

Drumlin formation by subglacial meltwater erosion

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Some drumlins are shown to belong to a family of remnant erosional ridges associated with subglacial meltwater. The lengths of these ridges vary in scale from a few tens of millimetres to over 5 km. Similar form elements are illustrated for three scales of forms. It is concluded that some drumlins are composed of preexisting sediment or bedrock left upstanding in ridges as a result of the removal of surrounding materials. This erosional theory is related to an earlier theory in which drumlins are held to result from the infilling of subglacial cavities. The unifying factor for both theories is the role of sheets of subglacial meltwater.

Il est démontré que certains drumlins appartiennent à une famille de crêtes d'érosion résiduelles associées à l'eau de fonte sous-glaciaire. L'échelle de dimension de ces crêtes varie en longueur de quelques dizaines de millimètres à plus de 5 km. Des éléments de formes similaires sont illustrés pour trois échelles différentes de formes. L'étude mène à la conclusion que certains drumlins sont formés d'anciens sédiments ou de socle laissés en saillie dans les crêtes après l'ablation des matériaux environnants. Cette théorie fondée sur l'érosion rejoint une théorie plus ancienne suggérant que le développement des drumlins résulte du remplissage de cavités sous-glaciaires. Le facteur commun à ces deux théories est le rôle joué par les nappes qui résultent de l'eau de fonte sous-glaciaire.

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Introduction

There are a large number of publications dealing with drumlins; Menzies (1984) listed over a thousand. The participants at a recent symposium on drumlins failed to arrive at a consensus regarding their genesis. It is not appropriate in this short note to embark on a review of plausible drumlin-forming processes. Rather, we wish to expand on a recent suggestion that some drumlins were formed in subglacial cavities eroded upwards into overlying ice by sheet floods of subglacial meltwater (Shaw 1983; Shaw and Kvill 1984; Sharpe 1985). In this note we show that drumlins might also form as remnant ridges resulting from erosion of the glacial substrate by subglacial meltwater sheets. The original hypothesis has as its starting point the remarkable form analogy between drumlins in northern Saskatchewan and infilled erosional marks. The hypothesis presented here also starts with a form analogy between drumlins and other smaller scale remnant ridges. It goes on to explain the residual nature of the ridge material as opposed to the depositional nature of drumlins originating as cavity fills. Thus, an explanation is given for both so-called erosional and depositional drumlins in terms of the action of subglacial meltwater. However, a number of mechanisms, including meltwater processes, are required to explain drumlins.

Small-scale features

A number of relatively small-scale relief forms are found on

bedrock surfaces in formerly glaciated regions. Striations and crescentic and linear gouges are well represented in the literature, but a family of features, called rat tails by Prest (1983), is not so commonly reported. Rat tails are small ridges, a few millimetres wide, occurring to the lee of an obstacle of similar width (Fig. 1). The ridges are remnant forms similar to the scour remnant ridges of Allen (1982). A crescentic scour occurs to the upstream side of the obstacle and extends downstream in the form of paired parallel furrows about 5–20 mm wide and a few millimetres deep. The furrows become wider and shallower downflow but may be traced for distances of about 0.5 m to several metres. As the furrows widen and shallow, the rat tails taper and become lower downstream. The surface texture of the crescentic scour and parallel furrows is smooth and polished, unlike the rough surface of adjacent striated surfaces (Fig. 2). Obstacles may be small garnet crystals in marble (Fig. 1), chert nodules in dolomite (Prest 1983, Fig. 21b), iron pyrite crystals in slate (Gray 1982), or any resistant inclusion, such as a pebble, concretion, or fossil.

The small forms described are clearly made up of a remnant medial ridge behind an obstacle. Preferential erosion occurred on either side of the medial ridge and upstream from the obstacle. The smooth, polished nature of the scour surface, the crescentic scour upstream from the obstacle, and the lengths of the furrow are indicative of erosion by a fluid of low viscosity. They can be accounted for by the pattern of turbulent, unidirectional flow around an obstacle (Fig. 3). The low-viscosity fluid producing these forms may have been air or water. How

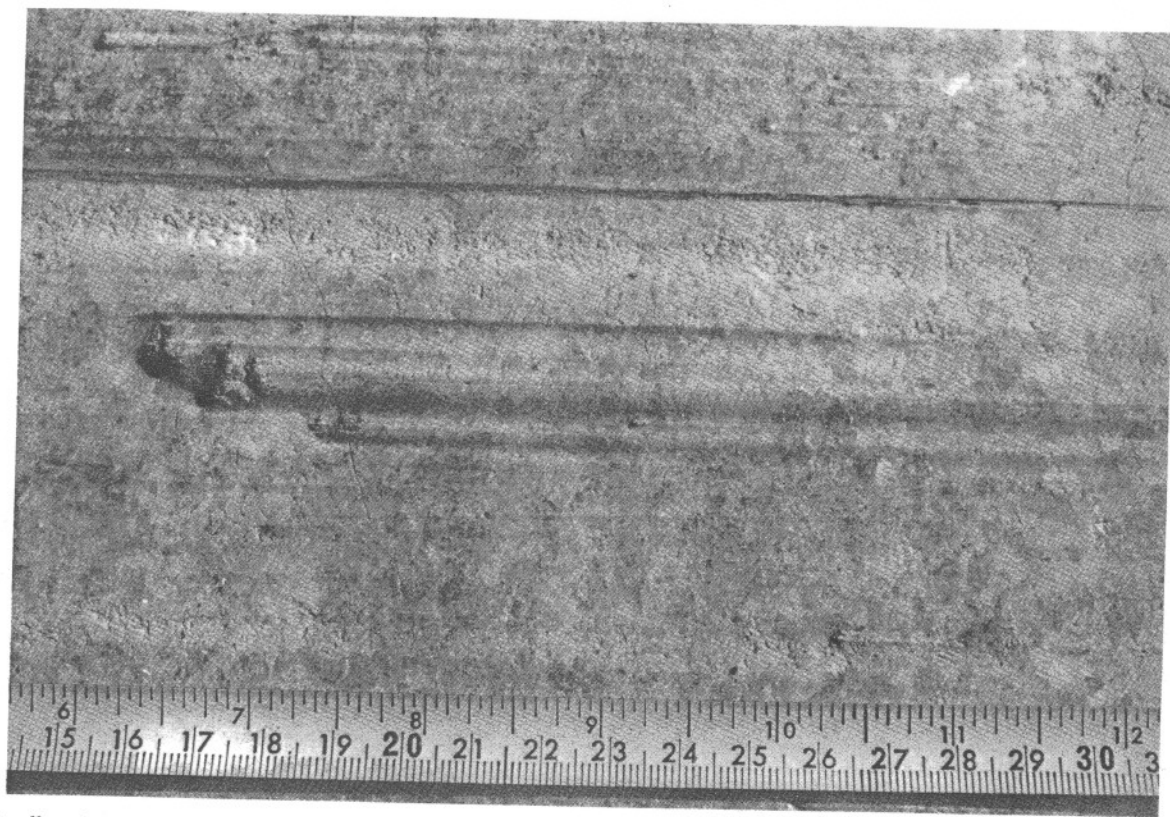


FIG. 1. Small-scale rat tails near Seeleys Bay, southeastern Ontario. Flow from left to right. Note the smooth crescentic scours to the stoss side of the obstacles. Scale in centimetres and inches.

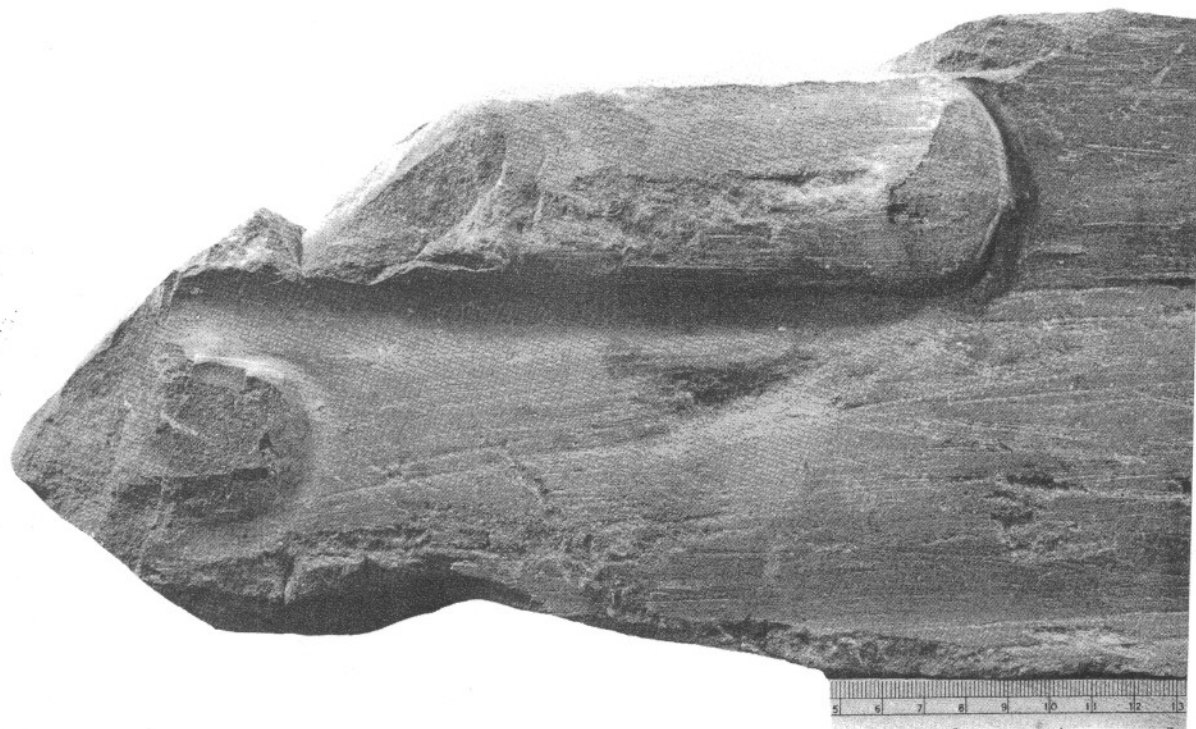


FIG. 2. Broad rat tails, Niagara Escarpment, St. Catharines, Ontario. Flow from right to left. Note the smooth nature of the crescentic scours and furrows compared with the heavily striated adjacent surfaces. Courtesy of J. Terasmae, GSC 200171-C.

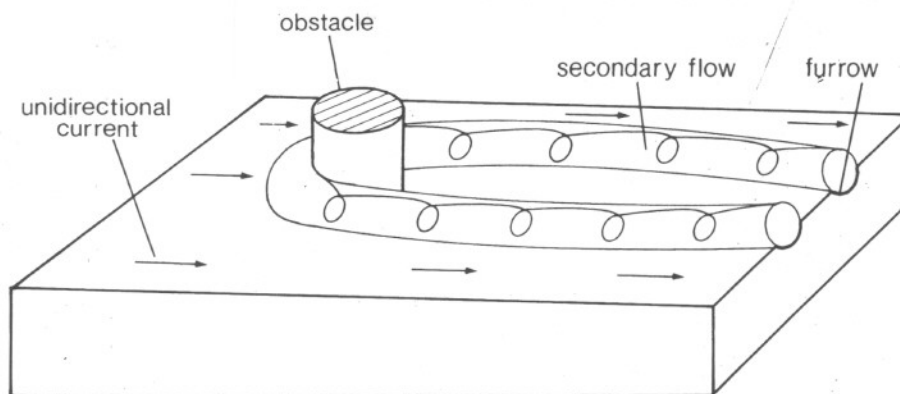


FIG. 3. Sketch of flow around an obstacle in unidirectional flow. The secondary flow responsible for the formation of rat tails and associated furrows is illustrated.

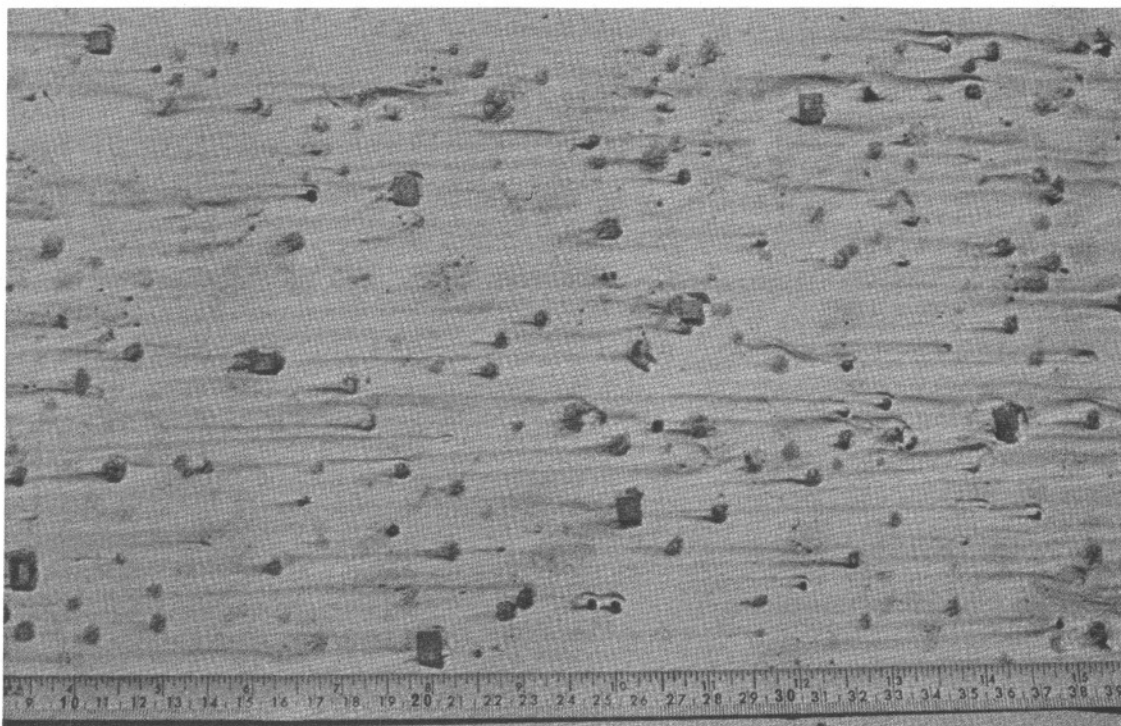


FIG. 4. Rat tails produced in a small flume by water flow around obstacles set in a plaster of Paris slab. Flow from right to left; mean flow velocity, 0.386 m/s; flow Reynolds number, 6160. Scale in centimetres and inches.

ever, their evident subglacial origin points to their formation by subglacial meltwater (Prest 1983).

Such small-scale features can be produced by running water in a cavity over a soluble plaster of Paris slab with inset obstacles (Fig. 4). The Reynolds number for the flow producing the rat tails of Fig. 4 was 6160, indicating a fully turbulent flow. That these features are produced by water in the absence of ice indicates that ice abrasion is not necessary for their formation.

Intermediate-scale features

Features similar in form to the rat tails also occur on a variety of bedrock types. Sichelwannen (Dahl 1965) occur commonly on felsic intrusive rocks of the Canadian Shield.

These have a shallow chute leading into a crescentic scour that wraps around a bulbous medial ridge and extends downstream in a pair of remarkably straight furrows (Fig. 5). Such sichelwannen are about 1–2 m in width. Furrows extend for 2–3 m and are a few tens of millimetres deep. Similar, but more elongate, forms occur on Paleozoic carbonate rocks and on Precambrian metasediments in southeastern Ontario and southern Quebec (Figs. 6 and 7). Note that whereas the large trough in Fig. 7 has only a very small remnant medial ridge, in the lower parts of the rock wall (above the man) the medial ridges are more pronounced. These elongate forms are 1 m to a few metres wide and are at most about 0.5 m deep; their lengths are on the order of a few tens of metres. Obstacles to flow in these forms are clearly related to relatively resistant elements

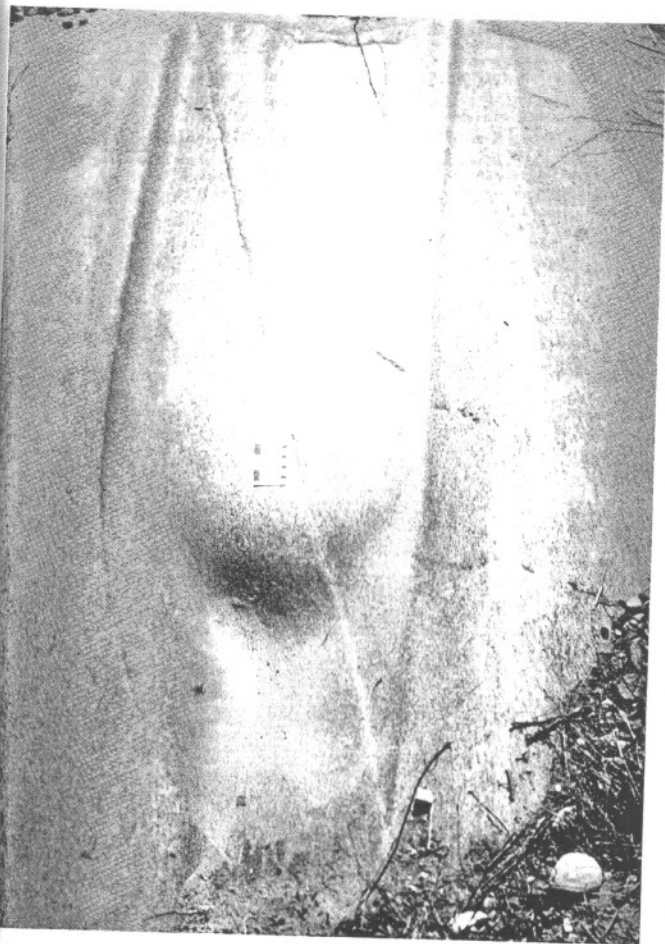


FIG. 5. Sichelwannen in felsic intrusive rock, Morton, southeastern Ontario. Flow towards top; scale bar, 0.08 m.

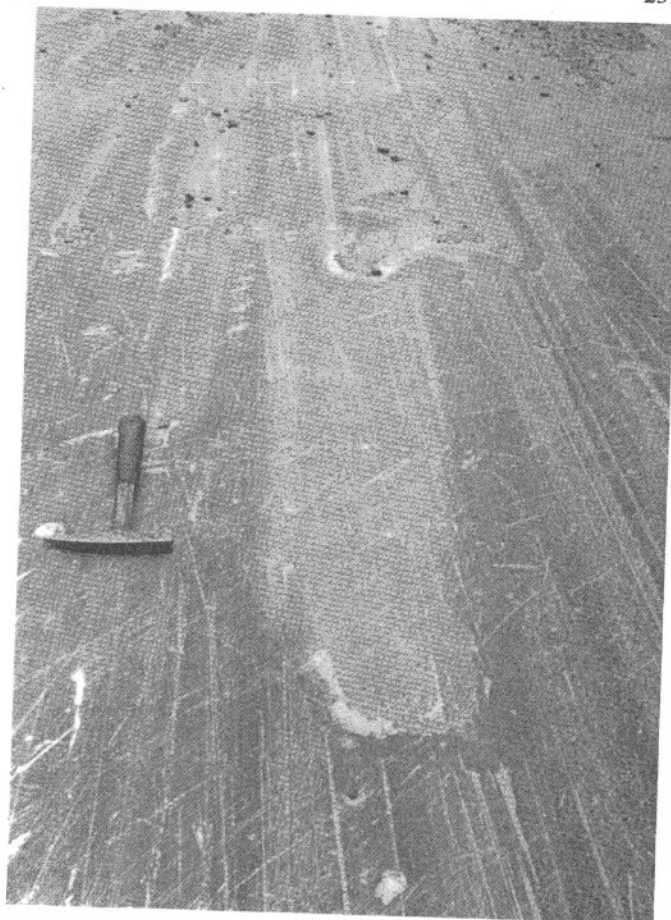


FIG. 6. Erosional marks in Paleozoic limestone, Wilton Creek, southeastern Ontario. Flow away from the viewer. Note the truncation of striations by the crescentic scours.



FIG. 7. Erosional marks in metasediment, Cantley, southern Quebec. Flow from right to left. Note the small, remnant medial ridge in the largest erosional mark.

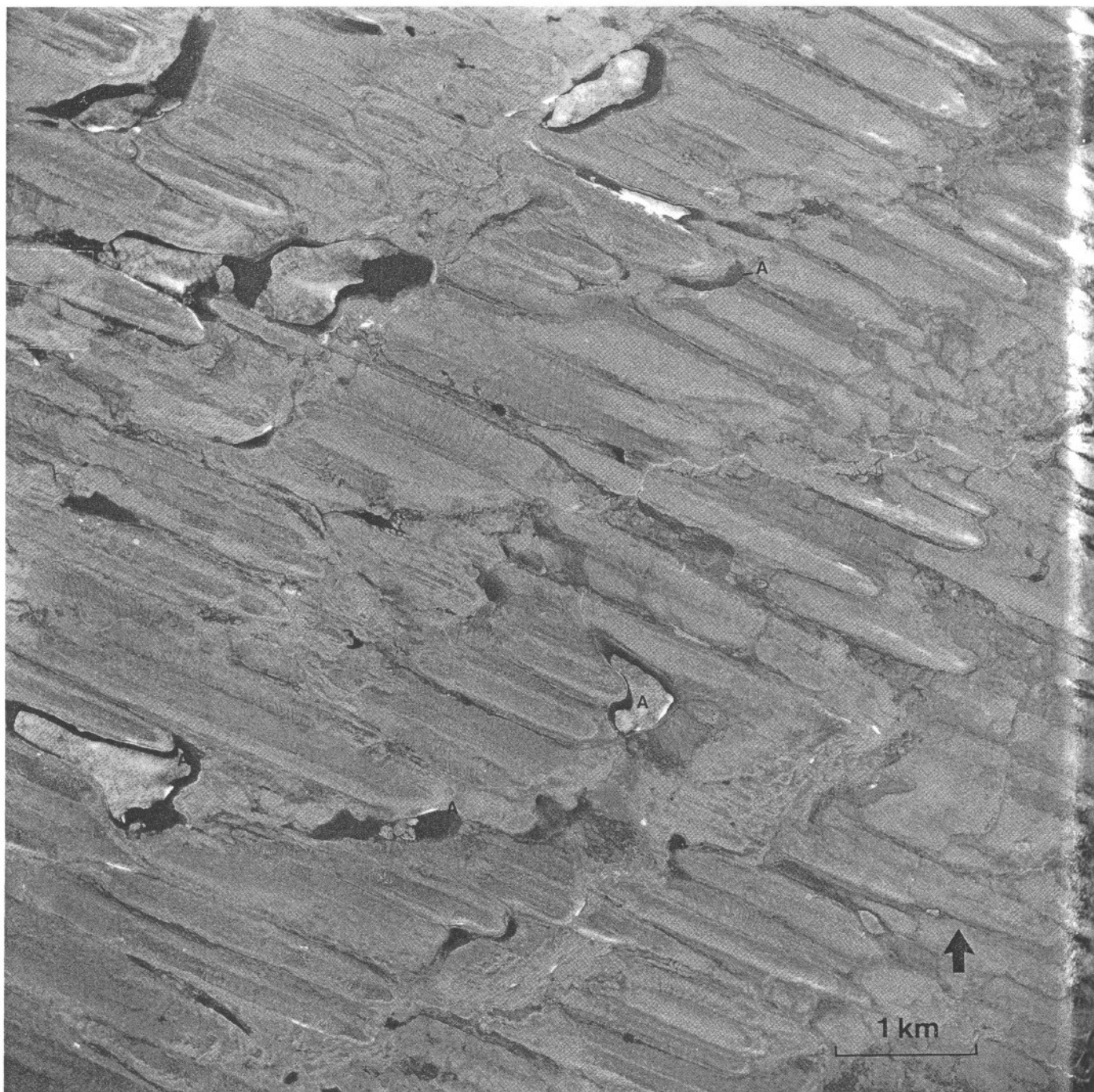


FIG. 8. Drumlin field southwest of Beverley Lake, District of Keewatin, Northwest Territories, NAPL T300C-39 (Prest 1983, Fig. 37). Flow towards the northwest. Note the prominent crescentic scours (A) around the proximal ends of the drumlins.

of the bedrock. Smaller forms within the large trough of Fig. 7 indicate local flows oblique to the axis of the trough.

The intermediate-scale features and the small-scale features are identical in form, in surface texture, and in their relationship to obstacles. It follows that the intermediate-scale forms were also produced by subglacial meltwater. The location of the forms in Fig. 7 on a near-vertical face suggests flow of water between the ice and bedrock. Such flows would occur under the high pressure of the overburden weight of ice. The oblique flow indicated by the smaller features in Fig. 7 is evidence for the secondary flow illustrated in Fig. 3.

Drumlins and flutings

Streamlined landforms with widths of up to 0.5 km and lengths in excess of 4–5 km show exactly the same form elements as the small- and intermediate-scale forms discussed above. Figure 8 (Prest 1983, Fig. 37) shows part of a drumlin field in Keewatin. The drumlins appear as medial ridges defined by parallel furrows on either side. All drumlins in this photograph show an upstream crescentic scour that is in place occupied by a small lake. The drumlin crest areas are relatively flat and are accordant in height. The furrows are eroded mainly into bedrock, which is exposed on the sides of the ridges.

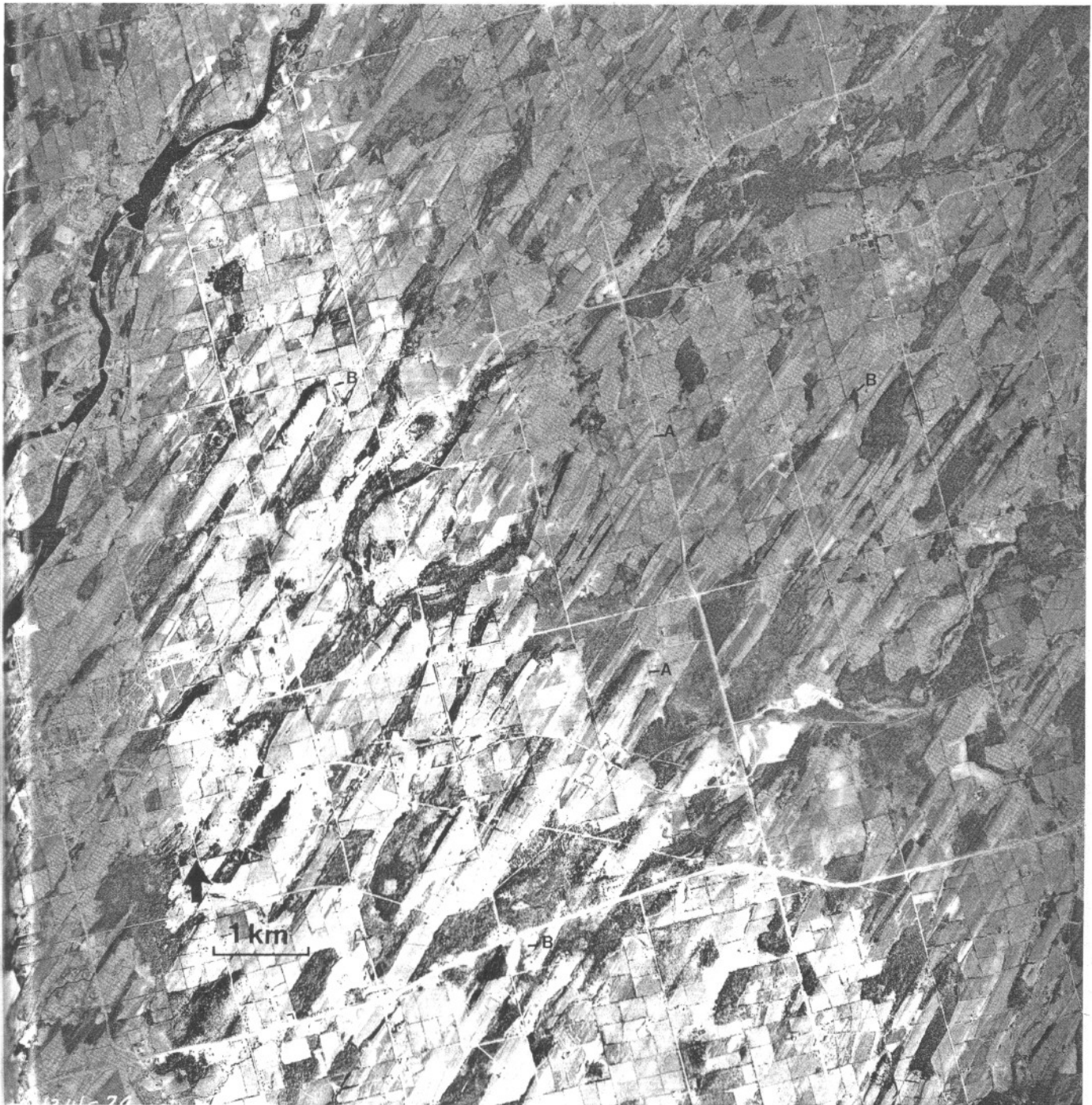


Fig. 9. Fluted drumlins in the Peterborough drumlin field, southeastern Ontario, NAPL A24314-29. Flow towards the southwest. Note the prominent fluting (A) on the large drumlins and the furrows (B) extending around the drumlins.

Clearly, the ridges are largely remnant forms left upstanding with the erosion of the furrows. Smith (1948) described large-scale grooves in the Northwest Territories similar to these drumlin furrows. W. Kupsch (personal communication, 1986) investigated features, similar to those of Fig. 8, west of Bloody River, Northwest Territories. He found tails of till-covered rock behind eroded rock bosses and referred to such comparatively landforms as crag-and-tail drumlins. These drumlins are mainly bounded by lateral furrows and proximal crescentic troughs. Other examples of upstanding ridges are shown for the Peter-

borough area of Ontario (Fig. 9). These drumlin forms are remarkably straight, and in several cases there are crescentic scours around their proximal ends. Gravenor (1957) suggested that some of these drumlins are formed from preexisting surficial sediment.

Other than scale differences, these large-scale forms show all the morphological details of the smaller scale forms. The drumlins are clearly remnant forms that reflect the erosion of the intervening furrows. Crescentic erosion marks around the upstream end of these drumlins represent flow separation as

illustrated in Fig. 3. The similarity of form and the remnant nature of the drumlins and other medial ridges discussed here suggest a similar process of formation. In addition, crag-and-tail features (Sissons 1971) and crescentic scours on the proximal sides of bedrock hills (Lassila 1985) that have been attributed solely to ice erosion may be wholly or partly products of meltwater erosion. Detailed study of bedrock erosion surfaces should reveal the small-scale erosion forms described above if water was the principal erosive agent. Broad sheets of subglacial meltwater are considered as having produced the drumlins shown in Figs. 8 and 9.

Discussion

Some drumlins have recently been ascribed to formation by subglacial meltwater (Shaw 1983; Shaw and Kvill 1984; Sharpe 1985). On the basis of a form analogy with recognised erosional marks (Allen 1982), the authors proposed that some drumlins were formed in cavities that were eroded by meltwater upwards into overlying ice. The drumlins are said to have resulted from sedimentation in these cavities. The form, sedimentary characteristics, and landform associations for these drumlins support the cavity-fill hypothesis. The remnant nature of the drumlins described here precludes their explanation by deposition in cavities. However, the sheet floods thought to have been responsible for eroding the cavities upwards into ice should also be capable of producing erosional forms on nonresistant bedrock or soft surficial sediment. With erosion of the substrate, medial ridges are left upstanding as drumlins. The material within these remnant drumlins and their internal structure are not expected to be related to the drumlin-forming process unless intense pressure gradients produce some internal deformation in the form of diapirs and clastic dikes. Thus, some drumlins are composed of preexisting materials, which may be bedrock or unlithified sediment.

This note presents a unifying theory for both erosional and depositional drumlins through their common origin by processes of subglacial meltwater sheet flows. In this concept, the sheets were as wide as drumlin trains and their lengths were measured in tens of kilometres. In the context of the dimensions of the Laurentide Ice Sheet, these sheet floods were mere streams.

An immediate concern is raised with the question of why there are no major coarse lags associated with the erosional drumlins. These might be expected if meltwater erosion produced the drumlins. Two explanations apply. First, the flows that produced the drumlins must have been competent to transport all the sediment provided to them as the drumlin forms were produced. If this had not been the case, the drumlin-forming process would have halted as soon as a lag surface covered the developing drumlin. No lag is expected to be produced by such powerful flows. Second, a period of active ice flow may have occurred subsequent to the formation of the drumlins by meltwater. This ice may have modified the drumlins slightly by minor erosion and deposition, which were sufficient to remove or bury any lag deposits.

There is also a need to account for the vast volume of sediment eroded from between the drumlins. One possibility is that large proglacial lakes acted as sediment traps, and we should examine their sediments for evidence of large inflow events. Alternatively, some of the material eroded from troughs was added to the ridge as till or fluvio-glacial sediment. A final possibility is that the sediment was discharged directly into the oceans, and evidence for large sediment discharge events

should be sought in the marine record around the margins of the Laurentide Ice Sheet.

A final problem relates to the source of the subglacial floodwaters. They may be related to catastrophic drainage of large subglacial water bodies (Shaw 1983) or even large supraglacial lakes (Echelmeyer and Harrison 1986). Regardless of the source, there was no shortage of water in the late stages of the Laurentide Ice Sheet.

A final comment is that the drumlin fields of the Laurentide Ice Sheet (Prest *et al.* 1970) and the Fennoscandian Ice Sheet (Punkari 1982) may represent enormous outpourings of cold fresh water, which may account for Late Glacial climatic fluctuations related to a cold freshwater lid over the North Atlantic (Ruddiman and McIntyre 1981; Kerr 1983).

Acknowledgments

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- ALLÉN, J. R. L. 1982. Sedimentary structures. Vol. 2. Developments in sedimentology. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.
- DAHL, R. 1965. Plastically sculptured detail forms on rock surfaces in northern Nordland, Norway. *Geografiska Annaler*, **49**: 83–140.
- ECHELMAYER, K., and HARRISON, W. 1986. Tidal and seasonal fluctuations of Jacobshavn Glacier and their relation to glacial sliding. American Geophysical Union, Chapman Conference on Fast Glacier Flow, Abstracts, p. 23.
- GRAVENOR, C. P. 1957. Surficial geology of the Lindsay–Peterborough area, Ontario. Geological Survey of Canada, Memoir 288.
- GRAY, J. M. 1982. Unweathered, glaciated bedrock on an exposed lake bed in Wales. *Journal of Glaciology*, **28**: 483–497.
- KERR, R. A. 1983. An early glacial two-step. *Science*, **221**: 143–144.
- LASSILA, M. 1985. Glacial troughs caused by steep rock forms. In First International Conference on Geomorphology. Edited by T. Spencer. Abstracts of Papers, p. 349.
- MENZIES, J. 1984. Drumlins: a bibliography. Geo Books, Norwich, UK.
- PREST, V. K. 1983. Canada's heritage of glacial features. Geological Survey of Canada, Miscellaneous Report 28.
- PREST, V. K., GRANT, D. R., and RAMPTON, V. N. 1970. Glacial map of Canada. Geological Survey of Canada, Map 1253A, scale 1 : 500 000.
- PUNKARI, M. 1982. Glacial geomorphology and dynamics in the eastern parts of the Baltic Shield interpreted using LANDSAT imagery. *Photogrammetric Journal of Finland*, **9**: 77–93.
- RUDDIMAN, W. F., and MCINTYRE, A. 1981. The mode and mechanism of the last deglaciation: oceanic evidence. *Quaternary Research*, **16**: 125–134.
- SHARPE, D. 1985. The stratified nature of drumlins from Victoria Island and Ontario, Canada. In First International Conference on Geomorphology. Edited by T. Spencer. Abstracts of Papers, p. 539.
- SHAW, J. 1983. Drumlin formation related to inverted melt-water erosional marks. *Journal of Glaciology*, **29**: 461–479.
- SHAW, J., and KVILL, D. 1984. A glaciofluvial origin for drumlins in the Livingstone Lake area, Saskatchewan. *Canadian Journal of Earth Sciences*, **21**: 1442–1459.
- SISSONS, J. B. 1971. The geomorphology of central Edinburgh. *Scottish Geographical Magazine*, **87**: 184–196.
- SMITH, H. T. U. 1948. Giant glacial grooves in northwest Canada. *American Journal of Science*, **246**: 503–514.