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IMPORTANCE OF THE REGELATION PROCESS TO CERTAIN PROPERTIES OF BASAL TILLS DEPOSITED BY THE LAURENTIDE ICE SHEET IN IOWA AND ILLINOIS, U.S.A.

by

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ABSTRACT

Recent stratigraphic studies have characterized the sequence and nature of tills deposited in Iowa and Illinois by Quaternary Laurentide ice sheets. Basal tills within the sequence are each dominated by matrix-size materials and exhibit uniform matrix properties over hundreds or thousands of square kilometers. This uniformity suggests that matrix-size materials were effectively mixed for each basal till. Three mixing processes seem probable: differential shear in debris-rich basal ice; continuous subglacial deformation of the till; and repeated erosion-transportation-deposition of matrix-size materials during recurrent regelation in the basal ice. Shearing and subglacial deformation appear to have been only locally important. Most of the mixing may have occurred during regelation. Particles on the bed may have been frozen into the basal ice during regelation freezing, and transported until deposited during subsequent pressure-melting on a down-glacier obstacle. During recurrent regelation on fine-grained beds such as occurred in this area, particles may have been subject to several periods of erosion-transportation-deposition, and mixed through time over long transport distances. This mixing process was certainly not the only process taking place, but it appears to have been the dominant subglacial mixing process.

INTRODUCTION

Iowa and Illinois are situated at or near the southernmost termini of the various Quaternary-age Laurentide ice sheets. During the past 15 years extensive stratigraphic studies have been undertaken by a number of investigators to determine the physical properties, stratigraphic relations, and areal distribution of the glacial deposits. The results of these studies have created an enormous new data base that can be used for regional synthesis of variations in glacial processes and ice dynamics of the Laurentide ice sheet(s) in this area. This paper addresses one aspect of the till lithology and stratigraphy: the apparent homogeneity in matrix properties found both laterally and vertically for the basal tills. In order to understand what is meant by the "homogeneity" of the basal tills and the possible causes for such homogeneity, it is essential to understand the nature of the deposits, their differentiation, and their stratigraphic setting.

TILL DIFFERENTIATION AND STRATIGRAPHIC SETTING

The till deposits in Iowa and Illinois are formally classified into formations and members. A till member is a lithologically distinct unit, in most cases representing a single phase of glacial deposition. A formation consists of several till members related lithologically and/or temporally.

Results from recent studies of till properties and depositional processes on existing glaciers (summarized in Boulton 1972 and 1976, Dreimanis 1976, Sugden and John 1976, Lawson 1979) have provided a much greater understanding of the spectrum of till depositional processes, and the properties of the resulting sediments. As a consequence, significantly more refined genetic differentiation of till deposits in Iowa and Illinois are now being made (Hallberg 1980 [a] and [b], Kemmis, unpublished, Von Rhee, unpublished, Wickham, unpublished), and till members are informally differentiated into genetic parts (Fig. 1). In order to avoid confusion with previous methods, the present practices used for genetic till differentiation and interpretation are outlined below.

On the gross scale (Fig. 1), a till member may be differentiated into subglacially and supraglacially deposited increments. These two increments are further differentiated, based on criteria given by Dreimanis (1976), Boulton (1976), Lawson (1979), and other authors, which include: (1) the nature of the sediment sequence

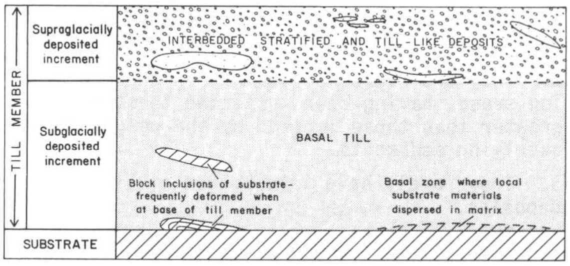

Fig.1. Hypothetical diagram of genetic components for an individual till member in Iowa and Illinois.

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and the position of till-like materials within it; (2) structural features, including folding, faulting, jointing, shear banding; (3) fabric, on all scales; and (4) geotechnical properties, particularly density and consolidation (in the engineering sense) where the till has not been subjected to major post-depositional changes.

The supraglacially-deposited increment commonly consists of till-like materials interbedded with stratified sediments of various textures (Fig. 2). Where easily recognized or where suitable data exist, these supraglacially-deposited sediments may be further differentiated into various categories of supraglacial melt-out till, till flows, and resedimented deposits following the criteria of Boulton (1971, 1972, 1976), Lawson (1979), among others. The thickness of supraglacially-deposited sediments for till members in Iowa and Illinois is variable.

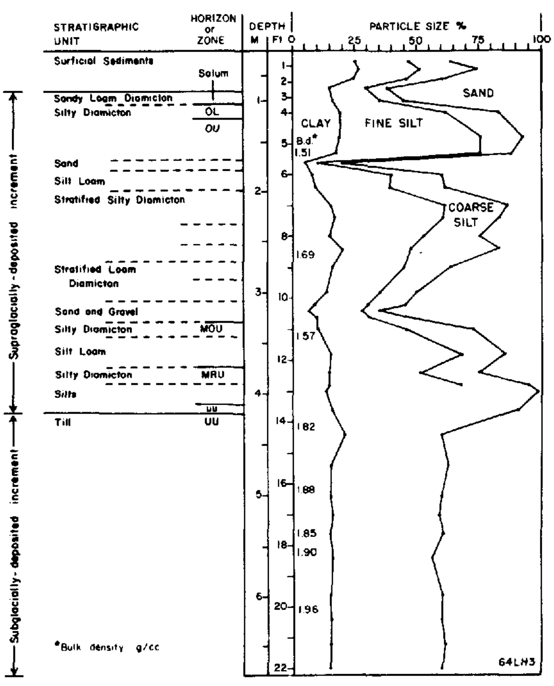

Fig.2. Textural and stratigraphic characteristics of sub- and supraglacially deposited increments in till from the late Woodfordian (Wisconsinan) Des Moines glacial lobe in Iowa (boring log 64LH3; location: long. 93° 13'54"W, lat.42°00'29"N.).

The basal till increments of till members in Iowa and Illinois have several properties in common:

1. They are matrix-dominated, rather than clast-dominated or well-graded (following the classification of Derbyshire and others 1976). Clay-through-sand size materials constitute the bulk of the till, commonly 80 to 95%.

2. They are overconsolidated, in the engineering sense, having been subjected to stresses greater than those imposed by the weight of the overlying sediments.

3. They rarely have interbedded stratified deposits.

4. They are characterized by uniform matrix properties (Figs. 3 and 4; Table I). For each till member there is a distinctive narrow range for matrix texture, clay-mineral composition, coarse sand fraction lithology, and many geotechnical properties (such as density,

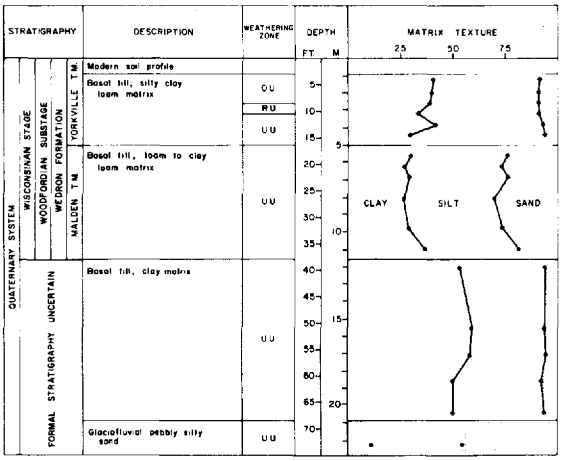

Fig.3. Three till sequences encountered in boring B-49 in north-east Illinois showing uniformity and distinctiveness of each basal till (location: long.88°15'38"W, lat. 41°51'14"N). Weathering zone terminology after Hallberg (1978).

Atterberg Limits, natural moisture content), as well as systematic color and matrix carbonate composition. This uniformity has been documented in a large number of recent stratigraphic studies summarized in Willman and Frye (1970), Johnson (1976), Hallberg (1980[b]), and Hallberg and others (1980). This uniformity, and the fact that the till members each have their own distinctive range of matrix properties (see Figs. 3 and 4 for examples), allows the till members to be differentiated and mapped. Two exceptions to the uniformity of basal tills in Iowa and Illinois occur locally (Fig. 1): (a) the common occurrence of a zone at the bottom of the basal till in which the local substrate material occurs dispersed and thoroughly mixed with the farther-travelled debris; this basal zone generally shows a gradational change upward from dominantly local material at the base to the farther-travelled material that constitutes the basal till regionally (Fig. 5); and (b) the occasional occurrence of block inclusions of older substrate materials (either Quaternary sediments or bedrock) which may locally occur anywhere within the basal till; when these block inclusions occur at the base of the till they are often found to be deformed.

Regional variability of till members in Iowa and Illinois has received little study to date. The basal till of most till members has remarkable homogeneity in matrix properties both vertically at any particular site, and laterally over areas measured in several hundred to a few thousand km^2. Wickham and Johnson (1981) suggest, however, that spatial and temporal variations in basal thermal regime may have resulted in areal (lateral) variations in matrix properties for some of the till members of the Woodfordian (Wisconsinan) Lake Michigan glacial lobe in north-eastern Illinois.

5. The basal tills tend to occur as sheet-like deposits. The uniform, homogeneous basal till of an individual till member extends over areas several hundred to a few thousand km^2. Basal-till thicknesses generally range from 3 to 10 m. Thicker values than this occur locally in end-moraine areas (Wickham, unpublished) and in pre-existing valleys (Hallberg 1980[b]). However, basal-till thicknesses greater than 15 to 20 m tend to be exceptional. These variations in

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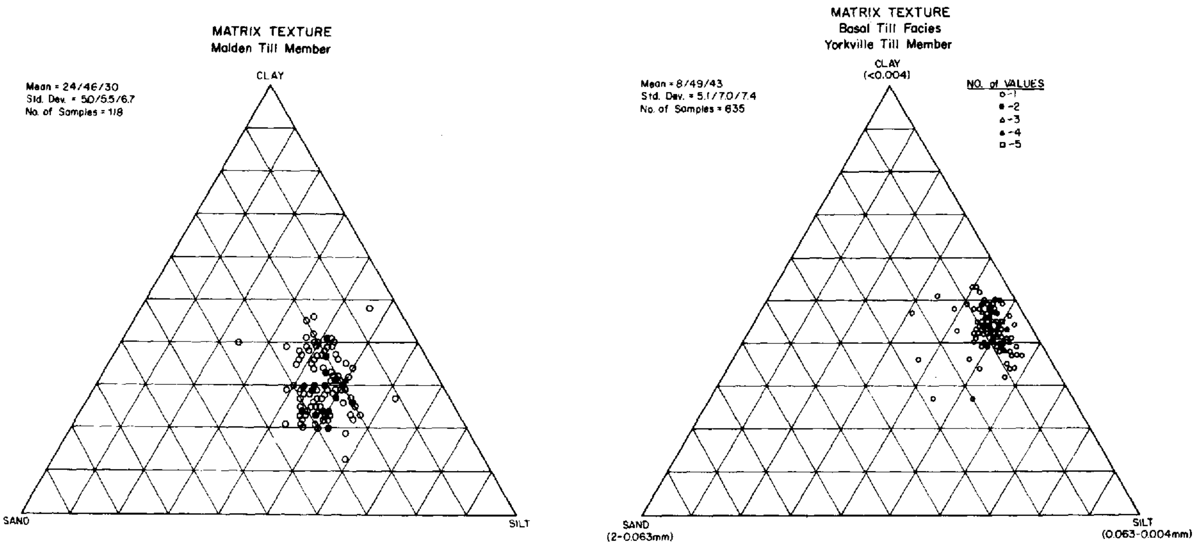

Fig.4. Regional textural characteristics of the basal till increments of the Yorkville and Malden Till Members from closely-spaced borings over a 36 km^2 area in north-eastern Illinois. Note the uniformity for each.

thickness are related to differences in original depositional thickness and to post-depositional truncation (both by subaerial erosion and, where appropriate, by subsequent erosion due to younger glacial advances).

Two other factors should be recognized concerning the basal tills. First, a large number of till members are recognized, each with lithologically distinct basal tills. For example, the Illinois State Geological Survey currently recognizes 15 Wisconsinan-age till members (Lineback 1979). Secondly, the till members occur in a well-defined stratigraphic sequence. Details of the stratigraphy in Iowa and Illinois are summarized in Willman and Frye (1970), Johnson (1976), Ruhe (1969), Hallberg and Boellstorff (1978), Hallberg (1980[a] and [b]). It should be noted that there is generally a sequence of tills that occur at any one locale in Iowa and Illinois (see Fig. 3, for example). Consequently, in this area there is not a simple sequence of one till over bedrock. Only the base of the lowermost till in the sequence is consistently in contact with bedrock. The younger till members overlie (1) older tills; (2) stratified sediments; (3) loess; (4) buried soils; and (5) occasionally bedrock. For the younger till members, particularly the younger Wisconsinan and Illinoian tills, probably only a very small percentage of the sub-till member is bedrock. Those areas where bedrock directly underlies the tills are restricted to local bedrock "highs" and to other local areas where erosion (glacial or other) was effective in re-

TABLE I. SUMMARY OF REGIONAL DATA FOR THE BASAL TILL INCREMENT OF THE LATE WOODFORDIAN (WISCONSINAN) YORKVILLE TILL MEMBER IN NORTH-EASTERN ILLINOIS (from Kemmis, unpublished)

Property	Mean value	No. of samples	Standard deviation
Matrix texture (% sand-silt-clay of the <2 mm fraction)	8/49/43	635	5.1/7.0/7.4
Clay mineralogy (% expandables-illite kaolinite plus chlorite)	3/76/21	58	0.9/2.2/2.2
Carbonate mineralogy (% < 74 μm fraction)			
Calcite	6.9	29	1.1
Dolomite	18.2	29	2.9
Preconsolidation pressure (from one-dimensional consolidation tests; Schmertmann method)	$2.2 \cdot 10^6$Pa	3	$2.8 \cdot 10^5$Pa
Dry density	1 870 kg/m^3	505	100 kg/m^3
Natural moisture content	17.3	733	2.7
Liquid limit	29.2	424	3.9
Plasticity index	13.1	424	2.8

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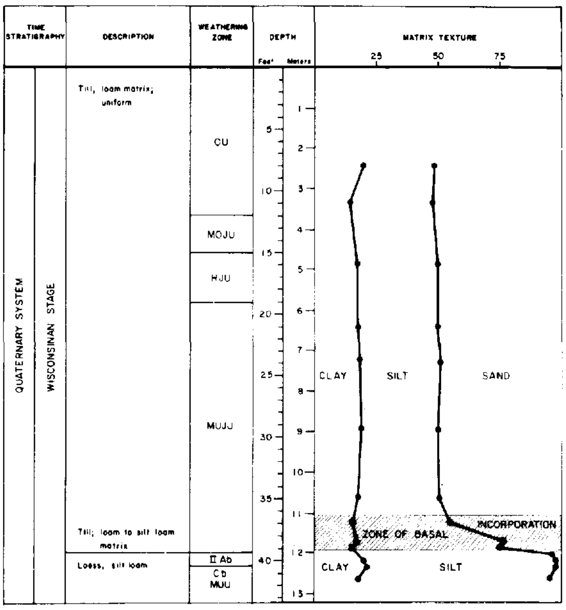

Fig.5. Basal till from the late Woodfordian (Wisconsinan) Des Moines glacial lobe in Iowa showing a zone of basal incorporation where local substrate material (loess) has been incorporated and dispersed within the till matrix. This locally-derived matrix material becomes progressively diluted upward until only the farther-travelled, better-homogenized matrix which constitutes the till regionally is found (location: long. 93°21'22"W, lat.42°30'49"N).

moving pre-existing sediments. Consequently, the bed for younger tills over widespread areas in Iowa and Illinois was comprised of a complex of Quaternary sediments, not bedrock. Bedrock in Iowa and Illinois consists predominantly of Paleozoic and Cretaceous sedimentary rocks. It should be noted that both the bedrock and the Quaternary strata are relatively flat-lying, implying that a single substratum may occur over a relatively widespread area.

THE HOMOGENEITY PROBLEM

The most striking features of basal tills along the southern margin(s) of the Laurentide ice sheet(s) in Iowa and Illinois are:

(1) their uniformity or homogeneity; (2) the fact that they can be differentiated because each homogeneous basal till has its own distinctive ranges for matrix properties; and (3) their distribution individually over areas measured in hundreds or thousands of km^2. These features suggest that the Laurentide ice sheet effectively mixed the matrix-size components of each basal till over widespread areas and vertically through several meters of till.

The uniformity of the basal tills perpendicular to the flow direction is apparently related to the general nature of the substrate materials: relatively uniform materials which may sub-crop over widespread areas. The uniformity found for each till member vertically through several meters of till and laterally along a flow path tens to hundreds of kilometers in length most likely resulted from mixing caused by at least three glacial processes: (1) differential shear in debris-rich basal ice; (2) mixing of subglacial sediments by continuous or near-continuous deformation; and (3) mixing of matrix-size materials by repeated erosion-transportation-deposition during recurrent regelation.

Differential shear in the basal ice may be one component contributing to glacier flow. Mixing would occur as particles are transported differentially on either side of the shear zone. Differential shear undoubtedly took place in the basal ice of the Laurentide ice sheet in Iowa and Illinois. Evidence for its occurrence are the deformation structures which infrequently occur in sediments locally incorporated at the base of a till member, the deformation structures developed in the top of a till member overridden by a younger advance, and block inclusions of older substrate, which require differential shear as a transport mechanism for this particular plucking process (Moran 1971). Even though differential shear did occur in the basal ice, it is doubtful that it played the most important part in the mixing and homogenization found for the basal tills. The amount of shearing required longitudinally along flow lines tens to hundreds of kilometers in length, areally over hundreds to thousands of km^2, and vertically through thicknesses of several meters would be enormous. Shearing on such a scale is not compatible with that observed from existing glaciers nor is the mode of flow it would generate compatible with observed processes of glacier flow. Such shearing would also be expected to form structures (folds, low angle faults or joints, etc.) and discrete compositional zonation. These features are only rarely encountered, however, and are important only on the local level in Iowa and Illinois. The bulk of the basal till, where not affected by subaerial weathering, is massive (or vertically jointed) and uniform as previously discussed. Furthermore, it is difficult to understand how shearing could form the commonly encountered zone at the base of the till where local substrate materials occur dispersed within the till matrix, becoming progressively diluted upward by the farther-travelled material which constitutes the till regionally (Fig. 5).

A second process which might promote mixing of matrix-size material is subglacial deformation of soft sediment (Boulton 1981). Deformation of glacial substrate composed of unlithified sediments has been observed by many investigators. Boulton suggests that unlithified sediments beneath widespread areas of the southern terminus of the Laurentide ice sheet may have undergone continuous or near-continuous deformation over very long distances. The great strain to which these various materials would have been subjected may ultimately have caused them to become effectively mixed. However, the sedimentary record in the basal tills of this region suggests that deformation does not account for the observed mixing. First, deformation structures are observed only locally. Second, if deformation was an effective mixing mechanism, one would not expect to find the sharp boundaries between strata at the base of the basal tills. And finally, the widespread occurrence of soft, undeformed sediments beneath till members, including peat, loess, and buried soils, indicates that subglacial deformation of sediments beneath the Laurentide ice sheet in Iowa and Illinois was minimal. It is also uncertain if such deformation of subglacial materials could account for the zone at the base of the till (Fig. 5) where local substrate materials occur dispersed in the matrix, becoming progressively diluted upward by farther-travelled, better-homogenized material that constitutes the till regionally.

The regelation process provides an attractive mixing mechanism for fine-grained (matrix-size) debris. Fine-grained debris on the bed might be entrained (eroded) by becoming suspended in freezing regelation melt water, transported passively in the basal ice, and then deposited during subsequent regelation melting. Where recurrent regelation is taking place on the bed, individual matrix-size particles (which may be aggregates of smaller particles) may be subject to several periods of regelation erosion-transportation-deposition. The transport of debris in such a situation would be analogous to the bed load of a stream in that individual particles would be deposited and transported alternately, the time of deposition and length of transport being variable for each particle. Mixing of the particles along a flow path could thus occur through time over the long transport distances possible in the Laurentide ice sheet. The particle-by-particle regelation mixing process successfully explains not only the homogeneity found for the matrix properties of the basal tills but also the commonly-encountered lower zone in the basal tills (Fig. 5) where local substrate materials are found disseminated in high concentration at the base of the till. Where these zones occur, local substrate material may have been picked up particle by particle and disseminated, diluting the normal, farther-travelled debris. As net deposition takes place on the bed, more and more local source materials would become covered up, no longer contributing to the debris load. Thus with time the character of the basal till would change: initially, local materials would dominate, progressively forming lower and lower proportions of the matrix materials as more of the local substrate is covered up until, finally, only the farther-travelled, better-homogenized material constitutes the till matrix.

A remaining question to be considered is the effectiveness of large-scale erosion and deposition by regelation processes. For regelation to occur, the basal ice must be at the pressure-melting point. For the Laurentide ice sheet(s) the only way this can be evaluated is, of course, by modeling. Sugden (1977) has constructed a model for the Laurentide ice sheet at its maximum. Although Sugden's steady-state model may not be precisely accurate for the oscillating front, ice dynamics known to have occurred near the Laurentide margin, Iowa and Illinois are shown to be well within a broad zone along the southern margin of the Laurentide ice sheet where the ice is predicted to have been at the pressure-melting point. So at least during its maximum extent, widespread areas of the Laurentide ice sheet in Iowa and Illinois were probably at the pressure-melting point.

Another question is, were suitable obstacles present on glacier beds in Iowa and Illinois to promote regelation in the basal ice? No observations have been made of the minimum obstacle size necessary to promote regelation. Kamb and LaChapelle (1964) have observed regelation taking place for obstacles of the order of 5mm. Certainly obstacles of this size were present wherever the bed was composed of till or gravel. Furthermore, Walder and Hallet (1979) have shown in their study of subglacial water flow that, where the basal ice is at the pressure-melting point, regelation has taken place over large areas of the bed (up to approximately 80%). It thus seems plausible that regelation mixing could have taken place in or in transit to the Iowa-Illinois area: (1) the basal ice is likely to have been at the pressure-melting point, at least during some period of its history; (2) it seems probable that matrix-size debris can be eroded, transported, and deposited during the regelation process; (3) abundant matrix-size particles were available on the beds for most of the till members over widespread areas; and (4) sufficient obstacles were present on the bed to promote widespread regelation.

Regelation mixing may have been the dominant *mixing* mechanism taking place for matrix-size materials. However, it should be stressed that there was probably a complex interaction of processes taking place by the Laurentide ice sheet in Iowa and Illinois. For example, although some matrix-size materials may have been ultimately deposited by regelation melt-out, clast-size particles may have concurrently been deposited mechanically by true lodgement, a process discussed in detail by Boulton (1974, 1975). Other portions of the matrix-size basal load, as a result of local ice dynamics, may have been transported down-glacier to englacial or supraglacial positions where deposition subsequently took place as either basal or ablation melt-out, portions of this material being subject to further supraglacial flow or reworking. It is also recognized that the Laurentide ice sheet probably had a complex basal thermal regime (Hooke 1977, Sugden 1977, among others). Spatial and temporal variations in basal thermal regime must have in turn affected spatial and temporal variations in glacial processes, ultimately affecting till provenance and properties (Wickham and Johnson 1981).

The matrix uniformity found for basal tills in Iowa and Illinois is probably just regionally significant. It is probably important to this region because (1) relatively uniform substrate materials, forming a relatively low relief bed, occur over generally sizeable areas; (2) regelation is likely to have taken place over widespread areas; (3) abundant matrix-size materials were present on the bed; and (4) long transport paths existed. Other glaciers, or even other regions of the Laurentide ice sheet(s) did not have similar conditions and consequently do not exhibit the same uniformity in basal till matrix properties.

The mixing aspects of the regelation process have previously received little attention. In view of the apparent importance of this process to widespread areas near the southern margin of the Laurentide ice sheet, further field and theoretical studies seem warranted.

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