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CORRESPONDENCE

The Editor,
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SIR,

Modeling the influence of till rheology on the flow and profile of the Lake Michigan lobe, southern Laurentide ice sheet, U.S.A.: discussion

Subglacial deformation of sediment and the importance of such deformation to the dynamics of large ice sheets is a relatively new and exciting development (Boulton and Jones, 1979; Alley and others, 1986). In a recent paper, Beget (1986) discussed these developments and, based on the strength properties estimated for a diamicton formed by a late Wisconsinan sediment flow in central Illinois, concluded (1) that sediment beneath the outermost part of the Lake Michigan lobe at the time of the sediment flow had similar low-strength properties, (2) sediment was deforming beneath the lobe, and (3) the southern Lake Michigan lobe of the Laurentide ice sheet had a low profile at that time. Although we suspect that some of Beget's conclusions may be valid, we question the premise on which he approached the problem and based much of his discussion, and therefore suggest his conclusions are not justifed.

Beget (1986) used data and observations from a paper by Hester and DuMontelle (1971) that described a large sediment-flow deposit in front of the Shelbyville moraine at the terminus of the Lake Michigan lobe (Fig. 1). We agree with the general origin of the sediment-flow deposit as

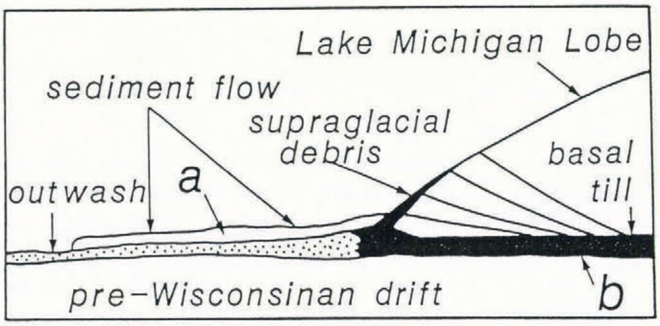

Fig. 1. Inferred geologic relationships at the terminus of the Lake Michigan lobe at the time of the deposition of the large sediment flow. Modified from Beget (1986).

originally interpreted by Hester and DuMontelle and described by Beget (1986). However, it should be noted that Hester and DuMontelle's description of the diamicton is not adequate to determine whether it resulted from one thick, extensive flow or several thinner, possibly overlapping flows; such a difference has significant implications with respect to the interpretation of the flow's properties and strength.

One aspect of Beget's discussion that we question is the origin of the debris on the glacier surface. He suggested that it was "derived from subglacial till which had been sheared into the glacier and up to the glacier surface ...", and further on (p. 237) stated "The large volume of the flow till [sediment-flow deposit] suggests it can be considered a representative sample of the basal till, brought to the glacier surface along multiple intraglacial thrusts ...". We believe that the supraglacial debris in the terminus zone was more likely derived from ablation of debris-rich basal ice exposed at the active margin by compressive flow and/or thrusting over stagnant ice and marginal deposits, processes that have been widely documented at modern glacier margins (e.g. Boulton, 1968; Lawson, 1979). The existence and importance of thrusting as a sediment entrainment and depositional mechanism has never been documented (see discussion in Weertman (1961)). This difference in origin is significant with respect to Beget's model. If his conclusions regarding the strength of the subglacial till are correct, his proposed "thrusting of till" to the surface cannot be accurate because the material would deform by flow rather than by failure.

Beget calculated an approximate yield strength of 8 kPa for sediment-flow material using the geometry of the sediment-flow deposit, an estimation of its wet density, and an equation developed by Johnson (1970) (although we note that Johnson and Rodine (1984) deleted the analysis developed by Johnson (1970) and used by Beget). Because the resulting diamicton was similar in texture and composition to Shelbyville till (the assumed source), he concluded (p. 237) that "The rheological properties of the flow till [sediment-flow deposit] also characterized identical Shelbyville till; shear strength of water-saturated till beneath the southern Lake Michigan lobe therefore was also approximately 8 ± 2 kPa". Beget then went on to assume that the outer 400 km of the Lake Michigan lobe rested on material of this approximate strength. Observing that glacier profiles would be more or less adjusted to the strength of the subglacial sediment (because it was much weaker than the overlying ice), he calculated a profile for the Lake Michigan lobe that indicated it was much lower (thinner) than modern ice sheets.

The critical question is: does the strength of the material in a sediment flow off the terminus of a glacier (position "a" in Figure 1) tell us much, if anything, about the properties of subglacial sediment and whether deformation is occurring beneath that glacier (position "b" in Figure 1)? Beget would have us believe that it does. Certainly, whether subglacial sediment deformation took place beneath Pleistocene glacial lobes in Illinois or elsewhere, and what effect sediment deformation had on ice dynamics, are critical research questions. However, we do not think that Beget's analysis provides much enlightenment to them.

We agree that the diamicton of the sediment-flow deposit is generally similar to the basal (Shelbyville) till that was being deposited beneath the lobe. However, three points should be considered further in relating the strength of the two materials: (1) the number and size of particles >2 mm; (2) the structure or fabric of the subglacial sediments; and (3) the water content of the sediment flow. With respect to the first, Lawson (1982) has shown that significant down-current textural modification of sediment flows is common in glacigenic environments. For example, larger clasts may remain as a lag in the source region or move as traction load in the lower part of a flow. In their original work on the sediment-flow deposit, Hester and DuMontelle (1971) demonstrated that matrix texture (<2 mm) of the deposit and till were similar. However, they reported that the maximum particle size was generally <2.5 cm, and not "erratic boulders" as curiously reported by Beget (1986, p. 236). The absence of larger clasts suggests that the flow may not have had the competence to tranport them. Large clasts (cobbles and a few boulders) have been observed in Shelbyville till by one of us (W.H.J.); they would have had an important effect on both ice flow and subglacial sediment deformation (Boulton, 1975, 1987; Brown and others, 1987). Their absence in the sediment flow thus makes it less appropriate as an "analogue" material for Shelbyville till.

Secondly, debris in the supraglacial environment undergoes mixing through re-sedimentation processes (Lawson, 1979, in press), and thus primary structure (fabric, joints, soil structure, stratification, etc.) that subglacial sediment (including till) may have had is lost or modified. These structual and stratigraphic characteristics would be significant during initiation and early stages of deformation, and are not taken into consideration by using a sediment flow as an analogous material.

Thirdly, many workers have recognized that water content plays an important role in debris-flow rheology (e.g. Hampton, 1975; Lawson, 1982; Johnson and Rodine, 1984). Sediment flows in the glacigenic environment exhibit significant variations in flow strength and behavior primarily because their water contents and resulting wet densities vary widely (Lawson, 1982). Beget (1986) assumed a "water-saturated" debris flow with a wet density of 2000 kg/m^3, a value that probably is reasonable given the available data. However, along the ice margin there must have been other contemporaneous flows of similar texture with both lesser and greater water contents. Which one, among a continuum of flows of varying strength, is representative of the rheology of the subglacial sediment? Is it just the one flow that Hester and DuMontelle described?

Our most critical questions concern Beget's extrapolation of the flow's strength to the subglacial sediment and the resulting implications with respect to subglacial hydrology. For Beget's analysis to be valid, subglacial sediment beneath the Lake Michigan lobe must have supported essentially no load, i.e. the normal load (the weight of the glacier) was supported by pore-water pressure in the subglacial sediment. Such a situation is required because Beget's analysis assumes no contribution to strength from internal friction (zero effective stress) and any strength in the subglacial sediment comes only from cohesion.

Effective stress in this case is determined by two major unknowns: the pore-water pressure in the sediment and the thickness of the ice at the location. The latter clearly is in part dependent on the former, which in turn is controlled by several other inter-related factors, i.e. basal thermal regime, local basal melt rates, nature of subglacial drainage (whether in thin water layers, Röthlisberger channels, Nye channels, or subglacial sediment), and the properties of the subglacial sedimentary sequence, particularly those that affect drainage. Pore-water pressure may have approached or equaled glaciostatic pressure as Beget assumed, but the strength of the sediment flow indicates only that it is possible for material similar in texture and composition to Shelbyville till to have low strength, and nothing with respect to subglacial conditions, particularly hydrology, and certainly not to the thickness of the glacial lobe.

Beget offered two independent "field tests" of his proposed low profile for the Lake Michigan lobe, but neither is valid. First, he referred to moraine profiles from Hester and DuMontelle (1971) which "indicate the terminal parts of the Lake Michigan lobe rose to the north at approximately 7.6 m/km" (Beget, 1986, p. 238). Slopes reported by Hester and DuMontelle are for the front of the Shelbyville moraine, and have no direct bearing on the gradient of the paleo-ice surface. These slopes cannot be used to support a low profile as Beget did.

Secondly, Beget used an approach originally suggested by Flint (1971, p. 484) to estimate a minimum ice thickness at the center of the Lake Michigan lobe 400 km north of the Shelbyville moraine. This test involves using the elevation (450 m) of marginal deposits along the eastern edge of the Driftless Area in central Wisconsin (not "Michigan") and the depth of Lake Michigan (−180 m) to obtain a minimum ice thickness of 630 m (Beget, 1986, p. 238). Beget, as did Flint, neglected to mention that these are marginal deposits of the Green Bay lobe, which was located between the Driftless Area and the Lake Michigan lobe. Nevertheless, Beget acknowledged that the medial thickness of the Lake Michigan lobe would have been greater than this minimum value, but he observed that an ice thickness of 835 m predicted for the location from his reconstructed profile "is a reasonably good fit to the field data" (p. 238). In fact, it [630 m] is a minimum value and only that; it is possible that the ice thickness was significantly greater. In addition, the elevation figures do not consider the possibility that differential isostatic adjustments during and following glaciation may have been significant.

We do not deny that subglacial sediment deformation took place during the last glaciation in Illinois (e.g. deformed subglacial sediment and stratigraphic contacts at a locality 80 km from the glacier margin; see figure 5d and e in Hansel and others, 1987). It is noteworthy that at this same locality, where evidence for subglacial deformation has been observed, there is also evidence that at some times subglacial deformation was not occurring (e.g. relatively undeformed subglacial channel deposits and stratigraphic contacts; see figures 5f, 6a and d, and 7a in Hansel and others, 1987). In addition, one of us (W.H.J.) has observed several (>six) sections within and near the Shelbyville moraine where the A horizon of the Farmdale geosol and/or a moss layer on Morton loess immediately subjacent to or within 15 cm of Shelbyville till have not been deformed (Frye and others, 1962; Johnson and others, 1971; Follmer and others, 1979). Subglacial channel deposits within till in the Shelbyville moraine generally are not deformed. However, the A horizon of a Farmdale geosol at a locality 70 km north of the Shelbyville moraine shows much evidence of internal deformation. We suspect there was considerable temporal and spatial variability in subglacial deformation beneath the Lake Michigan lobe during the last glaciation.

Beget used an apparently novel approach for estimating the rheological properties of till beneath the Lake Michigan lobe during the late Wisconsinan glaciation. We do not question the possibility that the Lake Michigan lobe was thin, nor the probability that deforming sediment played an important role in affecting the dynamics of the lobe. We do not accept Beget's analysis as being valid, however, and urge caution in using minimal data and such a questionable approach and gross generalization to modeling a large glacial lobe. In particular, it will require careful and detailed study of Lake Michigan lobe deposits and geomorphology before the contribution of subglacial deformation to flow of the lobe will be fully known.

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Department of Geological Sciences,
University of Illinois,
Chicago,
Illinois 60680, U.S.A.

PETER U. CLARK*

U.S. Army Cold Regions Research and Engineering Laboratory,
Hanover,
New Hampshire 03755, U.S.A.

W. HILTON JOHNSON†

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* Present address: Department of Geology, Oregon State University, Corvallis, Oregon 97331, U.S.A.

† Permanent address: Department of Geology, University of IIllinois, Urbana, Illinois 61801, U.S.A.

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Reply to: "Modeling the influence of till rheology on the flow and profile of the Lake Michigan lobe, southern Laurentide ice sheet, U.S.A.: discussion"

I thank P.U. Clark and W.H. Johnson for an opportunity to address the concerns raised in their discussion. While they agree with some of the major conclusions of my paper, they question several of the assumptions I made in developing a pseudo-plastic model of ice-sheet thickness for a "soft-base" Lake Michigan lobe of the Pleistocene Laurentide ice sheet. Their concerns seem to lie with (1) the validity of modeling deforming subglacial till as a viscous or Bingham-type plastic-viscous fluid, and (2) with the boundary conditions of the pseudo-plastic model. Since I wrote this paper in 1985, much new data has become available from modern glaciers which overlie deforming till, particularly at Ice Stream B in Antarctica, and several sophisticated models of soft-base glacier flow have been published. Important aspects of these new data appear to be generally consistent with my paper, and are relevant to the discussion of Clark and Johnson. Clark and Johnson may not have been aware of this new body of data when they wrote their comment.

Clark and Johnson do not believe that viscous and Bingham-type sediment flows are appropriate rheologic analogues for deforming, water-saturated basal tills. However, this analogy is fundamental, and has been accurately called upon by others workers in several recent papers. For instance, Clarke (1987, p. 9023), in discussing basal tills, noted that "rheologically, the water-saturated matrix is like a viscous fluid capable of transporting the clasts with it as a slurry". Boulton and Hindmarsh (1987) modeled basal tills as both Bingham and viscous fluids, and Alley and others (1987a, b) compared the rheologic properties of water-saturated deforming till beneath Ice Stream B in Antarctica with mud flows. Several pertinent field descriptions of water-saturated basal till which document rheologic and textural similarities to mud flows or sediment slurries were cited in my original paper, and in Boulton and Jones (1979).

The rheologic properties of till are poorly understood. I argued in my paper that basal tills, like surface sediment slurries, are likely characterized by Bingham or plastic-viscous rheologies, as particle interactions must be overcome before sediment shear can occur, imparting a characteristic yield strength. Boulton and Hindmarsh (1987, p. 9059) noted that "the sediment flow processes of most concern to geologists reflect behavior after failure. Quantitative sediment flow laws are difficult to derive from laboratory experiments because of the problems of sustaining steady conditions for large strains". I addressed this problem in my paper, and suggested that shear deformation of a very large representative sample of Lake Michigan lobe basal till during emplacement as a flow till constituted a natural "shear box" for testing the rheologic properties of this till. The shear stress applied to such sediment flows is easily determined, sustained strain occurs during flow, and the morphology of the sediment-slurry deposit reflects the rheologic properties (i.e. yield strength) of the till. Because all textural, mineralogical, clay mineralogical, granulometric, and sedimentological data indicate the flow till described by Hester and DuMontelle (1971) and coeval Lake Michigan lobe basal till are essentially identical, Clark and Johnson's contention that the rheology of basal till and identical flow till are unrelated reduces to an argument that the rheology of sediments is controlled by their physical location, rather than their physical characteristics and properties.

Clark and Johnson question my contention that deforming basal tills and sediment slurries can attain similar levels of water saturation. However, since subglacial shearing can produce porosity in dilated basal till which is comparable to that of uncompacted sediment (Boulton and Hindmarsh, 1987), and since water content in saturated sediment is closely related to porosity, texturally indentical sediment packages with identical porosity, as discussed in my paper, can attain comparable levels of water saturation. Clark and Johnson seem to argue that water saturation of similar sediment packages with similar porosity can involve very dissimilar amounts of water.

Blankenship and others (1987) demonstrated that water-saturated deforming till beneath Ice Stream B in Antarctica has a porosity of 0.3–0.4, a value identical to that expected for unconsolidated sediment at the ground surface. Thus, while Clark and Johnson present no data consistent with their objections, recently obtained field data from glaciers overlying deforming till and other theoretical models show good agreement with the physical boundary conditions assumed for subglacial till deformation in my 1986 paper. High subglacial till porosity is likely to be characteristic of "soft-base" glaciers. Water content in sheared, dilated subglacial tills can approach that found in unconsolidated surface sediments.

Clark and Johnson rightly note that sorting during flow sometimes produces progressive changes in low-strength slurries, which can affect sediment texture, porosity, water content, and strength characteristics (Lawson, 1982). However, such effects are accompanied by changes in granulometry, which were not observed in the debris flow of Hester and DuMontelle (1971). Voluminous sediment flows are commonly characterized by Bingham rheology in which plug flow predominates and little or no sorting occurs above the critical depth (Johnson, 1984). The identity of textural, mineralogical, and clay mineralogical characteristics between subglacial till and the voluminous coeval flow till of the Lake Michigan lobe discussed by