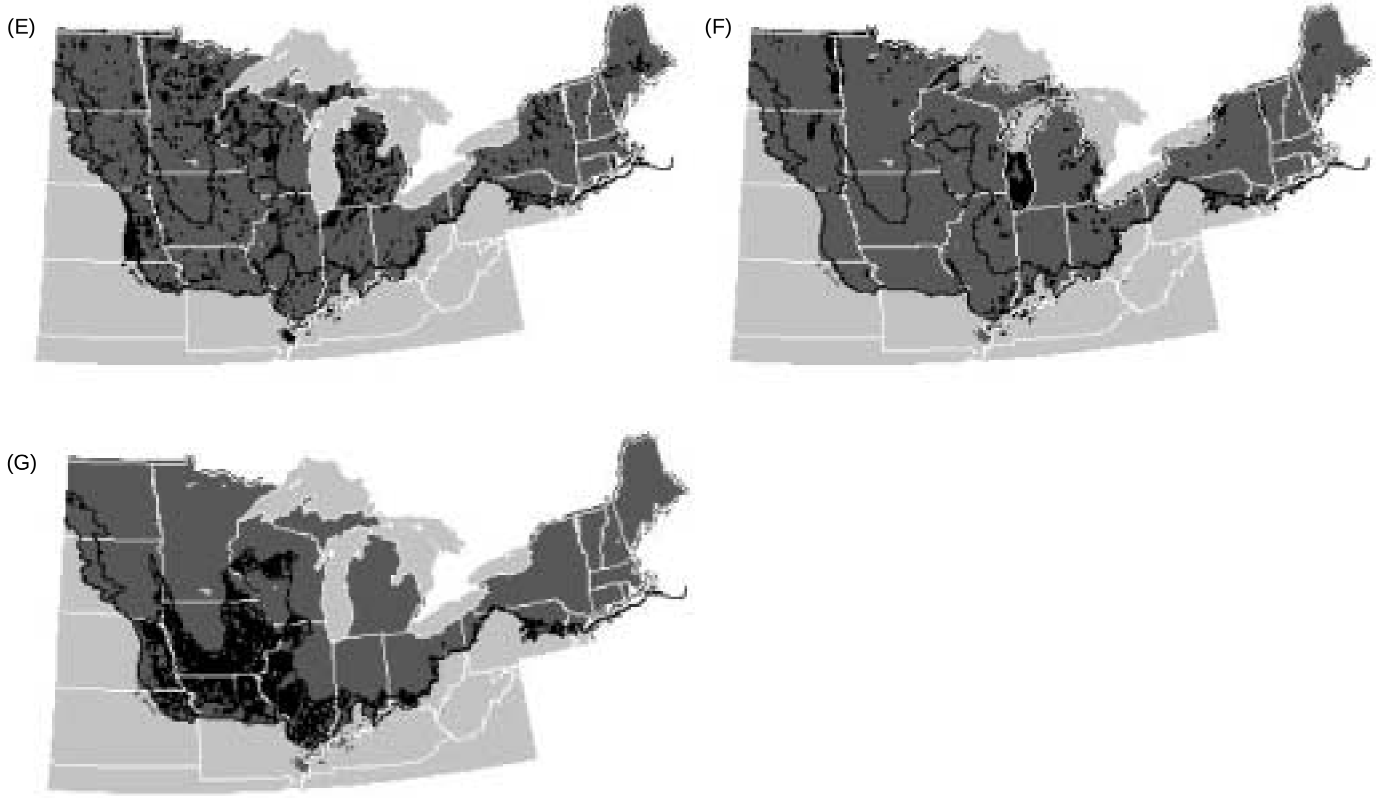


Figure 6.6 Landsystem maps of the area covered by the southern margin of the Laurentide Ice Sheet. Each cell (7.5’ × 7.5’) corresponds to a classification set shown in Fig. 6.5. Dark line shows the extent of Late Wisconsin glacial maximum. Light grey line shows the maximum extent of Pleistocene glaciation.

6.5.1 Landsystem A – Low-Relief Till Plains and Low-Relief End Moraines

Landsystem A occurs extensively in Ohio, Indiana, Illinois, Michigan, Minnesota, Iowa, North and South Dakota. It formed when ice was at or near its maximum southern extent and during retreat (Fig. 6.6A). We divide landsystem A into two zones: ice-marginal and subglacial (Figs 6.7 and 6.8). We interpret that landsystem A primarily reflects subglacial sediment transport and subsequent deposition as basal till.

6.5.1.1 Ice-Marginal Zone

This zone is composed of a ramp of diamicton inclined up-glacier. Steeply sloping fans composed of outwash and debris flow sediment occur along the outer edge of this zone. Proglacial outwash deposits merge into valley train deposits. Along the outermost margin of the ramp, older glacial and non-glacial deposits are deeply dissected by stream erosion. Fine-grained sorted sediment is present in major stream valleys.

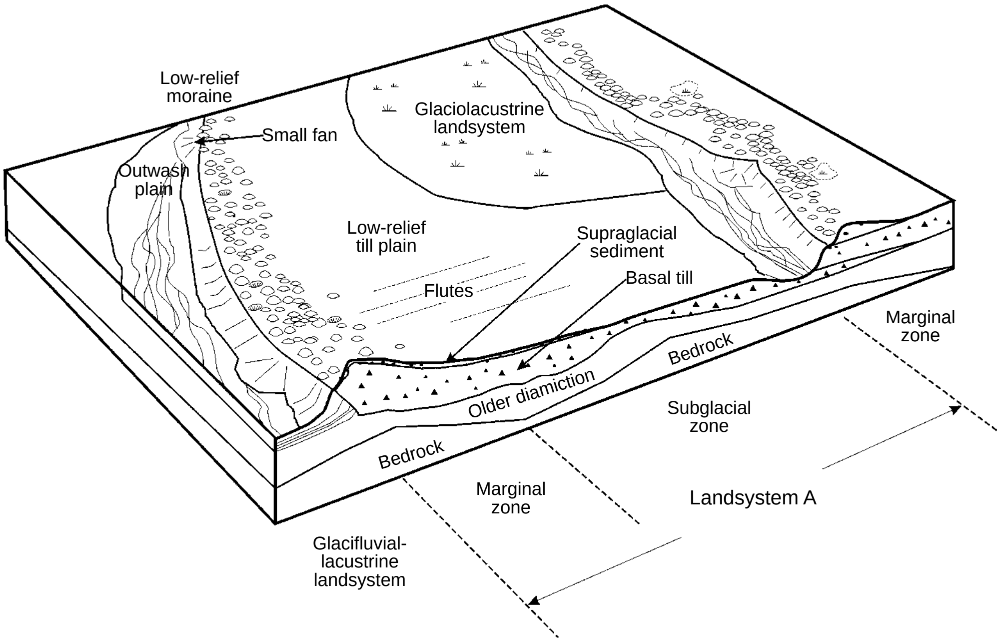


Figure 6.7 Schematic diagram showing the distribution of landforms and sediments in landsystem A. The marginal zone consists of a broad, low-relief end moraine composed primarily of basal till over older glacial drift with a cover of supraglacial sediment. The subglacial zone consists of till plain also composed of basal till with few features except for rare flutes. In the subglacial zone supraglacial sediment may be completely absent. Glacifluvial (landsystem E) and glacilacustrine (landsystem F) landforms and sediments fronted this landsystem in the proglacial area or were superimposed on this landsystem during deglaciation. Bedrock in this area only rarely crops out, and glacial deposits area generally greater than 15 m thick. During retreat, ice-marginal zones of landsystem A were superimposed on older landsystems as is shown on the right of the diagram. In the southern Great Lakes region in Illinois, Indiana, and Ohio each readvance deposited a wedge-shaped sheet of basal till on top of older sequences during retreat.

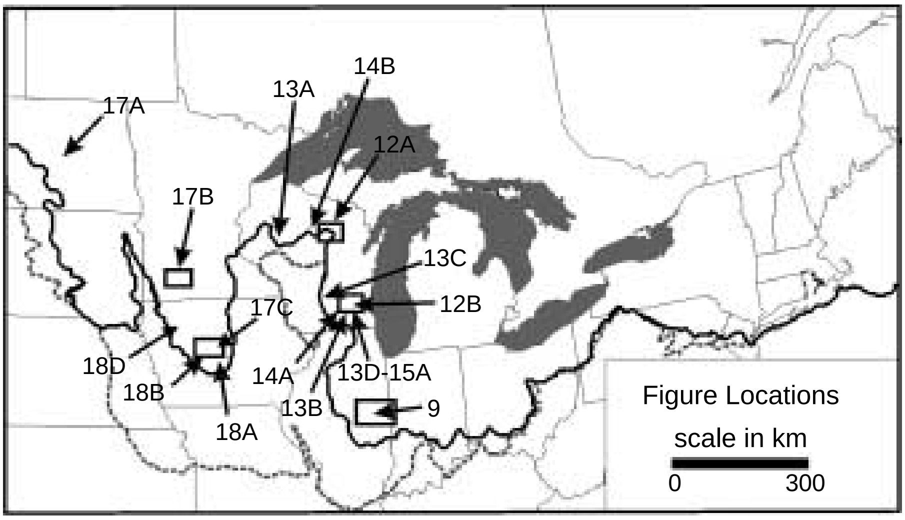


Figure 6.8 The location of aerial photographs and images cited in the text.

End moraines in landsystem A are 2–20 km wide, with asymmetric cross sections (Figs 6.9 and 6.10). The distal sides of the moraines have 1–2 per cent slopes, whereas the proximal slopes are less than 1 per cent (Hansel and Johnson, 1999). The moraine surface is smooth, except for postglacial gullies cut into surfaces (Fig. 6.9). Low-relief hummocks and closed depressions are rare and the internal moraine relief is generally less than 3 m. Moraines are mostly composed of homogenous diamicton interpreted to be basal till capped with a thin layer (<2 m) of heterogeneous diamicton that may be supraglacial sediment. Although some of the material in the moraines is local, it has been suggested that most of the sediment originated a considerable distance up-ice and was transported into the area with little modification except clast abrasion (Hansel and Johnson, 1999). Many of the moraines have far-travelled erratic boulders concentrated at or near the surface.

6.5.1.2 Subglacial Zone

Behind the end moraine lies a flat or gently undulating till plain (Figs 6.7 and 6.9). The plain has few distinct landforms and generally a local relief less than 3 m. Rarely, a few low-relief flutes are present (Hansel and Johnson, 1999). Much of the diamicton is basal till, although locally there is a thin veneer of supraglacial sediment and a loess cap.

Stacked sequences of late Wisconsin diamicton and sorted sediments make up both moraines and till plains (Johnson and Hansel, 1990; Hansel and Johnson, 1996, 1999). Many of the moraines are composite forms and were modified during more than one advance or period of stability during the late Wisconsin. Palaeosols have been preserved between diamicton sheets. Diamicton units are wedge shaped, with their thickest end in the moraine zone and thinning to a wedge under the till plain. Sub-diamicton contacts are generally clear and show little thrusting or folding-in of older sediment. In some places, sub-bed material has been incorporated into the overlying diamicton. At a few sites, clast concentrations and clast pavements have been reported, but these appear to be neither continuous nor widespread.

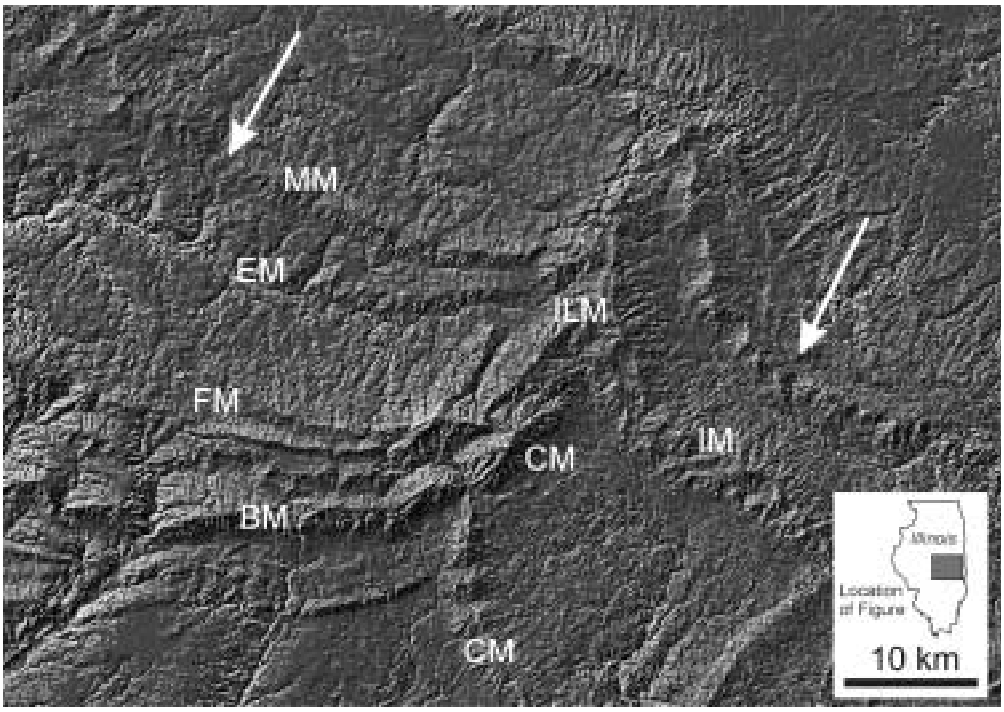


Figure 6.9 A shaded-relief image derived from a 30 m US Geological Survey DEM of the southern part of Lake Michigan lobe area. Moraine names are from Hansel and Johnson (1996). MM = Minonk moraine, EM = El Paso moraine, FM= Fletchers moraine, BM = Bloomington moraine, CM = Champaign moraine, IM = Illiana moraine, ILM = area of interlobate moraine. Each end moraine has a steep distal margin and a ramp-like proximal margin. Note that much of the surface roughness is the result of postglacial fluvial erosion as gullies and streams. Both the marginal and subglacial zone have very little original roughness or internal relief.

6.5.2 Interpretation of Landsystem A

The characteristics of landsystem A, with its till plains, and broad low-relief moraines suggest the following:

1. subglacial sediment transport as englacial and subglacial deformation till
2. little accumulation of debris on the ice surface and deposition as supraglacial sediment
3. ice motion dominated by some combination of sliding, ploughing and subglacial deformation
4. active ice with progressive retreat of the terminus.

There appears to have been very little, and perhaps no subglacial erosion of pre-existing sediments in the marginal areas. Widespread paleosols present on older units, indicate limited erosion. Certainly, abrasion was taking place, and striated surfaces, rare clast-pavements and striated boulders are present throughout the area. The wedge-shaped till sheets suggest erosion by later advances but probably only at their up-ice ends.

Unlike landsystem B, drumlins are absent. With the exception of a few low-relief flutes, there appear to be no streamlined features. Tunnel channels, a common feature in landsystems B and C are also absent. Likewise, ice-thrust masses and composite ridges, a common feature of landsystem C, and to a lesser extent landsystem B, are also absent. Eskers are nearly absent. The distribution of outwash along the former ice margins suggests that water was delivered to the ice margin in small subglacial or englacial tunnels as opposed to being concentrated in large discharge events or esker tunnels as in landsystems B and C.

Permafrost may have been present in Illinois, Indiana and Ohio (Johnson, 1990), but it was probably thinner than that in areas farther north. Wood preserved in tills in Illinois, Indiana and Ohio suggests that the Lake Michigan, Saginaw, Huron and Erie lobes advanced into areas with trees so it is likely that permafrost was discontinuous (Mickelson *et al.*, 1983; Ekberg *et al.*, 1993; Hansel and Johnson, 1999).

We support the conclusions of others that till in this landsystem was transported and deposited at the base of the ice, perhaps as a deforming bed (Boulton and Jones, 1979; Beget, 1986; Alley, 1991a; Clark, 1992; Hansel and Johnson, 1999). Ice motion was probably accommodated for by a combination of sliding, ploughing and subglacial deformation. What is not clear is whether transport prior to deposition was as a subglacial deforming bed of dimensions metres-thick, or as melt-out of debris-rich ice in slabs detached near the terminus.

In summary, landsystem A with its till plains and broad low-relief moraines suggests:

1. predominantly subglacial sediment transport
2. little accumulation of debris on the ice surface
3. ice motion dominated by some combination of sliding, ploughing and subglacial deformation
4. initial advance over an unfrozen subglacial bed followed by progressively retreating active ice during deglaciation.

6.5.3 Landsystem B – Drumlins and High-Relief Hummocky End Moraines

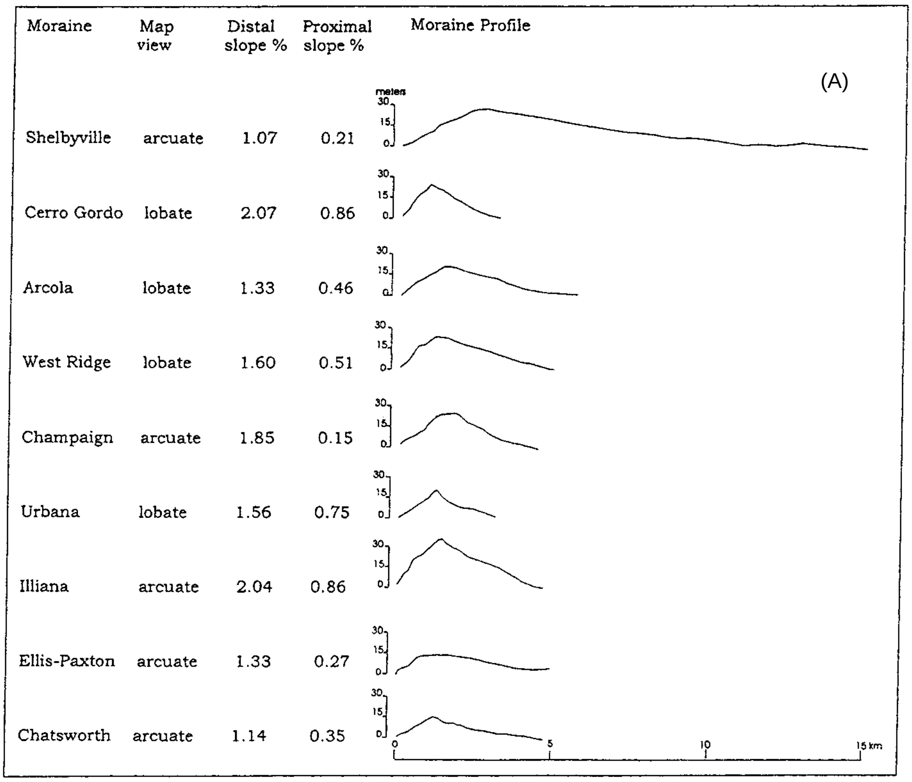
Landsystem B is located in North Dakota, Minnesota, Wisconsin, northern Michigan, Pennsylvania, New York, New England and as a small window in southern Michigan (Fig. 6.6A). It is dominated by drumlins, sandy diamicton and high-relief, hummocky end moraines. We interpret that this landsystem reflects subglacial erosion and supraglacial deposition near an active ice margin.

6.5.3.1 Ice-Marginal Zone

This zone is a landscape that has always been mapped as end moraine (Figs 6.11 and 6.12). The zone is 2–20 km wide and consists of moderate- to high-relief hummocks in end moraines. The end moraine stands 5–40 m above the surrounding landscape (Fig. 6.10B). Distal and proximal slopes of the end moraine exceed 2 per cent. The internal relief of hummocks is much higher than in the smooth moraines of landsystem A. In most places the moraines are narrower (<2 km), but are about the same height as moraines in landsystem A. Within wider hummocky end moraines are large flat plateaux of sorted sediments and glacilacustrine sediment that have been interpreted as ice-walled lake plains (Johnson *et al.*, 1995; Ham and Attig, 1996). Ice-walled lake plains are found in Minnesota, North Dakota, Wisconsin, Michigan and in southern New England (as the ‘high kames’ of Stone and Peper, 1982).

Moraine composition is different from that in landsystem A. There is a much larger component of glacifluvial sand and gravel and much thicker accumulations of diamicton interpreted to be supraglacial sediment. Layers of sand and gravel, supraglacial sediment and basal till are stacked-up in this zone (Lundqvist *et al.*, 1993; Johnson *et al.*, 1995). Some of the gravel in the moraine was deposited in subglacial tunnels close to the ice margin (Lundqvist *et al.*, 1993). Erratic boulders are scattered on the moraine and were carried long distances from the Canadian Shield. In moraine exposures, beds of gravel and till are steeply dipping in the up-ice direction, indicating ice push and localized ice-thrusting (Oldale and O'Hara, 1984; Mooers, 1990).

Unlike landsystem A, the distribution of proglacial outwash outside the margin is concentrated in a few places. Large volumes of outwash were deposited as alluvial fans from the mouths of tunnel channels. Tunnel channels intersect the outermost moraine about every 5–10 km in Wisconsin and Minnesota. Most of the sediment in the outwash plains in front of the ice margin was delivered by these tunnel channels (Wright, 1973; Attig *et al.*, 1989; Mooers, 1989a; Patterson, 1994; Clayton *et al.*, 1999; Cutler *et al.*, 2001; Cutler *et al.*, 2002). Tunnel channels are about 0.5–1 km across where they intersect the moraine. Sometimes a steep-sided channel is present within the moraine, but often it is filled with hummocky sand and gravel, which collapsed as ice melted. Mapping of the channels in the Green Bay lobe indicates that water was driven up as much as 80 m in elevation (Fig. 6.10B) as it approached the ice margin



Moraine	Map view	Distal slope %	Proximal slope %
Shelbyville	arcuate	1.07	0.21
Cerro Gordo	lobate	2.07	0.86
Arcola	lobate	1.33	0.46
West Ridge	lobate	1.60	0.51
Champaign	arcuate	1.85	0.15
Urbana	lobate	1.56	0.75
Illiana	arcuate	2.04	0.86
Ellis-Paxton	arcuate	1.33	0.27
Chatsworth	arcuate	1.14	0.35

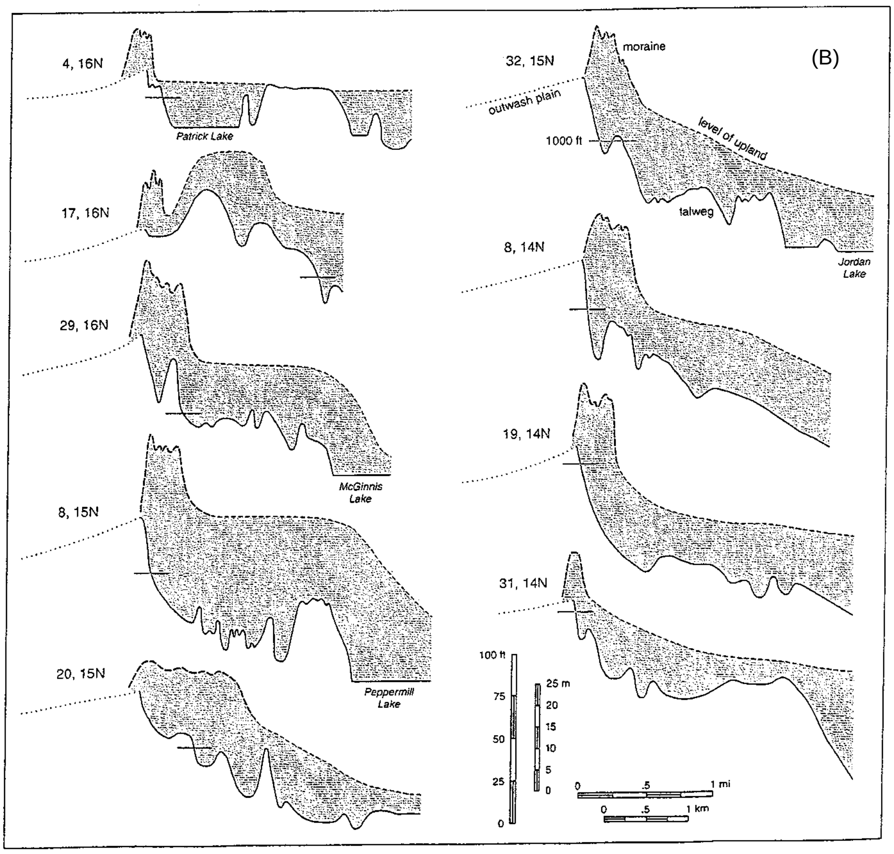


Figure 6.10 A) Distal and proximal slopes of Lake Michigan lobe moraines (from Hansel and Johnson, 1999). B) Topographic profiles through end moraines of the Green Bay lobe showing moraine surface profiles in grey and tunnel channel bottom with the lower solid line. The dotted lines to the left of each profile show the slope of tunnel channel outwash fans (from Clayton *et al.*, 1999). Note that the horizontal and vertical scales are different for each figure.

(Clayton *et al.*, 1999). Some sediment within the fans is extremely coarse. Intermediate axes of boulders of up to 2 m have been described in the proximal part of the fans, grading into fine sand in the distal part of the fan (Cutler *et al.*, 2002).

A considerable volume of sand and gravel, and supraglacial sediment is present in interlobate areas and in the moraines themselves, indicating that there was more sediment on the ice surface than in landsystem A. During the retreat phase there was substantial sediment transport by supraglacial and englacial streams on and within the ice.

6.5.3.2 Subglacial Zone

The landforms in the subglacial zone are strikingly different from those in landsystems A and C. In landsystem B most of the surface has been streamlined by ice flow (Figs 6.12 and 6.13). Drumlins and megaflutes up to 50 m high and as long as 30 km occur throughout this zone

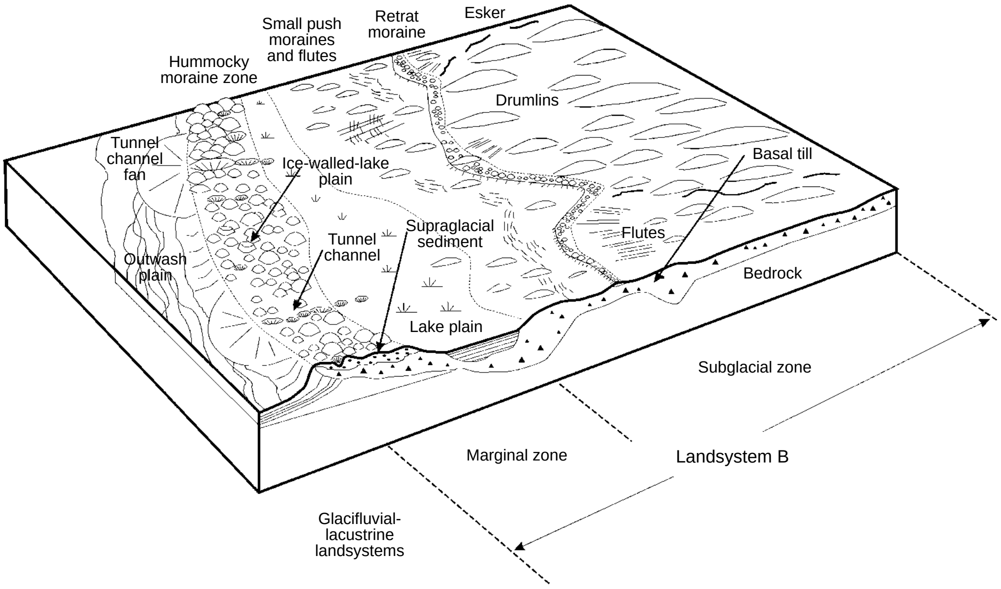


Figure 6.11 A schematic diagram showing the landforms and sediments in landsystem B. The marginal zone is dominated by high-relief hummocky topography. This zone contains a thick cover of supraglacial sediment, over basal till and sand and gravel. The subglacial zone is dominated by drumlins and flutes. This area contains less supraglacial sediment as a very thin cover sometimes existing as small moraines that were deposited during retreat. Eskers and other ice-contact material were also deposited during retreat. Bedrock in this area is usually covered with glacial sediments, but in many areas the glacial sediment cover is very thin (<5 m).

(Colgan and Mickelson, 1997). Thousands of drumlins occur in eastern Minnesota, in Wisconsin, Michigan, New York and in southern New England.

The composition of most of the drumlins is not known. In Wisconsin, New York and Massachusetts, some drumlins are composed of stratified sand and gravel (Upham, 1894; Alden, 1905; Fairchild, 1907; Whittecar and Mickelson, 1977, 1979; Stanford and Mickelson, 1985). Other drumlins are composed of diamicton, some have bedrock cores and some contain lake-sediment (Alden, 1905; Colgan and Mickelson, 1997). In Wisconsin and southern New England at least, the drumlins appear to be composed to a great extent of material that pre-dated the drumlin-forming phase (Whittecar and Mickelson, 1977, 1979; Stanford and Mickelson, 1985; Newman and Mickelson, 1994). Thus, drumlins appear to be partly erosional features, although certainly part of their height and length is attributable to growth beneath the ice from sediment moving toward the axis of the drumlin and deposition of diamicton and down-ice accretion of eroded material (Boulton, 1987). It has been argued (Mooers, 1989b) that drumlins formed at different times during retreat, but the largest fields formed when ice was near its outermost position. Smaller drumlin fields were then superimposed on larger forms as ice retreated and briefly stabilized at other positions (Colgan and Mickelson, 1997).

Throughout landsystem B, diamicton is fairly thin. In many places the diamicton of the last glacial maximum lies directly on bedrock. Basal till in the subglacial zone contains a high

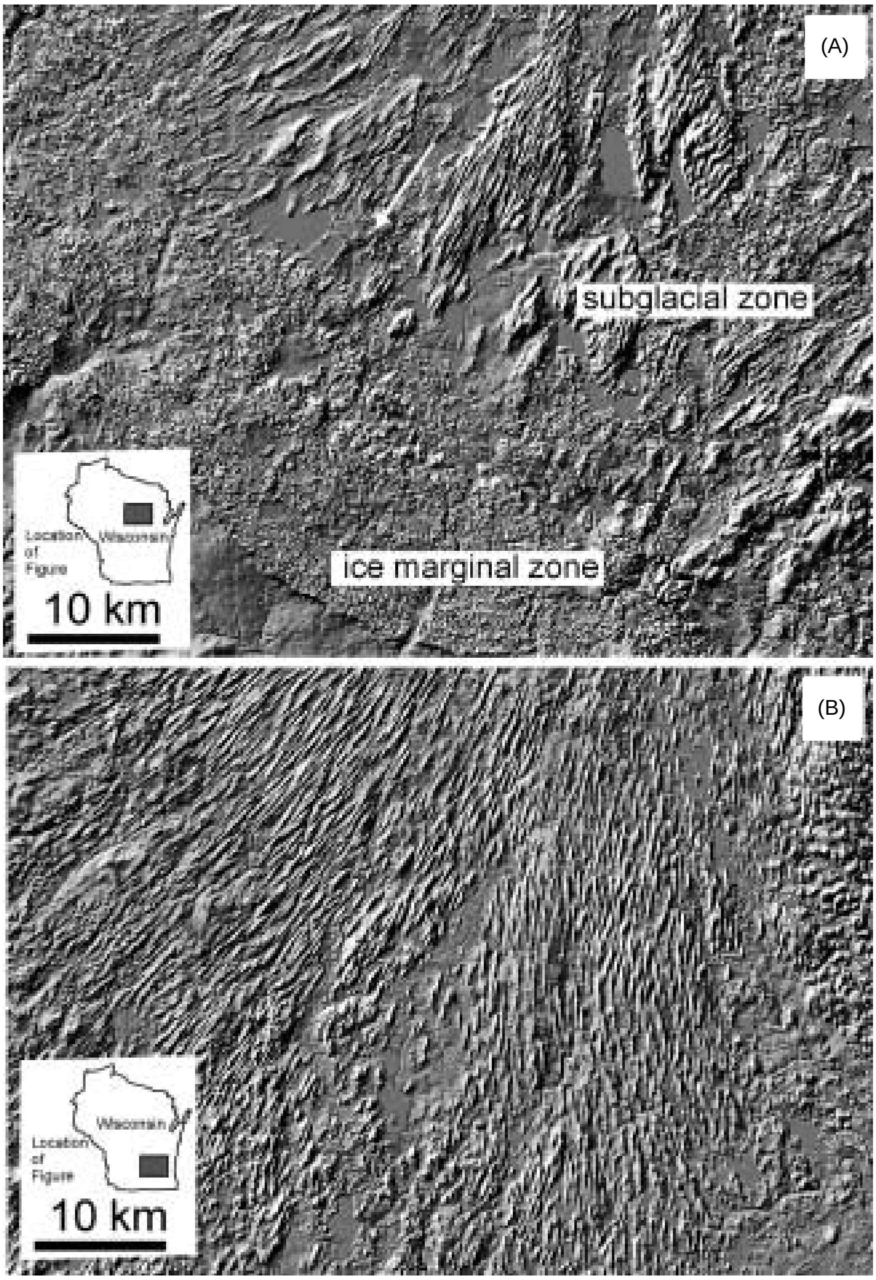


Figure 6.12 A) A shaded-relief image showing the topography of landsystem B in northern Wisconsin. This landsystem was created by the Langlade lobe from about 21,000–16,000 ^{14}C years BP. Note the distinct contact between proglacial glacifluvial deposits and hummocky end moraine. B) A shaded relief image showing the subglacial zone of landsystem B in southeastern Wisconsin created by the Green Bay lobe between 21,000 and 16,000 ^{14}C years BP.

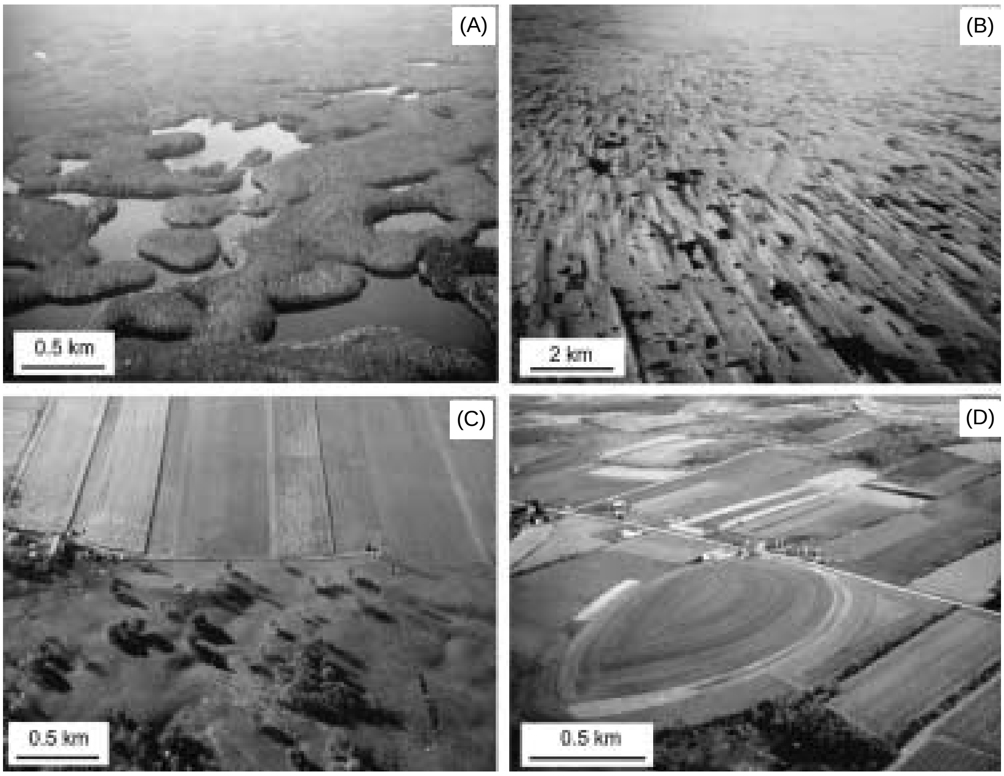


Figure 6.13 Oblique aerial photos of landforms in landsystem B. A) High-relief hummocky topography and ice-walled lake plains deposited by the Chippewa lobe in northern Wisconsin. B) Green Bay lobe drumlins of the Madison drumlin field. This photo is of the same region shown in the DEM of Fig. 6.12B. C) Hummocky topography of the Johnstown moraine deposited by the Green Bay lobe. D) A single drumlin of the Madison drumlin field.

percentage of local material. Far-travelled material is more common in supraglacial sediment in the marginal zone. This is different from the far-travelled nature of till in landsystem A and indicates much more local erosion. Striated rock surfaces are present even in the marginal areas, but striated boulder pavements are rare. Many bedrock exposures show indications of plucking and removal of large clasts as well as abrasion.

There are other major differences between landsystems B and A. The low-relief till plain of landsystem A is absent. Additionally, numerous small moraines are commonly superimposed on the drumlinized surface (Fig. 6.14). We believe that these are similar in origin to annual moraines formed in Iceland (Boulton, 1986; Krüger, 1994a), but different from the aligned hummocks found in landsystem C (see Colgan, 1996; Clayton and Attig, 1997; Ham and Attig, 2001).

6.5.4 Interpretation of Landsystem B

Most of the moraines in landsystem B were developed by the stacking of basal till slabs on top of layers of sand and gravel and supraglacial sediment (Lundqvist *et al.*, 1993). For some time

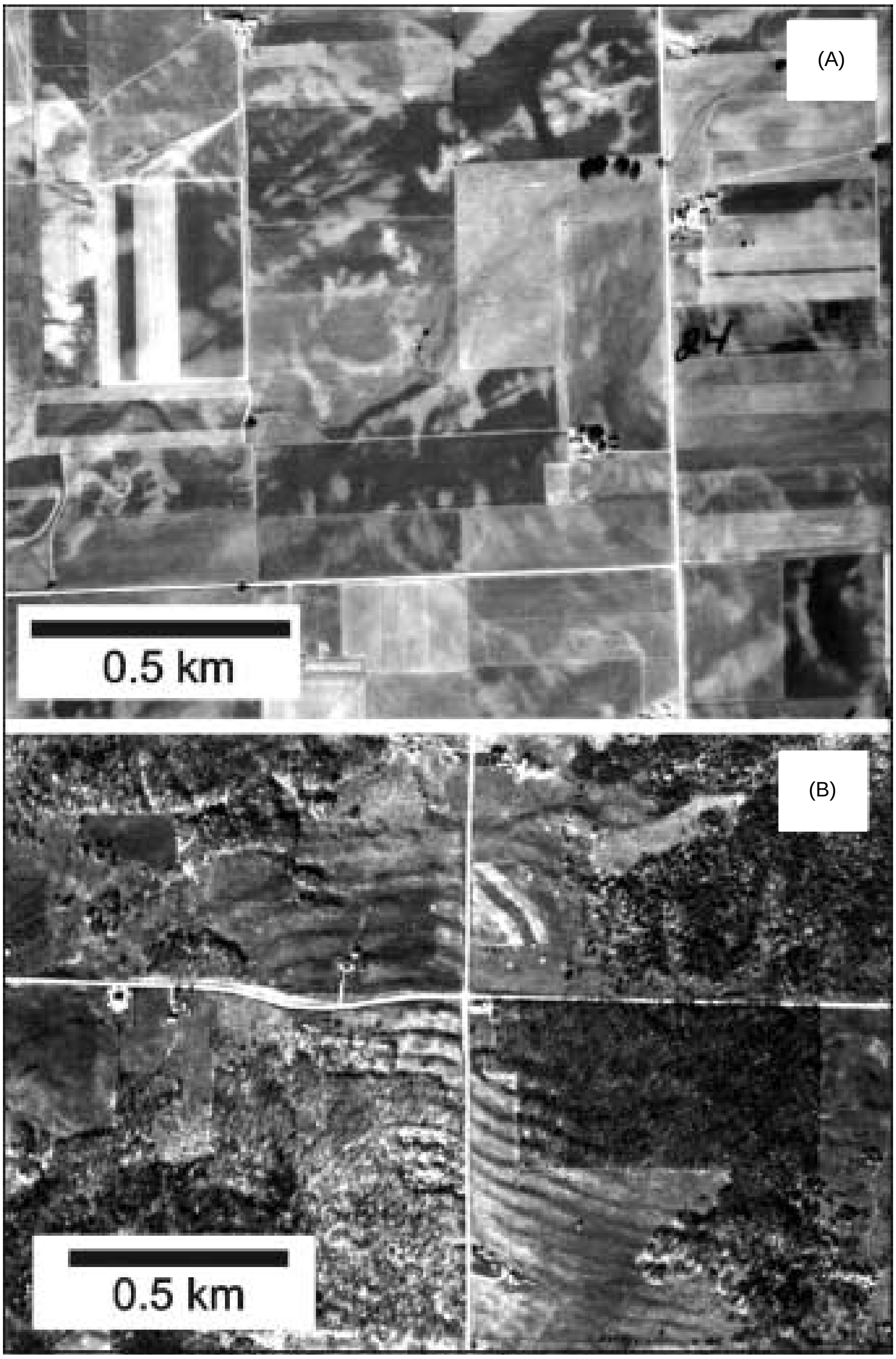


Figure 6.14 A) Aerial photograph showing small push moraines deposited by the Green Bay lobe during its retreat (photograph from USDA, WU-3P-26,1955, Dane County, Wisconsin). B) Aerial photograph showing small moraines deposited by the Wisconsin Valley lobe in northern Wisconsin (Ham and Attig, 2001).

when ice was at its maximum, extensive outwash was being generated along the ice margin as well as from tunnel channels. We interpret the tunnel channels as indicators of large discharges of subglacial water, perhaps stored as an extensive subglacial layer and then released during discrete events (Cutler *et al.*, 2002).

Wood is not present in the tills of landsystem B. We believe the absence of wood is an indication that continuous permafrost and tundra conditions existed when ice advanced to its maximum position in the area of landsystem B (Fig. 6.15). Both outside and inside the outermost margin of the ice in landsystem B there are indications of former permafrost. Patterned ground can be observed on aerial photographs (Fig. 6.15), particularly on outwash surfaces created during the last glacial maximum (Black, 1976b; Péwé, 1983; Ham, 1994; Johnson *et al.*, 1995; Colgan, 1996; Clayton and Attig, 1997; Clayton *et al.*, 2001).

The abundance of locally derived basal till suggests that material was eroded at the base of the ice and there was relatively little upward movement of basal sediment, except for stacking of debris-rich slabs near the terminus. Incorporation of local material and the prevalence of streamlined forms suggest that erosion was the dominant process occurring behind the terminus. This zone of erosion was time-transgressive and changed in size during advance and retreat because of the interaction of the thermal regime of the lobe and the underlying subglacial permafrost (Cutler *et al.*, 2000).

Another indication of the prevalence of subglacial erosion is the rarity of paleosols. There are a number of buried soils and organic deposits in Michigan associated with landsystem B, but most of these are in buried valleys where they have been protected by a thick cover of glacifluvial or glacilacustrine sediment.

In summary, the characteristics of landsystem B, with its drumlins and high-relief moraines suggest:

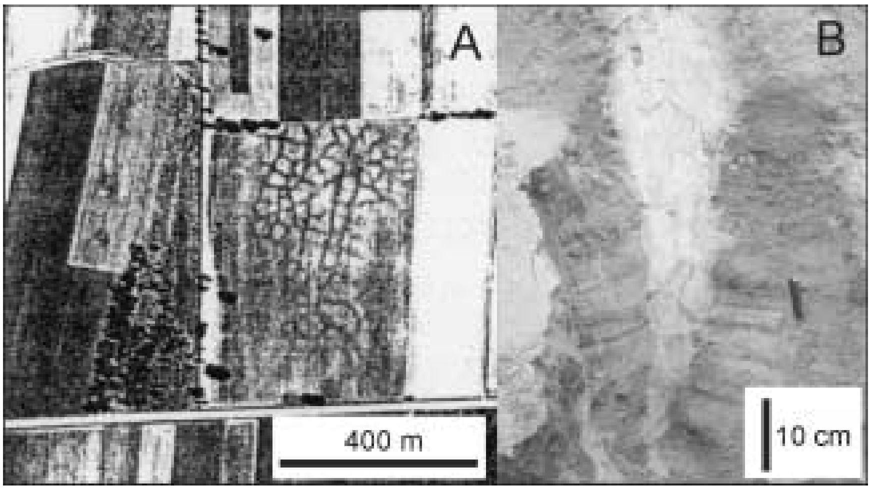


Figure 6.15 A) Aerial photograph showing relict ice-wedge polygons developed in outwash (USDA AX-5R-188, 1956, Dodge County, Wisconsin). B) Photographs of ice-wedge casts located in southern Wisconsin.

1. subglacial sediment transport and extensive subglacial erosion and deformation in the drumlin zone
2. extensive accumulation of debris on the ice surface in a narrow marginal zone 2–20 km wide
3. ice motion dominated by some combination of sliding and subglacial deformation
4. initial advance over a frozen subglacial bed followed by progressively retreating ice during deglaciation.

6.5.5 Landsystem C – Low-Relief Aligned Hummocks and Ice-Thrust Masses

Landsystem C occurs in North and South Dakota, western Minnesota, Iowa and in a small part of eastern Ohio (Fig. 6.6A). We interpret that this landsystem primarily reflects ice-lobe surges and widespread ice stagnation over large areas (Clayton *et al.*, 1985). While it is possible that glacier surges have occurred in areas where landsystems A and B are dominant we do not see evidence for large-scale ice stagnation in zones greater than 20 km wide as we do in landsystem C.

6.5.5.1 Marginal Zone

The marginal zone consists of a steep ramp of till and in places outwash, leading to the highest distal part of a hummocky end moraine (Figs 6.16 and 6.17). The hummocky end moraine

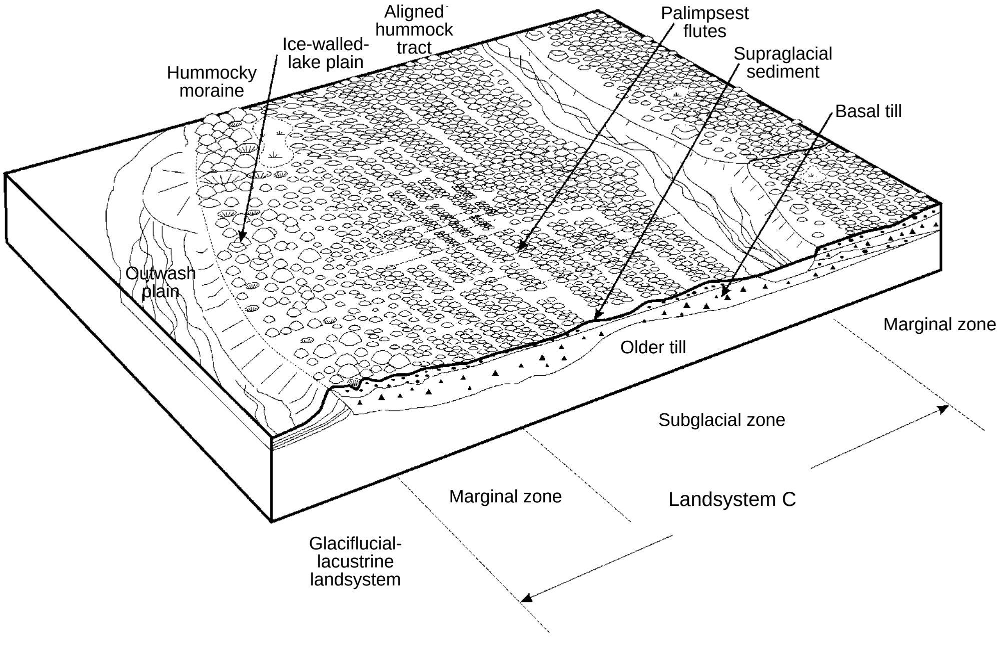


Figure 6.16 Schematic diagram showing landforms and sediments in landsystem C. End moraines are rare and consist of zones of thick supraglacial sediments (>3 m) over basal till. Hummocks are not well aligned in the end-moraine zone or may be superimposed on a broad end moraine. Aligned hummock tracts cover nearly the entire subglacial zone. In a few places, aligned hummocks may be seen to drape over flutes. In the subglacial zone, supraglacial sediments are thinner (<3 m). Older glacial deposits of loess and older tills underlie most of the area and can be quite thick (generally >30 m).

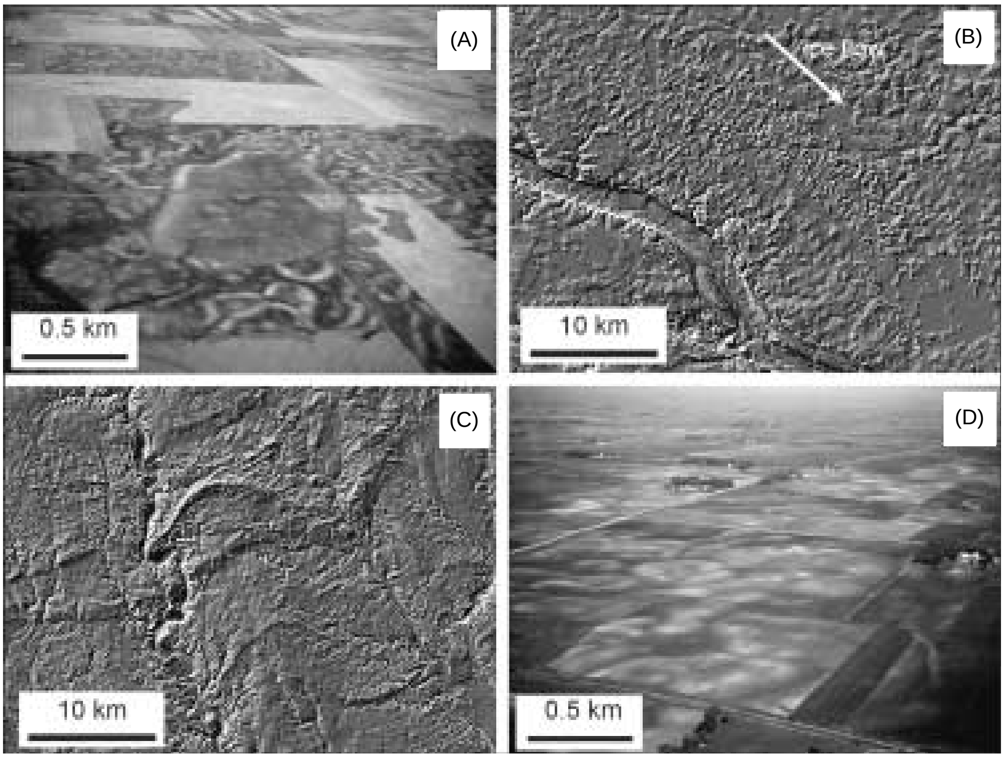


Figure 6.17 A) Oblique aerial photograph of low-relief hummocks in North Dakota. B) DEM of area in southern Minnesota where aligned hummock tracks are superimposed on till plain of basal till. The hummocks are composed of thin supraglacial sediment and basal till. C) A DEM showing rare end-moraine ridges covered by aligned hummock tracts in central Iowa. The curved moraine ridges have been mapped as the Altamont moraine in Iowa. Aerial photographs show that this entire area is covered with aligned hummock tracts. D) Aerial photograph of aligned hummock tracts in central Iowa deposited by the Des Moines lobe.

slopes gently downward on the proximal side. In some areas hummocky end moraines are not present near the terminus and the subglacial zone of aligned hummocks begins at the terminus. Low-relief hummocky topography creates closed depressions that are generally less than 3 m deep (Fig. 6.18). End moraines are generally 2–20 km wide but are less continuous than in landsystem A and B. Another landform found in the marginal zone of landsystem C in North Dakota is the ice-thrust mass (Moran *et al.*, 1980; Bluemle and Clayton, 1984; Clayton *et al.*, 1985; Aber *et al.*, 1989). This mass appears as a hill of sediment or bedrock up to 1 km across and a few meters to a few tens of meters high. Generally, the thrust mass is paired with a depression of similar size up-glacier. These masses have moved down-ice with very little internal deformation except faulting and drag folding along faults at the base. These 'hill-hole pairs', generally formed within 1 or 2 km of the terminus. Far more common are larger thrust masses of Cenozoic and Cretaceous shale and sandstone that have been moved up to several km in the down-ice direction at the bed of the glacier (Moran *et al.*, 1980).

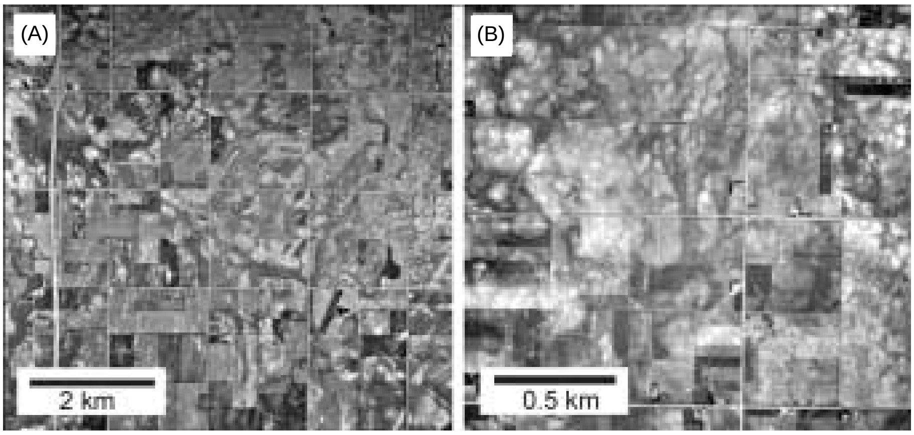


Figure 6.18 A) Aerial photograph of aligned hummock tracts in Story Count, Iowa (NAPP photograph 2122-121, 1990). B) Circular aligned hummocks grading into disintegration rings in central Iowa (USDA BZI-2JJ-78, 1968). C) Disintegration rings in central Iowa (USDA photograph BZR-2V-28, 1958). D) Disintegration rings in central Iowa (USDA photo BZF-1JJ-243, 1968). These photographs show that aligned hummocks are transitional features to disintegration rings. Both features are a product of ice stagnation and deposition of supraglacial and englacial debris.

6.5.5.2 Subglacial Zone

A major difference between landsystems C and A occurs behind the moraine. Here instead of flat till plain, the surface in most places has small (1–3 m high) ridges that have been called ‘washboard moraines’ or ‘minor moraines’ (Gwynne, 1942, 1951; Elson, 1957; Foster and Palmquist, 1969; Kemmis *et al.*, 1981; Stewart *et al.*, 1988). Colgan (1996) called these features aligned hummocks because they consist of individual hummocks about 10–30 m in diameter, aligned in rows perpendicular to flow (Figs 6.17 and 6.18). We believe that they are not end moraines and did not form at the terminus, but instead formed in a zone of stagnant ice within 40 km of the terminus (Colgan, 1996). These features are transitional to hummocks superimposed on the end moraine of the marginal zone. In many places where no end moraine exists, these features extend to the former terminus of the lobe.

The subglacial zone is up to 40 km wide and consists mostly of aligned hummocks oriented perpendicular to the ice margin (Fig. 6.18). They grade into larger hummocks in the marginal zone. Spacing is about 200 m between groups of aligned hummocks. Detailed mapping of these features in central Iowa indicates that areas of aligned hummocks are grouped into coherent tracts up to 10–40 km behind former ice-margin positions (Colgan, 1996). In Iowa there are at least seven such ice-margin positions and associated aligned hummock tracts (Colgan, 1996). These features merge with disintegration doughnuts and other features that clearly suggest widespread ice-stagnation (Parizek, 1969; Clayton and Moran, 1974). Their close association with circular doughnuts and the transitions commonly seen between aligned hummocks and doughnuts suggest that they are genetically related as ice-stagnation features showing various degrees of structural control by stagnant ice features such as crevasses and ice foliation (Fig. 6.18). In at least a few places in Iowa and in North Dakota aligned hummocks are superimposed on megaflutes assigned by us to landsystem B (Bluemle *et al.*, 1993). Basal till is up to 10 m thick in the marginal zone (Kemmis *et al.*, 1981), and Clark (1991) showed that striated clast pavements are also common in this area at the base of till units.

Megaflutes underlie aligned hummocks in North Dakota and in parts of northern Minnesota. In North Dakota streamlined landforms are long and narrow, commonly about 0.1 km wide and 1–5 km long. Some are up to 27 km long (Bluemle *et al.*, 1993). Megaflutes appear to be erosional or ice-moulded features. They contain till, sand and gravel, lake clay, shale and other sediments that were at the bed at the time of the last glacial advance. Bluemle *et al.* (1993) report evidence of squeezing and flow of material into the megaflute form. This is a good example of how one landsystem can be superimposed over another. In this case, landsystem C has been superimposed over landsystem B.

6.5.6 Interpretation of Landsystem C

Several researchers have examined the origin of aligned hummocks in Iowa. Stewart and others (1988) called them ‘corrugated moraines’ and suggested they formed by thrusting of basal debris. Kemmis (1992) referred to the depressions between hummocks as ‘linked depressions’ and concluded that doughnut topography and associated aligned hummocks are mostly englacial sediment that accumulated in crevasses or other openings in stagnant ice. Other observations (Stewart *et al.*, 1988; Patterson, 1997b) suggest that aligned hummocks are subglacial in origin with only a drape of supraglacial sediment over them. Similar to this, Colgan (1996) hypothesized that they formed when basal debris-rich ice was extended and then compressed longitudinally within 40 km of the terminus during a surge event. After this, dead ice melted in this broad zone of compressed ice, aligned hummocks formed where concentrated basal debris-rich layers melted out and were then partially reworked as supraglacial sediment into patterns reflecting ice fabric in the zone of compression. In some areas further up-ice where longitudinal extension of ice occurred some of the aligned hummocks may have directly formed as basal crevasse fills (Colgan, 1996; Patterson, 1997b). The discussion of the origin of these features has been somewhat confused in the past, probably because some of these features formed near the terminus (the aligned hummock tracks) related to compression of stagnant ice, while other features formed far up-ice as basal crevasse fills. The basal crevasse fills described by Patterson (1997b) in southwestern Minnesota are much more ridge-like and linear than are the aligned hummocks in central Iowa (Kemmis *et al.*, 1981; Kemmis, 1992; Colgan, 1996).

It has been suggested that megaflutes, ice-thrust masses and aligned hummocks are genetically related (Clayton and Moran, 1974; Moran *et al.*, 1980; Mickelson *et al.*, 1983; Bluemle and

Clayton, 1984; Evans *et al.*, 1999b). This could be the case, as these extremely long, streamlined features are very different from the drumlins found in landsystem B. It is clear that the megaflutes are palimpsest features and that aligned hummocks, crevasse fills and eskers are superimposed upon them, and this is what would be expected if supraglacial sediment was draping basal till. Megaflutes may have formed during ice streaming to the ice maximum or during surge events that produced ice-thrust masses, and then longitudinally deformed basal debris formed the overlying aligned hummocks as this material melted out. Presumably where supraglacial sediment was thick enough, megaflutes would be completely buried. In both Iowa and North Dakota, streamlined landforms can be seen to underlie a thinner layer of supraglacial sediment in a few places.

Ice-thrust features in North Dakota overlie sand and gravel aquifers in buried valleys. It has been suggested (Moran *et al.*, 1980; Bluemle and Clayton, 1984) that ice-thrust masses occur because of steep groundwater gradients in the terminal zone caused by the blocking of subglacial drainage by subglacial permafrost at the ice margin. They may also be associated with surges and share a common genesis with similar features in Iceland (Evans *et al.*, 1999b).

Although basal till is common it appears that more supraglacial sediment is present in landsystem C than in either landsystem A or B (Clayton *et al.*, 1985). The aligned hummocks and basal crevasse fills are composed primarily of basal till in their lower parts with varying amounts of supraglacial sediment deposited on them during wastage of stagnant ice (Kemmis *et al.*, 1981; Kemmis, 1992; Colgan, 1996).

We believe that the superposition of landsystem C over megaflutes in this zone suggests that the glacier surges or that the fast flow dominated post-LGM readvances in this part of the ice-sheet margin (Clayton *et al.*, 1985). The timing of the maximum ice extent in this region (at 14,000 ^{14}C years BP) was out of phase with the rest of the southern LIS margin. This suggests that these lobes were advancing when more basal water was available during warmer post-LGM climatic conditions (Kemmis *et al.*, 1981; Clayton *et al.*, 1985). Megaflutes and boulder pavements could have formed during rapid basal sliding during the surge event or as fast steady flow fed by an ice stream up-ice (Patterson, 1998). Ice and basal debris were longitudinally compressed near the terminus perhaps during the propagation of a surge wave through the glacier. Ice thrusting of proglacial and marginal material and compression of basal debris-rich ice resulted in the formation of ice thrust masses, aligned hummocks and widespread ice disintegration features (Colgan, 1996).

In summary, the characteristics of landsystem C, with its aligned hummocks and broad low-relief moraines suggest:

1. predominantly englacial and subglacial transport and ice stagnation over large areas
2. extensive accumulation of debris on the ice surface in a broad zone 10–40 km wide, and
3. ice motion dominated by unsteady surge-type or fast ice flow followed by stagnation of ice over a broad area behind the terminus.

6.5.7 Landsystem D – Bedrock-Dominated Landscapes

This landsystem is common in New England, New York, Pennsylvania and New Jersey. It consists of high-relief bedrock terrain draped by till, with glacifluvial and glacilacustrine sequences filling most valleys. We make the interpretation that most of this region reflects glacial erosion of a pre-existing high-relief bedrock terrain during advance to the last glacial maximum.

Ice-contact and glacofluvial (landsystem E), and glacilacustrine/glacimarine deposition (landsystem F) dominated as a progressively retreating terminus developed local ice-stagnation zones near the margin. After about 13,000 ^{14}C years BP, ice probably become regionally stagnant in northern New Hampshire and Maine as it became isolated from the main body of the dwindling LIS. Features such as cols, ice-marginal channels, eskers and other ice-contact deposits suggest that as the ice wasted, high peaks were exposed as nunataks followed by isolation of ice in major valleys (Goldthwait and Mickelson, 1982). Detailed mapping of striations also suggests that ice flow reversed direction in northern Maine as ice was drawn down in the St Lawrence lowland (Lowell *et al.*, 1986).

Besides the well-formed and mapped end-moraine systems in southern New England that we have classified as landsystem B or E (Oldale and O'Hara, 1984), large end moraines are relatively rare in New England (Koteff and Pessl, 1981). Very small moraines in Connecticut, Maine and Massachusetts are present, but these features are most similar to the small push moraines present in the Great Lakes region (Stone and Peper, 1981; Goldsmith, 1987). Small recessional moraines in Maine occur in association with glacimarine deposits and may be similar in origin to DeGeer moraines (Kaplan, 1999). Most of this area where these moraines occur has been classified as landsystem B or F.

The dominance of glacifluvial deposition in bedrock valleys during deglaciation has been described in detail by Koteff and Pessl (1981), Mulholland (1982), and Stone and Pepper (1982). Outwash sequences called 'morphosequences' (Koteff and Pessl, 1981) were created by a progressively retreating ice margin that stagnated near the terminus in zones 2–5 km wide (Mulholland, 1982). Each morphosequence includes glacifluvial and glacilacustrine deposits that are graded to an ice margin position and a local base level established briefly during a progressive retreat. A zone of stagnant ice several km wide formed as ice retreated over high-relief bedrock surfaces. In this zone ice-contact sand and gravel were deposited. Temporary lakes also formed in this bedrock-controlled landscape, and many of the valley sequences include deltaic and varved sediment (Ashley, 1975). Bedrock ridges oriented parallel to the ice margin were particularly effective at detaching zones of stagnant ice from active ice as the margin retreated northward over the terrain.

6.6 DISCUSSION

We hypothesize that the types of landforms and sediments within a particular region are the result of how the ice sheet responded to the fundamental influences of climate, bed geology and topography. These influences were filtered in a non-linear manner by the ice sheet. The combination of these factors produced different dynamic behaviours of the ice-sheet margin and different depositional environments in various regions of northern USA. Below we discuss the influence of each factor on glacier dynamics and the resulting landsystems in each region.

6.6.1 The Role of Climate in the Genesis of Landform-Sediment Landsystems

Climate is a first-order control on glacier behaviour. Besides determining mass balance and the extent of ice, climate also influences the temperature of ice as well as its bed near the margin. It also influenced the amount and nature of water movement. During the LGM the climate along the southern LIS margin varied spatially (Kutzbach, 1987). In the western and northern Great

Lakes regions, and perhaps in northern New England, permafrost formed before, during, and even after the LGM (Péwé, 1983). It is likely that the ice-sheet margin advanced over this permafrost many times. It may have taken several thousand years for this overridden permafrost to melt, depending on the initial thickness of the permafrost and the thickness and temperature of the overlying ice (Cutler *et al.*, 2000). In the southern Great Lakes region of Illinois, Indiana and Ohio, permafrost was probably discontinuous (Johnson, 1990). Abundant wood in tills in this region (Ekberg *et al.*, 1993; Hansel and Johnson, 1999) suggests that ice advanced into a warmer region than that in Wisconsin, Michigan and Minnesota, where till contains no wood and sub-till organic material indicates tundra conditions. In New York and New England ice may also have advanced over permafrost as relict ice-wedge casts and ice-wedge polygons are reported there also (Péwé, 1983). In southern New England the proximity to the Atlantic Ocean may have warmed this part of the margin compared with areas to the north or west (Gustavson and Boothroyd, 1987).

In Wisconsin and Minnesota this permafrost lasted until about 13,000 ^{14}C years BP in the south, disappearing northward about 3,000 years later (Clayton *et al.*, 2001). Not only was permafrost overridden, it must have reformed at times on the deglaciated surface, between 17,000 and 13,000 ^{14}C years BP. Discontinuous permafrost may have also been present in some areas of landsystem A (Johnson, 1990), but we believe this permafrost was not sufficiently extensive to have had the same impact as it did in the area of landsystem B. Throughout most of landsystem A ice advanced into spruce forest.

The marked difference between landsystem B and landsystems A and C is the presence of drumlins, tunnel channels and high-relief hummocky end moraines. We believe that these features are consistent with an interpretation that ice advanced onto permafrost and eroded pre-existing landforms and sediments. We suggest that when ice was at its maximum position, a zone of subglacial permafrost up to 100 km wide was present. Behind this zone, a zone of partially frozen bed may have been present back to the up-ice edge of the drumlin zone. Subglacial water was produced at the bed in this zone and probably accumulated behind the wedge of frozen ground near the terminus because insufficient water was able to drain through the groundwater drainage system. The trapped water was eventually released through tunnel channels that intersected the end moraine (Attig *et al.*, 1989; Clayton *et al.*, 1999; Cutler *et al.*, 2002). We attribute the mobility and deformation of sediments in the drumlin zone in part to the likely high pore pressure and the high water content of the subglacial sediments upstream from the frozen margin.

In the southern Great Lakes region, where landsystem A is dominant, we suggest that the glacier bed was thawed and that basal motion, through some combination of glacier sliding, ploughing and bed deformation, was the primary result of ice motion. We suggest that little erosion was accomplished in this region. Mickelson and others (1983) report radiocarbon dates on wood between 23,000 and 14,000 ^{14}C years BP in Illinois and Indiana. Much of the wood is spruce and this suggests that ice advanced into a spruce forest or spruce parkland throughout the late Wisconsin, with the exception of the period between 17, 500 and 16,000 ^{14}C years BP, when there are no wood dates from Illinois. Permafrost features are not as abundant as they are to the north, although Johnson (1990) reports ice-wedge casts and other permafrost features on late Wisconsin deposits that may have formed during this interval after ice advance to the maximum position. We conclude that the absence of drumlins in this area is because of the prevailing thawed-bed conditions and not because of a difference in topography or till texture.

Drumlins are present on Illinoian surfaces just outside the late Wisconsin margin in Illinois in till of similar texture to that of late Wisconsin till plains (Lineback *et al.*, 1983), indicating that texture was not a significant influence on the presence or absence of drumlins.

6.6.2 The Role of Bed Geology and Topography in the Genesis of Landsystems

In addition to climatic controls, the behaviour of the ice sheet was influenced by bed geology and topography. The distribution of bedrock lithologies was important to ice dynamics and hence landsystem distribution for several reasons. First, differences in the lithology, and therefore rate of bedrock erosion, have influenced the regional topography (Fig. 6.19) and hence regional patterns of ice flow. The lobate nature of the southern LIS was determined by bedrock topography, with lobes channelled down each of the basins in the Great Lakes region. For example, these and other major basins must have been present prior to the last glaciation, and were deepened by an unknown amount during the late Wisconsin. The style of ice-marginal behaviour differed between areas where the ice was advancing up a regional slope and those where it advanced down a regional slope. In addition, large lake basins significantly altered the mass balance and ice-surface profiles (Cutler *et al.*, 2001). In the high-relief areas of central and northern New England, the style of deglaciation and resulting deposits were greatly controlled by topography (Koteff and Pessl, 1981; Mulholland, 1982; Stone and Peper, 1982; Goldthwait and Mickelson, 1982).

Second, the rate of erosion of bed materials also influenced the amount of debris being carried by the ice, and topography determined if that material could be transported away from the terminus. Ice in northern Wisconsin and in southern New England retreated progressively up a surface that was gently sloping away from the ice margin. This produced detachment of stagnant ice from active ice in zones up to 20 km wide (Koteff and Pessl, 1981; Mulholland, 1982; Stone and Peper, 1982; Gustavson and Boothroyd, 1987; Ham, 1994; Johnson *et al.*, 1995). As these stagnant-ice zones melted, they produced large hummocky moraines with ice-walled lake plains (called ‘high kames’ in New England). In the Dakotas, Minnesota, Wisconsin, New York and northern New England, ice retreated into lake basins and lowlands. This produced ideal conditions for the formation of proglacial lakes that trapped fine-grained sediments. Subsequent readvances after the LGM incorporated large amounts of these glacilacustrine silts and clays (Acomb *et al.*, 1982; Clark, 1994b) and deposited these as fine-grained tills (Fig. 6.19).

Lithology also influenced the nature of subglacial fluvial deposits. For example, the texture of glacier deposits controls the present appearance of glacial landforms (Fig. 6.19). High relief and steep slopes tend to occur where till is sandy. Silt- and clay-rich tills tend to have low-relief landforms because of postglacial weathering and erosion (Clayton and Moran, 1974). Finally, the nature and abundance of glacifluvial deposits must in part be a function of the availability of coarse material. Eskers and outwash fans cannot occur unless there is sufficient coarse sediment to be deposited.

Finally, the hydraulic conductivity of the glacier bed controls subglacial drainage and therefore water pressure and basal motion (Arnold and Sharp, 1992; Clark and Walder, 1994). The effective stress at the bed is in part controlled by the ability of water to drain towards the ice margin. If flow is impeded, effective pressure declines and basal motion may be enhanced. Consequently, lithologically dependent hydraulic properties of bedrock and overlying sediments

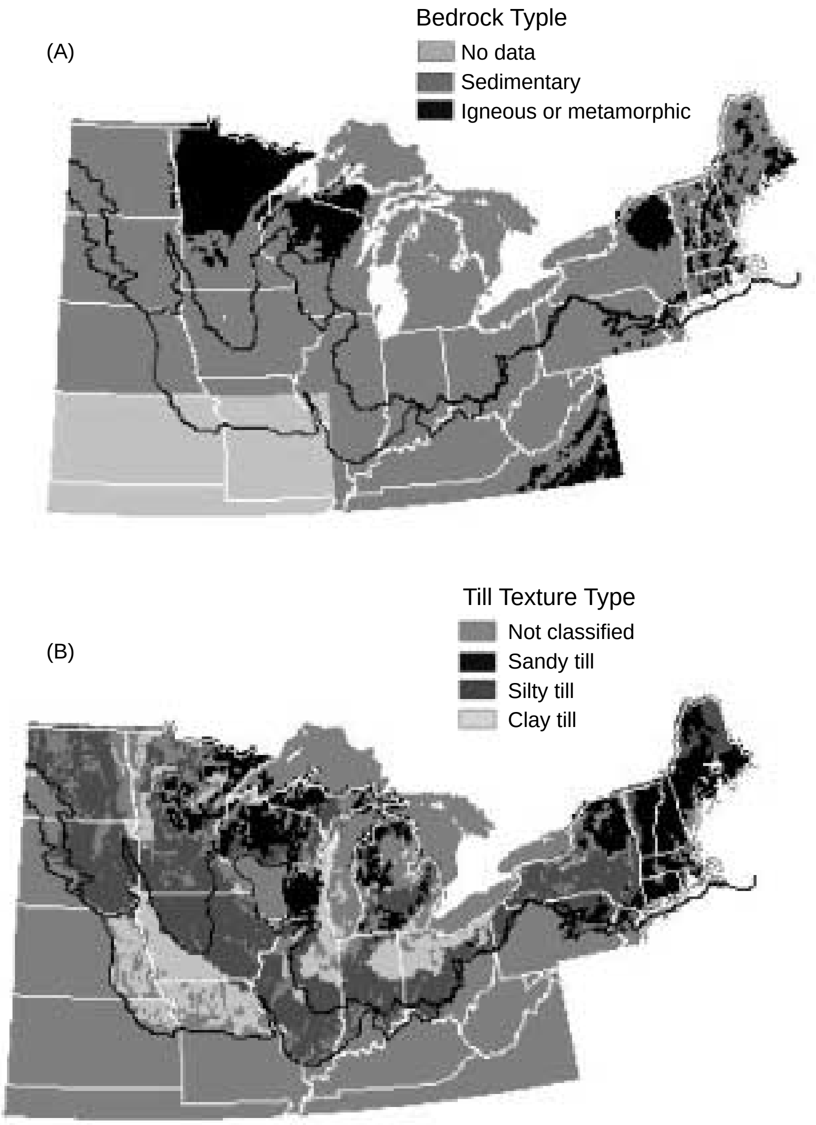


Figure 6.19 A) Map showing bedrock types in the northern USA (map derived from the digital version of the geologic map of the US, Schruben *et al.*, 1999). B) Map showing the dominant texture of till matrix in the northern USA (map derived from data of Soller and Packard, 1998).

exert a direct influence on spatial variations in ice dynamics. The distribution of landsystems found around the southern LIS reflects this influence. In the western region and the southern Great Lakes region where landsystem A and C dominate, the bed is composed of thick silty or clayey tills derived primarily from Palaeozoic sedimentary rocks. This bed would have been soft, smooth and easily deformed, with low hydraulic conductivity. Low basal shear stress would result in low-profile, unstable glacier lobes. Enhanced subglacial sliding, bed deformation or surging behaviour would be associated with this bed type. In the northern Great Lakes and New England where landsystem B dominates, the bed is composed of igneous or metamorphic rocks or sandstone. This bed would have been hard, rough, thinly covered by sediment, and had a higher hydraulic conductivity compared with soft-bedded areas. This may have caused ice lobes to be thicker and more stable than those advancing over a soft bed.

6.6.3 The Role of Glacier Dynamics in Influencing the Distribution of Landsystems

A final factor in producing various landsystems is the dynamic behaviour of the ice sheet during advance to its maximum extent, and during deglaciation (Fig. 6.20). Dynamic behaviour directly results from the climate and bed geology discussed above. The ice margin appears to have retreated progressively at rates of between 50 and 500 m/year along much of the southern margin of the LIS in the Great Lakes and New England regions (Andrews, 1973; Mulholland, 1982; Colgan, 1996; Ham and Attig, 2001). Evidence for this includes radiocarbon chronologies, small push moraines, numerous well-defined retreat moraines, and extensive and well-dated varve deposits in proglacial lakes (Ashley, 1975; Johnson *et al.*, 1999). In the western prairie region it appears that ice surged into lowlands several times and then experienced regional stagnation (Clayton *et al.*, 1985). Retreat rates in this region were higher than 700 m/year and could have been as high as 2000 m/year (Fig. 6.20). As these rates are much higher than advance-retreat rates of normal glaciers it has been suggested that they reflect regional stagnation following each surge of a lobe in the areas west of the Great Lakes (Clayton *et al.*, 1985).

Lobes in the western prairie region also advanced to their maximum advance position out of phase with the rest of the ice sheet margin (Fig. 6.20) (Clayton and Moran, 1982; Mickelson *et al.*, 1983; Clayton *et al.*, 1985). The Des Moines lobe reached its maximum at about 14,000 ^{14}C years BP when the rest of the margin was rapidly wasting (Kemmis *et al.*, 1981; Hallberg and Kemmis, 1986). We believe that this is an indication that these lobes surged. The resulting landforms and sediments (landsystem C), consisting of widespread ice-thrust and ice-stagnation features are compatible with surging as a major process in this region after the LGM.

Reconstructed ice-surface profiles also provide information about ice-lobe behaviour that ties in with our interpretations of landform-sediment landsystems. Most of the major lobes have been reconstructed from ice-marginal features and moraine elevations for their LGM positions and for some deglaciation phases (Mathews, 1974; Beget, 1986; Ridky and Bindschadler, 1987; Clark, 1992; Colgan, 1996; Colgan and Mickelson, 1997; Socha *et al.*, 1999). These profiles show that glacier lobes that created landsystem B in the northern Great Lakes and New England regions had comparatively steep ice-surface profiles. Lobes that created landsystem A in the southern Great Lakes region had lower ice-surface profiles. Finally, the lowest ice-surface profiles have been reconstructed for lobes in the western region (landsystem C), and for lobes that readvanced out of lake basins during deglaciation.

These ice-surface profiles reflect a combination of lithologic and climatic influences, as well as, in the case of the lower-profile lobes, internal ice-dynamic behaviour related to surges. In contrast with steep ice-surface profiles that suggest high basal shear stress and progressively (steadily) advancing and retreating lobes, the extremely low profiles of the western region suggest that ice was very thin and stagnant following surges (Clayton *et al.*, 1985).

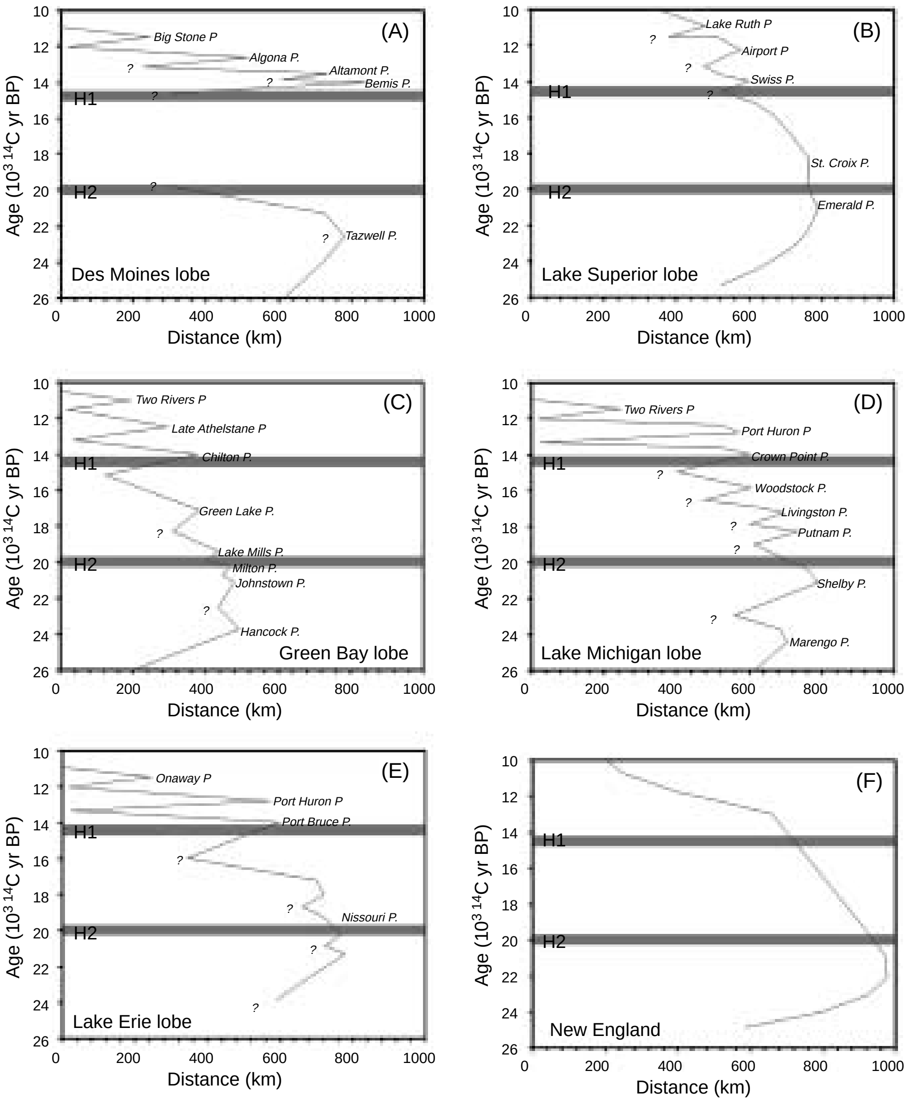


Figure 6.20 Time-distance diagrams for lobes of the southern margin of the Laurentide Ice Sheet. A) Des Moines lobe in the western region. A major advanced occurred in phase with the rest of the margin at about 21,000 ^{14}C years BP, but this was not the maximum advance. The maximum advance occurred at about 14,000 ^{14}C years BP when the rest of the margin had retreated 100–300 km behind the Last Glacial Maximum margin (Kemmis *et al.*, 1981; Hallberg and Kemmis, 1986). B) Superior lobe (Attig *et al.*, 1985). C) Green Bay lobe (Colgan, 1996). D) Lake Michigan lobe (Hansel and Johnson, 1999). D) Lake Erie lobe (Clark, 1994). F) New England (Clark, 1994). Grey shading shows Heinrich events at about 14,500 (H1) and 20,500 (H2) ^{14}C years BP.

6.7 CONCLUSIONS

The thrust of this paper is to point out that there are striking differences in glacial landforms and sediments along the southern margin of the LIS. We believe that these differences are significant from a palaeo-glaciological point of view, and we encourage further research on the genesis of glacial landsystems and their significance to reconstructions of former ice sheets and ice lobes.

It is clear that climate and bed geology were important controls on the landforms that developed. Another important control was temperature at the base of the ice and in particular whether the bed was frozen or unfrozen. We postulate that there was an area (landsystem A) along the southernmost margin of the ice sheet where wet-based ice advanced into a spruce forest, and that permafrost was probably discontinuous and formed later than the maximum advance and then quickly disappeared. This area was dominated by basal melting, and broad end moraines were developed almost entirely of basal till. Behind this, subglacial sliding, ploughing and deformation produced a flat till plain with only small-scale flutes on the surface. Subglacial sediment was brought to the ice surface in interlobate areas and a few locations where bed slope was upward toward the ice margin, particularly along deep basin margins. This was particularly true during the short-lived readvances out of Great Lakes basins when large volumes of lake sediment were moved short distances into end moraines.

Further north in landsystem B, we believe ice advanced over permafrost that was tens if not hundreds of metres thick and extended laterally tens of kilometres under the advancing ice margin. The thickness of the permafrost probably increased to the north. This permafrost wedge must have had a major influence on subglacial drainage, on subglacial pore pressures, and on subglacial processes in general. In the marginal zone in the southern part of landsystem B, where the subglacial permafrost zone was fairly narrow (tens of kilometres), significant upward thrusting and stacking of material took place. Further north, where the frozen zone was wider, an extensive area of high-relief hummocky topography now marks the location of that frozen bed. Tunnel channels, which probably formed by drainage of subglacial water dammed behind this frozen wedge, are common in landsystem B and northward, but are absent in landform landsystem A. Likewise thrust masses and drumlins also appear to require the presence of a permafrost zone near the ice margin for their formation. There are thousands of drumlins in landsystem B, but drumlins are absent in landsystem A and commonly palimpsest in landsystem C. Most eskers in the northern landsystems appear to be later features, formed when climate warmed and water was present at the bed in marginal areas.

To the west, where regional stagnation of lobe margins followed surges, vast areas of ice-stagnation topography were produced (landsystem C). Low topographic relief, the presence of large shallow lake basins, and the fine-grained nature of tills in the area may have predisposed these lobes to unstable dynamic behaviour, particularly after the LGM when the climate warmed and subglacial water was available. Similar features and behaviour seem also to have occurred around all the Great Lakes basins during deglaciation.