Sequence of till deposition and erosion in drumlins

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Extensive sand and gravel workings have exposed structural and compositional features of 17 gravel-cored drumlins of late Wisconsin age in eastern Wisconsin. The drumlins are blanketed by 3 m of sandy basal till which truncates lower tills of earlier advances, outwash gravels, and an overlying till which is conformable to the gravel bedding and indistinguishable in composition from the surface till. Sands and gravels in the interior of some drumlins are deformed into large overturned folds, and into clastic dikes of fine sand and silt which penetrate to the top of the drumlin and warp overlying gravels. Both the folds and horizontal bedding are truncated by either the drumlin edge or the till blanket.

We interpret the conformable, truncated, and in some cases folded, till as a basal till deposited during glacial advance. The capping, truncating till is viewed as a basal till left by retreating ice.

The following sequence of events is suggested: (1) advance of ice over outwash, and deposition of till in a zone near the margin; (2) thickening of the ice and erosion of the drumlin shapes; (3) local folding of the gravels and continued erosion; (4) retreat of ice and deposition of basal till under thin ice; (5) deposition of localized ablation till and stratified deposits.

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Studies dealing with the rate and timing of till deposition suggest that an area of deposition exists near the margin of actively flowing glaciers (e.g. Boulton 1970; Mickelson 1973). Other workers concerned with thermal regimes and basal meltwater have proposed the zonation of erosional and depositional mechanisms within a glacier (e.g. Weertman 1961; Boulton 1972); these arguments can be used to explain a near-margin area of subglacial till deposition. Furthermore, it seems quite likely, as Gravenor (1953) and others have implied, that basal till should be deposited by advancing ice as well as by retreating ice, even though ice over an area is getting thicker. The irregular movements of an ice margin and changes in permeability and slope of the bed materials probably account for till deposition during glacial advance. We suggest, therefore, that any area perhaps more than 5–25 km back from the terminal moraine goes through a stage of till deposition during advance, a period of primarily erosion while the ice is at the terminal moraine, then deposition during retreat. However, field recognition of such 'advance' basal till is difficult for two reasons: either it would closely resemble the till left by the retreating ice margin, or erosion of the advance till under thicker ice could completely remove it. (The terms 'advance' and 'retreat' till are used informally here to distinguish tills which we believe to be deposited during advance and subsequent retreat of the same ice mass.) Assuming no change in source material takes place, one can show the presence of two tills deposited by one glacier only by finding structural relations which imply the relative ages of the two periods of deposition.

Gravel pit exposures in drumlins (Alden 1918) just west of Milwaukee, Wisconsin (Fig. 1) show such cross-cutting relationships between two otherwise indistinguishable tills which seem to have been deposited during one advance. The lower, older (advance) till is clearly truncated by the younger (retreat) till which is draped over the drumlin form. These exposures further show that the shape of these drumlins is due primarily to erosion of pre-existing glacial deposits.

Field and laboratory relationships

The drumlin field consists of approximately 650 drumlins and related streamlined features formed by late Wisconsin ice advancing out of the Lake Michigan basin (Fig. 1). Westward

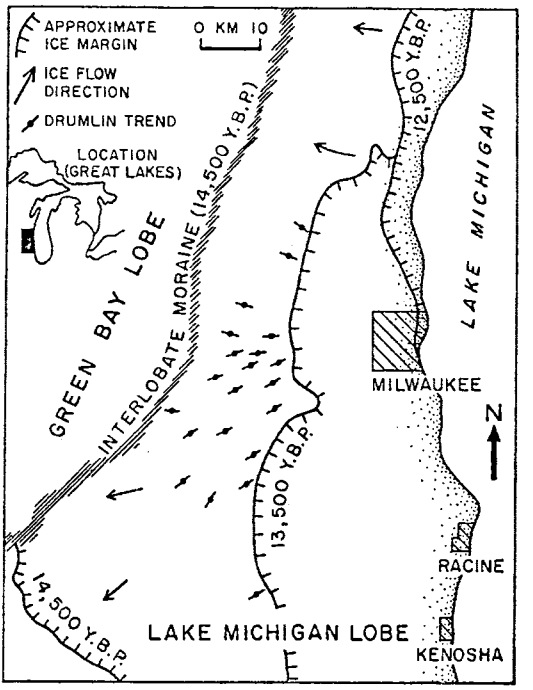


Fig. 1. Map of eastern Wisconsin showing location of drumlin field relative to lobe boundaries. Dates on ice margin positions are only approximate and are not well documented. From Alden 1918.

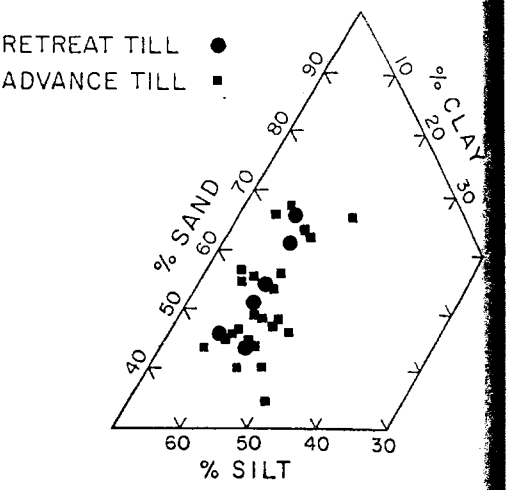


Fig. 2. Portion of triangular diagram showing sam silt-clay percentages of advance and retreat til Boundaries used are 2 mm, 0.0625 mm, and 0.002 mm

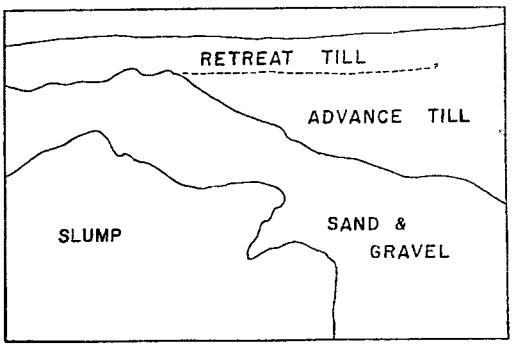
ice flow out of the basin was impeded by southeastward flow from the adjacent Green Bay lobe and the gentle eastward slope of the Niagaran dolomite cuesta. This drumlin-forming advance overran drift of Early Wisconsin age and these tills are in turn partly covered by till of a slightly younger readvance (Fig. 1) at the eastern edge of the drumlin field.

The basic internal structure found within all of the drumlins is that of horizontal beds of sand, gravel, and till. Many features demonstrate that these units are pre-drumlin age. Imbricated outwash gravels containing spruce logs dated at 30,800±1000 years B.P. (Black & Rubin 1968) are one indication. A paleosol formed in silt and gravel is exposed within one of the drumlins and distinctly different tills are often present, usually separated by thick gravel layers. The tills are correlative with known advances in other parts of southern Wisconsin and northern Illinois. The interbedded till and gravel sequences can exceed 50 m thick and comprise 60–95% of each drumlin exposed by gravel operations. Flat lying, sandy till is conformable over the upp gravels and is usually found in the top centr portion of the drumlins.

Truncating all of this typically flat drift the drumlin slope which is commonly covere by a uniformly thick sandy basal till. Usual less than 3 m thick, this capping till is i distinguishable (by lithology or textures) fro the uppermost truncated till in the centr portion of the drumlins (Fig. 2). We belie that these tills were deposited during advanc then retreat, of one ice mass. Both tills ha relatively strong and uniform fabric in t pebble fraction. The amount of rounding nearly the same in both tills. These chara teristics and their nearly identical mechanic composition argue against the upper till bei a surface melt-out (ablation) till.

Although it cannot be proven, it seems like that the tills do represent only one advan Not only are the tills very similar, but we ha never seen any evidence of fluvial materi between the two tills that was not sheared i the contact. Usually, with such excellent ex sures, tills from two glacial advances wo show some evidence of glaciofluvial deposit places along the contact. Further, we beli the structural relationships discussed later best explained as two tills deposited by advance. It remains a possibility, however, the two tills which we refer to as 'adva

Fig. 3. Photo and sketch of folded gravel and advance till truncated by retreat till. Axis of clastic dike is oblique to cut and to left of photo. Ice flow was right to left. Plane of photo is parallel to drumlin axis. Pit wall is approximately 8 m high.



and 'retreat' tills are from two advances closely spaced in time.

The structure and composition of their interiors show that the shape was carved subglacially from a preexisting glacial landscape modified by deposition at the margin of the advancing ice. The location and fan-shaped distribution of the drumlins suggest that a wide drumlin-forming zone of erosion and probably compressive flow existed up-ice from the margin. This might have been an area of irregular basal refreezing of water produced by basal melting under thicker ice. Whatever the basal ice conditions in this zone, these drumlins clearly were formed by erosion at the sole of the glacier.

Of the 17 drumlins partly exposed, all show units truncated at the sides of the drumlins, and all contain flat-lying internal beds. Deformation features seen in parts of seven of the drumlins are also truncated by the drumlin shape. These folds commonly disturb all of the sediments above them, except for the surface (retreat) till, and alter bed attitudes considerable distances laterally.

Two types of deformation features seem significant:

(a) *Clastic dikes* of fine sands, silts, and till warp the thick overlying gravels (Fig. 3). These dikes are at least 30 m high and their cores occasionally extend to the top of the drumlin. Although the warped gravels are close to verti-

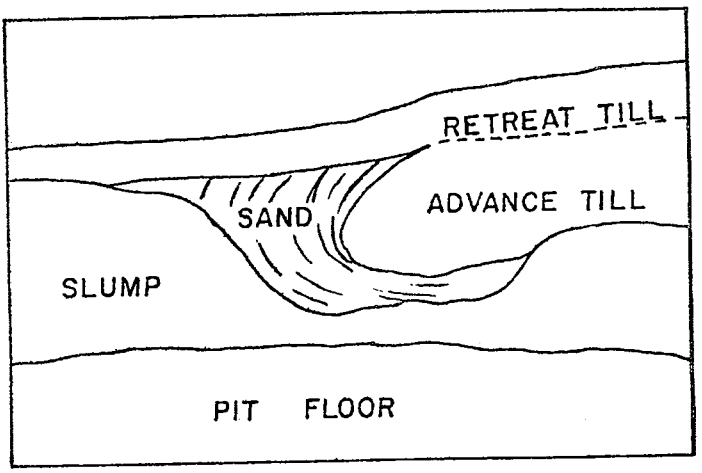


Fig. 4. Photo and sketch of advance till and sand and gravel truncated by drumlin form and retreat till. Photo plane is parallel to drumlin axis. Ice flow was left to right. Pit wall is approximately 10 m high.

cal beside the dike, they return to horizontal 15–30 m from the fold axis. Dike axes have trends either parallel or perpendicular to the long axis of the drumlin and have no preferred location within a drumlin.

(b) *Overturned folds* vary in height from 1 to over 30 m. Fold axes are either parallel or oblique to the long drumlin axis. In a few exposures, these folds are faulted and displaced beyond reconstruction. Since some overturned folds are genetically related to clastic dikes, further gravel mining may indicate that they all are interrelated.

In all of the drumlin sections showing these folds, there seem to be two tills that can be distinguished only by their relation to the gravel bedding. One till lies conformably on the stratified materials and is folded with th gravel. The other till follows the drumlin shap and truncates the folded till an avel. Whe the upper till cuts the lower c they appe massive and inseparable, except in rare ca where thin lenses of sand separate them (F 4).

From the cross-cutting relationships seen drumlin exposures of both flat-lying and formed stratified drift, it is apparent that truncated till was deposited before dru erosion and events of localized deforma Furthermore, the truncating basal till was sequently spread over the cial sub with a minimum of topographic contro interpret the truncated till as partly remains of basal till deposited under th

as the glacier advanced. As noted previously, however, it is possible that these tills represent two advances. If this is the case, it does not alter the sequence of events, but simply the interpretation of the lower till. The truncating till is believed to also be a basal till, but one deposited during retreat of the ice. There is no evidence to suggest that this is an ablation or surface melt-out till.

The advance and retreat tills in this case would be, as far as can be determined, indistinguishable except for structural relationships. This is presumably because ice-flow direction and source did not change appreciably between the time of advance and the time of retreat. In cases where source area of the till changed between advance and retreat, advance and retreat tills might be distinguishable where the advance till is preserved.

We feel that many till drumlins may actually be composed of an advance and retreat till sequence which would be difficult to recognize. Perhaps some of the 'two-till' drumlins recorded in the literature in areas like northeast U.S. might actually consist of an inner core of advance till and an outer veneer of retreat till. If both advance and retreat tills are common features, then we should be careful with the interpretation of individual stratigraphic units (tills) as separate glacial events. In some cases, if a change in source material takes place while an area is ice covered, one could deposit a till with certain characteristics, have partial erosion of this till take place while the source changes, and then have another till deposited on top during retreat of the same ice.

Summary

Based upon the internal characteristics of the drumlins, the following sequence of events is proposed:

(1) Advance of glacier ice and deposition of outwash and ice-contact stratified drift. Deposition of advance till in a zone near the margin. This till is conformable with the surface and, when over outwash, with outwash bedding.

(2) Continued advance and thus thickening of ice over the study area. At this time the area may have been in a zone of regelation beneath the ice sheet. Erosion of drumlin shape.

(3) Local folding of gravels and injection of fines in clastic dikes. This may have been partly contemporaneous with erosion of the areas between the present drumlins, although erosion truncates folds.

(4) Retreat of ice and deposition of basal till over the eroded surface. This retreat till was deposited near the retreating margin and is overlain in localized areas by ablation till, ice-contact stratified deposits and outwash.

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