



The genesis of the northern Kettle Moraine, Wisconsin

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Abstract

Interpreting past glacial dynamics from the glacial record requires that the depositional environments of glacial sediments and landforms be understood. In the case of interlobate deposits, models that incorporate various components of pro, supra and subglacial deposition have been developed and tested in the northern Kettle Moraine (nKM), Wisconsin; a large interlobate deposit that formed between the Green Bay and Lake Michigan lobes of the Laurentide Ice Sheet during the last deglaciation. In this paper, we interpret a new genesis for the nKM using sediment analysis and distribution along with landform distribution. In Sheboygan County, the nKM consists of two steep-sided, high-relief, hummocky ridges separated by a low elevation and low-relief central axis. Gravel in the bounding hummocky ridges is well-sorted and well-rounded. Some bedding is collapsed. Large, isolated moulin kames are restricted to the axis area and composed of relatively poorly sorted, more angular gravel and diamicton. The distribution of these different sediments and landforms are explained by the accumulation of supraglacial debris that insulated the ice below the axis of the nKM, while the melting of cleaner ice on either side formed channels on the ice surface. As deglaciation proceeded, a substantial thickness of well-rounded, stream-deposited sand and gravel accumulated on ice in the bounding channels. Eventual collapse of this sediment formed the two hummocky ridges. Poorly sorted debris along the axis fell and slid into moulins and larger collapse areas in the ice. Thus, differential debris insulation and ice ablation controlled the mainly supraglacial deposition of this part of the nKM.

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1. Introduction

Glacial landforms record a valuable history of glacial transport and deposition that are linked to ice sheet dynamics. The sedimentary architecture of such features helps explain genesis and provides a better understanding of the paleoglaciology of ice sheets. Proglacial (Chamberlin, 1878; Fraser, 1993), supra-glacial (Attig, 1986), and subglacial (Brennand and

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Shaw, 1996; Santos, 2002), or some combination of these processes (Mickelson and Syverson, 1997; Punkari, 1997), have been proposed to explain the genesis of interlobate zones. Many of these have been applied to the Kettle Moraine of eastern Wisconsin, a well-known glacial landform that is now part of the Ice Age Scientific Reserve and the Ice Age Trail. The genesis of the Kettle Moraine, however, is still poorly understood.

The sediment in the Kettle Moraine was deposited between the Green Bay lobe (GBL) and Lake Michigan lobe (LML) of the Laurentide Ice Sheet during retreat from its Last Glacial Maximum position (Fig. 1). The actual timing of deposition is poorly constrained because of the persistence of permafrost in northeastern Wisconsin and paucity of organic material for radiocarbon dating (Clayton et al., 2001). The Kettle Moraine roughly parallels the western shore of Lake Michigan, extends from southeastern to northeastern Wisconsin, and is characterized by a single, ~3 km wide, hummocky ridge for ~90% of its

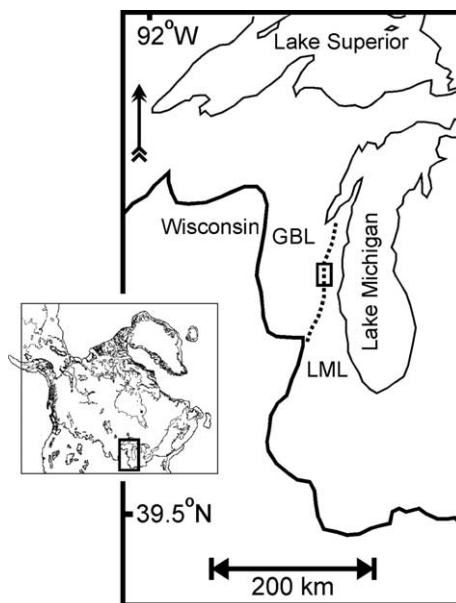


Fig. 1. Location of the Kettle Moraine, Wisconsin (dashed line), Last Glacial Maximum ice margins (thick line), and Great Lakes (thin line). Coordinates in decimal degrees. Box indicates the location of the double ridge of the northern Kettle Moraine and Fig. 2. Inset shows the study area location (box) relative to North American Last Glacial Maximum ice margins.

200 km extent. A double ridge, however, is present along 25 km of the interlobate zone beginning ~80 km south of its northern extent. These two ridges are separated by a relatively low relief, central low area (CLA; Fig. 2).

The name moraine is a misnomer because the Kettle Moraine is made up almost entirely of stream-deposited sand and gravel, not an accumulation of subglacially deposited till which denotes the position of a former ice margin (Mickelson et al., 1983). The name, however, is thoroughly engrained in the literature and popular usage; thus, we continue to use it here as a proper name.

Chamberlin (1877) named the Kettle Moraine and attributed its formation to fluvial sedimentation in a trough between the GBL and LML during ice retreat. Alden (1918) assigned more specific names to landforms in the Kettle Moraine, but maintained the mainly proglacial model of Chamberlin (1877, 1878) that subsequent research has supported (Thwaites, 1946; Thwaites and Bertrand, 1957; Black, 1969, 1970). Attig (1986), however, suggested a different genesis for the double ridged part of the northern Kettle Moraine (nKM), arguing that it is a supraglacial deposit because its topographic surface indicates extensive underlying ice at the time of deposition. The purpose of this article is to present new sedimentological data from the nKM that implies a somewhat different, more complex genesis than previous genetic models and also explains the landform and sediment distribution in the nKM.

2. Previous models of the genesis of interlobate zones

Chamberlin (1878) proposed a proglacial model for the nKM and suggested that the ridges bordering the CLA were thrust moraines formed during an advance that overrode proglacial sediment. Meltwater from the lobes drained across the ridges and southward, through channels in the CLA. Subsequent research on the nKM has supported this proglacial genesis (Alden, 1918; Thwaites, 1946; Thwaites and Bertrand, 1957; Black, 1969, 1970). A similar genesis has been ascribed to an interlobate system in the Wabash Valley, Indiana, where proglacial meltwater

from the LML and Huron-Erie lobe deposited sediment between the two lobes (Fraser, 1993).

Syversen (1988) and Mickelson and Syversen (1997) envisioned a different model for the nKM in Washington County, Wisconsin, immediately south of our study area. They suggested that supraglacial debris accumulated in a low area between the two ice lobes and formed the single ridge in southern and central Washington County. They proposed that the two marginal ridges of the nKM in the northern part of the county, however, were deposited in sub or englacial tunnels and are large eskers. This partly supraglacial and partly subglacial model has also been applied to interlobate deposits of the Scandinavian Ice Sheet (Punkari, 1997).

A predominately subglacial model was suggested by Brennand and Shaw (1996) for the Harricana glaciofluvial complex, Quebec, which was previously interpreted as an interlobate moraine (Veillette, 1986). They compared sedimentary facies and structures from the Harricana complex to esker deposits and inferred that deposition in a conduit formed by a subglacial flood event could explain at least 250 km of the 1000-km-long complex. All 80 km of the Kent Interlobate Moraine, Ohio was also attributed to subglacial flood deposition (Santos, 2002).

Attig (1986) proposed that the nKM was deposited in subaerial ice-walled channels. Similar interpretations have been made of smaller landforms where

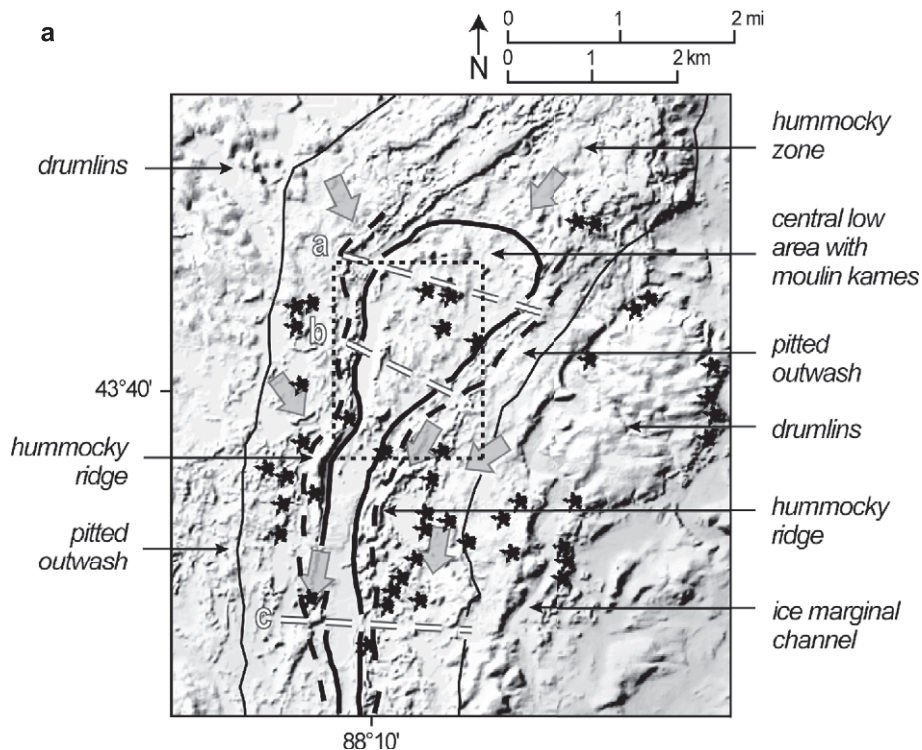


Fig. 2. (a) Digital elevation model of the northern Kettle Moraine with landform distribution and paleo-meltwater flow (arrows) indicated. Stars show the location of exposures examined. Thick solid line denotes the border between the central low area and the double hummocky ridges; thick dashed line denotes the axis–distal edge of the double hummocky ridges, thin solid line indicates the gradational boundary between the hummocky zones and pitted outwash. Coordinates in decimal degrees. The sediment distribution in the landforms is as follows: the central low area contains little debris; moulin kames contain angular to sub-angular sediment; the double hummocky ridges, hummocky zones and pitted outwash have well-rounded sediment. The thin dashed box shows the location of panel b and lettered dashed lines denote locations of cross-sections in Fig. 3. (b) Topographic map of the central low area, moulin kames, double hummocky ridges and hummocky zones (northeast part of the Dundee, WI 7.5 minute quadrangle). Various landforms are labeled; the solid line denotes boundary between the central low area and hummocky ridges and the dashed line outlines a moulin kame field. Contour interval is 3 m.

b

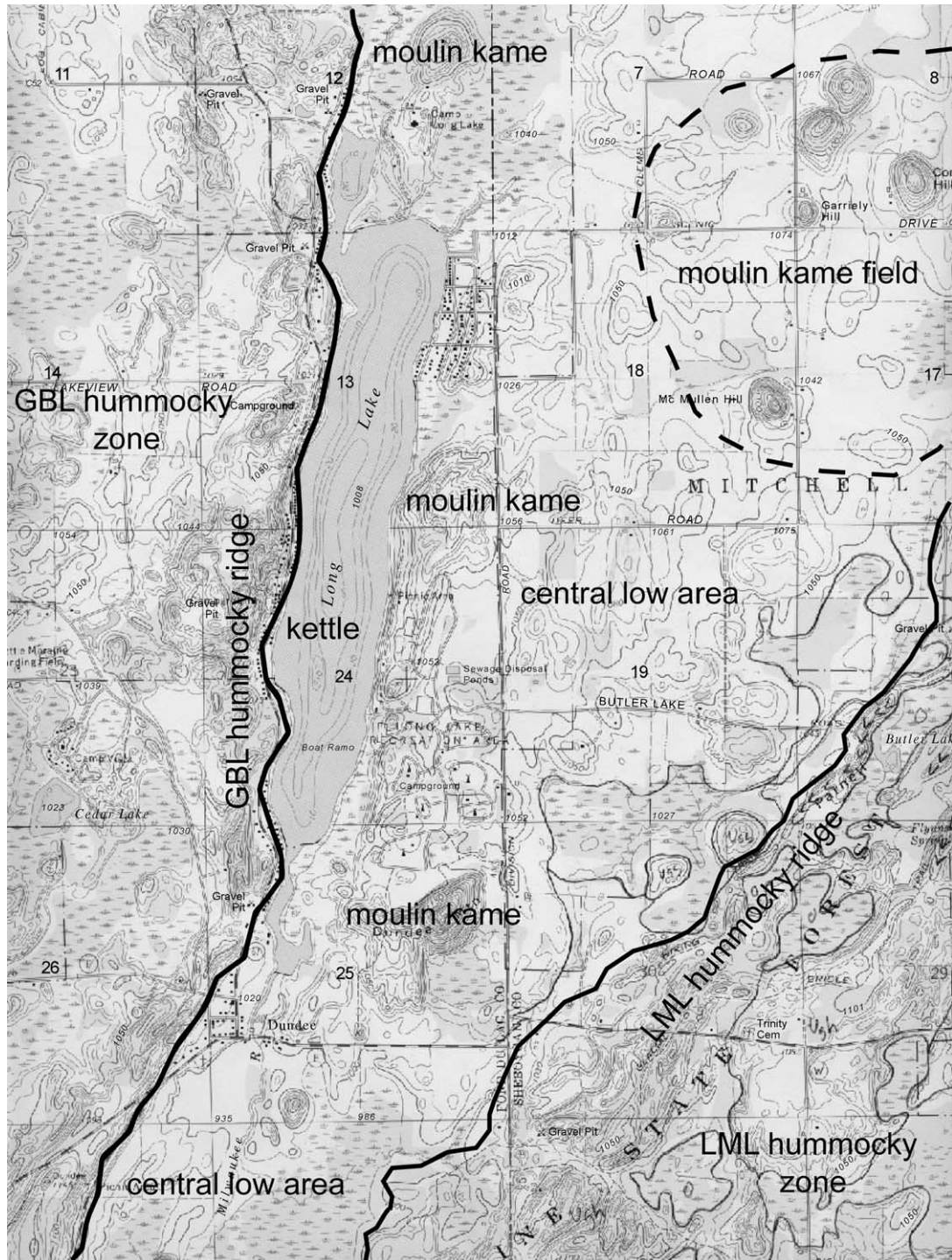


Fig. 2 (continued).

sediment accumulated in supraglacial, ice-walled channels, and meltout left steep-sided ridges; such as the Carstairs esker, Scotland (Thomas and Montague, 1997) and sediment ridges on Homlstrømbreen and Vegbreen, Svalbard (Bennett and Glasser, 1996; Huddart et al., 1999).

3. Methods

Interpretations of depositional processes and sequence of genetic events were made from stratigraphic and sedimentological analysis of 45 exposures (see Fig. 2a), the distribution of landforms, air photos,

digital elevation models, and topographic maps. The exposures are active and abandoned sand and gravel mining pits, and stream cut banks. Active pits provided clean faces for stratigraphic and sedimentological interpretation while abandoned pits and cut banks required excavation of clean surfaces. Sediment was classified based on field texture. Hand- and truck-mounted solid stem augers were used to retrieve subsurface samples where exposures are absent, such as in the CLA. Four holes were drilled by truck-mounted auger and another four holes by hand-auger in the CLA. These samples were analyzed by dry sieving and hydrometer analysis at the Quaternary Research Laboratory, University of Wisconsin–Mad-

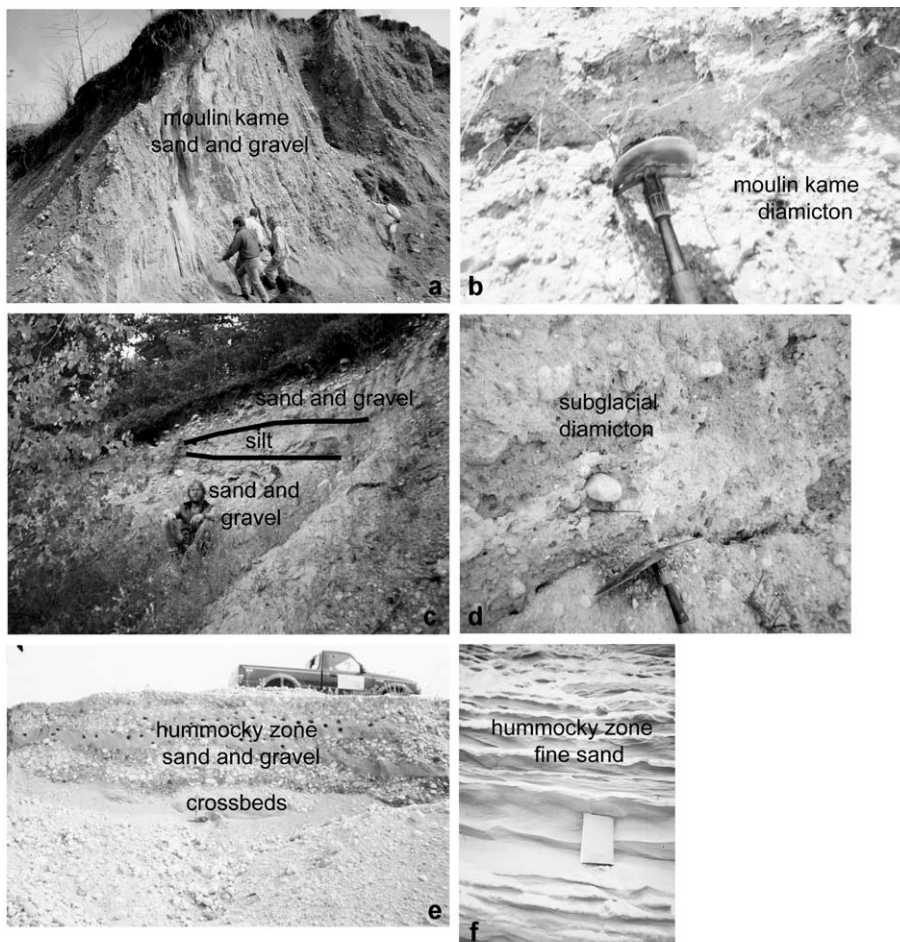


Fig. 3. (a) Moulin kame sand and gravel exposure. (b) Close up of moulin kame diamicton. (c) Exposure in moulin kame with silt interbedded with sand and gravel. (d) An example of Lake Michigan lobe subglacial diamicton. (e) Well-rounded sand and gravel overlying crossbedded sand, typical of the hummocky areas. (f) An example of the well-sorted sand found in the hummocky areas.

ison. Eleven measurements of cross-bed orientations and clast imbrication were taken in fluvial sediment to determine paleocurrent (e.g., Fig. 3e). The number of measurements is limited by the low number of clearly nondisturbed exposures. Much of the sediment has experienced postglacial collapse, and, in some cases, stream flow direction recorded by the sediment could have been modified. The consistency of flow directions between adjacent sites, however, indicates that collapse did not alter grain orientation enough to cause misinterpretation of flow directions. From 22 exposures, average roundness of clasts from gravel (19 exposures) and diamicton (3 exposures) facies was calculated by taking the mean roundness of 50 clasts (2 to 10 cm long axis length) using the scale of 0.1 (very angular) to 0.9 (well-rounded). The number of measurements (22 total measurements) is limited to the number of outcrops with sufficiently large clasts because auger samples do not produce a representative sample of the gravel fraction. Topographic cross-sections were constructed from topographic maps.

4. Landforms and sediment

The CLA is 20 to 50 m lower than the hummocky ridges on either side and 0.8 to 2.4 km wide. It is

underlain by rolling diamicton (2 to 4 m thick) with 6 to 15 m of relief and relatively uncollapsed outwash. The diamicton is compact and similar to basal till of the LML and GBL to the east and west of the nKM (Fig. 3d). The outwash is fine-grained, mainly silt to silty sand, and contains few small clasts (<20 cm). The CLA lacks the high-relief topography of the hummocky ridges on either side (Figs. 2 and 4).

Large conical moulin kames (Alden, 1918), rise 15 to 55 m above the CLA and rest directly on top of basal till (Figs. 2 and 4). The sides of the moulin kames are at the angle of repose. The few exposures in moulin kames contain diamicton, well-sorted to poorly sorted sand and gravel, and laminated silt (Fig. 3a, b and c). These sediments are steeply dipping and interbedded with one another. Diamicton and poorly sorted sand and gravel comprise the majority of sediment seen in the exposures. Maximum clast diameter is 1 m. Several of these hills have eskers (3 to 18 m high) extending up to 400 m from the southern flanks.

Long, hummocky ridges border both sides of the CLA and rise steeply 20 to 50 m above the CLA (Fig. 2). Deep kettles about the ridges on either side (Fig. 2b). The two ridges contain well-sorted, well-rounded, sand and gravel with clast diameter <1 m

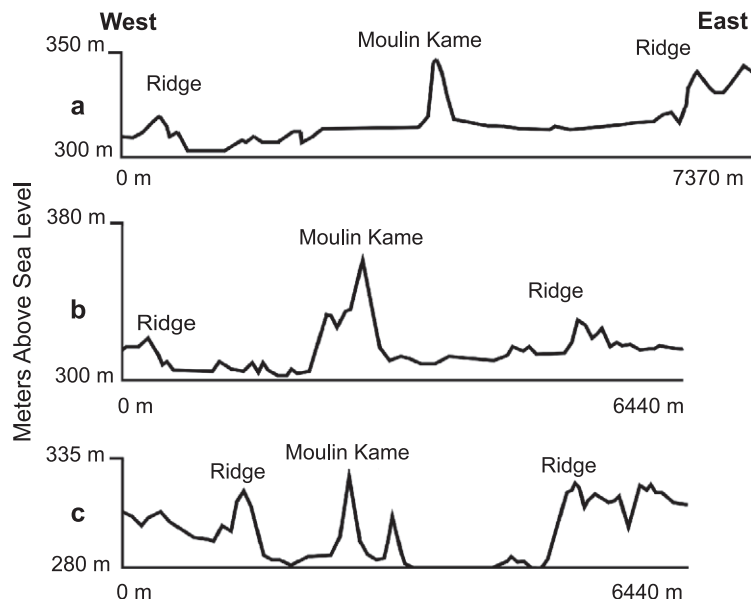


Fig. 4. Topographic cross sections from the northern Kettle Moraine. Vertical exaggeration is 24 times. Locations denoted in Fig. 2.

Table 1

Roundness data: 0.1=very angular, 0.9=well rounded

Sediment type (no. of samples)	Average Roundness (1 sigma)
Moulin kame (7)	0.55 (0.09)
Marginal ridge (3)	0.79 (0.02)
Hummocky zone (6)	0.79 (0.01)
Pitted outwash (3)	0.77 (0.03)
Combined average	0.78 (0.02)
Basal Till (3)	0.64 (0.04)
Transport path	Modern roundness range
Basal	0.5 to 0.8
Englacial	0.2 to 0.7
Glaciofluvial	>0.7

Average roundness is calculated with 1σ error. Modern transport data are from Bennett and Glasser (1996).

(Fig. 3e). These marginal ridges grade east and westward into broad zones (up to 1.6 km wide) of lower relief (<20 m) hummocky gravel with kettles up to 2.5 km² in area, which grade into pitted outwash plains with incised channels (Fig. 2). Sediment in the hummocky areas ranges from well-sorted, well-stratified sand to poorly sorted, more massive sand and gravel (Fig. 3e and f), and diamicton near ice contact faces. Most of the sediment is fairly well-sorted sand and gravel with maximum clast size between 0.5 and 1 m. Similar hummocky topography characterizes the single ridge north and south of the double ridge.

Two contrasting areas of sediment exist in the nKM. The CLA contains diamicton, which was likely deposited directly by overlying ice, and some fluvial sediment that is finer grained than in the hummocky areas. Moulin kame deposits contain mainly diamicton and poorly sorted sand and gravel, and have significantly less rounding (0.37 to 0.65; Fig. 3a and b) than gravel in the surrounding hummocky areas (0.71 to 0.81; Fig. 3e and Table 1). Rounding values associated with moulin kame sediment have nearly the same range as the till samples (0.55 to 0.63; Fig. 3d) and suggest englacial transport. The second depositional area consists of the hummocky marginal ridges, lower relief hummocky zones, and pitted outwash plains, which are differentiated based on morphology. These sediments are more rounded and better sorted than sediment in the CLA, and are consistent with more glaciofluvial transport (Table 1).

5. Sediment transport paths

Limited paleocurrent estimates indicate that meltwater flowed southeasterly on the western GBL side of the axis and southwesterly on the eastern LML side (Fig. 2a). In the single ridge north of the CLA, meltwater flowed along the nKM axis. This indicates that most of the surface water associated with the nKM drained toward or oblique to the CLA, but little glaciofluvial debris is found in the CLA except for the coarse sediment in moulin kames that underwent little fluvial transport. A lack of collapse features also occurs within the sediment in the CLA where the only appreciable relief results from the moulin kames and abrupt rise of the marginal ridges on either side of the CLA (Fig. 4). The steep sides of these landforms suggest that they were deposited in contact with ice. Moulin kame tops are generally higher in elevation than the adjacent marginal ridges (Fig. 4) and imply that during deglaciation the ice surface in the CLA was higher than the ice surface under what are now the hummocky ridges.

6. A new hypothesis for the genesis of the northern Kettle Moraine

During retreat from its maximum extent, ice overlying what is now the nKM thinned and the GBL and LML began to separate, opening an interlobate area first in the south, then expanding northward. Compressive flow in both ice lobes carried basal debris high in the ice of each lobe, where it melted out to produce supraglacial debris. Initially, debris accumulated in a low area formed along the interlobate axis (Fig. 5a). Relatively debris-free areas to the east and west of the debris-covered axis downwasted more rapidly because thick debris insulated ice along the nKM axis. This produced supraglacial channels that routed meltwater parallel to and on either side of the axis, and stopped glaciofluvial sedimentation along the axis (Fig. 5b). This explains the paucity of collapsed, well-rounded, well-sorted glaciofluvial sediment in the CLA, and instead, its accumulation in hummocky ridges on either side.

Debris flowed and slid off the high central area into the southwest flowing streams in the supraglacial channels on both sides. Some of this debris also

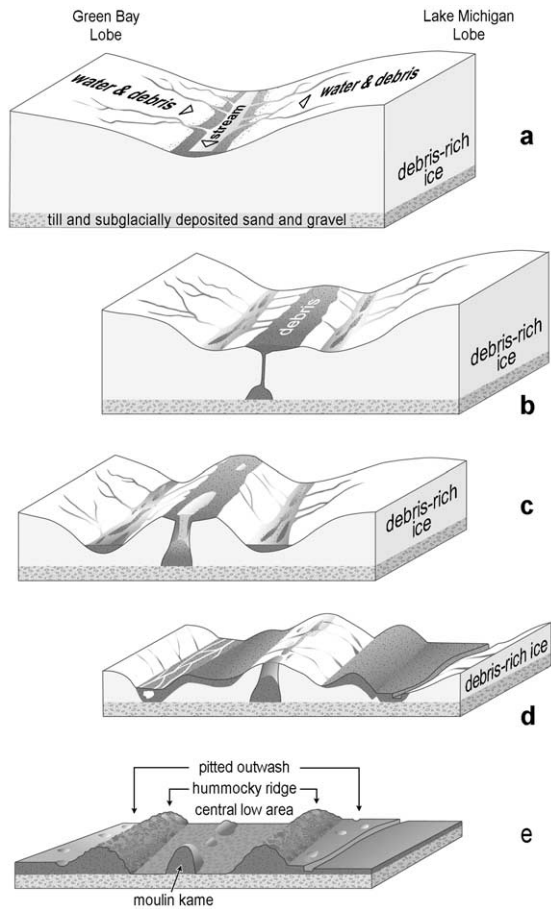


Fig. 5. Genetic model for the northern Kettle Moraine. Sequences a–e explained in the text.

accumulated in moulins and larger collapsed areas in the ice along the axis (Fig. 5c). These were initially small, probably penetrating to the base of the ice (Alden, 1918), and meltwater drained into subglacial tunnels. Continued sedimentation in the moulins and enlargement by collapse of overlying ice produced what are now large moulin kames composed of poorly sorted, poorly rounded sediment and associated eskers.

As ice retreat continued, meltwater abandoned the channels parallel to the nKM axis and drained southward between the retreating ice margins and the now high, ice-cored ridges on either side of the nKM axis (Fig. 5d). The GBL retreated westward with a north–south-oriented ice margin (Colgan, 1999). Its meltwater flowed southeastward down the regional slope and deposited a broad outwash plain against the

nKM. The western ice-cored gravel ridge of the nKM blocked the flow of GBL meltwater and thus protected the nKM axis from fluvial deposition. The LML retreated eastward down the regional slope and its margin remained roughly parallel to the nKM axis (Colgan, 1999; Carlson, 2002). Meltwater was trapped between the ice lobe and eastward-sloping land, and flowed southward depositing a broad outwash plain in which ice marginal channels were incised. Later, buried ice melted out of the ice-cored ridges and outwash plains, and produced high relief, hummocky topography and kettles, and eventually exposing moulin kames in the CLA (Fig. 5e).

Where the nKM is a single ridge north and south of the double ridge that we describe here, it appears that only one supraglacial channel formed along the axis, and meltout and collapse of this sediment produced the single hummocky ridge. One possible reason for the formation of the double ridge in the nKM and nowhere else along the Kettle Moraine is the orientation of the nKM axis with respect to ice flow direction. The double ridge coincides with the only part of the Kettle Moraine that is oriented approximately north–south and where the ice margins on either side remained almost parallel to the Kettle Moraine axis forming an acute interlobate angle during retreat. This may have concentrated supraglacial debris along the nKM axis that initially insulated ice and allowed channels to form on either side of the axis. These channels protected the axis from subsequent glaciofluvial sedimentation. North and south of the double ridge, meltwater flowed down the ice surface slope into a broader interlobate angle and was not confined to the axis because the GBL and LML retreated at an oblique angle to the axis (Mickelson and Syverson, 1997; Principato, 1999; Chapel, 2000).

7. Discussion

Previously proposed models can explain deposition along part, but not all of the nKM. The proglacial model accounts for the hummocks (buried ice eventually melted out) and CLA (a proglacial meltwater channel), but not eskers or moulin kames in the CLA that require overlying ice to be present during deposition. Little evidence exists of fluvial deposition in the CLA and the moulin kames show no sign of

fluvial modification, suggesting that the CLA is not a meltwater channel. If the CLA were a meltwater channel, then the melting of debris-rich ice in the hummocky marginal ridges would have deposited alluvial fans in the CLA, but these are not present (Fig. 2). In addition, the two marginal ridges contain well-sorted, well-rounded glaciofluvial sediment, not diamicton, which would be expected if these ridges were moraines. The proximal sides of these ridges rise steeply, suggesting that they are ice-contact slopes and that ice was between the ridges during deposition of the sediment in the ridges. If the two marginal ridges were deposited in subglacial tunnels, then an accumulation of glaciofluvial debris would occur along the nKM axis because no topographic high would have blocked supraglacial meltwater from flowing towards and along the axis during deglaciation. The paucity of glaciofluvial debris along the axis requires the development of these supraglacial channels on either side of the axis. This evidence argues that the hummocky ridges are supraglacial fluvial deposits that were separated by stagnant ice that had a thin debris cover, not moraines separated by a meltwater channel or subglacial tunnel deposits.

8. Conclusions

The double ridges of the nKM of eastern Wisconsin were deposited in large supraglacial channels that flowed southwestward on either side of a relatively debris-poor area of stagnant ice along the nKM axis. The presence of these channels explains the distribution of rounded, glaciofluvial sediment in the two marginal hummocky ridges on either side of a debris-poor CLA that contains mainly angular moulin kame deposits. The landform and sediment distribution in the nKM resulted from the north–south orientation of the nKM axis relative to the retreat directions of the GBL and LML. This orientation initially concentrated sediment along the nKM axis that preserved stagnant ice and allowed supraglacial channels to form on either side of the axis. These channels limited further sedimentation along the axis. Thus, in this part of the Kettle Moraine, ice insulation, ablation, and interplay with supraglacial streams were the dominant controls on sedimentation and landform genesis.

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