Journal of Glaciology, Vol. 27, No. 97, 1981

CONJECTURES, HYPOTHESES, AND THEORIES OF DRUMLIN FORMATION

(In memory of Stanisław Baranowski)

By IAN J. SMALLEY

(Soil Bureau, Department of Scientific and Industrial Research, Lower Hutt, New Zealand)

ABSTRACT. Recent investigations have shown that various factors may affect the shear strength of glacial till and that these factors may be involved in the drumlin-forming process. The presence of frozen till in the deforming zone, variation in pore-water pressure in the till, and the occurrence of random patches of dense stony-till texture have been considered. The occurrence of dense stony till may relate to the dilatancy hypothesis and can be considered a likely drumlin-forming factor within the region of critical stress levels. The up-glacier stress level now appears to be the more important, and to provide a sharper division between drumlin-forming and non-drumlin-forming conditions.

RÉSUMÉ. *Conjectures, hypothèses et théories de la formation des drumlins.* Des recherches récentes ont montré que différents facteurs peuvent affecter la résistance au cisaillement des argiles glaciaires et que ces facteurs peuvent intervenir dans le processus de formation des drumlins. La présence de moraines gelées dans la zone en déformation, la variation de la pression de l'eau dans les pores de la moraine, et la présence de filons de moraine caillouteuse dense ont été examinés. La présence de moraine caillouteuse dense peut être en rapport avec l'hypothèse d'une dilatabilité et peut être considérée comme un facteur probable de formation de drumlin dans les régions à niveaux critiques de contrainte de cisaillement. Le niveau de contrainte en haut du glacier semble maintenant jouer le rôle le plus important, et procurer le meilleur moyen de distinguer les conditions propres à la formation des drumlins de celles qui ne le sont pas.

ZUSAMMENFASSUNG. *Schlüsse, Hypothesen und Theorien zur Drumlin-Bildung.* Neuere Untersuchungen haben gezeigt, dass verschiedene Faktoren die Scherfestigkeit glazialen Schuttes beeinflussen und dass diese Faktoren bei der Bildung von Drumlins eine Rolle spielen können. In Betracht gezogen wurden das Vorhandensein gefrorenen Schuttes in der Deformationszone, Schwankungen des Porenwasserdruckes im Schutt und das Vorkommen zufällig verteilter Ansammlungen aus dichtem Blockschutt. Das letztere führt zur Dehnungs-hypothese und kann als wahrscheinliche Ursache der Drumlin-Bildung innerhalb des Bereiches kritischer Spannungszonen betrachtet werden. Das Spannungsniveau gletscheraufwärts scheint nunmehr den grösseren Einfluss zu besitzen; es ermöglicht eine schärfere Trennung der Voraussetzungen dafür, ob sich Drumlins bilden oder nicht.

IN the *Journal of Glaciology*, Nos 87 and 88, there were four items bearing on the problem of drumlin formation; it is apparent that this topic still excites considerable interest among glaciologists, and that the problem still awaits a convincing solution. In fact, Whittecar and Mickelson (1979, p. 357) go so far as to suggest that "Drumlins have fascinated geomorphologists perhaps more than any other glacial landform" and Baranowski (1979, p. 435) claimed that ". . . until the mechanism responsible for drumlin formation is fully understood, some of the key glaciological problems related to the glacier bed will remain obscure". Some synthesis of the new ideas and observations presented could be to their mutual benefit, and is attempted in this discussion.

Boulton (1979, p. 31) has outlined what he suggests might be the most powerful drumlin-forming process, and he and Menzies (1979[a]) have cited a simple modified Coulomb stress law to which it could be useful to refer some of the variables discussed:

$$S = C + (P - P_w) \tan \phi$$

where S is the shear strength of the drumlin-forming till, C is the cohesion of the till, ϕ its angle of internal friction, P is the ice pressure, and P_w the water pressure. With reference to this equation, we can consider some of the factors proposed in contending theories.

Menzies (1979[a]) emphasized the P_w factor and suggested that it is a major control of the drumlin-forming mechanism. He proposed two possible mechanisms for pore-water removal; when these operate, P_w is reduced and the strength of the till rises and a drumlin can be formed. The pore water may be removed from localized patches within a mobile layer of till at the ice–glacier-bed interface, thus creating nuclei of higher-strength till around which the deforming till may adhere; or removal of water initially from the thin water film at the base of the glacier may result in increased pressure-melting of the ice, leading to till melt-out and subsequent loss of pore water from the deposited till. The loss of water at the glacier bed may be either via permeable subglacial deposits or bedrock, or within subglacial depressions.

https://doi.org/10.3189/S0022143000011552 Published online by Cambridge University Press

Baranowski (1979) postulated that it is possible to explain the origin of drumlins via the temperature and not the pressure changes occurring in the glacier substratum. Essentially, it appears that Baranowski requires the appearance of frozen till in the deforming region; this presumably has the effect of causing a large increase in C and thus also a large increase in S. This hypothesis has been under development for a number of years (see Baranowski, 1969, 1977) and there seems no reason why the frozen-ground factor should not contribute to drumlin formation.

The Whittecar and Mickelson (1979) contribution cannot be reduced to such a simple summary; they appear to opt for an erosional origin for drumlins which rather puts them in the opposite camp to other current investigators who favour some dynamic process in the deforming till at the glacier–terrain interface. They suggested that a significant factor in the development of a drumlin's size is the relationship between the rate of erosion of the drumlin and the rate of movement of material into the drumlin form, and the two rates may be entirely independent. They postulate that material is moved into the drumlin from below. It is a bit difficult to relate the Whittecar and Mickelson paper to those by Menzies, Baranowski, and Boulton, because their approach is essentially traditional while the other three authors are looking more towards what Menzies (1979[b], p. 350) has called the "soil mechanics approach". It appears (and this may not do them justice) that Whittecar and Mickelson are describing conditions for drumlin formation while the others are looking for the actual mechanism.

Boulton (1979, p. 31) has proposed that the strength of subglacial till can be expected to increase in an up-glacier direction (i.e. towards the glacier source) and at some point the drag force imposed by the moving glacier will be insufficient to cause deformation of the bed, which suggests that P may be the critical factor. If an inhomogeneous till deforms beneath a glacier, the coarser parts will tend to deform less rapidly than other parts and will block movement of material on their up-glacier sides, thus producing transverse-flow components and providing a shadow-zone in their lee in which material will be relatively protected from deformation. Drumlins forming in such a system will represent areas of net accumulation and the inter-drumlin zones will be areas of net erosion.

This process, suggested Boulton, may be a very powerful geomorphological agent, and it will always operate in the marginal zone of temperate glaciers, where the final forming of the drumlins will be done. The process is similar to that proposed by Smalley and Unwin (1968) in that it requires deformation of the glacier substratum, and appears most effective in the same proposed region, but it does not require that the substratum be dilatant.

The dilatancy theory has been around for 14 years now (Smalley, 1966; Smalley and Unwin, 1968) and it may be time to have another look at it. The theory proposed by Boulton is, in fact, remarkably like the dilatancy theory in its main aspects. The dilatancy theory in its fully developed form (Smalley and Unwin, 1968) required the subglacier stress levels to increase in an up-glacier direction and it did propose a set of critical stress levels. As Baranowski (1979, p. 435) commented, the stress levels were not too closely defined but they did represent, in part, the first attempt at a genuine "mechanism" of drumlin formation. Baranowski (1979) made a series of criticisms of dilatancy and it may be less significant than was initially proposed, but the concept of critical stress levels in the subglacial region still seems to be a major step forward. If the dilatant factor is to come into play, the particles in the till (the larger particles) must interact in a positive manner. This will have the effect of increasing ϕ and thus $\tan \phi$. Since $\tan \phi$ is a multiplying factor, it is an effective modifier of S and, since a small increase in ϕ causes a relatively large increase in $\tan \phi$, this factor could very well be the most significant variable in the modified Coulomb equation.

The critical stress levels can be related to critical zones in the subglacial environment. There is a zone in which the critical drumlin-forming events occur; it is bounded in the up-glacier direction by a stress-level "barrier" beyond which the subglacial stresses are in general too high for the required proto-drumlin obstacles to form. It is bounded in the down-glacier direction by the stress barrier beyond which there is insufficient shear stress in the important regions to produce continuous deformation of the till. In the critical zone, a condition is required in which an intermediate situation arises: where parts of the till are able to resist deformation and become shaped into drumlins while the rest of the material deforms normally.

Smalley and Unwin (1968, fig. 3) attempted a diagrammatic representation of these requirements, and related the drumlin-forming events in the intermediate region to the dilatant nature of the till. Boulton (1979, p. 31) identified the drumlin-forming areas as those where the coarse particles are clustered, and these areas eventually become regions of net accumulation and the inter-drumlin zones areas of net erosion. The requirements seem to be virtually identical; in the Smalley–Unwin model, a high degree of interaction of coarse particles is required (tan ϕ increasing) and in the Boulton model a region of coarse till is specified. A little too much emphasis has, perhaps, been placed on the term "dilatancy" with respect to the Smalley–Unwin model: a high-density till with a large proportion of large angular rock fragments will inevitably be dilatant if there is a significant amount of interaction between the coarse particles. Boulton may not require his substratum to be dilatant but it probably is anyway.

The major difference between the Smalley–Unwin and Boulton models (the critical point in this discussion) is the assumed behaviour at the glacier–terrain interface up-stream of the stress barrier separating the drumlin-forming region from the up-stream non-forming region. Smalley and Unwin assumed that the stress levels were above a certain critical level and that *too much* deformation occurred for drumlins to form. Boulton has the strength of the till being greater than critical and deformation *not* occurring.

A suggested consequence of the Smalley–Unwin proposal was that the drumlin-field boundary would be much less well defined in the up-stream direction than in the down-stream direction. In what could be a critical observation, Crozier (1975, p. 188) has reported that the opposite was in fact observed in the Peterborough field. This could indicate that the Boulton model is closer to reality, and that as the stress level rises above the critical and till deformation begins, then drumlins form but, as the level of deformation drops in a down-stream direction, the conditions fail to be fulfilled and drumlin formation becomes sparser.

In conclusion, it should be observed that, if Baranowski is correct and drumlin formation needs to be understood before one can understand important subglacial processes, we all have an added impetus for drumlin research. The mechanism by which the till becomes a drumlin still needs precise definition. We have moved on a stage from the simple laying down of conditions under which drumlins may form to actually looking at what goes on under the ice. Our present state is that we are looking at factors affecting the strength and nature of the drumlin-forming till; it may be that many factors affecting C, P, P_w, *and* ϕ are involved. What we now have to do is to decide which are critical and which is most important. The conceptual framework is developing; as Crozier (1975) pointed out, the dilatancy "theory" was better called an hypothesis, and a lot of the earlier suggestions were certainly conjectures; hopefully, we are now approaching a genuine theory of drumlin formation.

MS. received 4 June 1980

REFERENCES

Baranowski, S. 1969. Some remarks on the origin of drumlins. *Geographia Polonica*, No. 17, p. 197–208.

Baranowski, S. 1977. Regularity of drumlin distribution and the origin of their formation. *Studia Geologica Polonica*, Vol. 52, p. 53–68.

Baranowski, S. 1979. The origin of drumlins as an ice–rock interface problem. *Journal of Glaciology*, Vol. 23, No. 89, p. 435–36. [Abstract.]

Boulton, G. S. 1979. Processes of glacier erosion on different substrata. *Journal of Glaciology*, Vol. 23, No. 89, p. 15–38.

Crozier, M. J. 1975. On the origin of the Peterborough drumlin field: testing the dilatancy theory. *Canadian Geographer*, Vol. 19, No. 3, p. 181–95.

Menzies, J. 1979[a]. The mechanics of drumlin formation with particular reference to the change in pore-water content of the till. *Journal of Glaciology*, Vol. 22, No. 87, p. 373–84.

Menzies, J. 1979[b]. A review of the literature on the formation and location of drumlins. *Earth-Science Reviews*, Vol. 14, No. 4, p. 315–59.

Smalley, I. J. 1966. Drumlin formation: a rheological model. *Science*, Vol. 151, No. 3716, p. 1379–80.

Smalley, I. J., *and* Unwin, D. J. 1968. The formation and shape of drumlins and their distribution and orientation in drumlin fields. *Journal of Glaciology*, Vol. 7, No. 51, p. 377–90.

Whittecar, G. R., *and* Mickelson, D. M. 1979. Composition, internal structures, and an hypothesis of formation for drumlins, Waukesha County, Wisconsin, U.S.A. *Journal of Glaciology*, Vol. 22, No. 87, p. 357–71.