Boulton, G.S. 1975. Processes and patterns of subglacial sedimentation: a theoretical approach. *In* Wright, A.E. and F. Moseley, *eds. Ice ages: ancient and modern*. Liverpool, Seel House Press, 7-42.

Boulton, G.S. 1987. A theory of drumlin formation by subglacial sediment deformation. *In* Menzies, J. and J. Rose, *eds. Drumlin symposium.* Rotterdam and Boston, MA, A.A. Balkema, 25-80.

Boulton, G.S. and A.S. Jones. 1979. Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. *J. Glaciol.*, **24**(90), 29-43.

Brown, N.E., B. Hallet, and D.B. Booth. 1987. Rapid soft bed sliding of the Puget glacial lobe. *J. Geophys. Res.*, **92**(B9), 8985-8997.

Flint, R.F. 1971. *Glacial and Quaternary geology*. New York, John Wiley and Sons.

Follmer, L.R., E.D. McKay, J.A. Lineback, and D.L. Gross. 1979. Wisconsinan, Sangamonian, and Illinoian stratigraphy in central Illinois. *Ill. State Geol. Surv. Guideb. Ser.*, 13.

Frye, J.C., H.D. Glass, and H.B. Willman. 1962. Stratigraphy and mineralogy of the Wisconsinan loesses of Illinois. *Ill. State Geol. Surv. Circ.* 334.

Hampton, M.A. 1975. Competence of fine-grained debris flows. *J. Sediment. Petrol.*, **45**, 834-844.

Hansel, A.K., W.H. Johnson, and B.J. Socha. 1987. Sedimentological characteristics and genesis of basal tills at Wedron, Illinois. *Geol. Surv. Finl. Spec. Pap.* 3, 11-21.

Hester, N.C. and P.B. DuMontelle. 1971. Pleistocene mudflow along the Shelbyville moraine front, Macon County, Illinois. *In* Goldthwait, R.P., *ed. Till: a symposium.* Columbus, OH, Ohio State University Press, 367-382.

Johnson, A.M. 1970. *Physical processes in geology*. San Francisco, CA, Freeman, Cooper and Co.

Johnson, A.M. and J.R. Rodine. 1984. Debris flows. *In* Brunsden, D, and D.B. Prior, *eds. Slope instability*. New York, John Wiley and Sons.

Johnson, W.H., H.D. Glass, D.L. Gross, and S.R. Moran. 1971. Glacial drift of the Shelbyville moraine at Shelbyville, Illinois. *Ill. State Geol. Surv. Circ.* 459

Lawson, D.E. 1979. Sedimentological analysis of the western terminus region of the Matanuska Glacier, Alaska. *CRREL Rep.* 79-9.

Lawson, D.E. 1982. Mobilization, movement and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska. *J. Geol.*, **90**(3), 279-300.

Lawson, D.E. In press. Glacigenic resedimentation: classification concepts and application to mass movement processes and deposits. *In* Goldthwait, R.P. and C.L. Matsch, *eds. Genetic classification of glacigenic deposits and their landforms*. Rotterdam, A.A. Balkema.

SIR,

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

Hester and DuMontelle (1971) indicates that little or no sorting occurred during the sediment flow, and that the sediment flow is a representative sample of the basal till. This indicates that both sediment packages would be characterized by virtually identical bulk density, porosity, and rheologic characteristics when unconsolidated, dilated, and water saturated. Clark and Johnson present no data which contravene the well-documented sedimentologic similarities. Their discussion of multiple flow units is not supported by the available field data, which included studies of outcrops and 14 test borings, and in any event is irrelevant to the rheologic significance of the morphometry of the discussed flow terminus.

Clark and Johnson further contend that my assumption of high subglacial water pressures associated with deforming till is not realistic. However, a very large body of glaciologic data indicates that subglacial water pressures approach glaciostatic levels in many glaciers. More pertinently, studies of Ice Stream B in Antarctica by Alley and others (1987a, b) suggest that deforming till and water pressures very close to or at glaciostatic levels occur together over much of the glacier bed. Blankenship and others (1987) presented evidence that subglacial pore-water pressures are 99.5% as large as glaciostatic loads in the deforming till under Ice Stream B. Boulton and Hindmarsh (1987) showed that subglacial water pressures are variable but approach glaciostatic levels in deforming till at Breiđermerkerjökull in Iceland. Also, Clarke (1987), Alley and others (1987a, b), and Boulton and Hindmarsh (1987) showed in independent theoretical models that high subglacial water pressures are required for efficient subglacial till deformation to occur. I believe this assumption was justified, and that high subglacial water pressures were associated with deformable till in some marginal parts of the Laurentide ice sheet.

Clark and Johnson also curiously state that "the existence of thrusting as a sediment entrainment and depositional mechanism has never been documented", citing a theoretical paper published almost 30 years ago as evidence. Although this subject is somewhat peripheral to my paper, it still must be noted that their contention is inaccurate. The general recognition of the importance of subglacial shearing to englacial sediment content and the superglacial depositional environment has come only in the last two decades, although Goldthwait (1951) made important early observations. Boulton (1970, p. 213) discussed subglacial shearing, and stated "observations ... show that debris is transported to different levels within the glacier along thrust planes, and it seems entirely reasonable ... that this debris can also be transported from a subglacial into an englacial position by thrusting". Boulton (1971, fig. 1) also suggested flow tills may be generated where sediment-charged shear zones intersect the glacier surface. Moran (1971), after studying deposits of the southern Laurentide ice sheet, suggested that subglacial thrusting had locally produced large increases in the thickness of englacial sediment layers. More recently, Sharp (1985, p. 268), during field studies of Eyjabakkajökull, observed "intense folding and thrusting during which basal debris-rich ice is elevated into an englacial position in a narrow marginal zone. As that terminal area of the glacier stagnates ... debris from this ice is released supraglacially and deposited by meltout and sediment flows". Echelmeyer and Zhongxiang (1987) recently observed and described sediment-charged shear zones which entrain subglacial sediment and transport it up into the Urumqi glacier. The observations of Goldthwait, Boulton, Moran, Sharp, and Echelmeyer and Zhongxiang resemble the process I suggested to account for the large volume of flow till found adjacent to the compressive, terminal regions of the Pleistocene Lake Michigan lobe. Other processes may have been equally or more important, including the ablation of sediment-charged regelation layers. However, the Urumqi glacier observations seem to me to be particularly relevant, as they were made on a glacier where till deformation is known to contribute significantly to glacier flow. Other papers also document these processes, and brief reviews are found in several recent textbooks, including those by Drewry (1986, chapter 8), Ashley and others (1985, chapter 2), Eyles (1983, chapters 1, 2, and 3), and Sugden and John (1976, chapters 8 and 11).

Finally, Clark and Johnson suggest that the Lake Michigan lobe may have been significantly thicker than suggested by my pseudo-plastic model or recorded by marginal glacial deposits. However, given the well-documented southward flow pattern recorded by subglacial drumlins and other glacial features, the cross-glacier driving forces of the Lake Michigan lobe probably did not exceed the southward down-glacier driving forces. This places limits on the elevation and surface gradients of the glacier, even in its central regions. The pseudo-plastic model presented in my paper suggested the central Lake Michigan lobe was *c.* 835 m thick about 400 km from its terminus, while glacier deposits indicate a minimum thickness of 630 m at the ice margin and place constraints on the slope of the down-glacier profile. If the Lake Michgian lobe was significantly thicker in its medial region, cross-glacier surface gradients would have exceeded down-glacier gradients. If Clark and Johnson favor a significantly thicker reconstruction, and yet agree that lateral moraine profiles and gradients are related to glacier profiles, they must be prepared to explain how the glacier flowed south when thicker reconstructions result in the principal deviatoric stress being oriented across the glacier, i.e. from its thick center to its thin flank.

The pseudo-plastic models presented in my 1986 paper and in Begét (1987) rely on a simplification of the complex rheological properties of tills, and constitute a first attempt qualitatively and quantitatively to evaluate relationships between the rheologic properties of Pleistocene tills and geologic reconstructions of the morphology of inferred "soft-base" marginal areas of the Laurentide ice sheet. Pseudo-plastic modeling of ice-sheet profiles has a long history in glacial geology, and may be particularly appropriate for glaciers overlying deforming till with Bingham rheology and a specific yield strength. The boundary conditions used for the 1986 model are consistent with subsequent observations of the actual conditions associated with subglacial till deformation, particularly at Ice Stream B in Antarctica. The boundary conditions are also consistent with those utilized in sophisticated models of deformation of subglacial tills by Alley and others (1987a, b), Clarke (1987), Boulton and Jones (1979), and Boulton and Hindmarsh (1987).

Water-saturated basal tills can be physically and rheologically similar to water-saturated sediment slurries. Utilization of a large flow till as a natural "shear box" indicates coeval subglacial till of the Lake Michigan lobe was characterized by low shear strength when unconsolidated and water-saturated. A pseudo-plastic model of the ice-sheet surface profile based on an estimate of till yield strength suggests the Lake Michigan lobe was unusually thin when compared with typical marginal profiles of the Antarctic or Greenland ice sheets. This result is consistent with the geologic field data. The Lake Michigan lobe and other glaciers around parts of the margin of the Laurentide ice sheet were probably underlain by deforming till, and may have resembled modern soft-base glaciers like Ice Stream B in Antarctica.

I thank P.U. Clark and W.H. Johnson for the opportunity to reply to the many interesting points raised in their discussion.

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25 January 1989

REFERENCES

Alley, R.B., D.D. Blankenship, C.R. Bentley, and S.T. Rooney. 1987a. Till beneath Ice Stream B. 3. Till deformation: evidence and implications. *J. Geophys. Res.*, **92**(B9), 8921-8929.

Alley, R.B., D.D. Blankenship, S.T. Rooney, and C.R. Bentley. 1987b. Till beneath Ice Stream B. 4. A coupled ice-till flow model. *J. Geophys. Res.*, **92**(B9), 8931-8940.

Ashley, G., J. Shaw, and N. Smith. 1985. *Glacial sedimentary environments.* Tulsa, OK, Society of Economic Paleontologists and Mineralogists.

Beget, J.E. 1986. Modeling the influence of till rheology on the flow and profile of the Lake Michigan lobe, southern Laurentide ice sheet, U.S.A. *J. Glaciol.*, **32**(111), 235-241.

Beget, J.E. 1987. Low profile of the northwest Laurentide ice sheet. *Arct. Alp. Res.*, **19**(1), 81-88.

Blankenship, D.D., C.R. Bentley, S.T. Rooney, and R.B. Alley. 1987. Till beneath Ice Stream B. 1. Properties derived from seismic travel times. *J. Geophys. Res.*, **92**(B9), 8903-8911.

Boulton, G.S. 1970. On the origin and transport of englacial debris in Svalbard glaciers. *J. Glaciol.*, **9**(56), 213-229.

Boulton, G.S. 1971. Till genesis and fabric in Svalbard, Spitsbergen. *In* Goldthwait, R.P., *ed. Till: a symposium.* Columbus, OH, Ohio State University Press, 41-72.

Boulton, G.S. and R.C.A. Hindmarsh. 1987. Sediment deformation beneath glaciers: rheology and geological consequences. *J. Geophys. Res.*, **92**(B9), 9059-9082.

Boulton, G.S. and A.S. Jones. 1979. Stability of temperate ice caps and ice sheets resting on beds of deformable sediment. *J. Glaciol.*, **24**(90), 29-43.

Clarke, G.K.C. 1987. Subglacial till: a physical framework for its properties and processes. *J. Geophys. Res.*, **92**(B9), 9023-9036.

Drewry, D. 1986. *Glacial geologic processes.* London, Edward Arnold.

Echelmeyer, K. and Wang Zhongxiang. 1987. Direct observation of basal sliding and deformation of basal drift at sub-freezing temperatures. *J. Glaciol.*, **33**(113), 83-98.

Eyles, N., *ed.* 1983. *Glacial geology; an introduction for engineers and earth scientists.* Oxford, etc., Pergamon Press.

Goldthwait, R.P. 1951. Development of end moraines in east-central Baffin Island. *J. Geol.*, **59**(6), 567-577.

Hester, N.C. and P.B. DuMontelle. 1971. Pleistocene mudflow along the Shelbyville moraine front, Macon County, Illinois. *In* Goldthwait, R.P., *ed. Till; a symposium.* Columbus, OH, Ohio State University Press, 367-382.

Johnson, A. 1984. Debris flow. *In* Brunsden, D. and D. Prior, *eds. Slope instability.* Chichester, etc., John Wiley and Sons, 257-361.

Lawson, D. 1982. Mobilization, movement and deposition of active subaerial sediment flows, Matanuska Glacier, Alaska. *J. Geol.*, **90**(3), 279-300.

Moran, S.R. 1971. Glaciotectonic structures in drift. *In* Goldthwait, R.P., *ed. Till; a symposium.* Columbus, OH, Ohio State University Press, 127-148.

Sharp, M. 1985. Sedimentation and stratigraphy at Eyjabakkajökull — an Icelandic surging glacier. *Quat. Res.*, **24**(3), 268-284.

Sugden, D. and B. John. 1976. *Glaciers and landscape; a geomorphological approach.* London, Edward Arnold.

SIR,

River-ice mounds on Alaska's North Slope

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) was contracted by the U.S. Department of Interior, Fish and Wildlife Service (FWS) to conduct water-availability studies in the Arctic National Wildlife Refuge (ANWR) during March 1988. The objective was to identify the presence of unfrozen water beneath selected rivers and lakes in the ANWR using a UHF short-pulse radar mounted to a helicopter. It was generally believed before the study by both CRREL and FWS personnel that unfrozen water would be found only in the *aufeis*-formation zones down-river of the known water sources (hot springs) and in the deeply cut coves of the foothills defining the southern boundary of the coastal plain. If unfrozen water did exist beneath the shallow streams of the flood plain and coastal deltas, it would be a "needle in a haystack" for our low and slow airborne radar to find. Instead, however, we were confronted with myriads of ice mounds, most existing as small ridges and often grouped in twos and threes, throughout the entire length of all the major rivers, with about 70% of them containing unfrozen water. Generally, these mounds rose 2–3 m above the level of the surrounding ice sheet. Drilling into two of these mounds revealed water under pressure.

The major waterways studied were Canning, Tamayariak, Katakturuk, Sadlerochit, Hulahula, Okpilak and Jago Rivers, and Itkilyariak and Okerokovik Creeks, shown in Figure 1. We used topographic maps to identify our positions in general and a satellite-based Global Positioning System (Mororola Mini-Ranger) to define the end points of our transects. A full data report is being published through CRREL (Arcone and others, 1989) in which the transects are *approximately* placed on 1955 USGS topographic maps. We were based at Barter Island where the USGS coordinates for the aircraft hangar agreed with our GPS reading to within 3" of latitude and longitude. Most of our radar profiles deliberately traversed the mounds.

The radar equipment we used was an Xadar control unit mated to a GSSI Model 3102 antenna unit mounted off the skids of a Bell Long Ranger helicopter. Details of this equipment and its operation for river-ice surveying have been discussed recently in this journal (Arcone and Delaney, 1987). The graphic output is a horizontal composition of thousands of echo scans (~30/cm) wherein darkness is proportional to signal intensity, the horizontal axis is proportional to distance, and the vertical axis to time of return. Helicopter altitude was generally 4–6 m and flight speed about 5 m/s. Fluctuations in altitude and helicopter clutter are apparent in the radar data.

Figure 2a is a photograph of one of the mounds encountered on Sadlerochit River. These mounds were 2–3 m

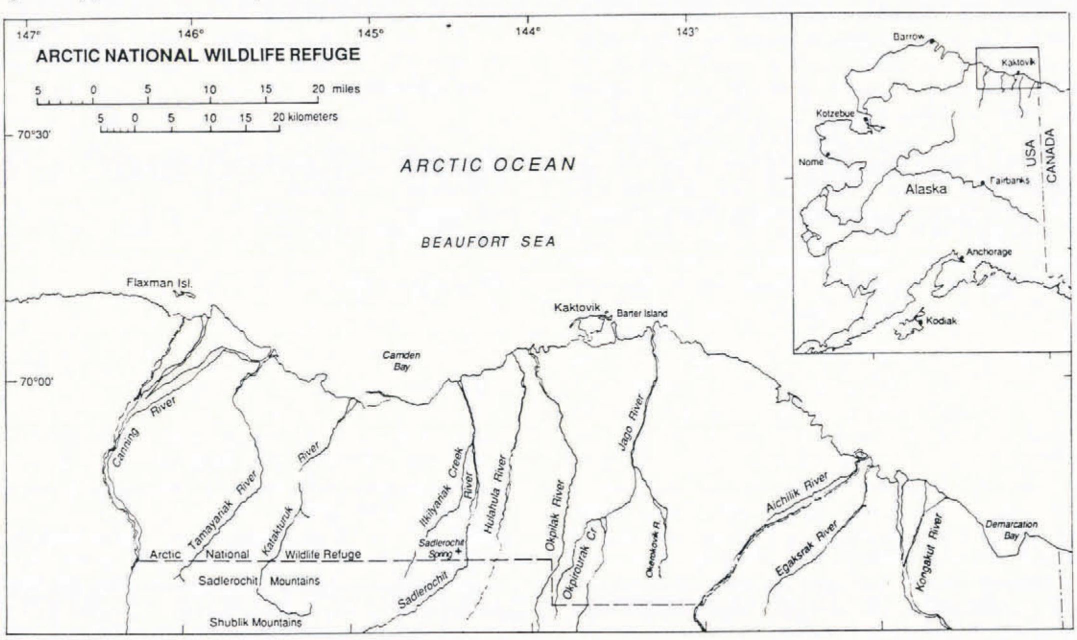

Fig. 1. Location of waterways studied in the Arctic National Wildlife Refuge.

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