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FABRIC AND DEPOSITIONAL STRUCTURES IN DRUMLINS NEAR WAUKESHA, WISCONSIN

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ABSTRACT

Deep gravel-pit exposures reveal the distribution and structure of till and underlying sand and gravel in drumlins near Waukesha, Wisconsin. The subglacial sediment is interpreted to have moved laterally into the drumlin sites because the till thickens from the margin to the core of the drumlins, the stone orientation in the till is perpendicular and oblique to ice flow on the drumlin margins, and recumbent isoclinal folds occur in sand on the drumlin margins with axes parallel to the drumlin axes. The resulting accumulations of sediment presented obstacles to ice flow and were streamlined into the minimum-drag drumlin shape by erosion on the margins and by remolding of material in the core of the drumlins. These drumlin nuclei may have formed at spots where there was low normal stress on the bed due to thin ice. The subglacial sediment became mobile as a result of high pore pressure that may have formed at spots where there was low normal stress on the bed due to thin ice. The subglacial sediment became mobile as a result of high pore pressure that may have developed as groundwater and subglacial meltwater were trapped behind a frozen bed at the ice margin. However, under certain conditions, lateral sediment flow might also have occurred if the sediment was frozen.

INTRODUCTION

This paper describes the distribution and fabric of till and the structure of sand and gravel exposed in gravel pits in drumlins near Waukesha, Wisconsin. Inferences about the stresses on and strength of the subglacial material during drumlin formation are then drawn from these observations. This study is an expansion and continuation of the work of Whittecar (1976) and Whittecar and Mickelson (1977, 1979), who first described and interpreted the till stratigraphy and deformational structures in the drumlins. Previous workers in this area include Alden (1905, 1918) who first described the morphology and regional distribution of the drumlins, and Evenson (1971), who measured fabric in several drumlins as part of a general study on the origin of till fabric.

Two drumlin fields occur in southeastern Wisconsin: a small field near Waukesha formed by ice of the Lake Michigan Lobe, and a large, 90-km wide arcuate belt of drumlins behind the outermost end moraine formed by the ice of the Green Bay Lobe (fig. 1). For this study, nine drumlins in the Waukesha field and two in the Green Bay Lobe field were examined (fig. 1). Three of these drumlins are field-trip stops described by Mickelson and others (1983), (sites 2, 5, and 10 on fig. 1). Based on the correlation of the drumlin-forming Horicon and New Berlin tills with the Haeger Till Member in Illinois, both the Waukesha and Green Bay Lobe drumlins are thought to have formed during advance of ice to the Darien, Johnstown, and West Chicago Moraines approximately 14 500 B. P. (Whittecar and Mickelson, 1979). The Waukesha drumlins are clustered on uplands (Whittecar, 1976), are commonly

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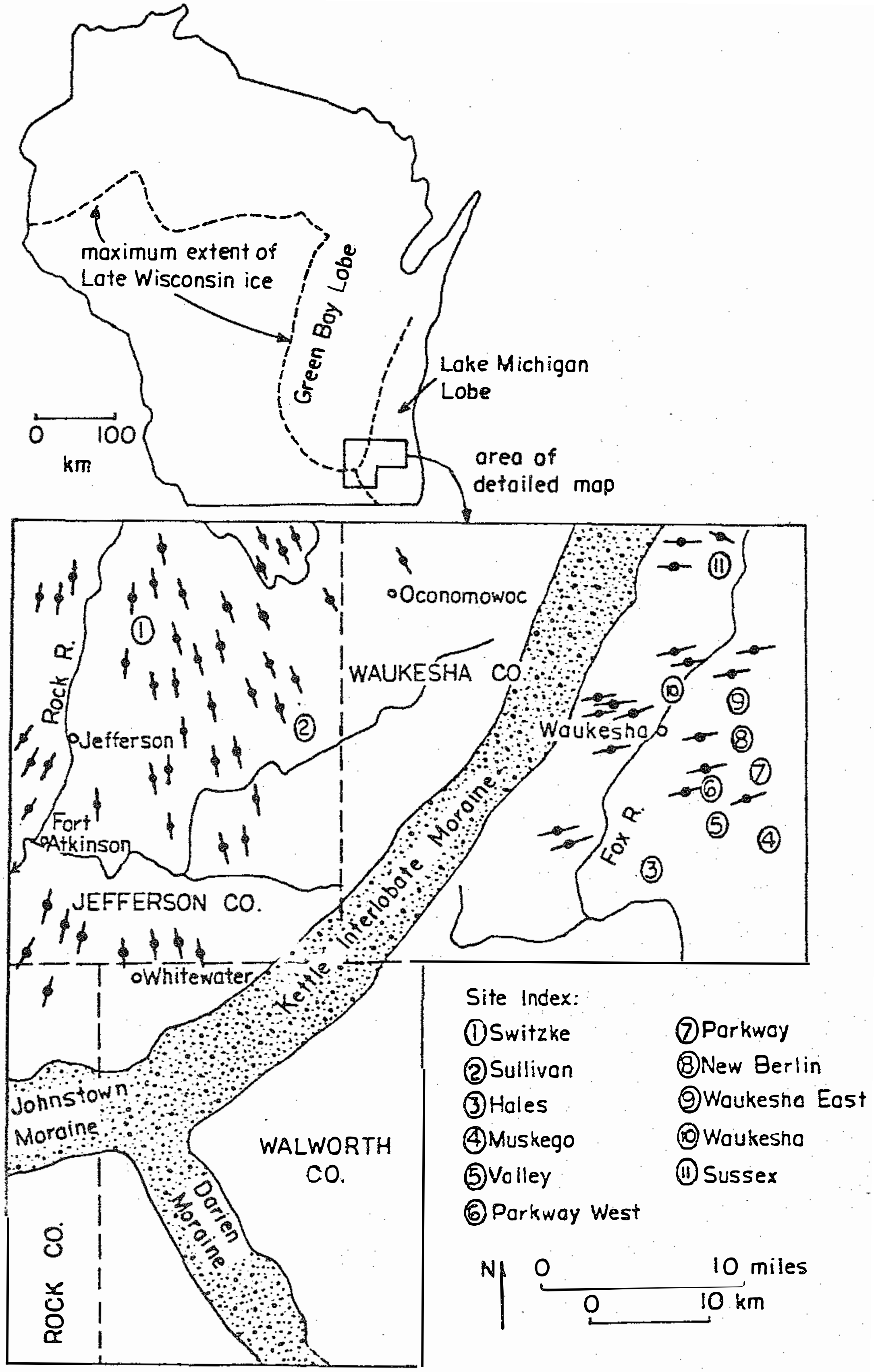


FIGURE 1.--Map of Wisconsin and more detailed map showing location of drumlin trends, prominent moraines, modern drainage, and sites examined.

overlapping or composite in form, and, in places, are gradational to or superimposed on linear ridges that parallel the drumlin axes. The Green Bay Lobe drumlins are generally longer and narrower than the Waukesha drumlins (Mills, 1972, 1980), and they are discrete hills with a less marked tendency to cluster on uplands.

DISPOSITION OF TILL IN THE DRUMLINS

Both the Green Bay Lobe and the Waukesha drumlins are at least partially cored and carpeted with very pale brown (10YR 7/4) sandy loam or loam till. In places till near the surface of the drumlin is enriched in sand and contains stratified sandy and pebbly lenses, suggesting that patches of supraglacial debris were let down atop the drumlins during final melting, but the bulk of the till in the drumlins has a uniform, well-compacted matrix and was probably deposited subglacially. In all but one of the drumlins where the base of the till is exposed, the basal contact of the till dips downard and the surface rises as one proceeds from the margin to the core of the drumlin, thus defining a pod-shaped body of till that is thickest beneath the drumlin crest. Figure 2 summarizes thickness measurements in five drumlins and demonstrated thickening of the till toward the center of the drumlins. This pattern suggests that till accumulated preferentially at the drumlin sites. In a few places the basal till can be separated into a lower, deformed unit of basal till and an upper, undeformed basal till unit that conforms to the drumlin shape, suggesting that there were two episodes of subglacial deposition during the drumlin-forming glaciation--possibly one during ice advance and the other during retreat of the ice--separated by a period of erosion, deformation, and drumlin formation (Whittecar and Mickelson, 1977).

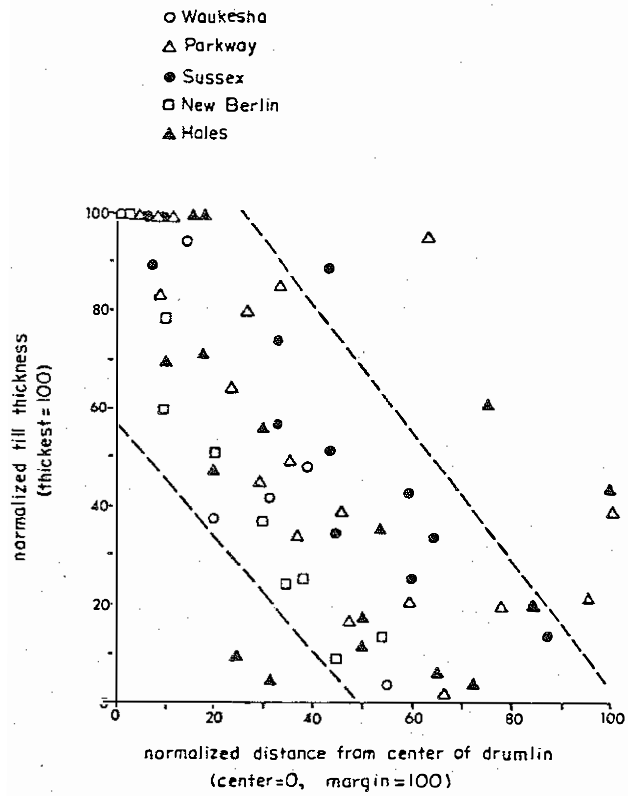


FIGURE 2.--Summary of till thickness distribution of five drumlins, indicating thickening of till towards drumlin cores.

TILL FABRIC

In order to investigate the structure of the drumlin-forming till, fabric was measured at 84 sites in ten pits. For each fabric measurement, bearing and plunge of 25, 30, or 50 pebbles with long axis to intermediate axis ratios of 3:2 or greater was determined using a Brunton compass. Most pebbles measured were dolomite, usually prolate ellipsoids in shape.

The origin of till fabric has been the subject of a number of papers. In theory, elongate particles immersed in a flowing medium (whether it be water, ice, or viscous sediment) will orient to attain a position of minimum torque. Rusnak (1957) presents the following equation for the torque (T) on a particle in terms of the fluid density (ρ), fluid velocity (μ), length of the long (a) and intermediate (b) axes of the particle, and the angle (β) between the a-axis of the particle and the mean velocity vector:

$$T = -\pi\rho(a^2 - b^2)\ \mu^2 \sin\beta \cos\beta.$$

The torque goes to zero--indicating a stable position--when $\beta = \pi$ (that is, long axis transverse flow) and when $\beta = \pi$ (that is, when the long axis is parallel to flow [parallel]).

For a lone particle lying parallel to flow, slight velocity fluctuations in the fluid will tend to rotate the particle into a transverse alignment; thus, the transverse position is more stable. But if a number of particles impinge on each other in the fluid the transverse orientation gives rise to frequent collisions, and the longitudinal orientation is more stable. Thus, in a pebble-rich material such as till or debris-laden ice a longitudinal orientation would be expected to be the stable condition and therefore fabric maxima should indicate the direction of movement of the ice or of viscous till. However, transverse orientations in debris-rich material have been described in areas of compressive flow where fluid above and behind the particle is moving faster than fluid below and in front. For example, transverse fabric is observed on the margins of debris flows and in sheared-up debris bands in ice (Boulton, 1971). Possibly this transverse fabric is produced by the velocity gradient set up across the up-flow and down-flow ends of a particle in longitudinal orientation when it enters a compressive-flow regime. Fluid moving against the up-flow end of the particle will have a slightly higher velocity than fluid moving at the down-flow end. Any slight fluctuation in the flow direction will thus set up a torque tending to rotate the up-flow end until a transverse orientation is attained and there is no appreciable velocity gradient across the particle. In general, then, longitudinal fabric forms in debris-rich flow and transverse fabric forms in compressive or debris-poor flow.

The deep exposures available in the Waukesha area afforded a rare opportunity to measure till fabric in complete drumlin cross sections. Fabric was measured at depths ranging from 2 to 39 m below the surface. At eleven sites where gullies were eroded into the pit walls fabric was measured at several depths to determine vertical as well as lateral variability within the drumlin. Figure 3, and the maps for Stops 1 and 3 in Mickelson and others (1983), show the location of structural data and lower-hemisphere equal-area projections of fabric measurements.

As can be seen on the maps, most of the fabric measurements have maxima that are parallel to the drumlin axes, but measurements having maxima perpendicular and oblique to ice flow are not uncommon (fig. 3, and Stop 6). The perpendicular fabric measurements tend to occur between the margin and core of the drumlins at depths greater than 6 m, and where overlying fabric can be measured (for example, at Waukesha), it is parallel to ice flow. The measurements that are perpendicular to ice flow are in uniform basal till that is clearly traceable to, and is not visibly or analytically different from, till having fabric parallel to ice flow.

Given its position in the drumlins, it is unlikely that the fabric that is perpendicular to ice flow is a transverse fabric produced by compressive flow in the ice itself or by compressive conditions transmitted from the ice into the underlying till. In accordance with Bernoulli's Theorem, fluids will experience increased pressure and decreased velocity (a compressive regime) on the up-flow end of an obstacle but on the sides and down-flow end

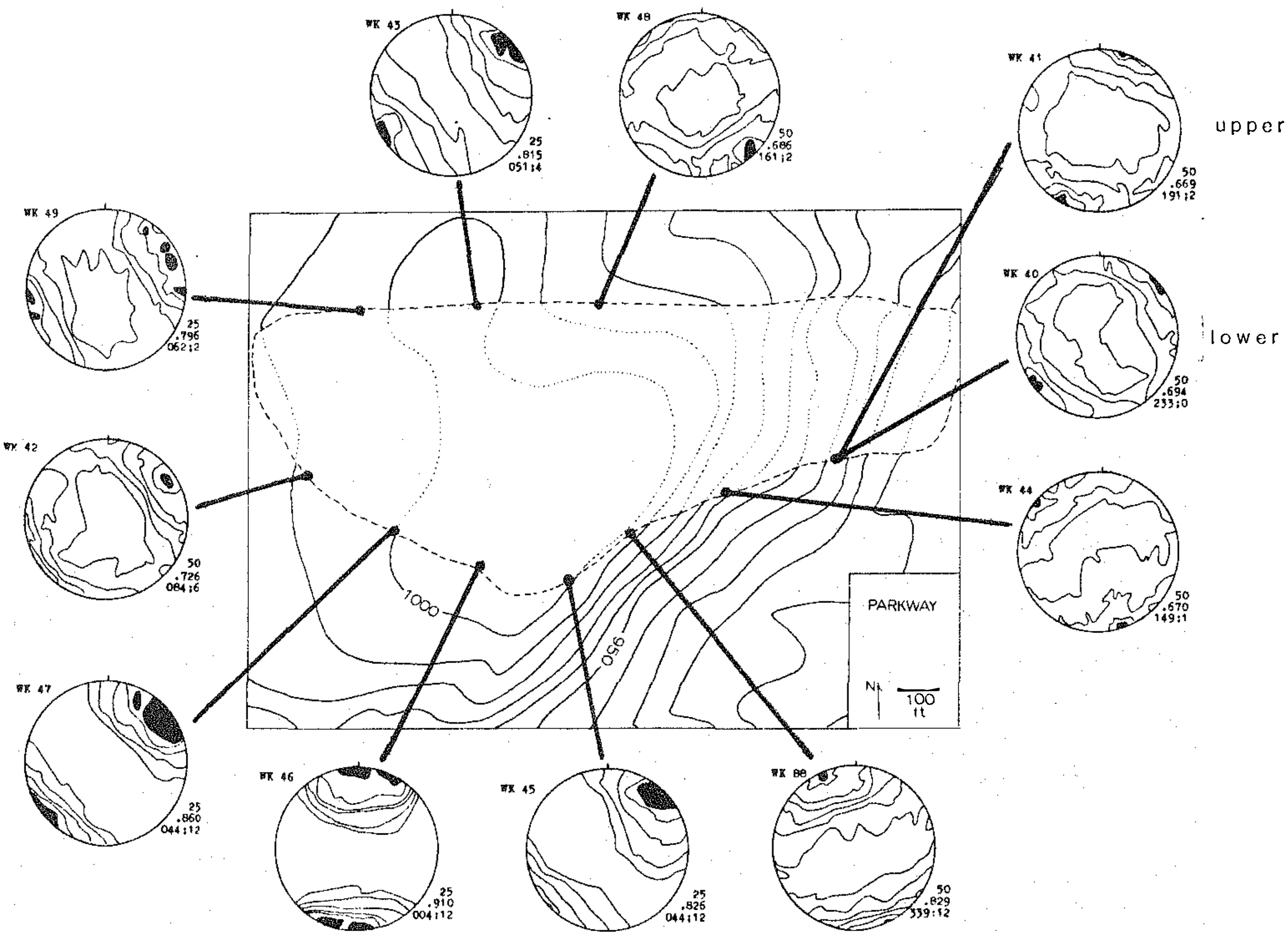


FIGURE 3.--Parkway pit map with fabric and structural data. Note perpendicular fabric (WK48, WK44, WK88).

of the obstacle pressure drops, velocity increases, and extending flow results (see also Savage, 1968). Ice flowing around a drumlin, then, would not be under compressive flow at the marginal position in which the fabric perpendicular to ice flow is commonly found.

Another intepretation is that the fabric that is perpendicular ice flow is longitudinal fabric formed by lateral flow of remobilized till toward the drumlin site rather than fabric created by shear or deposition from flowing ice. This remobilization fabric would then be similar in origin to the squeeze-up fabric in flutes described by Boulton (1976). Such fabric, as the product of flow within previously-deposited till, may be wholly independent of the ice flow direction. Furthermore, the observed coincidence of fabric perpendicular and oblique to ice flow on the drumlin margins with thickening of the till towards the core of the drumlins is complementary evidence for movement of till into the drumlin.

Fabric perpendicular to ice flow was not found in the Valley pit (Stop 3 in Mickelson and others, 1983). This pit was excavated in a ridge that trends parallel to ice flow and is more elongate than the other drumlins examined. In addition, present exposures do not reveal appreciable thickening of the upper till in the core as in the other drumlins, but some thickening was noted in the past (D. M. Mickelson, personal communication, 1982). These observations suggest that there was little referred accumulation of till at the Valley pit (and thus no transverse fabric) and that the ridge is primarily an erosional feature rather than a streamlined depositional feature. Alternatively, the large amount of excavation in the Valley pit may have removed till sections with transverse fabric.

Measurements having maxima parallel to ice flow are more common and are found in the cores and on the margins near the surface of the drumlins. Parallelism with ice flow suggests that such fabric is primarily longitudinal fabric produced during original deposition rather than a remobilization fabric. This deposition, however, was probably not synchronous with drumlin formation, because, if wide-spread deposition of till occurs primarily in a zone near the ice margin, as suggested by many authors (for example, Sugden and John, 1976; West, 1977; and Whittecar and Mickelson, 1979), and if drumlins are formed up-ice from this zone of deposition (Whittecar and Mickelson, 1979), it is unlikely that primary deposition from ice at the time of drumlin formation was responsible for the bulk of the till in the drumlin or for the fabric of that till. Instead, the fabric parallel to ice flow may have been produced either during predrumlin or postdrumlin subglacial deposition, or it may be postdepositional fabric imprinted during shearing of till by ice moving over and around the drumlin. This latter possibility is particularly applicable to fabric paralalel to ice flow near the surface that overlies fabric perpendicular to ice flow (for example, at Waukesha).

STRUCTURE OF THE SAND AND GRAVEL

Thick sand and gravel occurs beneath the till in the drumlins. It is predominantly either horizontally bedded or tilted and truncated by the till. However, intense deformation is not unusual, especially in sand. This deformation is of three types: recumbent isoclinal folds, upright isoclinal to open folds, and clastic dikes. Faults, although described by Whittecar (1976), were not observed during this study.

The recumbent isoclinal folds occur between the edge and core of the drumlins, usually under relatively thin till (1.5 to 6 m thick). Axes of these folds are consistent at a given location and tend to be either nearly perpendicular to the drumlin axis or nearly parallel to the axis. Where the folds occur in sand, amplitudes are on the order of 0.3 to 1 m and wavelengths are usually less than 0.6 m. In gravel, amplitudes are more than 3 m and wavelengths are about 1.5 to 3 m. This difference in size is due both to the thicker bedding in the gravel and to the greater angle of internal friction of the gravel (both in the dry and frozen state). The greater angle of internal friction of the gravel imparts a greater shear strength than that of sand and hinders internal deformation, thereby preventing small-amplitude folds.

The recumbent folds with axes perpendicular to ice flow probably are drag folds produced by shear from overriding ice. Recumbent folds with axes parallel to the drumlin axis are probably not the result of drag from overriding ice. Instead, these folds may be similar to recumbent folds that have been observed and experimentally produced in liquefied sand.

Williams (1960) observed that loosely packed fine sand and silt collapses when sheared. If such sediment is saturated, confined, and then sheared, it liquefies; that is, its shear strength drops as the loose packing disintegrates and the pore fluid assumes the load. Liquefaction, in turn, allows flow when an external force is applied (as, for example, by unequal vertical loading). Flow is laminar, and recumbent folds develop as manifestations of flowing bands moving at different velocities. Fold axes are perpendicular to the flow direction. Similar behavior is described by McKee and others (1962) for a sand layer confined by silt strata. High pore pressure in the sand led to recumbent folds when a horizontal total head gradient was applied across the sand layer.

Applying these observations to the recumbent folds with axes parallel to the drumlin axes suggests that they formed by flow of liquefied sediment into the drumlin either in response to a greater weight of ice in the interdrumlin areas or to flow of water through the sediment towards the drumlin. The parallelism of the fold axes with ice flow rules out drag from overriding ice, and the regularity of the folds and lack of thinning or thickening of the beds rules out downslope slump. Sites where fold axes have oblique or ambiguous orientations with respect to the drumlin axis may have undergone two folding episodes: an original set of folds was produced by flow towards the drumlin and a later set was produced by ice drag, resulting in a deformational pattern similar to that described by Boulton (1976) in modern flutes.

Upright folds are less common, though more spectacular, than the recumbent folds. They occur singly and are of much larger amplitude (as much as 12 m) than the recumbent folds, suggesting the presence of a larger-scale stress field. These folds are composed of sand, gravel, and till layers and are found both on the margin and in the core of the drumlins. Axes of these folds are both parallel and perpendicular to ice flow.

The origin of these upright folds is more problematic than that of the recumbent folds because no clear analog exists in nonglacial sediment. Those folds having axes perpendicular to ice flow may be drag folds that did not become overturned and were later truncated by erosion. The marginal folds with axes parallel to ice flow are probably not related to the ice flow, and the presence of silt, gravel, and thin till layers, as well as their upright, large-amplitude geometry and isolated occurrence, rules out liquefied sediment flow because horizontal flow of liquefied sediment would not produce upright folds involving several sediment layers folded concordantly. One possibility is that they are compressive folds produced by the weight of ice in the interdrumlin areas acting laterally against the drumlin margin. Under these conditions, upright marginal folds of large amplitude might be formed locally, especially if high pore pressure lowers the yield strength of the sediment so as to induce ductile deformation.

Clastic dikes are vertical bodies of layered sand and, in some cases, gravel and till, which intrude upward into and, at places, through the upper till. They generally occur in the drumlin cores and commonly trend parallel to the drumlin axis, although several dikes described by Whittecar (1976) are perpendicular to the drumlin axis. Dike widths range from 1 to 9 m; vertical dimensions are more obscure because the bottoms of the dikes are rarely exposed. Minimum vertical dimensions range from 1.5 to 6 m. At two sites where longitudinal dimensions could be observed, the dikes were linear and tabular in shape, although Whittecar (1976) described several dikes that are domes or doubly-plunging antiforms.

Till fabric was measured in and near the dikes at two locations. Fabric in the intruded till near the margins of the dikes does not show steepened plunge but does tend to be reoriented towards the dike. Fabric in till in the dikes or immediately next to the dikes does show steepened plunge. These findings suggest that the till enclosing the clastic dike did not deform in concert with the material in the dike but rather acted as a rigid layer into and through which the underlying sediment intruded.

A striking feature of the clastic dikes is the preservation of primary stratification. Stratification, defined by interbedded layers of varying grain size, is always continuous, parallel to the dike walls, and only rarely interrupted by isolated, small-scale intrafolial isoclinal folds (with axes parallel to the dike). At several sites this stratification is traceable laterally to horizontal strata, indicating that it is primary stratification and not flow-banding.

Stratification is not commonly observed in dikes in sedimentary rock (Potter and Pettijohn, 1977), and, where it has been described (Waterson, 1950; Peterson, 1968), it is interpreted as an intrusion phenomenon rather than as primary depositional layering. This absence of primary bedding in dikes in sedimentary rock is perhaps the result of turbulent flow during injection or of the massive or thickly bedded character of the source beds. Presumably, however, there is a continuum from low-viscosity, rapid-injection density-inversion structures such as clastic dikes in which turbulent flow occurs and bedding is not preserved, to high-viscosity, diapiric density-inversion structures such as salt domes or load structures in which laminar flow occurs and bedding is preserved. The fact that bedding is preserved in the drumlin dikes, then, is indicative of a laminar, diapiric rise of low-density, liquefied sediment into a denser, rigid till cap. The presence of thin layers of till and gravel (which do not readily undergo liquefaction) in the dikes perhaps indicates either that movement of the enclosing liquefied sand was capable of deforming the interstratified till and gravel or that gravel and till strata were penetrated and upwarped by the upwelling sand (Whittecar, 1976).

BEHAVIOR OF THE SUBLACIAL MATERIAL

The fabric pattern in the till and the folds and dikes in the sand and gravel are indicative of ductile deformation but give no direct indication of whether the sediment was wet or frozen or of the origin of the stresses responsible for deformation. In the case

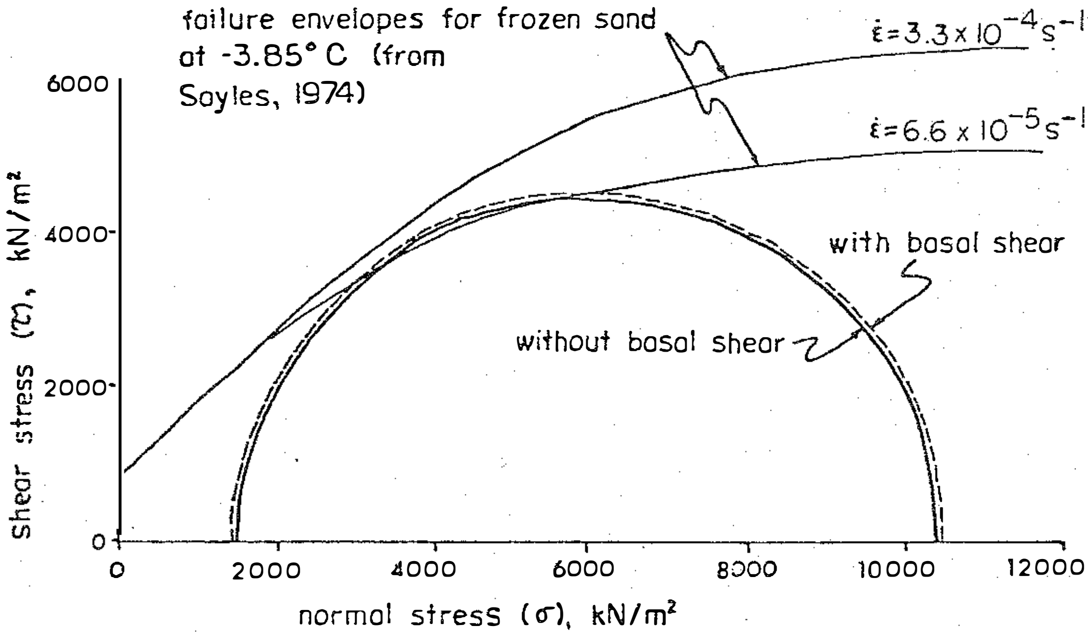


FIGURE 4.--Mohr circle for subglacial stress conditions at Waukesha during maximum extent of ice, assuming an Antarctic-type ice surface profile, a temperature of approximately -5°C, and Poisson's Ratio for frozen sandy till of 0.10.

of wet-sediment deformation, high pore pressure is necessary in order to lower the shear strength of the material to the point where the observed ductile deformation becomes possible. The effect of pore pressure is expressed by the Mohr-Coulomb equation:

$$\tau = C + (\sigma_n - \mu) \tan \phi,$$

where τ = shear strength, C = cohesion, σ_n = normal stress, μ = pore pressure, and ϕ = angle of internal friction. As the equation indicates, increases in pore pressure that are not countered by equivalent increases in normal stress (in this case, the weight of overlying ice) lower the shear strength. In subglacial sediment beneath a temperate glacier (or a sufficiently thick polar glacier), abundant water would be expected due not only to basal melting, but also to compaction and dewatering of fine-grained sediment by ice advance (Vaiden and others, 1982) and by blockage by permafrost of preglacial groundwater discharge areas (Mickelson and Clayton, 1981). If this water is trapped by underlying aquitards (Moran, 1971) and, perhaps, by freezing of the glacier onto its bed at the margin, high pore pressure would develop and sediment (especially the sand and silt subject to liquefaction) would become mobile.

However, ductile deformation could also have occurred if the sediments were frozen. Using an Antarctic-type ice-surface profile, and assuming a basal temperature of approximately -5°C based on findings reported by Tsytovich (1975) and a Poisson's Ratio (the ratio of transverse to longitudinal strain for a material) of 0.10 for the frozen sandy till at Waukesha, the stress conditions during the maximum extent of the drumlin-forming glaciation can be reconstructed (Stanford, 1982). Comparing the resulting Mohr circle for the postulated stress conditions with failure envelopes derived from triaxial compression tests on frozen sand performed at slow strain rates by Sayles (1974) indicates that the long-term yield strength of the frozen sandy till would have been exceeded (fig. 4), and deformation might have ensued. In addition, strain rates slower than the 6.6×10^{-5} s^{-1} of Sayles would be expected beneath the ice; this would further reduce the long-term resistance of the material to deformation.

Given the possibility of frozen deformation, though, it is still not clear whether the large viscosity contrast implied by the observed intrusion of the clastic dikes into a rigid till would be possible with frozen material. Furthermore, the strength of frozen material increases rapidly as temperatures drop (Sayles and Haines, 1974; Tsytovich, 1975; Haynes and Karalius, 1977), and stress on the material drops as the ice-surface profile becomes more gentle. In summary, then, although it is possible that either wet or frozen sediment would have been mobile beneath the ice at Waukesha, the observed structures seem to indicate high pore pressure and wet conditions.

GENESIS OF THE DRUMLINS

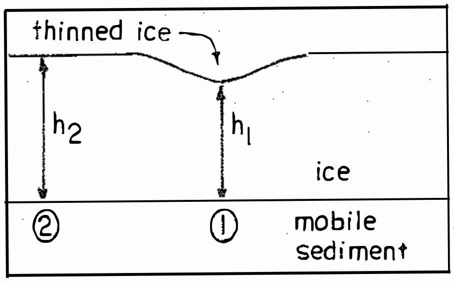
Drumlins are streamlined subglacial landforms that present minimum drag to ice flow around an obstacle (Chorley, 1959). As such, two questions seem pertinent to the origin of drumlins: (1) How was the obstacle produced, and (2) How was streamlining achieved? As emphasized by Boulton (1976), drumlins are morphologically-defined landforms, and, because a number of processes may produce similar or identical morphologies, there need not be a single origin for all drumlins. Thus, there are no doubt several correct answers to the above questions, and any postulated origin for drumlins applies, of necessity, to a specific set of drumlins.

With this limitation in mind, we suggest the following sequence of events in the formation of the drumlins in southeastern Wisconsin (modified from Whittecar and Mickelson, 1979):

(1) Basal till was deposited in a marginal zone as the ice advances, resulting in a sheet of till blanketing the pre-advance topography.

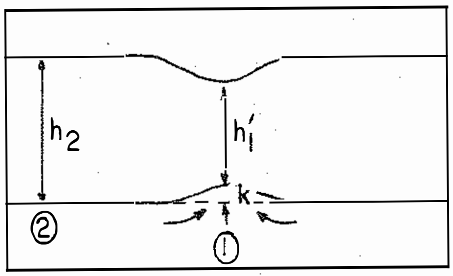
(2) Till and underlying sand and gravel--if mobile--flowed laterally into sites on the bed, beneath the thinnest ice [for example, perhaps below a crevassed area.] At these sites, the normal stress on the bed is lower than on surrounding parts of the bed. Lateral flow of sediment continues until the weight distribution above an arbitrary horizon is equalized, that is, when the thinned ice column is compensated by a thickened sediment column (fig. 5, panels 1 to 3). The observed thickening of the till from the margin to the core of the drumlins is evidence for accumulation of sediment at the drumlin site, and the observed presence of till pebbles that are perpendicular to ice flow and of recumbent folds in sand with axes parallel to ice flow in the margins of the drumlin is evidence for lateral sediment flow towards the drumlin site. The sediment accumulations that resulted from this flow are drumlin nuclei: they were obstacles to ice flow, and consist of sediment that could be shaped by erosion and remolded into a streamlined form.

If the sediment were completely frozen, flow occurred only under special combinations of ice thickness, temperature, strain rate, and ice content. However, if the sediment were unfrozen or partially frozen, increases in pore pressure that were not matched by equivalent increases in normal stress reduced the effective stress, lowered the shear strength, and readily enhanced sediment mobility. Such increases in pore pressure could be produced by rapid loading and compaction of slowly drained or undrained sediment due to ice advance (Vaiden and others, 1982) and by blockage of preglacial groundwater discharge areas by ice. Drainage of the subglacial water, in turn, would be impaired or halted by aquitards (Clayton and Moran, 1974) and by freezing of the glacier onto a permafrost bed at the margin (Mickelson and Clayton, 1981). Thus, advance of ice over water-bearing sediment, in conjunction with a frozen margin and



1. Prior to lateral flow of sediment.

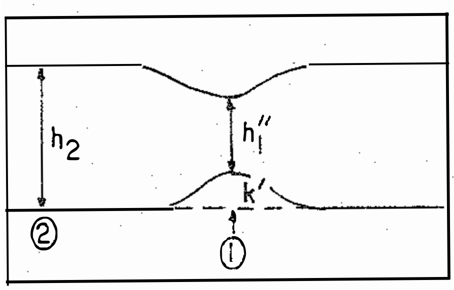
$$\sigma_1 = \gamma_{ice}\ h_1$$
$$\sigma_2 = \gamma_{ice}\ h_2$$
$$h_1 < h_2$$
$$\therefore \sigma_1 < \sigma_2$$



2. Initiation of lateral sediment flow.

$$\sigma_1 = \gamma_{ice}\ h_1' + \gamma_{sediment}\ k$$
$$\sigma_2 = \gamma_{ice}\ h_2$$
$$\gamma_{sediment} > \gamma_{ice}\ ,\ h_1' < h_1$$

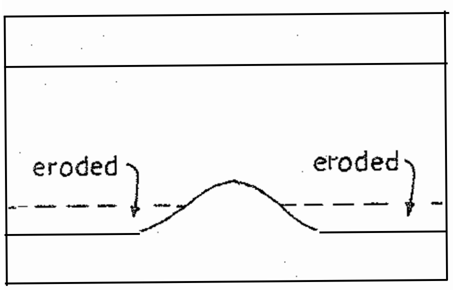
$\therefore$ σ_1 approaches σ_2 in magnitude as flow continues.



3. Termination of lateral sediment flow.

$$\sigma_1 = \gamma_{ice}\ h_1'' + \gamma_{sediment}\ k'$$
$$\sigma_2 = \gamma_{ice}\ h_2$$
$$k' > k \text{ such that } \sigma_1 = \sigma_2$$

$\therefore$ Flow stops because there is no stress gradient.



4. Definition of drumlin by erosion and remolding of the sediment accumulation into a streamlined shape.

FIGURE 5.--Schematic illustration of drumlin formation near Waukesha.

aquitards surrounding the sediment, induced abnormally elevated (excess) pore pressure in the sediment and thereby created conditions favorable for drumlin nucleation.

(3) The accumulation of material in these proto-drumlin sites was an obstruction to ice flow, and flowlines were diverted around the obstacle. Streamlining of the obstruction into the minimum-drag drumlin shape was achieved by remolding and erosion (fig. 5, panel 4). Till in the center of the drumlin flowed into a streamlined shape in response to shear transmitted from overriding ice seeking a flow pattern of minimum drag. More rapid flow (and possibly frozen-bed conditions) on the drumlin flanks and interdrumlin areas promoted extensive erosion of the till and underlying outwash from these areas, also emphasizing the streamlined form. The observed truncation of the till and bedded sand and gravel at the drumlin flanks indicates extensive erosion of interdrumlin areas, and the prevalence of till fabric oriented parallel to ice flow, especially close to the drumlin surface above fabric oriented perpendicular to ice flow, may reflect local remolding from overriding ice.

(4) Next, another basal till was deposited as a carpet over the drumlinized topography, either during retreat of the ice margin or under thick ice shortly after formation of the drumlins.

(5) Lastly, a discontinuous blanket of supraglacial till was deposited on the landscape during final melting of the ice.

On a regional scale, the occurrence of drumlins in a belt parallel to the ice margin may mark the location of a zone of ice that was partially frozen to the bed. This zone, in turn, marks the transition from a frozen bed at the margin to an unfrozen bed farther upglacier. On the basis of geomorphologic evidence, Mickelson and Clayton (1981) argue that a frozen bed was present at the margin of the Green Bay Lobe and the northern Lake Michigan Lobe during Late Wisconsinan time. As mentioned above, this might allow high pore pressure to develop in unfrozen-bed areas behind the margin. Erosion would occur in areas where ice under compressive flow was freezing-on to the bed and thereby lifting material off the bed. These observations suggest that the drumlins may have formed in the unfrozen-bed portions of the partially-frozen zone where mobile sediment was present and that interdrumlin areas where extensive erosion has occurred may represent frozen-bed portions of the partially-frozen zone.

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