Chapter 3

Bedrock Control of Drumlin Morphology and Orientation
ABSTRACT

In the central Upper Peninsula of Michigan and northeastern Wisconsin, the Menominee drumlin field contains at least a thousand drumlins. They formed from 11,850-11,500 years ago as the Green Bay lobe of the Laurentide ice sheet moved south, then westward across central Upper Michigan and northern Wisconsin. No drumlins formed on the east side of the lobe (outside the geographic extents of the present study area). During its advance toward the west, the ice mass passed over three different types of bedrock. Ordovician limestone occurs beneath glacial deposits near the center of the lobe, a belt of Cambrian sandstone outcrops in a north-south trend immediately west of the limestone (in a down-ice direction), and granitic basement is exposed yet farther to the west. The end moraine of the drumlin-forming advance overlies the granitic bedrock about 20 kilometers west of the sandstone/granite contact, and 35 kilometers west of the sandstone/limestone contact. Drumlins overlie only the limestone and sandstone lithologies.

Drumlin form and orientation in the northern portion of the Menominee field change nearly precisely at the contact between the limestone and sandstone bedrock. The drumlins over both types of bedrock formed contemporaneously; there is a smoothly continuing but distinct orientation change in the landforms from one bedrock type to the other. Mean length, width and height measurements show that drumlins are smaller and more elongated over the limestone bedrock. They are characteristic of the "ideal" spindle-shaped drumlin form; i.e., blunt nose with a long, low-sloping tail and a length/width ratio greater than six. Those drumlins are uniformly oriented toward the southwest with a mean
orientation of about S50°W. Drumlins that occur over sandstone bedrock are larger, typically more complex in shape, and have length/width ratios of four or less. They are oriented toward the west (N90°W). Many of the drumlins overlying sandstone are complexes of several drumlin forms and flutes superposed on yet larger landforms oriented in a more northerly direction (approximately N50°W).

These observations suggest that the bedrock type controlled the subglacial processes that formed the drumlins. The complex processes are interpreted to have involved spatial variations in pore fluid pressure that affected subglacial sediment shear strength and resistance to erosion and deformation. We suggest that drumlin form and orientation were influenced by the physical environment of their formation; specifically, the hydraulic conductivity of bedrock and subglacial sediments controlled pore-water pressure in the subglacial environment, leading to variations in sediment shear strength. These variations are reflected by the change in form and orientation of drumlins and flutes that occurs at the bedrock contact.
INTRODUCTION

Current research into subglacial processes and resulting landforms may be approaching a unified theory that may help to explain the variability in form, sedimentology, occurrence and distribution of a whole range of subglacial bedforms (Menzies, 1979; Bindschadler, 1983; Shoemaker, 1986; Menzies and Rose, 1987; Boulton and Hindmarsh, 1987; Menzies, 1989; Patterson and Hooke, 1995; Boulton, 1996). Patterson and Hooke (1995) summarized studies describing physical conditions of drumlin formation from seventeen different fields around the world. The study was undertaken in an attempt to find factors that were common to all observed cases of drumlin formation. They found that all drumlins are influenced by three variables. The first is linked to ice physics: drumlins form in zones where the longitudinal strain is compressive and the transverse strain is extensional. Such areas are typically located up-glacier from a frozen margin in a zone 2-25 km wide. Because of the strain conditions in these areas, the ice is thin, which is the second common factor common to all drumlin fields. The third condition necessary for drumlin formation is high subglacial porewater pressure. In fact, they found "no drumlin fields in areas where elevated water pressures would have been unlikely" (p. 37). However, the lithology or texture of substrate materials (bedrock or unconsolidated sediments) were not specifically regarded to be a factor. Of the bedrock substrate types described in their study, only a small fraction are lithologies that normally have high hydraulic conductivity (of all bedrock lithologies in their study, one-third are shales and slates, one third are crystalline rocks, one quarter are...
carbonate rocks, while sandstone, conglomerate, and basalt make up the remainder). Of these, only sandstone and conglomerate are normally considered highly permeable.

Menzies (1979, 1984) and Menzies and Rose (1987) compiled many studies in an attempt to find a common process or physical parameter that explains the enormous variability of drumlin form and sedimentology. They concluded that changes in pore-water pressure in the subglacial environment is the unifying factor that accounts for variations in drumlin morphometry, sediment characteristics, structures, etc. Similarly, Goldstein (1989) studied drumlins in the Wadena field, Minnesota and suggested that variability in substrate transmissivity is responsible for variations in sediment shear strength and that drumlin cores form where shear strength is greatest. Coarse-grained sediment masses are less deformable than fine-grained sediments (under shear stress) because of their higher transmissivity, which reduces pore water pressure and greatly increases sediment shear strength.

Boulton (1979, 1987) and Menzies (1984, 1989) suggest that masses of sediment with relatively high shear strength become nuclei for drumlins while more deformable sediments are forced around them. Drumlin growth then occurs in one of two ways; sediments gradually plaster around the core by subglacial lodgement, or the sediments mobilize into low-pressure cavities formed at the lee of the obstacle thereby forming a drumlin tail. Cores of resistant sediment masses may form where permeability of the bedrock or sediment allows reduced pore pressure (greater effective pressure) in the sediment, or where sediment textural properties increase its shear strength, or where a bedrock protrusion forces ice to stream around it. In one example (Figure 1), Boulton
Areal patterns dictated by pre-existing sediment distribution

Patterns of channels and bars in ice-contact outwash fans

Drumlins initiated by coarse gravel masses

Stream portals at glacier terminus ice-contact slope

inter-drumlin streaming enhances erosion

Location of former ice-contact slope

Figure 1. Drumlin formation by ice streaming around resistant cores of outwash sand and gravel (after Boulton, 1987).
(1987) shows how drumlins may be initiated by ice streaming around resistant cores of sediment that originally formed the head of an outwash plain. Menzies (1989) introduces terminology to define sediment rheologic conditions as a function of porewater pressure: "M" beds are "mobile soft beds" that pervasively deform under high pore water pressure; "H" beds are beds typified by a "hard" or rigid state. In such beds pore-water pressures are low, sediments have high shear strength, and most ice movement occurs through sliding at the bed-ice interface. "Q" beds are transitional between "M" and "H" beds (Figure 2). Drumlins form under dominantly "M" or "Q" bed conditions, according to Menzies. Usually, anisotropic rheologic variations (small scale "H" beds) in the sediment bed form the nuclei for drumlin growth, while "M" bed sediment deforms around them. The cause of such variations may be locally high hydraulic conductivity of the bed, freezing of the sediments, variations in grain size, consolidation, or increased shear strength of the sediment (Menzies, 1989).

Another hypothesis for drumlin formation was presented by Shaw (1983), Shaw and Kvill, (1984), Shaw and Sharpe (1987), and Shaw et al. (1989). They cite subglacial meltwater flow as the unifying factor controlling drumlin formation. In their theory, two processes are proposed to explain the variety of drumlin form and internal sedimentary structures. In the first process, turbulent, separated sheetflow of subglacial meltwater scourcs cavities upward in the base of the ice, which are then filled with sediments transported by hyperconcentrated flow. Secondly, subglacial meltwater sheetflow erodes into pre-existing sediments through the action of "horseshoe vortices on subglacial materials" (p. 177, Shaw et al., 1989) creating a drumlin form as a result. The latter
Figure 2. Glaciological evidence suggests that pore water pressure plays an important role in surges, jökulhlaups, and bedform genesis. Menzies (1989) suggests terminology to describe variations in porewater pressure and the effects on subglacial sediments. Hard ("H") beds occur where beds are stable, porewater pressure is low, and most deformation occurs at the ice-bed interface. Mobile ("M") beds occur where porewater pressure is high and beds have little shear strength. "Q" beds are transitional between "H" and "M" beds (after Menzies, 1989).
hypothesis draws upon the striking similarity of drumlin form with erosion marks formed by turbulent fluid flow over any surface (a block of plaster-of-paris with inset obstacles was used to produce drumlin forms in an experiment they conducted, for example). Their evidence for both processes includes sedimentologic features, such as internal drumlin sediment texture (e.g., fluvial sediments), structures (e.g., cross-bedding), and stratigraphy (e.g., grain size variations). This process explains the occurrence of stratified fluvial sediments found in many drumlins, while the former explains the undeformed pre-existing structures and sediments (e.g., fine-grained till) found in other drumlins.

Shaw et al. (1989) also introduced a qualitative drumlin-shape classification system that allows comparison of drumlin forms to similar erosion forms of any scale: spindle forms are those with length/width ratios of about 5:1, parabolic and parabolic with arms are forms that begin with pointed stoss ends but widen downflow such that the outline is parabolic in plan (they resemble barchan dunes), and transverse asymmetric forms have small forms and flutes superposed atop a larger, transverse-oriented mass of sediment (also called shield drumlins). Similar drumlin shapes are recognized in the present study area and the terminology of Shaw et al., (1989) is used in this paper.

This study relates the subglacial processes described by Boulton (1987, 1996), Menzies (1984, 1989), Shaw and Kvill (1984), Shaw and Sharpe (1987) and Shaw et al., (1989) to the form and orientation of drumlins found in the Menominee field, Michigan and Wisconsin. In this study, it is suggested that spatial variations in the hydraulic conductivity of the underlying bedrock and the texture and thickness of subglacial sediments influenced subglacial porewater pressure and consequently, rheological
properties of the sediments. Drumlins that formed over bedrock with low hydraulic conductivity and thin beds of sediment are longer, narrower, and oriented toward the south-southwest. Drumlins that formed over permeable bedrock and in thicker glacial sediment or supra-bedrock deposits are short, wide complexes of several drumlin forms, and are oriented toward the west. The change in drumlin characteristics occurs over the contact between the limestone and sandstone bedrock lithologies that have different hydraulic conductivities. Thickness and texture of the glacial sediment also change across the contact. It is also suggested that late in the drumlin forming process, subglacial meltwater flow modified the shape of established drumlin forms by scouring channels into them and around them. In this study, drumlin form, orientation, and sedimentology are analyzed with respect to their spatial location over limestone and sandstone bedrock.

**STUDY AREA**

The drumlins of the current study are located in the south-central Upper Peninsula of Michigan and northeastern Wisconsin, which encompasses part of the Menominee drumlin field. The drumlins were previously described by Russell (1905, 1907), Bergquist (1941), and more recently by Mills (1987). The whole field contains over one thousand drumlins in approximately four thousand km² area extending southward to Green Bay, Wisconsin. The area of detailed study encompasses a small portion of the entire field (Figure 3).

The bedrock geology of the study area consists of three major units (Figure 4). Ordovician limestone and Cambrian sandstone are found in the east and east-central part,
Figure 3. Location of the detailed study area showing the Menomitee drumlin field and the ice-marginal position as the drumlins formed.
Figure 4. Bedrock Geology. Archean granite and gneiss compose the bedrock in the west-central part of the study area, Proterozoic-aged metasediments are found in the extreme north and in the southwest, and Paleozoic sandstone and limestone compose the southeastern third (after Morey, et al., 1982).
respectively, and Archean granite underlies the western portion of the study area.

Proterozoic metasediments exist in the study area but are not overlain by drumlins. The Cambrian and Ordovician sedimentary rock lithologies comprise the basal formations of the Lake Superior Group deposited during early evolution of the Michigan Basin (Reed and Daniels, 1987).

Topographically, surface elevations around the drumlin field range from about 420 meters above mean sea level (AMSL) at the end moraine (west), to about 180 meters AMSL in the east, near the center of the lobe. The horizontal distance between drumlins located at the lobe center and the end moraine is about 45 kilometers.

As an aquifer, the Ordovician limestone yields little water to wells. Its hydraulic conductivity (K) is about $3.528 \times 10^9$ m/s (Emmons, 1987). The sandstone, however, is texturally well-sorted and is highly permeable. It is one of the best bedrock aquifers in the region. It has a hydraulic conductivity of about $1.729 \times 10^5$ m/s (Young, 1992). In the western portion of the study area, the Archean granitic rocks are known to be poor aquifers (Regis, 1989). No drumlins exist there, however.

Physical properties of the glacial sediments, such as texture, composition, and thickness vary as a function of bedrock. Over limestone, till is generally fine-grained and comprised mostly of limestone fragments of all sizes. Textural analysis of the ≤2 mm fraction of fifteen samples averages 45% sand, 43% silt, and 12% clay. This texture is a loam according to the U.S.D.A. textural triangle. Fourteen samples of the ≤2 mm fraction taken from till overlying sandstone averages 68% sand, 24% silt, and 8% clay (sandy loam). Grains consist of both sandstone and limestone lithologies throughout all size
classes in till above the sandstone bedrock. The percentage of limestone grains in till that overlies sandstone decreases westward, away from their provenance. Till that overlies granitic bedrock is very sandy (76% sand, 20% silt, 4% clay, loamy sand), with a large component of sandstone and granite grains (all sizes).

Overburden thickness also appears to be related to bedrock geology and to have influenced the formation of drumlins. Sediment thickness across the drumlinized area is variable, but generally it is thinnest and least variable in the southeast portion (Figure 5). Thickness of overburden mostly ranges from 0-10 m over limestone bedrock, and increases in thickness (generally 5-50 m) to the north and west over sandstone bedrock. The sedimentary blanket is most variable over granitic bedrock (0-50 m). As Figure 5 shows, thickness of glacial deposits increases westward across the contact between the limestone and sandstone.

**METHODOLOGY**

Drumlin forms were identified on U.S.G.S. 1:24,000 scale topographic maps (contour interval 3 m). The lowest enclosing isoline was assumed to be the base of the forms, and the top was interpolated from the highest contour (Mills, 1987). Lengths, widths, heights, and spacing between drumlins were measured from the topographic maps and the dimensions were entered into a computer spreadsheet and exported to a statistical graphics program. General statistics for the drumlins were calculated (described in the next section) and compared to bedrock lithology.
Figure 5. Overburden thickness/geology/drumlin relationship. Sediment thickness increases and drumlin orientation changes toward the west, across the limestone/sandstone bedrock contact.
After identifying drumlin forms on topographic maps, field reconnaissance and sample collection was undertaken to evaluate sedimentary characteristics such as grain-size and sedimentary structure distribution within the drumlins. Observations were limited to roadcuts, excavations, and gravel pits that intersected drumlin interiors, and a few soil auger corings to a depth of about 1.5 meters. Although gravel pits are located where coarse-grained material is present and tend to bias observations, the information derived from these exposures is thought to be typical for most drumlins. For example, roadcuts through drumlins are not located with respect to the occurrence of gravel, yet roadcuts observed in this study have similar sedimentary texture and structure to those observed in gravel pits.

**DRUMLIN MORPHOLOGY AND ORIENTATION**

**Relationship to bedrock geology**

Through image processing techniques, Side-Looking Airborne Radar (SLAR) data and a scanned geologic map were co-registered, displayed on the computer monitor, and interpreted. The line of contact between limestone and sandstone bedrock was digitized over the SLAR dataset for reference and shown in Figure 6. The image clearly shows the relationship between drumlin morphology and orientation and bedrock geology. Spindle-shaped, isolated drumlin forms become much less prevalent west of the limestone-sandstone contact. Drumlin and flute orientations also vary on either side of the contact. A distinct westward shift in orientation occurs where the ice overrode sandstone bedrock. This can be explained by increased frictional drag between the glacier base and sediments.
Figure 6. Line of contact between Ordovician limestone and Cambrian sandstone draped over a Side-Looking Airborne Radar (SLAR) image. Drumlin features over limestone are oriented S50°W, are isolated, and are spindle-shaped; drumlins over sandstone are oriented toward the west-northwest and are complexes of multiple drumlins and flutes.
overlying the sandstone bedrock, which probably caused the ice velocity to decrease. The velocity decrease caused deflection in that part of the lobe (similar to refraction of light or sound waves).

Figure 7 shows examples of the "classic" spindle-shaped drumlin forms (symmetrical about the long axis, long and narrow, having a steep proximal side and long, gradual-sloping distal side) that are found overlying limestone. In contrast, drumlins above sandstone bedrock are composed of multiple, complex drumlin forms (Figure 7). The drumlins and fluted forms over sandstone are superposed on much larger (several kilometers in length and about one kilometer width) and thicker sediment masses having a general orientation of about N40-50°W. Usually, these complex drumlins begin (in the proximal direction) with a steeply-sloping, well-defined snout, but they then vary considerably in the distal direction. Some have multiple tails, or fan outward in the distal direction, so that they are several times wider at the tail than at the nose, or they have multiple crests that are adjacent and parallel to each other. Some drumlins have multiple crests in succession along the long axis, or two drumlins may begin as individual forms, but merge into one complex drumlin in the distal direction. Others have crests that are sinuous (rather than straight). Thus, drumlin form generally changes from isolated, single bodies of sediment in the eastern part of the study area (above limestone bedrock), to much more complex forms in the west (above sandstone bedrock).
Figure 7. Examples of some drumlin forms, with those on the right representing drumlins overlying limestone in the eastern portion of the study area, and those on the left representing drumlins overlying sandstone in the western part.
STATISTICS

Descriptive statistics were derived for drumlins in the northern part of the Menominee field from the region where the rate of orientation and form change is greatest (many drumlins exist south of the study area but do not exhibit such a dramatic change in form and orientation there). The mean length of all drumlins in the study region (n=244) is 1119 meters (standard deviation=489 m). The mean width is 262 meters (SD=104 m) and mean height is 16 meters (SD=7 m). Mean length/width and height/length ratios for all drumlins are 4.27 and 0.014, respectively. Ratios of length/width and height/length are commonly used as indicators of formative processes during interpretation of drumlins (Chorley, 1959; Muller, 1974; Embleton and King, 1975). Those with high length/width (or inversely, low width/length) or length/height ratios are attributed to fast-moving ice. High length/width ratios may also reflect the presence of thin glacial drift, a factor that contributes to fast ice movement (Miller, 1972), or uniform ice-flow direction (Mills, 1987).

Along with the overall appearance (i.e. simple vs. complex), the spacing (as measured perpendicular to long axes) between adjacent drumlins, and the mean length/width and height/length ratios vary with spatial location within the drumlin field. Comparisons of mean length, width, height, ratios, and spacing for drumlins located over limestone and sandstone are given below. Drumlins in the eastern portion of the study area are typified by relatively high length/width and height/length ratios. In contrast, drumlins in the western portion of the study area formed above sandstone bedrock and have lower length/width ratios and height/length ratios compared with the eastern region.
Mills (1987) found that drumlin length/width ratios vary as a function of bedrock lithology. He found that drumlins over limestone or shale have greater length/width ratios than those over granite or metamorphic bedrock. No explanation was offered, however, for the relationship between drumlin form and bedrock lithology. Also, Mills' study did not include drumlins that formed over highly permeable bedrock, such as sandstone.

**Table 1.** Drumlin statistics compared to bedrock geology (SD in parentheses).

<table>
<thead>
<tr>
<th>Bedrock</th>
<th>Length</th>
<th>Width</th>
<th>Height</th>
<th>L/W</th>
<th>H/L</th>
<th>Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>1205 m (254)</td>
<td>189 m (59)</td>
<td>14 m (5)</td>
<td>6.37</td>
<td>0.012</td>
<td>185-550 m</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1103 m (456)</td>
<td>275 m (87)</td>
<td>18 m (8)</td>
<td>4.01</td>
<td>0.016</td>
<td>375-2000 m</td>
</tr>
</tbody>
</table>

**DRUMLIN SEDIMENTOLOGY AND STRATIGRAPHY**

Many studies have presented data regarding drumlin stratigraphy and sedimentology (Whittecar and Mickelson, 1979; Moran *et al.*, 1980; Shaw and Kvill, 1984; Sharpe, 1987; Shaw *et al.*, 1989). Patterson and Hooke (1995), in an extensive review of literature describing drumlins all over the world, found that over half the drumlins with exposed interiors have massive till or coarse gravelly till at their core. Moran *et al.* (1980), for example, found that deep exposures of drumlins in the prairie region of North America reveal cores of granular material. Sharpe (1987) and Shaw and Kvill (1984) found that drumlin interiors in southern Ontario and Saskatchewan, Canada, respectively, contained several amalgamated layers composed of material such as stratified and normally graded sand. Many of these drumlins had several conformable deposits such
as sandy beds interspersed with beds of pebbly till. Many exposures also revealed
multiple, fining upward cycles of coarse to fine gravelly till. Dardis (1987) found similar
stratified deposits in drumlins in northern Ireland. Similarly, stratified sediments and
structures like those described by Sharpe and Dardis are found in drumlins of the
Menominee field (described later in this section). Thus, evidence shows that the specific
core material of drumlins may be highly variable (such as dense till, sand and gravel, etc.).

Within the present study area, several drumlin interiors were exposed by
aggregate operations and along roadcuts. Most exposures revealed a core of massive,
crudely-stratified till. Bergquist (1941, p. 460) also noted the presence of "rude bedding
planes . . . parallel to surface contour of the hills, which indicates that meltwater was
actively at work during the drumlin-shaping interval" in some Menominee field drumlins.
In many drumlins, although exposures were often incomplete, and at less than ideal
locations in the drumlin, some stratified sand and gravel deposits, and some laminated
sandy-silt deposits were also revealed. All of the sand deposits were moderately well
sorted, and some had gravel lenses interspersed within them. Thickness of the deposits
ranged from a few centimeters to a meter.

In one drumlin, where sediments at the proximal end are exposed in cross-section
from its center to its southern side, a several meter thick crudely bedded, fining-upward
succession of silt, sand and gravel overlies an erosional surface above finely laminated silt
(Figure 8). The sediments are matrix-supported, and lack primary structures. Above the
massive deposit is a sharp conformable contact with a normal-graded bed (Figure 9)
composed of cobbles, gravel and sand. The bed is about 0.75 m thick and parallels the
Figure 8. Photo of gravel pit exposing a drumlin interior. Normal-graded till forms the core material. An abrupt transition to a normally graded fluvial sand and gravel deposit, 0.75 m thick, occurs near the surface. A meltwater channel (2 m wide by 1 m deep) cuts both deposits. The drumlin is capped by a 0.75 m of ablation till. Shovel handle for scale is about one meter long.
Figure 9. Close-up view of the normally graded fluvial sediments from a position just to the right of the area shown in Figure 8. Lens cap for scale is 60 mm diameter.
surface of the drumlin, about 1 meter below surface. It is exposed across one-half of the pit (about 20 meters in length). The sediments fine upward from a $D_{95}$ of 30x25x15 cm to moderately well sorted, laminated silty sand. The deposit reflects very strong flow conditions as evidenced by the large clasts, and then a change in hydraulic energy to quiescent conditions. Also in the drumlin, at a position located about 1/3 of the way down the south side, trough cross-bedded sediments are present in a channel about 2 meters wide and 1 meter deep that cut into the massive deposit and the graded bed. Sediments in the channel are composed of coarse sand and gravel with little silt or clay. The channel appears to truncate the graded bed and is appears to have formed late in the drumlin-forming process. Ablation till about 0.75 m thick forms the surface deposit.

In another gravel pit excavated into the proximal end of a drumlin, three separate large-scale crudely fining-upward sequences of till are recognized within a single drumlin (Figure 10). The base of the exposure reveals till that is crudely graded (normally graded), overlain by a horizontally continuous deposit of stratified silty-sand. Above the silty-sand are two crude, normally graded deposits of till capped at the surface by about 1 meter of ablation till. The $D_{95}$ grain size for the base of the lower unit is 20x20x12 cm and this unit grades to sandy, gravelly till at the top, over a distance of 2 m. The finely laminated, well-sorted silty sand layer is continuous and horizontal across the entire exposure. The layer is 20-30 cm thick for its entire length. Each till deposit crudely fines upward from a matrix-supported, erosive base overlain primarily by cobbles and boulders. The uppermost deposit is composed of very coarse sand and gravel interspersed with cobbles throughout its 1.5 m thickness. In general, for most drumlin interiors, but especially
Figure 10. Drumlín interior exposure. Stratigraphically, there are three crudely graded till deposits, each with slight variations in the degree of grading, range of grain size, and thickness. Separating the lowest till from the middle unit is a laterally continuous layer of silty sand about 20-30 cm thick. The drumlin is capped by 0.5-0.75 m of ablation till.
where the proximal ends are exposed, matrix-supported cobbles and boulder deposits, lenses of stratified sand, or gravelly, crudely stratified till are present.

NON-DRUMLIN LANDFORMS

Troughs between drumlins

Russell (1907, p. 45) suggests the importance of the troughs between drumlins by stating "perhaps the most suggestive conclusion furnished by the study of the Menominee drumlin area, is that drumlin troughs . . . are fully as characteristic of drumlin topography as are the hills they separate". Indeed, many troughs separating drumlins exhibit forms that warrant explanation. Fortunately, some aggregate extraction pits are located in the troughs, so their origin may be interpreted. Where such operations exist, they invariably expose deposits of fluvial sand and gravel. In Figure 11, the "hooked" drumlin just northwest of the gravel pit appears to have been molded mostly by running water, as the south and east-facing side of the drumlin is sinuous like a stream channel. The gravel pit is located next to the proximal end of this drumlin, where the (presumed) meltwater flow would have been fastest. Elongate, flat limestone clasts in the pit have dimensions as large as 30x20x10 cm, and are imbricated S65°W, suggesting high velocity water movement from the northeast (Figure 12). The form of the drumlin and its spatial association with the channel suggests that subglacial meltwater erosion was responsible for shaping it late in the drumlin forming process.

Other drumlins in the Menominee field exhibit a form that suggests they were eroded and modified by flowing water or ice streaming during the drumlin-forming
Figure 11. Topographic map (Northland, MI quadrangle) showing drumlin forms and the bedrock contact. Note the hooked drumlin and gravel pit near its proximal end and the bisected drumlin to the north (see Figures 12 & 13). Many drumlins appear to be partially shaped by meltwater in the subglacial environment. Interestingly, the width of the Ford River (near the arrow, NW corner) width increases at the contact with no tributaries adding to its discharge. Surface water may be able to infiltrate the sandstone but over limestone, drainage is interpreted to occur mostly at the surface.
Figure 12. Photo of gravel pit at the eastern (proximal) end of the hooked drumlin in Figure 11. Large, flat limestone clasts are imbricated toward the southwest, indicating high velocity water flow from the northeast, around the proximal end of the drumlin. Subglacial meltwater flow appears to have shaped the drumlin. View is toward the northwest.
process, or after the general drumlin shape was established. For example, note how a pair of asymmetrical drumlins in the northeast portion of Figure 11 appear bisected along their long axis by a channel. The drumlins are nearly mirror images of each other. Figure 13 is a cross section through the drumlins. Steep banks oppose each another and the former drumlin sides remain intact. The floor of the trough between the two drumlin portions is composed of sand and gravel. Russell (1907) discovered a similar drumlin near the town of Hermansville, Michigan. The drumlin he described also appears to be cut along its long axis by erosion, except in that drumlin, a large part of one side is missing (p. 45), making it asymmetrical about its long axis.

Similarly, Clapperton (1989) described drumlins in Patagonia, Chile that also have marked asymmetry about the long axis. Clapperton attributes the asymmetry to changes in the orientation of the stress field immediately before the drumlins ceased to form from the orientation when the main drumlin shape developed. Differential stresses caused greater rates of deformation on the up-glacier side of the drumlins (reflected by the steeper slope) than the opposite side. Asymmetrical drumlins in the Menominee field do not appear to be formed by this process, for the reasons cited above.

Transverse feature

In a roadcut in Sec. 26, T44N R26W, the core of a transverse-oriented landform (perpendicular to ice motion) is exposed (Figure 14). The feature is located about a kilometer east of the limestone/sandstone contact. The transverse feature is likely a rogen moraine. Sugden and John (1986) suggest that rogen moraines form at low pressure take-
Figure 13. Cross section of the asymmetrical drumlins indicated in Figure 11. The drumlins appear to be formed by the bisection of a larger drumlin along its long axis. The hypothetical profile of the former drumlin is indicated by the dashed line.
Figure 14. Cross section through north-south oriented transverse (to ice flow) feature. Ice flow was from left to right. View is to the south-southwest. Stratified, planar-bedded sand deposits are folded into an anticline. It is interpreted to have formed at the take-off (low-pressure zone) of a shear zone in the ice which was the result of faster ice velocity over limestone (east) than over sandstone (west). Rogen moraines and transverse features such as this one are known to occur in take-off zones (Sugden and John, 1985). Pebbly, coarse-grained ablation till overlies the contorted fluvial sand deposit.
off zones at the base of the ice, due to internal shearing. Stratified sand forms the core of
the feature. Ice motion was perpendicular to the fold axis, directed at an azimuth (west)
into the photograph. The roadcut also exposes primary sedimentary structures such as
ripple cross lamination and planar beds, all of which are contorted and deformed into an
anticlinal fold structure (Figure 15). Cross-bedding was found in deposits of coarse sand
about 2 cm thick in another area of the same exposure. Current direction as measured
from the foreset beds was N75°W. The interpreted direction of flow is opposite the
present-day regional slope (toward the ESE), toward the ice margin. The feature may be
the result of advancing ice overriding and folding pre-existing outwash deposits that were
deposited in westward-flowing meltwater streams.

**Outwash fan and tunnel channel**

Other evidence for high pressure subglacial meltwater flow at the base of a glacier
is the existence of a tunnel channel (or valley) and outwash fan that probably formed
contemporaneously with the drumlins. Tunnel channels and outwash fans that formed
beyond the margin of the Laurentide ice sheet are described by Wright (1973), Johnson
(1986), and Attig *et al.* (1985) in Minnesota and Wisconsin. These features suggest high-
pressure meltwater evacuated to the glacier margin via subglacial channelways. Figure 16
is a Landsat Thematic Mapper (TM) image of the Green Hills moraine in the western part
of the study area. This image shows an outwash fan, and a tunnel channel that formed in
the study area, presumably at the time the drumlin/flute features were forming. Although
much of the former channel is now filled with collapsed supra-or-englacial sediment (and
Figure 15. Close-up of contorted strata from limb of transverse feature in Figure 14. Note the well-preserved, deformed beds and ripple cross-lamination. Water flow was from left to right (toward the west). Pencil is about 20 cm long.
Figure 16. Landsat TM image showing moraine, outwash fan, and tunnel channel that were probably created at the time drumlins formed. The Menominee drumlins are just out of the imaged area (to the east). The occurrence of these features suggests periodic, possibly catastrophic outbursts of pressurized subglacial meltwater beyond the margin of the ice sheet.
as a result, in many areas is a positive-relief feature), lithologic evidence reveals the source
of the deposits. Many soil units along the trend of the tunnel valley have anomalously high
pH (CaCO$_3$ enriched), and pebble counts show an abundance of carbonate clasts in the
sediment. Such evidence suggests a distant, up-glacier provenance, from the limestone
bedrock. Also, most of these soil units formed on sandy, fluvial parent materials. The fan
beyond the former terminus displays similar sedimentologic and lithologic characteristics
as those in the tunnel channel, and suggests contemporaneous formation with the channel.
The surface of the fan is dissected by braided channels that diverge away (westward) from
the point where the moraine and the tunnel channel intersect.

**BEDROCK CONTROL ON WATER PRESSURE**

Recent glaciological literature stresses the importance of subglacial meltwater
pressure in the role of glacier sliding, surges, jökulhlaups (Goodwin, 1988; Russell, 1989;
Mayo, 1989; Dreiger and Fountain, 1989, etc.), and importantly, bedform development
(Menzies, 1979, 1984, 1989; Boulton, 1987, 1996; Sharpe, 1987; etc.). The general
conclusion of these studies is that the geometry of basal water bodies and fluctuations of
subglacial water pressure are related to the deformation of subglacial sediments, and may
explain several phenomena. For example, Menzies (1989), and Boulton (1987, 1996)
describe how high subglacial water pressure directly relates to pervasiveness and depth of
shearing in subglacial sediment. The rheology of a deformable subglacial sediment is
shown by Menzies (1979) to be a basic principle of soil mechanics. Shear strength ($S$) of a
sediment mass is simply defined as its resistance to deformation, and is directly related to effective pressure \( (p_e) \) by the Mohr-Coulomb equation:

\[
S = p_e \tan(\phi) + C
\]

where \( C \) is cohesion and \( \phi \) is the angle of internal friction of the sediment (Terzaghi and Peck, 1948). Effective pressure \( (p_e) \) is equal to the pressure exerted by the overlying ice mass \( (p_i g h) \) minus pore pressure \( (\mu) \):

\[
p_e = p_i g h - \mu
\]

where \( p_i \) = density of the ice, \( g \) = acceleration due to gravity, and \( h \) = thickness of the ice over the point of measurement. Thus, as effective pressure decreases because of increased pore pressure, shear strength \( (S) \) of the sediment mass is reduced. Also, shear strength varies with textural variations in sediment \( (\phi) \) the angle of internal friction). Within a small region of one sedimentary body, however, \( (\phi) \) generally remains fairly constant and shear strength is controlled by variations in pore pressure \( (\mu) \). Excess meltwater not relieved by drainage through the subglacial aquifer system increases pore water pressure throughout the sediment mass. As porewater pressure increases, the sediment mass becomes unstable and forms a slurry (Menzies, 1989).

Pressure transmitted through the slurry is derived from the ice mass and additions of meltwater which sets up a potential that causes the water to flow toward zones of
lower head, usually toward the ice margin if the bed is frozen or impermeable (Shoemaker, 1986). At such times, the ice will decouple from the bed and move forward mainly by basal slip (Jansson, 1995). Meanwhile, pressurized water moving toward the glacier margin, coupled with the sliding ice mass, exerts a stress on individual sediment grains as water migrates through the pore spaces. Once the applied shear stress exceeds or is equal to the shear strength of the slurry, failure results in movement of the grains (Boulton and Hindemarsh, 1987). These studies show that the location where a sediment mass will fail depends on the distribution of sediments and their physical properties (i.e., $\phi$), porewater pressure, and boundary conditions along the path that porewater follows toward a lower potential area. Fine-grained, non-cohesive deposits fail first because the angle of internal friction ($\phi$) decreases with decreasing grain size. Boulton (1987) and Hart (1995) also showed that thin beds of sediment are more easily deformed than thick beds under moving ice. For example, in the Breidamerkurjökull glacier, Boulton observed that thick beds of sediment tend to transmit stresses throughout the bed. In such beds, there is an upper ("A") horizon of non-linear viscous deformation, while a lower ("B") horizon remains stable or shows little sign of strain. In contrast, thin beds deform throughout the entire thickness and have no "B" horizon. Thus, it is reasonable to assume that thin beds consisting of fine-grained, non-cohesive sediments such as fine sand or silty sand are likely to deform more easily than thick beds for a given shear stress.

Menzies (1987) showed that failure will occur once pore water content in these sediments reaches a critical volume concentration (c.v.c) of about 0.6. When pore-water content increases to this level, contact between sediment grains is reduced, failure occurs
and the sediment begins to behave like a slurry of finite viscosity. The rheology of the sediment changes from a rigid "H" bed to a soft, mobile "M" bed under such conditions (Menzies, 1989). Deposits of higher shear strength, coarse-grained sediments remain intact because they are resistant to deformation under the conditions that cause finer-grained sediments to mobilize. In order to evacuate meltwater under these conditions Boulton (1987) suggests that subglacial meltwater channels probably formed around the resistant cores by means of a piping mechanism (Freeze and Cherry, 1979).

Alternatively, Boulton (1987) describes how drumlins form as a result of ice streaming around resistant cores of sediment. Soft bed sediments ("M" beds) migrate around more resistant sediment masses ("H" beds), thus beginning the shape of the drumlin. In the lee of the stable masses, shear stresses on, and pore-pressure in, the slurry is reduced. This results in a migration of the still-mobilized sediments into those zones, where they stabilize. The process may be reflected by the poorly-sorted and crudely-graded, coarse-grained till in cores of drumlins of the Menominee field.

Shoemaker (1986) showed that the location, number and spacing of channels required to evacuate subglacial meltwater is dependent on the rate of meltwater development, sediment properties, and the subglacial aquifer system. Shoemaker assumed that the sediment layer was the aquifer, that it rested on an aquitard, and that all flow was horizontal. With high rates of meltwater production, fine-grained sediment, and an impermeable substrate, Shoemaker calculated that many channels are required to evacuate the meltwater. For sediments of low hydraulic conductivity ($K < 10^{-7}$ m s$^{-1}$), similar to the loam till overlying limestone in the present study area, Shoemaker calculated that a
minimum channel spacing of about 360 meters are necessary to sustain efficient meltwater evacuation (for 5 m thickness of sediment). As the ability of the sediments to transmit meltwater increases, so does the spacing of evacuation channels. Shoemaker showed that for hydraulic conductivities about $K > 10^{-7}$ m s$^{-1}$, meltwater is evacuated mostly through the interstitial pore spaces of the sediments, and because of the increased hydraulic conductivity, spacing between channels will increase exponentially. Under these conditions, sediment deformation occurs mostly at the ice-bed interface. In all of Shoemaker's calculations, the bed was considered an aquitard.

In a study of meltwater drainage and sediment deformation in the subglacial environment, Boulton (1987, p. 69) suggests that permeability and sediment shear strength are related to the integrated subglacial drainage network (sediment and bedrock). Locally high permeability of either favors high effective pressure and sediment shear strength. Considering the very low hydraulic conductivity of limestone bedrock in the current study area, it is likely that the hydraulic conductivity of the sediments alone dictated the path through which meltwater could be evacuated because the bedrock acted as an aquitard. However, over sandstone, meltwater could be forced into the bedrock aquifer, reducing the number of channels (in sediment) required for meltwater evacuation.

Using the equations and assumptions of Shoemaker (1986) and Boulton (1987), channel spacings between drumlins overlying sandstone and limestone in the Menominee drumlin area were calculated (Table 2). Hydraulic conductivity (K) and Coulomb friction angle ($\phi$) values for till of various textures are estimated from Mickelson (1993) and Shoemaker (1986), and thickness ($t$) is derived from water-well data within the study area.
Table 2. Glacial sediment characteristics.

<table>
<thead>
<tr>
<th>Overlies limestone</th>
<th>Overlies sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>Sandy loam</td>
</tr>
<tr>
<td>(45% sand, 43% silt, 12% clay)</td>
<td>(68% sand, 24% silt, 8% clay)</td>
</tr>
<tr>
<td>( K = 2.00 \times 10^{-7} \text{ m/s, } \phi = 7.5^\circ, \ t = 3 \text{ m} )</td>
<td>( K = 5.30 \times 10^{-6} \text{ m/s, } \phi = 25^\circ, \ t = 7 \text{ m} )</td>
</tr>
</tbody>
</table>

Equation 13 (p. 24) of Shoemaker permits estimation of distance (m) between channels \((d)\):

\[
d = \sqrt{\frac{8 \times K \times t \times \Delta P_p}{m \times \rho_w \times g}}
\]

where:
- \( K \) = the hydraulic conductivity of the sediments (m/s),
- \( t \) = the thickness of the sediment bed (m),
- \( m \) = the uniform basal melt rate (assumed to be 1 cm/yr),
- \( \Delta P_p \) = pressure drop between the calculated point and the terminus (1 bar is suggested by Shoemaker to be used as a constant),
- \( \rho_w \) = the density of water (kg/m³),
- \( g \) = the acceleration due to gravity (9.8 m/s²).

Channel spacing required to evacuate 1 cm/yr of subglacial meltwater (a rate suggested by Shoemaker for the thawed-bed zone of Pleistocene ice sheets) from subglacial sediments overlying limestone was calculated to be 393 meters. The value closely approximates the measured distance between inter-drumlin troughs in the Menominee field (185-575 m).

Channel spacing in glacial sediments overlying sandstone required to evacuate the same volume of meltwater was calculated as 2612 meters. The calculation of spacing over sandstone suggests that all porewater could be dissipated through the sediments, and implies that most ice-bed deformation would occur as shearing within the uppermost portion of the bed (Boulton, 1996). However, because the hydraulic conductivity of
sandstone is far greater than limestone, the assumption of the bed acting as an aquitard is
invalid and spacing would probably be larger. It is also noted that such calculations are
based on the assumption of uniform and predictable values of $K$. The true permeability of
till under subglacial conditions is unknown. For example, Menzies (1989) discusses how
the phenomenon of dilatancy, which occurs in the subglacial environment when
porewater-pressure is high, affects hydraulic conductivity in unconsolidated sediments.
He showed many factors affect sediment rheology and they are intrinsically related. That
is, changes in stability (and hydraulic conductivity) of the slurry may result from changes
in any one of the factors. The relationship is explained by:

$$K = \left( \frac{\gamma_s}{5\eta} \right)^{**} \left( \frac{n^3}{(1-n)^2} \right)^{**} \left( \frac{1}{S_o^2} \right)$$

where:
- $K =$ the hydraulic conductivity of the sediments (m/s),
- $n =$ porosity
- $\eta =$ viscosity (Pa/s)
- $\gamma_s =$ density of the slurry (kg/m$^3$)
- $S_o =$ surface area of particles per unit volume of slurry (m$^2$/m$^3$)
  (approximated by $S_o = 6/d_o$, where $d_o$ is the mean particle size diameter).

From this equation, Menzies (1989) showed that when $\gamma_s$, $S_o$, and $n$ are constant, a single
magnitude increase in $\eta$ would lead to a hundred-fold decrease in $K$. Other physical
properties (such as $n$) will change with changes in density, and lead to further effects on
permeability.

To test the effects of subglacial sediment permeability and boundary conditions
(bedrock hydraulic conductivity) on hydraulic head within the sediments of the present
study area, a 2-D finite element numerical groundwater flow model (SEFTRAN) was constructed. Boundary conditions and assumptions were established from information previously described. The hypothetical ice-sheet profile for the ice sheet at the time drumlins formed is approximated by the classic ice-profile formula (Shoemaker, 1986) to establish isostatic loading due to the ice.

\[ h = A \times x^{1/2} \]

where

- \( h \) = height above base of the ice (m)
- \( A \) = a constant (for Pleistocene ice sheets, estimates range from 0.3-1.0m\(^{1/2}\) depending on slope of the bed; Matthews, 1974)
- \( x \) = distance from the terminus (m).

For the eastern edge of the study area and the right edge of the model, using \( A = 0.80 \) (the ice was moving upslope), and \( x = 45,000 \text{ m} \) (measured from the moraine), \( h = 170 \text{ meters} \). Using 0.85 as the average density of ice overlying that point, the initial conditions were set such that the pressure head in the sediments overlying limestone (at the eastern edge of the study area, or the right side of the model) was sufficient to decouple the ice from the bed (head = 144 m). Steady state pressure head is calculated for each node within the sediment by the model, assuming a constant head in the subglacial sediments at the easternmost (right) side of the model, and an arbitrary datum slightly below the bedrock surface. Hydraulic conductivity values used in the model and sources for the values are given in Table 3.
Table 3. Values of hydraulic conductivity used in the SEFTRAN model.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (m/s)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty till</td>
<td>$2.00 \times 10^{-7}$</td>
<td>(Mickelson, 1993)</td>
</tr>
<tr>
<td>Sandy till</td>
<td>$5.30 \times 10^{-8}$</td>
<td>(Mickelson, 1993)</td>
</tr>
<tr>
<td>Limestone</td>
<td>$3.528 \times 10^{-9}$</td>
<td>(Emmons, 1987)</td>
</tr>
<tr>
<td>Sandstone</td>
<td>$1.729 \times 10^{-5}$</td>
<td>(Young, 1992)</td>
</tr>
<tr>
<td>Granite</td>
<td>$1.00 \times 10^{-10}$</td>
<td>(Freeze and Cherry, 1979)</td>
</tr>
</tbody>
</table>

Figure 17 is a graphical representation of the model with the bold line showing the values of head in the sediments. At the contact between limestone and sandstone, head dramatically decreases. Pore-pressure is reduced to 24 m above datum, which is 17% of the head over limestone. The results of the model shows that porewater pressure is greatly reduced in the sediments overlying sandstone and that the matrix of sediment would bear a much greater component of static pressure from the ice. Because of this, the sediment mass gained strength through reduced pore pressure. Consequently, shear strain and deformation was transferred to the ice-sediment interface and/or internally within the ice.

Evidence of Pleistocene groundwater movement into bedrock aquifers in the drumlinized area as suggested by the model is presented by Clayton et al., (1966), Seigel (1989) and Young (1992). They found that $\delta^{18}O$ values in water taken from bedrock formations in Wisconsin and Iowa are much lower than present-day water. The $\delta^{18}O$ anomaly is attributed the recharge of isotopically light water by precipitation in a much colder climate than the present in that region. Thus, recharge to the aquifer is thought to have been emplaced under very high hydraulic gradients beneath Pleistocene ice sheets (Seigel, 1989). Also, Seigel (1989) showed that total dissolved solids (TDS)
Figure 17. SEFTRAN 2-D finite element numerical groundwater model output. The model was constructed to estimate the effects of changing boundary conditions on pressure head within the subglacial sediments. While maintaining constant head at the easternmost (right) side, the model shows that hydraulic head in the sediments overlying sandstone would be reduced to 24 m. The model suggests that effective pressure over sandstone greatly increased, causing those sediments to bear a greater component of ice pressure than sediments over limestone. Units of "K" are m/s.
Concentrations in the groundwater of the drumlin region are anomalously high.

Concentrations of dissolved ions usually increase in the direction of regional groundwater flow systems (west-to-east through the Menominee drumlin field area) because of the longer residence time of water in the aquifer. Longer residence times result in a longer period of interaction with soluble minerals. However, highest TDS concentrations are in the present-day area of recharge (toward the west), where lowest concentrations are expected (Seigal, 1989). Most of the increase in TDS is caused by abundance of calcium and sulfate ions. Because there is no source for sulfate ions in bedrock of eastern Wisconsin, Seigal looked for another source. He concluded that the enrichment was due to isostatic loading by glacial ice during the Pleistocene which reversed the hydraulic gradient such that water-flow was from east-to-west. Pressurized subglacial meltwater carried sulfate-enriched brine from rocks in the Michigan basin which recharged the aquifers in Wisconsin.

DISCUSSION

The groundwater flow model, physical characteristics of drumlins, and the findings of Seigel (1989) and Young (1992) provide evidence that supports the hypothesis of this study. Over limestone, a poor aquifer overlain by thin deposits of silt-loam till, little water could be evacuated from the subglacial environment. Water could only be evacuated horizontally through the sediment, because vertical movement was impeded by the ice. Therefore, sediment shear strength was reduced as meltwater accumulated in the subglacial sediments, and the sediment mobilized, possibly as a slurry, once decreased
effective pressure reduced its shear strength. Closely spaced channels formed to evacuate the meltwater that allowed ice-streaming. The process resulted in the formation of long, narrow, spindle-form drumlins overlying limestone bedrock.

As the pressurized subglacial meltwater migrated toward the margin and crossed the contact between limestone and sandstone, boundary conditions changed. Over sandstone, with higher hydraulic conductivity in both the bedrock and overlying sediment, pressurized subglacial meltwater migrating from the east flowed with a greater vertical component. Subglacial sediment gained strength due to increased effective pressure. Thus, forward migration of the mobile, fluidized sediment flow (slurry) was slowed. A transition from "M" beds to "Q" and "H" beds (Menzies, 1989) occurred there. Also at the contact, strain that was formerly accommodated by pervasive deformation of thin beds of sediment was transferred to the upper "A" horizon in thicker sediment beds. Increased frictional resistance between the ice and bed caused the ice velocity to decrease. Flutes and multiple, shield complex or transverse asymmetrical drumlin forms eroded into the surface of stabilized sediment masses is evidence of the process.

As the meltwater migrated over sandstone, the pore pressure was reduced due to increased hydraulic conductivity of both the bedrock and the subglacial sediments. Increased effective pressure and frictional resistance at the ice-bed interface over sandstone caused the ice velocity to decrease. The decrease in velocity caused forward motion of the ice sheet to deflect westward (similar to refraction of light or waves). The deflection is interpreted from the observed change in orientation of drumlins and flutes across the bedrock contact. Higher strain rates over sandstone may also explain the
increased thickness of sediments found there, because increased frictional heat caused greater rate of meltout from the base of the glacier (alternatively, thick deposits of sediment may have existed over sandstone bedrock before the glacier re-advanced and formed the drumlins, or the sediments may have migrated from the high pressure area over limestone bedrock). Finally, the transverse feature (to ice flow) near the limestone/sandstone contact that exposes anticlinally folded, unconsolidated sediments is likely the result of differential ice velocity on either side of the contact. The latter feature probably formed because of thrusting, because the basal ice was in greater contact with its bed west of the bedrock contact. Reduced forward motion west of the contact caused differential rates of ice movement accommodated by internal shearing of the ice mass. Rogen moraines and transverse-oriented landforms such as the observed feature are known to form at the take-off points for such shear zones (Sugden and John, 1985; Bouchard, 1989).

Late in the process of sediment mobilization and drumlin formation, subglacial meltwater flow appears to have modified the established drumlin forms. Channels that apparently cut into the drumlins, the shape of many drumlins in the Menominee field (the "hooked" drumlin, for example), fluvial sediments near the surface of the drumlins, eskers, imbricated clasts in gravel pits adjacent to drumlins, and the tunnel channel and outwash fan beyond the moraine that was constructed while the drumlins formed all suggest high meltwater discharge rates. Discharge of subglacial meltwater could have occurred catastrophically, as in a jökulhlaup, evidenced by features described above. Finally, when the drumlin forming processes ceased, ablation till was deposited as the glacier stagnated.
and finally wasted into the Lake Superior basin, exposing the subglacial bedforms at the surface.

CONCLUSIONS

There were several processes occurring nearly simultaneously that formed drumlins beneath the waning Pleistocene ice sheet that covered the U.P. of Michigan and northeast Wisconsin. The main control on drumlin formation appears to be fluctuations in subglacial pore water pressure, which was controlled by the permeability of the subglacial sediments and the underlying aquifer. Variations in sediment texture and thickness also may have influenced drumlin formation.

Initially, pressurized subglacial meltwater accumulated beneath the thawed-bed zone of the ice sheet and then was forced toward the zone of lower hydraulic head (the glacier margin). Periodically, subglacial meltwater pressure elevated to the point where at least portions of the sediment mass began to deform. Collapse of sediment allowed movement as a slurry, which allowed ice to stream through channelways in the sediment mass, and the high-pressure meltwater/slurry mass to be transported toward the glacier margin.

The Ordovician limestone, a poor aquifer underlying the lobe center in the thawed-bed zone, allowed little infiltration of the subglacial meltwater. Water pressure in the subglacial sediments was likely highest there and that was probably the area where sediment collapse was initiated. When the pore water content reached the critical volume concentration (c.v.c.), fine-grained and/or thin beds of sediment likely mobilized toward
the glacier margin (westward). Some higher shear strength masses of sediment remained stable and formed the nuclei for drumlins. Evacuation of the high pressure water occurred through closely-spaced channels that formed in the sediments.

The slurry eventually moved toward the glacier margin and passed over the Cambrian sandstone, which is more permeable. The water was able to infiltrate the sandstone aquifer, thereby increasing the effective pressure in the sediment mass, allowing the weight of the ice mass to bear more weight on the skeletal matrix of the sediment. Consequently, the sediment shear strength increased, allowing less pervasive deformation of the mass, and more shearing at the ice/sediment interface. Flutes and complex, shield drumlins formed in thicker deposits there. Fewer channels were required to evacuate meltwater because of the increased hydraulic conductivity of both the bedrock and subglacial sediment, and the thicker beds. Because of the increased contact between ice and the sediments overlying sandstone, ice velocity was reduced. The reduction in velocity caused the ice to deflect toward the west, which is reflected by the dramatic change in drumlin and flute orientation above the limestone/sandstone contact. Continued meltwater discharge continued to modify the drumlin form after the general shape was established. Fluvial channelways are cut into the drumlins, and coarse-grained fluvial sediments are found near the surface of the drumlins. Grading in some of the fluvial beds suggest periodic, catastrophic discharge. Ablation till forms the surface deposit of all the drumlins. It was deposited as the ice stagnated and finally melted away.
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