PERGAMON

Quaternary International 90 (2002) 5–22

The meltwater hypothesis for subglacial bedforms

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Abstract

This paper presents an historical and in places informal account of the meltwater hypothesis, which invokes enormous outburst floods for the formation of subglacial bedforms. It begins with a brief discussion of the difficulties of determining processes of formation for landforms, which are not seen in formation. Analogy provides a solution to these difficulties. Analogy between erosional marks at the bases of turbidites and drumlins, which were the starting point for this hypothesis, rests on the idea that inverted erosional marks at the ice bed are subsequently infilled to form drumlins. Field tests on the sedimentology, architecture, and landform associations of drumlins in the Livingstone Lake drumlin field are outlined before more extensive work on bedrock erosional forms and flood routes is introduced. Bedrock erosional forms played a central part in establishing the hypothesis since their form and ornamentation are confidently interpreted as fluvial. Their form and genesis are discussed mainly with reference to sites at French River and Wilton Creek, Ontario, though some remarkable bedrock erosional forms in Antarctica support their regional extent. Initially in the meltwater hypothesis, drumlins were thought to be cavity fills and erosional drumlins were recognized later. This development is shown to be central to the realization that drumlin composition may be inferred from drumlin form. The scale of drumlin fields, measured at about $10^3\,km^2$, and the magnitude of the inferred floods require that the flood events were regional. Regional-scale flood tracts in Ontario, Quebec, Alberta and the Northwest Territories extending over 1000 km in length and several hundred kilometers in width, support this suggestion. Floods, had they occurred, would have caused rapid rates of sea level rise and may have changed climate through their effects on ocean stratification and sea surface temperatures. The meltwater hypothesis covers a range of bedforms besides drumlins and bedrock erosional marks—fluting, Rogen moraine, hummocky terrain, and transverse ridges. Recent work shows how these forms are best explained by the meltwater hypothesis. The roles of water storage and release, which underpin the theory of the meltwater hypothesis, remain poorly understood. © 2002 Published by Elsevier Science Ltd.

1. Introduction

The meltwater hypothesis attributes some subglacial landforms to erosion and deposition by outburst floods larger than any floods within historical time (Shaw, 1996). It is an alternative to current hypotheses on bedforms that invoke direct glacial action or the action of subglacial deforming beds. Choosing between these different approaches reduces to how well they explain landform characteristics, while obeying fundamental physical principles. Of course, each landform has its own origin and it is quite likely that some landforms are products of subglacial deformation and others of meltwater action. These two processes have different consequences for ice-sheet behavior and for extra-glacial oceanic and climatic effects.

But how do we judge the explanatory power of a hypothesis on landform genesis? We might examine the *coherence* of the hypothesis by asking how well its explanations fit together. Or we could look into hypothesis *consistency* in terms of agreement between prediction and observation for a large number of examples. For example, how commonly do drumlins, tunnel channels and eskers occur together in landscape associations? Any successful hypothesis should be *fertile*, giving rise to new ideas that extend its scope. Finally, *consilience* records the ability of a hypothesis to surprise by explaining what were previously unrelated phenomena (Whewell, 1860).

Subglacial bedforms are enigmatic because we do not see them under formation and there may never be sufficient evidence to explain them convincingly. Drumlins are perhaps the epitome of such features. They are perplexing simply because we know so little about the conditions under which they form. Yet, they are easily recognized, confidently identified as part of glaciated

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1040-6182/02/$ - see front matter © 2002 Published by Elsevier Science Ltd.
PII: S1040-6182(01)00089-1

landscapes and it is generally assumed that their parallel alignment and elongate form indicate shaping by a flowing medium, usually thought to be ice or a deforming bed. But the actual processes by which ice flow or bed deformation or any other mechanism forms drumlins remain elusive.

The meltwater hypothesis attributes drumlin formation to erosion and deposition by violent turbulent floods of enormous magnitude (Fig. 1). Besides sculpting the landscape, these floods are thought to have carried huge quantities of meltwater and sediment to the oceans. Large volumes of turbid, cold water entering the oceans is likely to have had dramatic effects on sea surface temperature and climate in glacial and transitional glacial/interglacial periods.

There is nothing new under the sun. Almost two hundred years ago, Sir James Hall (Hall, 1815) suggested that giant tidal waves had eroded flutes and what we now call hairpin scours into bedrock around Edinburgh, Scotland. His reasoning included the similarity of these forms to surface features of wind-scoured snow and that their regional distribution indicated an extensive flow. He imagined, as we do, a sheet of water surging over the landscape. Though he thought in terms of a tidal wave and we argue for subglacial sheet flows, our interpretation of individual erosional forms is essentially the same. For his insight he must be considered the founder of ideas on the erosional activity of water sheet flows on a regional scale.

Douglas Cox (Cox, 1979) also outlined much of the meltwater hypothesis in a remarkable paper entitled, “A diluvial origin for drumlins”. He uses much of the evidence that we use and appeals to the same hydraulic principles as we do to explain drumlins. He deserves recognition for his work, which was published before ours. As was the case with Sir James Hall, Douglas suggests a different fundamental cause for the sheet flow from ours. He suggests that land upheavals shed ocean water in immense currents. We were completely unaware of his work until it was found by chance in a web search. The probable reason for our lack of awareness is that his paper appears in a Creationist journal. Since coming across his work, we have enjoyed discussions about floods and drumlins without any of the friction that exists between science and creationism.

2. A hypothesis springs to mind

The evolution of a new hypothesis, involving ideas on such enigmatic features as drumlins and other subglacial bedforms, prompts thoughts about the true origin of landforms. I assume that each landform has a true origin, though we are not assured of finding it. We research this true origin through observation and ideas,

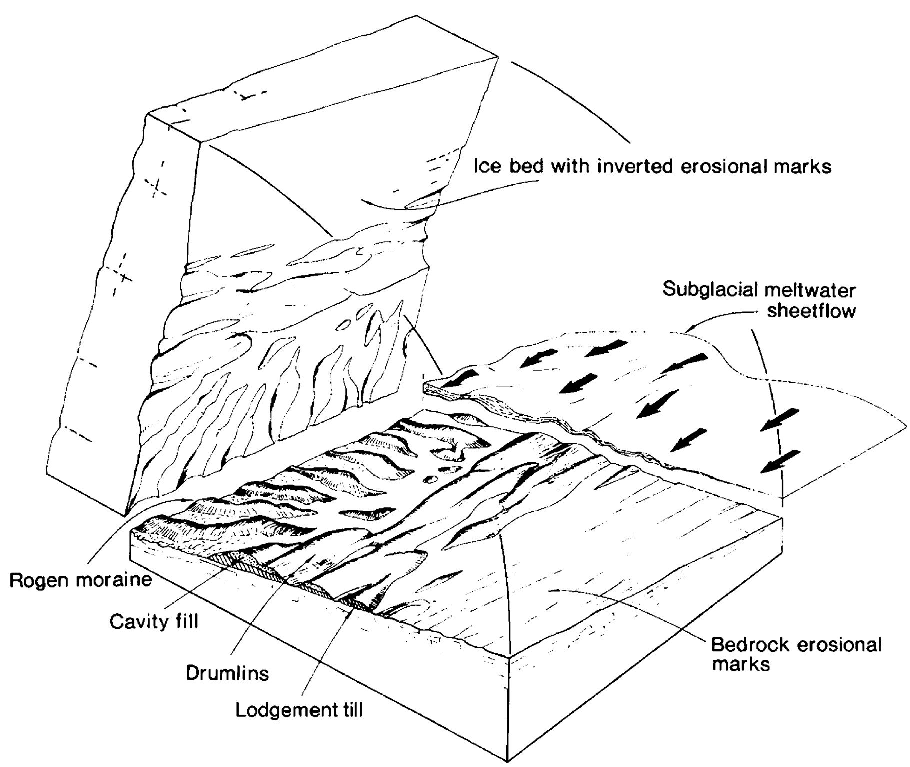

Fig. 1. A model showing the components of the meltwater hypothesis. The bedforms result from interactions between the ice bed, the ground surface and the broad meltwater flow. Areas of erosion (sculpting) are illustrated.

which ultimately determine the way forward. (Baker, 1996). But, first, the hypothesis emerges as an educated guess (Baker, 2000). Where do these ideas originate? Ideas on drumlins and other subglacial bedforms must develop around the realities of their forms, locations, patterns, orientations, composition and landform associations. Recognizing drumlins is not difficult: every glacial geomorphologist is able to recognize a field of drumlins as a field of drumlins. But recognition does not amount to explanation. Explanation for drumlins requires that postulated processes for drumlin formation accord with drumlin characteristics. The need for the accordance between process and characteristics in scientific explanation was recognized by Gilbert (1886) and further discussed by Baker (1996). Because the process of drumlin formation (cause) has not been observed, cause and effect cannot be established directly.

Analogy provides a solution to this difficulty. In form analogy, similar forms are considered to be of similar formation (Fig. 2). Thus, we might argue that, if the analogy is sound, drumlins are seen in formation with the sculpting of snow by the wind, the scouring of river beds, and erosion by rushing storm water in roadside gutters. Of course, there must also be good reason for using the analogy. For example, although the shape of an aspen leaf stressed and flipped over by the wind may look like a drumlin, it is highly unlikely that the processes of formation of drumlins and leaves are analogous. On the other hand, it is reasonable to propose a form analogy between turbidite erosional marks and subglacial erosional marks in rock. There is a real possibility that they are both products of erosion by turbulent fluids. Once we have a form analogy, we have a potential explanation for drumlins. Gilbert (1896) claimed analogy to be the source of hypotheses. The power of the analogy is increased if the presumed cause of drumlin form prompted by it is compatible with other properties of drumlins: locations, patterns, orientations, composition, and landform associations. As the following account indicates, the approach is retrodictive since we argue backwards in time from known effects (observations) to unknown causes (Englehart and Zimmermann, 1988). Such retrodiction involves a variety of evidence and goes far beyond the form analogy that triggered the hypothesis in the first place.

One afternoon in August 1982, as I was in the process of moving from Edmonton to Kingston, I wandered into my laboratory at the University of Alberta. A fleeting glance at some air photographs of the Livingstone Lake drumlin field (Fig. 3) produced a startling reaction:

"These drumlins look just like turbidite sole marks!"

My immediate response:

"But drumlins are hills, positive landforms, and sole marks troughs and hollows, negative bedforms."

An inversion of one of the forms was required if the analogy was going to work:

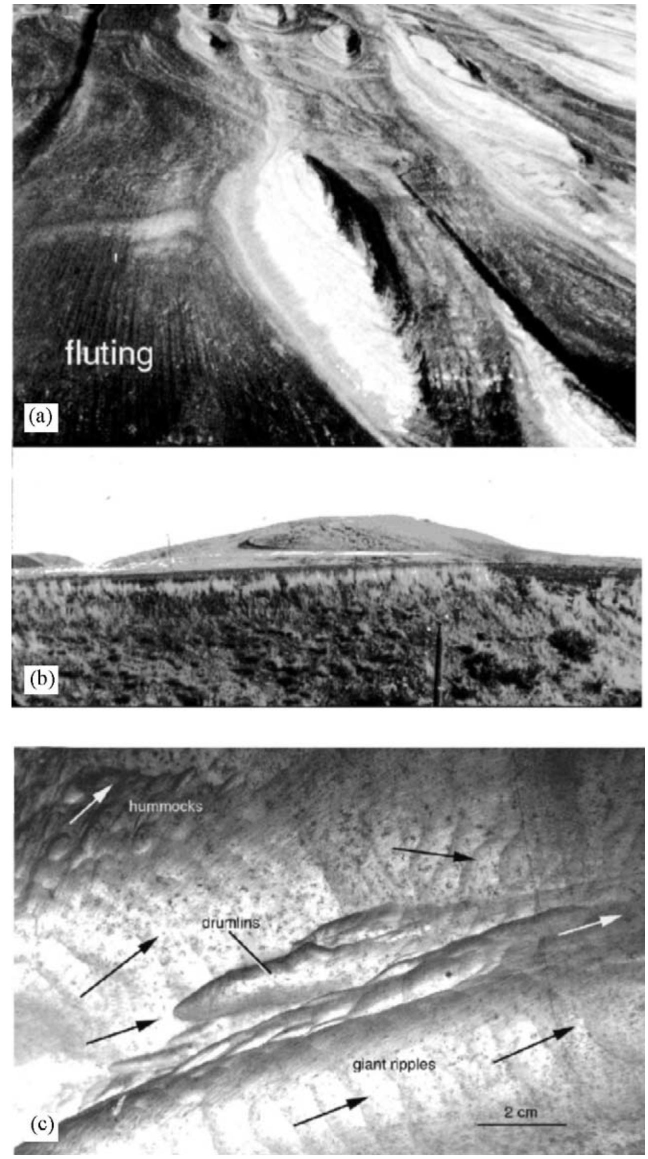

Fig. 2. Analogs for erosional drumlins related to water and wind: (B) Loess hill eroded by meltwater, Washington Scablands. (A) Yardangs Peru illustrating spectacular sculpting by the wind. (C) Eroded impellor used for driving oil sands and water through a pipe. Analogs are indirected.

"What if drumlins form in inverted erosional marks on the underside of glaciers?"

Yes, that would work.

"What about processes?"

By analogy, similar processes are implied for the formation of erosional marks in the ice bed and those at the base of turbidites. The marks must be infilled following erosion. In a matter of minutes, a genetic hypothesis for drumlins arose from analogy (Gilbert, 1896). The meltwater hypothesis came to life. Much has been written about the birth of hypotheses and it is clear that hypothesis testing and hypothesis creation are two different processes. The creative process is not readily communicated; as suggested by the title of this

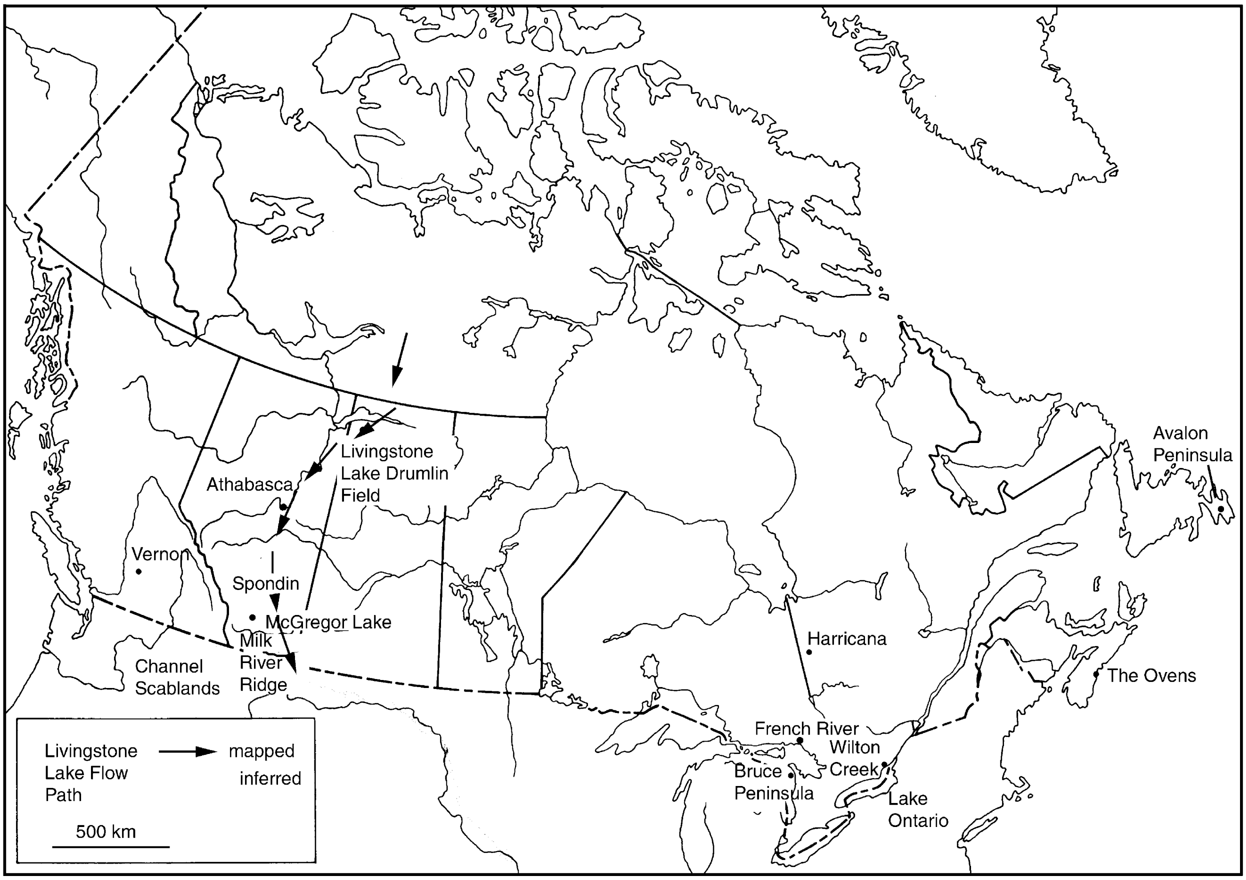

Fig. 3. Map of locations mentioned in the text.

section—the hypothesis literally springs to mind. This springing to mind is abduction (Baker, 2000). The testing process is more systematic and retrodictive.

As I have recounted elsewhere (Shaw, 1996), I was excited and wasted no time in checking erosional mark photographs with the air photographs of drumlins. I showed these photographs to Denis Johnson, a very artistic colleague. He was impressed by the similarities between the two forms. Soon afterwards, I pestered Bob Gilbert and Peter Ashmore about this simple hypothesis. Why had not someone else thought of it in the 150 years of drumlin study? They were patient and reassuring and have been ever since.

At this point, the meltwater hypothesis stated that: drumlins are formed in inverted erosional marks cut upwards into the beds of glaciers and ice sheets by meltwater. While the hypothesis was formulated quickly, in a matter of minutes, testing it is a slow process, which continues today.

3. First steps

Since the hypothesis starts with a form analogy, it seemed reasonable to test it by comparing the forms of drumlins and erosional marks, bearing in mind the inverted relationship between the two. It turns out that drumlins in the Livingstone Lake field have three dominant forms, *parabolic, spindle, and transverse asymmetrical* (Fig. 3). These forms are mimicked by classical erosional marks illustrated in Dzulinski and Walton (1965) and Allen (1971). Over the years, this form analogy has been highly criticized on the grounds that it is imaginary, especially since it is applied over a range of scales of several orders of magnitude (see Benn and Evans, 1998). This criticism is selective and misses the point that the form analogy is only the opening guess that introduces the hypothesis. A broad range of evidence interpreted retrodictively supports the hypothesis and gives it substance. This success suggests that the analogy is probably sound. Further confidence in the analogy stems from the use of bedforms in paleoflow reconstructions. It seems to me that all bedforms and erosional marks in rocks or recent sediment are recognized by form analogy. Ripples on a sandstone bedding plane are identified as ripples because their form resembles ripples seen on riverbeds or beaches. As well, ripples and some eolian dunes are analogous although they vary in scale by orders of magnitude. In this regard, we take comfort in the fact that erosional marks have been described on the seabed off California with forms and scales similar to those of inverted drumlins (Normark et al., 1979). Another way of considering this point is to turn the criticism around and ask why the subglacial deformation hypothesis for bedforms is so readily accepted when it does not provide form analogs for transverse asymmetrical drumlins, hummocky moraine, sichelwannen, and comma forms.

As stated above, the meltwater hypothesis goes beyond form analogy. For example, from the beginning, it was realized that composition and architecture would be important to understanding drumlins (Shaw, 1983). The hypothesis, as it stood in those early days, was that cavities in the ice bed are infilled with sediment, creating drumlins. This infilling might be by direct deposition from the flow that eroded the cavities. Alternatively, as the flow wanes and more of the glaciers weight is carried by the bed, saturated sediment or rock might be squeezed into the cavities such that, when the ice finally melts, the landscape is covered by hills molded at the glacier bed. Hypothetical drumlins would be, in one case, composed of sorted and stratified sediment and, in the other, of deformed beds of varying lithology.

Another way of evaluating the meltwater hypothesis is to check its consistency by looking at the landform associations of, say, drumlins in different fields. For example, the Livingstone Lake drumlin field shows a common association: drumlins, tunnel channels and eskers. The tunnel channels truncate the drumlins and the eskers wind over the floors of the channels. If the drumlins relate to erosional marks extending over the ice bed, this sequence represents a transition from sheet flow to channelized flow in broad Nye channels to flow in narrow Röthlisberger channels. This is the expected sequence for meltwater flow starting as a sheet flood in a subglacial environment.

The Journal of Glaciology published the first paper on these ideas (Shaw, 1983), though not before its rejection by another journal. There were two styles of review. Lee Clayton and David Sugden wrote generous comments praising, though not necessarily endorsing, the ideas. Others seemed to ask for the impossible.

4. The Livingstone Lake drumlin field: a field test

Don Kvill is the ideal field colleague: he is a helicopter mechanic and pilot, has a Ph.D. in geomorphology, and tells the best stories in vintage Prairie language. Amok kindly invited us to stay at their exploration camp on the shores of Carswell Lake, northern Saskatchewan. Don arranged the helicopter at an excellent rate since he flew and serviced it. We were all set for fieldwork in the Livingstone Lake drumlin field (Fig. 4). The first morning out we flew 50 or so kilometers to the drumlins. Our first impression, "Wow! They're big."

Fig. 4. Parabolic drumlins, Livingstone Lake drumlin field. Note the asymmetry, sharp pointed stoss ends and broad, indistinct lee ends, these forms hold little in common with classical drumlins and may have counterparts in erosional mark.

The drumlins, shrouded in mist, resembled the foothills of a mountain range, - perhaps like those in the Precambrian landscape of the Canadian Shield on which they stand. Our first landing, on top of one of the largest drumlins in the field, did little to reduce our sense of awe and feelings of insignificance. Boulders the size of a small car were embedded in the surface of the 80 m high drumlin. The spade I carried seemed woefully inadequate. With little hope of success, I started to dig. To our astonishment, the enormous surface boulders were set in clean sand. Heartened, we flew to Bish Lake, where we dug sections in the truncated face of a spindle-shaped drumlin (Fig. 5). Sure enough we encountered sand, which was mainly disturbed by syndepositional slumping, with dispersed cobbles and boulders. Sections in other drumlins also exposed sand and gravel. At Duck Pond Lake, we excavated graded sand and gravel from the stoss end of a parabolic drumlin. With the exception of minor faulting, the bedding was intact and in place. There was no sign of deformation in beds lying close to the ground surface. Thus, the drumlins were composed of sand and gravel as is predicted by the meltwater hypothesis for direct deposition in cavities.

We found sculpted (s)-forms (p-forms) on sandstone bedrock exposed between the drumlins and indicating approximately the same flow direction as the drumlin-forming flow. The presence of s-forms supports the meltwater hypothesis since these elaborately sculpted forms are generally considered to be water eroded (Ljungner, 1930; Hjulström, 1935; Dahl, 1965; Allen, 1982; Kor et al., 1991). At a later stage in this story, s-forms themselves played a central part in hypothesis testing. Striations superimposed on s-forms indicate glacial abrasion following meltwater sculpture. In the absence of complicated fluctuation in the position of the Laurentide ice sheet, this superposition suggests that, like the striations, these forms are also subglacial.

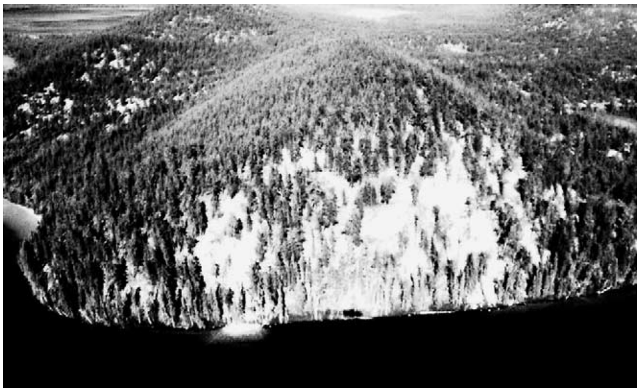

Fig. 5. Sections at Bish Lake, the high reflection shows that the sediment is largely derived from the PreCambrian Athabasca Sandstone.

This work was published in the Canadian Journal of Earth Sciences (Shaw and Kvill, 1984) and included examples of erosional marks that are analogous to drumlins. It also includes a map of all the drumlins in the Livingstone Lake field showing how drumlin form and size in a particular area tend to be similar. There are also concentrations of drumlins in flow parallel bands. Finally, drumlin asymmetry is arranged systematically in the field: drumlins to the south are skewed to the south; those in the center are symmetrical; and those to the north are skewed to the north. These general characteristics show the coherence typical of bedforms produced by wind and water and support the meltwater hypothesis.

Don Kvill, Bruce Rains and I returned to the Livingstone Lake field in 1984, where we sought to answer specific questions on the sedimentary architecture of the drumlins, on their composition and on their relationship to other landforms. The architecture was inferred from small sections cut into different drumlins and at different locations on the drumlins. It would have been more satisfactory to dissect a single drumlin, but that was not possible. Nevertheless, our results show that the sedimentary architecture of the drumlins is conformable with their surface slopes. The composition was determined by sampling clasts retrieved from excavations into the drumlins. The clasts were almost exclusively of subrounded to subangular Athabasca sandstone, the local bedrock (Fig. 6). Thus, the expectations of the meltwater hypothesis are borne out by the observed architecture and composition of drumlins. These tests might just as well have falsified the hypothesis. A new landform in the drumlin field, dry falls, with huge toppled blocks of sandstone, representing back wasting of a submerged bedrock step, attests to erosion by turbulent meltwater flow.

This work was published in 1989 and includes an estimate, based on energy considerations (Nye, 1976), of the total volume of water discharged during the formation of the Livingstone Lake drumlin field. The estimate of $84 \times 10^3\,km^3$ of water is equivalent to a 23-cm rise in sea level (Shaw et al., 1989). Shoemaker (1995), who considered it to be too high, subsequently disputed this estimate.

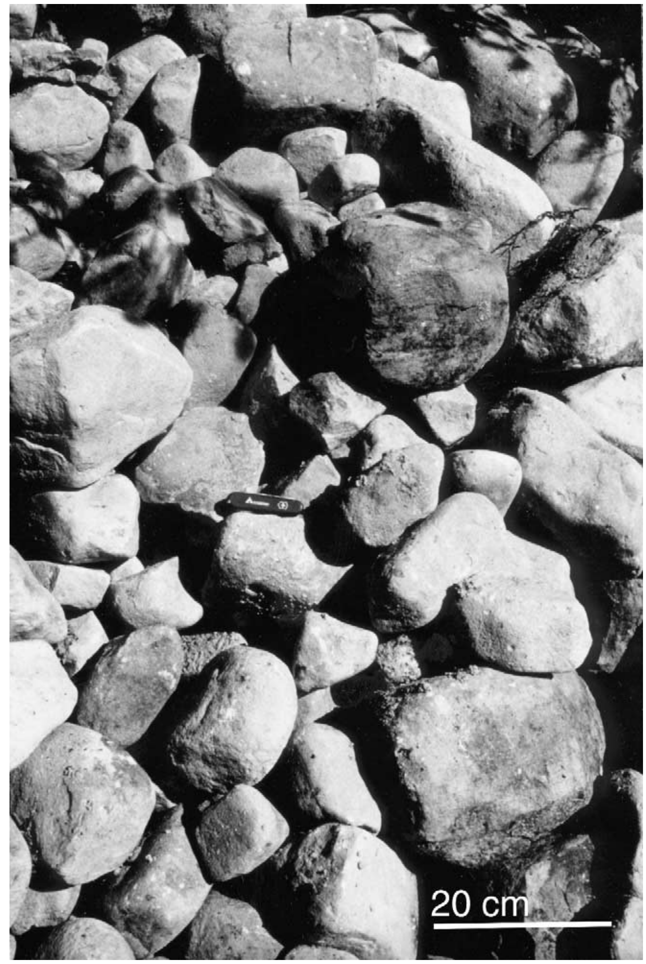

Fig. 6. Subrounded to subangular clasts of Athabasca Sandstone excavated from a drumlin, Livingstone Lake drumlin field.

5. Beyond the Livingstone Lake drumlin field

At the same time as the meltwater hypothesis was first considered, a team of geomorphologists in Ireland were also thinking about subglacial meltwater sediments associated with drumlins (Dardis et al., 1984; Dardis, 1987; Dardis and McCabe, 1987; Hanvey, 1987). Their conclusions were that the meltwater effects were more local than in the meltwater hypothesis. Nevertheless, undeformed sheet flood deposits within drumlins of Northern Ireland illustrate the plausibility of sheet flow in the drumlin-forming environment. Although, they did not attribute drumlin formation to meltwater, it might well be that the sheet floods inferred by the Irish group were precursors to the outbursts that formed the drumlins. Munro-Stasiuk (1999b) drew this conclusion from her work on hummocky terrain and its sediment in Alberta. In her case, the outbursts are thought to have formed hummocks rather than drumlins.

The Livingstone Lake studies encouraged others to apply the meltwater hypothesis to their own study areas. In some cases, drumlins and fluting were examined and, in others, bedrock erosional forms were studied in their own right. Sharpe (1987) recorded complex sedimentary successions in drumlins of Ontario and Victoria Island. He reported stratified and laminated sediment from gravel to clay intercalated with diamicton beds. The bedding was generally undeformed other than by local sagging and was conformable with the drumlin slopes. After considering conventional explanations for drumlins, Sharpe (1987) concluded that the drumlins he had studied were cavity fills. Zelcs and Dreimanis (1997) also suggested that cavities might have been an important element in the tectonic disturbance of sand and gravel in drumlins of Northern Vidzeme, Latvia. They suggested that flow acceleration over tectonic rises might have generated spindle-shaped cavities into which sediment was squeezed as the ice settled back to the bed.

Brennand and Sharpe (1993) concluded that fluting in Arctic Canada resulted from subglacial outburst floods that overtopped tunnel channels. In this case, the sheet flood crossed the tunnel channels at a high angle and sculpted their distal slopes. These interpretations of tunnel channels submerged in outburst sheet flow were to be repeated, though some researchers argue that tunnel channels were formed under non-catastrophic conditions (see Ó Cofaigh, 1996). Other spectacular examples of subglacial erosion are found in Ontario where powerful meltwater flows crossed escarpments. Tinkler and Stenson (1992) reported fluting cut into bedrock along the rim of the Niagara Escarpment by westward flowing outbursts which must have risen up and over the escarpment face like reversed Niagara Falls. Gilbert and Shaw (1994) used the detailed morphology of lakes in the Kingston area that dissect eastwards facing escarpments to interpret the lake basins as products of large-scale vortices in flows crossing the escarpments from the east. As well, Shaw et al. (2000) showed flutings preferentially located downflow from upstream facing tunnel channel slopes. There appeared to be a cause and effect between the slopes and the fluting. For example, Pollard et al. (1996) conducted experiments and made calculations using Computational Fluid Dynamics which show how flow structures set up by the slope become stretched and erode flutings downstream from the rim. This work is a benchmark because it is the first verification of geomorphological interpretations of large-scale fluting by experiment and theory.

6. Bedrock erosion

Naturally when first starting research on a new topic, the best evidence is yet to come: exactly that happened with the meltwater hypothesis. The evidence from bedrock erosional marks strongly supports the hypothesis and firmly contradicts other interpretations. But the true significance of the bedrock evidence was not realized until several years after the meltwater hypothesis was first proposed. Here was a perfect example of Whewell's (1860) consilience, the surprise incorporation of a new phenomenon into the meltwater hypothesis. It was only after serendipity drew me to spectacular bedrock erosional marks in Ontario that the light dawned. These bedforms were beyond imagination.

While out on reconnaissance for an undergraduate field trip around Wilton Creek in the Kingston area, Ontario, I noticed a farmer working in a field near the creek. I headed off down the valley side to speak to him and was brought to a halt by oval patches of sand set in carbonate rock. Beautiful, spindle-shaped erosional marks appeared in the limestone as I scooped the sand away. I never did speak to the farmer that day. As I moved to lower levels, more complex forms appeared: potholes, curved spindle flutes and intertwined spindle flutes. Shaw (1988) discussed the origin of these forms in detail, relating them to vortices. There are also large-scale flutes on the interfluve to the east of the valley. The absence of striations on the small-scale-flutes and their partial development on large-scale flutes, together with subglacial sands, deposited in and on the shoulder of the Wilton Valley and covering both sets of flutes, indicate that the flutes are subglacial and were formed by meltwater flowing in and adjacent to a tunnel channel. Clearly, to form the large-scale fluting the meltwater must have flowed as a sheet, overtopping the valley sides—another example of a tunnel channel submerged in a sheet flow. This was the first indication of broad flow, other than from the interpretation of drumlins. This broad sheet flow interpretation was also supported by Evelyn Murray's map of erosional marks in the greater Kingston region (Murray, 1988). She presented the first regional map of erosional marks. Paleocurrents derived from these erosional marks showed regionally coherent flow. Interpretation of erosional marks in rocks is not clouded by uncertainty, as is the interpretation of drumlins. Support for the meltwater hypothesis was strengthening.

The second serendipitous event was a meeting with Phil Kor at an Ontario Geological Survey open house. He asked me to look at some photographs of erosional marks he had discovered around the French River, Georgian Bay. I was astonished by the ubiquity of the marks; seemingly every inch of rock was beautifully scoured in classical erosional forms. Even that experience paled one cold November day when I first set sight on the actual marks from a helicopter (Fig. 7). They were everywhere! I remember seeing them in inverted relief, resembling dunes in desert sands (Fig. 8). Phil and I took rolls of film. But photographs of individual marks and sets of marks were not going to further the meltwater hypothesis.

Consequently, Phil, Dave Sharpe of the Geological Survey of Canada, and I got together to work out a study plan. With Murray's (1988) work in mind, it was clear that a map was needed showing the distribution of p-forms and flow directions indicated by them. We also felt a need to know what we were mapping, so we devised a classification of erosional marks (Kor et al., 1991), which leant heavily on the work of Ljungner (1930), Hjulström (1935), Dahl (1965) and Allen (1971, 1982). The publication arising from that research (Kor et al., 1991) is to my mind the most compelling of all the papers on the meltwater hypothesis. It shows that the classification is workable; gives a comprehensive explanation of the erosional features as meltwater forms;

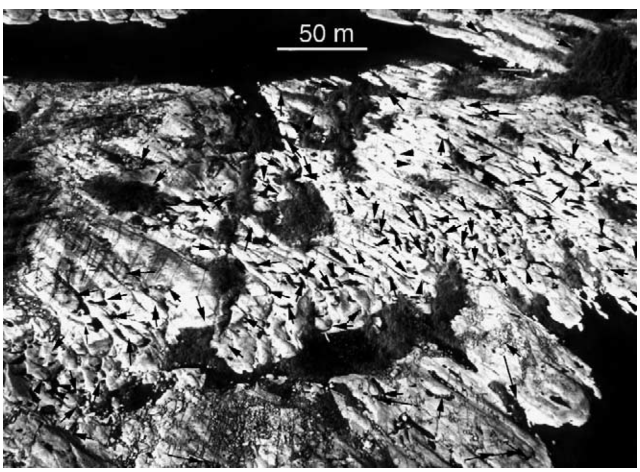

Fig. 7. Sichelwannen field on the stoss side of a bedrock rise, French River, Ontario. Selected sichelwannen are arrowed.

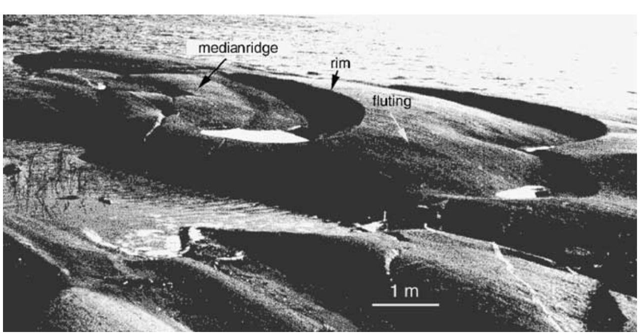

Fig. 8. Sichelwannen French River with, sharp, crescent rims and medial ridges between lateral troughs. Note the similarities in plan form of the crescent troughs of the sichelwannen and those wrapped around the erosional drumlins in Fig. 14. This similarity points to a common genesis for the two landforms.

and clearly demonstrates formation under a single, unidirectional sheet flow. Other proposed mechanisms, subglacial deformation or glacial abrasion, for example, cannot possibly account for erosional marks, with ornamentation by secondary flows, eroded into granite and gneiss (Fig. 8). Benn and Evans (1998) argue against a meltwater origin for s-forms where debris-rich ice lies in contact with the erosional marks (Boulton, 1974). This argument is unjustified: debris-rich ice on the bed does not mean that the bedforms were eroded by ice. In fact, such ice is expected on the bed following a meltwater event. As well, striations superimposed on s-forms are expected and observed (Fig. 9) and it is difficult to understand why Benn and Evans (1998) should write that the fluvial hypothesis could not explain striations on many s-forms. I cannot think of a single situation where striations could not be superimposed on s-forms. It is equally difficult to see why they saw a problem for the meltwater hypothesis where striations and s-forms indicate the same flow direction. This simply means that the potential gradients for ice and meltwater were the same (see Kor et al., 1991). Erosion of the French River s-forms in the subglacial environment could only have been by flowing water. The experience of standing amongst the erosional marks and appreciating the flow structures that caused them adds weight to the interpretation. The only other place I felt such certainty about a geomorphologic interpretation was at the Dry Falls of the Washington Scablands. The flood over the French River bedrock must have been at least 70 km wide to account for the distribution of erosional marks. Depths of several meters were required to transport boulders, contain large diameter vortices, and submerge bedforms (see Pair (1997) for an alternative opinion). Estimates of 10 m/s for flow velocities required to transport chatter-marked boulders up to 2 m in diameter are conservative. Thus, meltwater

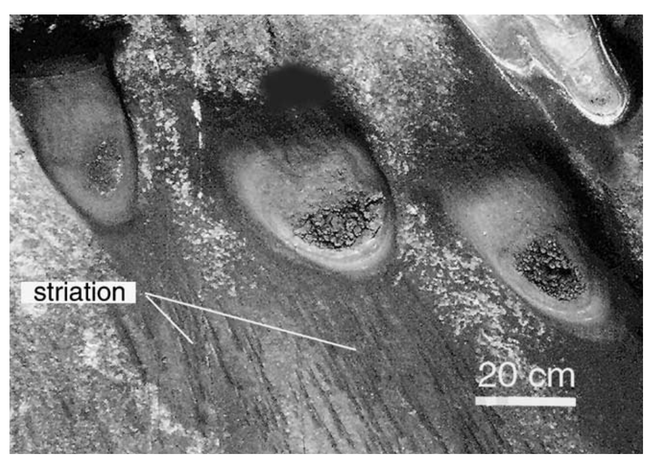

Fig. 9. Muschelbruchen with striations, French River, Ontario. The striations are short and coarse and do not extend through the muschelbruchen.

discharges of about $10^6 m^3/s$ must have swept across what are now the north shores of Georgian Bay.

Kor and Cowell (1998) followed the line of these flows southwestwards across Georgian Bay and over the Bruce Peninsula, where they found spectacular suites of erosional marks indicating a continuous flow from French River. This flow event or one like it might even account for the thick boulder gravels accreted as hummocky bedforms downflow in Michigan and Indiana to the south (Fisher and Taylor, 2000). Detailed mapping of the intervening area might reveal a regionally extensive flow tract like those discussed later.

The meltwater event thought to have eroded the bedrock forms at French River and the Bruce Peninsula is on the spatial scale of drumlin fields. Consequently, those who use scale arguments to dismiss the meltwater hypothesis, do so in the face of compelling evidence in its favour.

In an article that surprised us because we were totally unaware that Japanese scientists were working on Antarctic s-forms; Sawagaki and Hirakawa (1997) applied the meltwater hypothesis to bedrock landforms on the Soya Coast, northeast Antarctica. They illustrated a very similar suite of s-form erosional marks to those at French River. They also mapped a regional-scale field of erosional marks indicating considerable meltwater outbursts from the Antarctic Ice Sheet.

Sharpe and Shaw (1989) reported on the spectacular bedrock erosional marks in marble at Cantley, Quebec. This site exhibits half potholes, cavetos, spindle flutes and large rat-tails behind blocks of exotic lithologies in the marble. Some of these rat-tails are more than 10 m long. They are explained by horseshoe vortex erosion around bluff obstacles (the exotic blocks) in a turbulent flow.

In an interesting switch of roles, meltwater erosional marks have recently served as analogs for erosional marks scoured by tsunamis on shore platforms (Bryant and Young, 1996; Aalto et al., 1999). We think back to the erosional marks in the landscape around Edinburgh, which Sir James Hall (Hall, 1815) thought were the work of tidal waves. In terms of the marks, it is relatively easy to retrodict process from forms but, because the same processes operate in very different environments, it is sometimes difficult to specify the origin of the eroding flow.

7. Erosional drumlins: a step forward

At first, we thought drumlins were cavity fills (Shaw, 1983; Shaw and Kvill, 1984). We were confident about this; after all, our fieldwork on the Livingstone Lake drumlins supported the cavity fill idea very well. But our studies of erosional marks and the realization that not all drumlins could be explained as cavity fills sowed the seeds of doubt. On a hot Saturday afternoon in Mathieson, northern Ontario, I was flipping lazily through Prest's fine book, 'Canada's Heritage of Glacial Features' (Prest, 1983). Photographs of rat-tails caught my attention. These are residual marks like those formed around pebbles in streams (Karcz, 1973). They look like some classical drumlins and raised the question in my mind: Could some drumlins be meltwater erosional forms? Of course, although many other authors have interpreted drumlins as erosional forms (e.g. Gravenor, 1957; Boyce and Eyles, 1991), they have started with the assumption that formation was by ice or a deforming bed.

If drumlins are erosional, internal structure should be truncated at the land surface. As well, we would expect them to be closely analogous to other residual forms. Such analogy is particularly useful if the form can be related to process, because then it may be giving insight to drumlin forming processes.

Dave Sharpe and I soon went about comparing images of erosional residuals and drumlins. There are numerous form analogies, including the loess hills of the Washington Scablands, yardangs in the deserts of Peru (Fig. 2) and erosional forms on riverbeds (Shaw, 1996), and the internal structure of many drumlins reported in the literature is truncated (Shaw and Sharpe, 1987). Shaw (1994) wrote about the details of these analogies and the importance of horseshoe vortices in the formation of erosional drumlins defined by hairpin scours (Fig. 10), for example the drumlins around Prince George, British Columbia (Armstrong and Tipper, 1948). I stressed the fact that hairpin scours do not cross-cut one another. This observation implies that the scours were produced simultaneously and that fields of residual features were created as a whole and not piecemeal. Eyles and Boyce (1998a, b) challenged the use of this form analogy by pointing out that some forms created by ductile shear in fault gouge resemble rat-tails. They seem to argue from this observation that all rat-tails originate by ductile shear, thus falsifying the meltwater hypothesis. But rat-tails are formed by the wind in deserts, by fluvial action on riverbeds and in flume experiments. Obviously ductile shear does not deform the erosional surface into rat-tails in these environments. So why do rat-tails originating beneath glaciers *have* to be formed by ductile shear? As well, while there is a very poor form analogy between the set of gouge erosional forms and those created by water and wind, water and wind forms are very close to the set of rat tails on subglacial surfaces (Fig. 11).

Sawyer (2000) made high-resolution DEMs of the drumlins around Prince George using a Differential Global Positioning System. He used hill shade maps derived from the DEMs, stratigraphic sections and fabric analysis to demonstrate that the drumlins are erosional. His high-resolution hill shade maps, in a

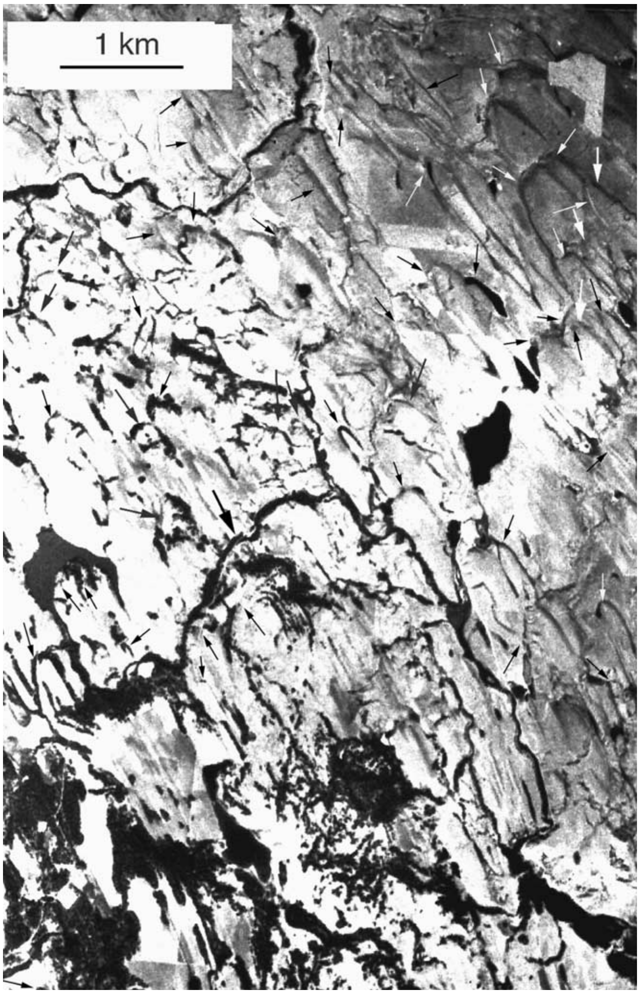

Fig. 10. Erosional drumlins defined by hairpin scours (marked by arrows) Vernon–Nicolet area, British Columbia.

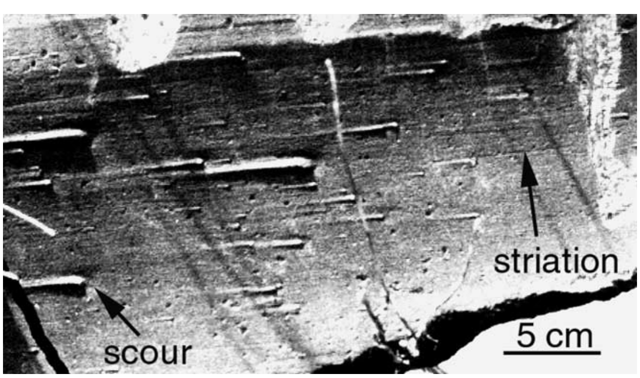

Fig. 11. Rat tails in basic volcanic rock formed within a trough. Road cut along Hwy 7 near, Sharbot Lake, Ontario. Note the delicate erosional scours around the stoss ends of the rat-tails.

variety of perspectives, reveal small-scale, fluvial erosional features superimposed on the drumlins and illustrate how smaller drumlins are created where longitudinal troughs dissect larger drumlins (Fig. 12). These troughs resemble extended stoss side troughs of

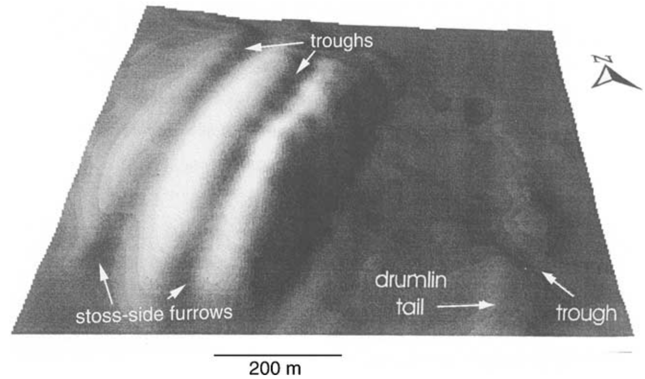

Fig. 12. Hill shade model of a dissected drumlin near Prince George, British Columbia. The stoss-side furrows and troughs are reminiscent of features eroded in bedrock (Kor et al., 1991). A large drumlin is clearly cut into three smaller drumlins by the process of dissection.

s-forms (Kor et al., 1991) and are similarly interpreted as meltwater erosional marks.

Fisher and Spooner (1994) studied drumlins in the Bow Valley west of Calgary with gravel composition and crescentic scours around their proximal ends. Nearby rock outcrops showed s-forms and they interpreted the landform sediment association as the work of meltwater outbursts.

Inclusion of erosional drumlins in the meltwater hypothesis was a major step forward. It simplified interpretation and explained such features as hairpin scours. As well, it brought together interpretations of drumlins and bedrock erosional forms such that drumlin fields and erosional mark fields could be integrated in regional reconstructions of flood paths.

8. Big pictures—the regional scale

It became clear that these flows must have been of enormous regional extent, once the magnitude of drumlin forming meltwater flows was realized. This insight marked a new stage in the meltwater hypothesis. Rather than concentrating on the origin of subglacial bedforms, meltwater was assumed as the formative agent and the emphasis shifted to investigating flow paths at a regional scale. Murray (1988) first mapped erosional marks to show their extent and the coherence of the flow lines derived from them in the Kingston area. Shaw et al. (1989) postulated that the Livingstone Lake drumlin field resulted from an outburst flood, the Livingstone Lake Event.

Shaw and Gilbert (1990) mapped flow lines from drumlin alignment to identify extensive outburst flood paths. They proposed that the Algonquin and Ontarian flood events formed drumlins in southeastern Ontario and northern New York State. As a result of complexity of flow lines around the Niagara escarpment, they may have plotted some lines incorrectly (Eyles and Boyce, 1998b). Nevertheless, the general conclusions stand and were spectacularly verified by swath bathymetry images of spindle drumlins the floor of Lake Ontario (Fig. 13) (Lewis et al., 1996). As expected, these images illustrate Ontarian drumlins and Algonquin drumlins are absent, although they are well displayed to the north and south of the lake. As predicted by Shaw and Gilbert (1990), the Ontarian event clearly eradicated Algonquin bed forms along the axis of present-day Lake Ontario.

Brennand et al. (1995) related the position of the Harricana esker in northern Quebec (Fig. 4) to a convergence of regional flow lines reconstructed from glacial lineations (mainly drumlins). If the lineations are interpreted as meltwater features, then the effects of convergence on specific discharge and ice melting rates favour the formation of a large conduit along the convergence zone. As well, sagging of the ice surface would concentrate supraglacial meltwater above the conduit and, with moulin connections; this meltwater would eventually feed the conduit flow. Late-stage infilling of the conduit would create the esker over its full length (Brennand, 1994). Such close interrelationships between observed landforms and inferred successions of hydrological conditions and geomorphological processes add weight to the meltwater hypothesis.

Much of the recent work on flood path reconstruction involves tracing the Livingstone Lake flood path from northern Saskatchewan along the length of the Province of Alberta. This was achieved by analyzing surficial geology and landform maps (Shetsen, 1987, 1990), a soil map of Alberta (Odynsky, 1962), air photographs and snow scene satellite images (Skoye and Eyton, 1992). After an intensive all-day session drawing and rejecting potential flood tracts for Alberta, Bruce Rains and I eventually identified promising sinuous tracts with thin to absent surficial sediments, and solonetzic soils along part of their length. These tracts carry large-scale flutings, aligned with the tracts and field observation shows many flutings to be cut into bedrock. Both the flutes and erosional plains carry cobble and boulder surface lags (Fig. 14). The tracts are also bordered by hummocky moraine. Rains et al. (1993) published these findings and suggested that the floods were much wider than the tracts themselves. They interpreted the hummocky moraine as flood-formed landscapes where erosion was less pronounced than in the tracts. This insight intrigued Mandy Munro who concentrated her Ph.D. research on hummocky terrain. The term terrain appears at this point because she considered the term moraine to be misleading. More on that later.

The tracts that Rains et al. (1993) had identified show up beautifully on hill shade DEMs of Alberta (Fig. 15). Our original hill shade was made up of a mosaic of areas covered by 1 : 25,000 NTS map sheets. Subsequently, we have been able to create a single image at higher resolution. With this image in hand and the image produced by the USGS (Thelin and Pike, 1991) we were able to follow the flood path into the United States where it extends to the Mississippi Delta. Bathymetric images on the delta surface reveal a hummocky surface related to widespread diapirism. Thus, Shaw et al. (1996) presented the first continental-scale-reconstruction of flood tracts and proposed an extension of the effects of floods to the ocean.

9. Sea level and climate

Sudden outbursts of meltwater from ice sheets in which it had been stored over millennia must of course

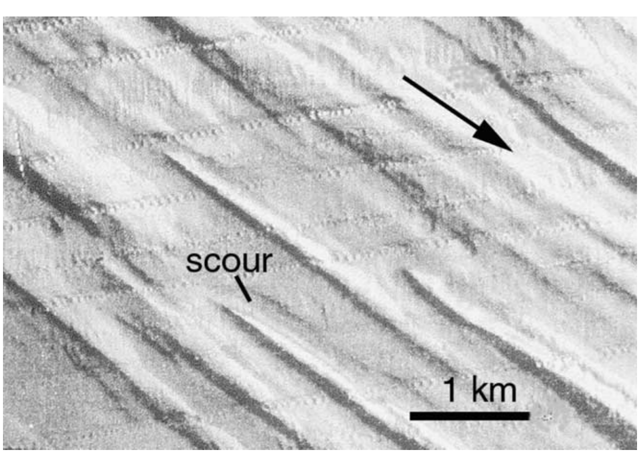

Fig. 13. Flutes or spindle drumlins on the floor of Lake Ontario recorded by swath bathymetry. The forms are cut into till and has been buried by about 10 m of late-glacial and Holocene sediments. Despite this cover, delicate scours are visible around the stoss ends of some fluting ridges. These scours resemble those around the rat-tails (Fig. 11).

Fig. 14. Boulder lag on a Prairie erosion surface, Berry Creek, Alberta. The boulders are mainly derived from the Canadian Shield and rest on Cretaceous sediments, their emplacement by frost heaving as an alternative to fluvial action is improbable.

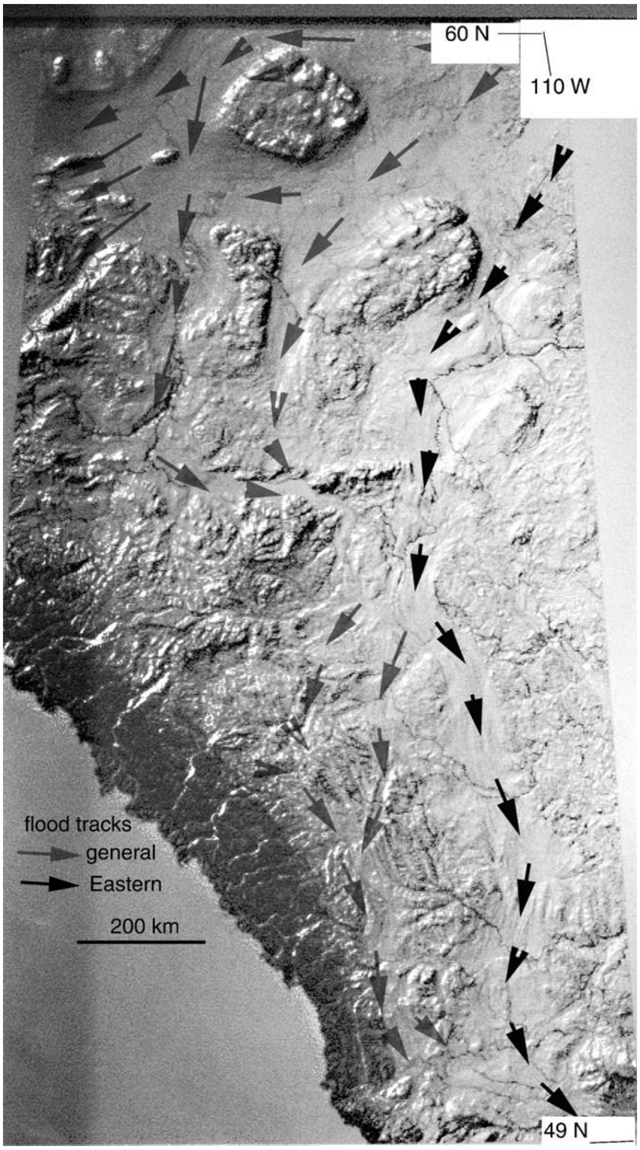

Fig. 15. Alberta hill-shade model based on 1 : 20,000 aerial photography. This relief model illustrates the low relief tracts interpreted here as flood tracts (arrowed). The prominent Eastern flood route follows an up-slope course from north to south.

affect the oceans. We would expect dramatic rise in sea level, disturbance of the ocean stratification, and ventilation of seawater with cold, turbid fresh water. Shaw et al. (1989) estimated the volume of meltwater forming the Livingstone Lake drumlin field at $8.4 \times 10^4\,km^3$. Although this flow was just a thin filament of the Livingstone Lake Event, it still represents about 0.23 m of sea level rise that would have taken place in a matter of weeks. Shaw (1989) argued that such sea level rises were probably on the order of meters. Changes in the isotopic composition of the waters of the Gulf of Mexico register dramatic spikes of water rich in δO^{16}, which indicates a source in the Laurentide ice sheet to the north (Kennett and Shackleton, 1975; Emiliani et al., 1975; Leventer et al., 1982). These spikes, together with sedimentary units carrying only a few fossils (Leventer et al., 1982) are as expected for outburst floods. They date at about 15 ka BP, which, since it is before the development of large proglacial lakes around the southern limit of the Laurentide ice sheet, implies that the floods originated within this ice sheet.

Blanchon and Shaw (1995) reported the dates of Catastrophic Rise Events (CRE) as recorded in coral reef drowning episodes from the Caribbean–Atlantic region. The drowning episodes correlate with Heinrich events and major climatic events recorded in the Greenland ice cores. Sea level rise during the CRE's was at rates $>45\,mm/a$ and total rise during an event was as much as the 13.5 (± 2.5) m recorded for the 14.2 ka event. Although these results have potential significance for oceanographers and climatologists, they have not been used yet in models of late-glacial change in climate and ocean circulation.

10. Associated landforms

Although drumlins are emphasized in this overview, common genetic elements place them in a set of associated subglacial landforms. Thus, drumlins, Rogens and hummocky terrain should be explained by the meltwater hypothesis, if it really does describe their genesis. As well, a set of landforms should record channelization of sheet flow. The most prominent of these are tunnel channels, which commonly crosscut subglacial bedforms. Eskers represent the latest stage of the drainage and, relatively speaking, record a non-catastrophic flow phase (Brennand, 1994).

Tim Fisher tackled Rogen moraines in a detailed morphological and sedimentological study of ridges on the Avalon Peninsula, Newfoundland (Fig. 4) (Fisher and Shaw, 1992). The moraine ridges resemble other Rogen moraine in Canada and Scandinavia and nothing new emerged from analysis of their form. It was the sediments that caught our attention. There are few good records of the internal structure of Rogen moraine. Tim cut sections in ridges and found large amounts of sorted and stratified sediment. Stratification conformed to the ridge shape, illustrating a depositional origin. Clasts were local, subrounded at best, and did not carry striations. The sediment was interpreted to include deposits from hyperconcentrated flows and subaqueous debris flows. The evident short transport of the clasts points to local erosion. All of these characteristics are consistent with the meltwater hypothesis. Naturally, subglacial fluvial deposition of a transverse ridge requires a transverse cavity in the ice; that is, the sedimentation infilled an inverted erosional mark. Fisher and Shaw (1992) noted that not all Rogen moraines fits this model and some might be erosional, perhaps in the style of hummocky terrain to be discussed.

Recognition of major flood tracts prompted further work on the critical areas within the tracts. Armed with high-resolution DEMs of central Alberta, Sjogren (1994) and Sjogren and Rains (1995) mapped remarkable scablands around pondin (Fig. 4). Subtle braided channels, delicate braid bars, pendant bars and remnant drumlins and fluting are cut in bedrock and thin surficial sediment over a width of about 80 km. The channels cross divides, indicating that the landscape association is subglacial. The landforms themselves are clearly fluvial and support a meltwater origin for the scabland.

Further to the south, the eastern and western flood tracts of Alberta converge where they cross the continental divide. A new set of landforms, transverse ridges (Fig. 16), drapes the divide and is dissected by tunnel channels with up-and-down long profiles (Beaney, 1998; Beaney and Shaw, 2000). The transverse ridges, about 15 m high and 0.75 km in wavelength, are eroded into the generally undeformed Cretaceous bedrock. The ridges are inferred to be bedforms related to internal waves in a subglacial sheet flow. Beaney and Hicks (2000) produced a hydraulic model for the initiation of tunnel channel flow where meltwater was just confined by the channel rims. They estimated discharge in the order of 10^6 m^3/s. In terms of tunnel channel formation by catastrophic drainage, E.C. Sjogren (1999) demonstrated that the Athabasca–Tawatinaw tunnel channel system, situated along the Eastern Flood tract in north-central Alberta, was submerged beneath a fluting-forming sheet flood.

Hummocky terrain (Fig. 17) has long been attributed to deposition of supraglacial debris from stagnant ice (e.g. Gravenor and Kupsch, 1959). Hoppe (1952) proposed another mechanism whereby basal till was squeezed into subglacial cavities. Stalker (1960) enthusiastically followed Hoppe and interpreted hummocky

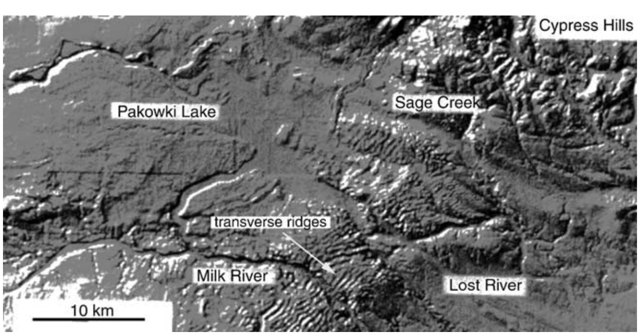

Fig. 16. Hill shade illustrating transverse ridges eroded into Cretaceous bedrock, Milk River Ridge, Alberta. Note the discordance of some ridge sets. Heights of the ridges are up to 30 m. The valleys of Milk and Lost rivers and Sage Creek operated as tunnel channels immediately following the Livingstone Lake sheet-flow stage which generated the transverse ridges. Hill shade prepared by C. Beaney.

Fig. 17. Hummocky terrain north of the Hand Hills, Alberta.

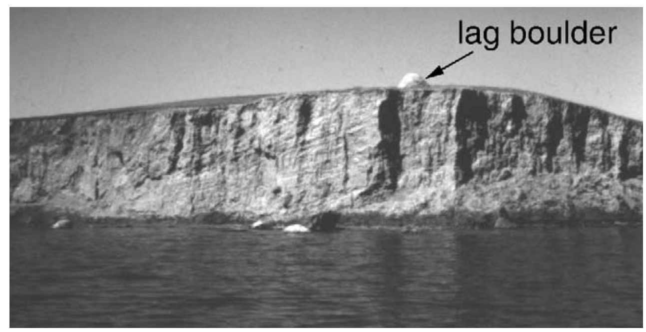

Fig. 18. Section in a hummock, McGregor Lake, Alberta. Undisturbed, inclined stratification is truncated by an unconformity at the ground surface. The single lag boulder illustrates the sparsity of such clasts where there were few boulders in the eroded sediments. Photo by M. Munro-Stasiuk.

moraine on the Alberta plains as ice-pressed landforms. Eyles et al. (1999) took a similar approach while invoking the importance of a deformable bed. Munro-Stasiuk (1999a, b), Munro and Shaw (1997) and D.B. Sjogren (1999) took a different approach. After examining many sections in hummocks, it became clear that the hummock form resulted from erosion: internal structures were truncated by the land surface (Fig. 18) and successive hummocks displayed identical stratigraphy. Hummocks contain bedrock, deformed and undeformed surficial sediment, till and stratified deposits, all truncated at the land surface. They carry boulder lags, are overlain by eskers and are truncated by complex tunnel channels. They border flood tracts. These characteristics are best explained if the hummocks are remnants of erosion by a meltwater sheet flow where the degree of erosion was less than in the adjacent flood tracts. The flood tracts, in this explanation, mark channeling of an extremely broad flow. This conclusion is surprising because it departs so drastically from the accepted genesis of hummocky terrain but, given the complementary nature of hummocky terrain, drumlins and fluting, it makes understanding them much simpler.

Geomorphology stands out in the Canadian north beyond the tree line. Vernon Rampton, one of Canada's leading mappers of surficial geology, recently published a paper on meltwater forms and sediments in the southern Slave Province, Northwest Territories (Rampton, 2000). The paper is remarkable for the range of landforms—drumlins, hummocky terrain, Rogen moraine, gravel bedforms, pot holes, plunge pools and reverse plunge pools—presented in fine detail. Areas of bedrock and adjacent zones with lags of rounded boulders strengthen the meltwater interpretation and make it possible to map the extent of the meltwater flows.

11. Theory

Earth science hypotheses usually start with observations of the real world, as did the meltwater hypothesis. Quantitative theory then follows qualitative arguments and acts as a sophisticated test. Probably, the most common question asked of the meltwater hypothesis is: What was the water source? From storage in the ice sheet is the easy reply. We have simply assumed that such storage is possible. Ed. Shoemaker could not accept such a facile answer; he wanted to know how stored water could be held in such large volumes. What triggered its release? How did it flow? He died this year (2000). I miss his insistent questions about Laurentide landforms and sediments and the long pauses on the phone as he listened to a favorite passage of music. It is fortunate that he put his mind to the questions of meltwater in the Laurentide ice sheet, its storage and release. His first work in this area investigated the necessary conditions for large lakes beneath ice sheets in which he demonstrated that such lakes could grow and cause a reduction in ice-sheet gradient (Shoemaker, 1991). He suggested that outburst floods from these lakes during glaciation formed drumlins. His second paper on outburst floods and low relief ice sheet lobes developed the idea that advance of ice sheets in low relief lobes depended on outburst floods (Shoemaker, 1992a). He arrived at this conclusion because the calculated shear stress beneath the lobes is less than the strength of subglacial sediment. While Shoemaker (1992a) presented the physical arguments underlying his conclusion, he also used drumlins and erosional marks in rock as supporting evidence. His pioneering work on sheet floods (Shoemaker, 1992a, b) drew criticism from Walder (1994) who argued that sheet flows were unstable and quickly broke down into channnelized flow. Shoemaker (1994) responded that Walder's calculations were based on laminar flow and turbulent flows, such as outburst floods, maintain sheet flows longer than do laminar flows. As an example, sheet flow of turbulent meltwater of meter depth may be stable for as much as one month.

The instability of sheet flow is widely used to refute the meltwater hypothesis. Yet, the 1996 Icelandic jökulhlaup maintained sheet flow over fans Skei∂arásandur for several tens of hours (Russell and Knudsen, 1999). In that time, it transported huge amounts of sediment, destroyed bridges and embanked roads, and severely altered the former outwash plain. In distal parts of the sandur the sheet flow was approximately 35 km wide (Fig. 19) (Worsley, 1997). Flow in the final stages was confined to channels. Thus, there can be no argument about the existence of sheet flows (though this term seems to arouse strong opinions and it might be better to call them broad flows)—they are observed in nature. Nor can there be any argument about the geomorphologic power of sheet flows, given our experience of the destructive forces of jökulhlaups. Interpretation of geomorphological evidence tells us that the postulated outburst floods of Pleistocene ice sheets also passed from a sheet to a channelized stage. Jökulhlaups show that this interpretation is plausible.

Shoemaker's (1995) first paper devoted exclusively to drumlins concerns the amount of water required for the formation of the Livingstone Lake drumlin field (Shaw et al., 1989). While he accepted our proposed flow structures and the mechanism of cavity fill, he differed from us in the mechanics of cavity formation. By introducing abrasion of ice by suspended sediment and considering variations in gap width between the ice and bed he suggested that our estimate of $84 \times 10^3\,km^3$ could be reduced by perhaps an order of magnitude. His approach also gives an explanation for maximum drumlin heights appearing in the highest parts of the Livingstone Lake field. Because gap width is reduced here, then velocity and, consequently, cavity size are increased. By combining theoretical water flow patterns associated with subglacial lakes and inferred conditions for drumlin formation, Shoemaker (1999) predicted the

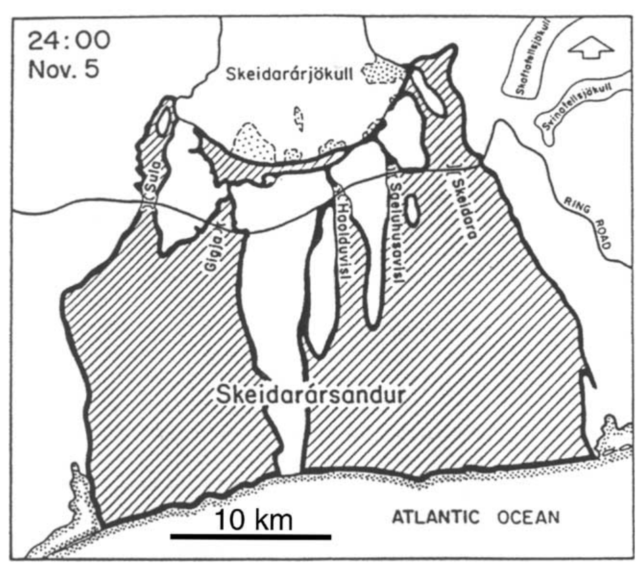

Fig. 19. Extent of proglacial flooding caused by the 1996 jökulhlaup at Skeidarárjökull, Iceland.

location of drumlins around the Great Lakes. In doing so, he added fundamental supported to the meltwater hypothesis.

While Shoemaker took a global view of ice sheet hydraulics and hydrology, others have applied hydraulic models to more specific elements of the flood hypothesis. As mentioned above, Beaney and Hicks (2000) used a hydraulic model to calculate discharge rates for a network of tunnel channels in southern Alberta.

It is disappointing that the evidence of water storage in the mid-latitude ice sheets and vast outburst floods has not been used in ice-sheet modeling. The resolution of such models is more than adequate to incorporate water bodies on the order $10^3\,km^2$ into numerical analysis. If this were done, it would be a powerful check on the feasibility of the meltwater hypothesis and might provide answers to outstanding questions regarding ice thickness and surface slope.

12. Conclusions

The meltwater hypothesis has gone through several critical stages from inception to field testing to theoretical support. In each of these steps, we have tried to test the hypothesis as rigorously as possible. In doing so, we have not been able to falsify it and added observation appears to add support, a reflection of the fertility of the hypothesis. That is not to say that the hypothesis has not changed by amendment over time. The addition of erosional drumlins and the inferred importance of horseshoe vortices to their formation was a major step in the evolution of the hypothesis. Another pivotal point came with the realization that bedrock erosional marks were not just singular curiosities, but they form fields just like drumlins and illustrate regional-scale flow. Inclusion of hummocky terrain, Rogen moraine and transverse, erosional ridges in the list of inferred meltwater forms makes the hypothesis comprehensive. Furthermore, when viewed as complementary members of the class of subglacial, fluvial bedforms, these meltwater landforms begin to make sense. As is to be expected of fluvial features associated with high rates of sediment transport, they may be erosional, depositional or a combination of both. Naturally, then, subglacial bedforms may be composed of sorted and stratified sediment where they are depositional and a range of material including till and bedrock where they are erosional. Shaw (1996) explains the morphological distinctions between depositional and erosional forms and, by its ability to predict composition from form, the meltwater hypothesis passes a fairly sophisticated test.

The meltwater hypothesis has implications for regional-scale landscapes, which allow predictions of surficial materials over large distances. The so-called flood tracts are either lacking in surficial sediment or it is thin. By contrast zones of hummocky terrain, which commonly flank the tracts, contain a variety of deposits in relatively thick sequences and, in some cases bedrock. It is also probable that intense glaciotectonic action was triggered by stress redistribution caused by subglacial meltwater separating ice Large-scale regional distributions and patterns of bedforms give extraordinary impressions of flood magnitude. Unfortunately, only a small proportion of Canadian flood tracks is mapped and it is not yet possible to estimate the total discharges of outburst floods. Without maps, it is also difficult to determine the synchroneity of flood events. Nevertheless, Brennand et al. (1995) established that flows were synchronous in parts of Quebec and Ontario, and Clark (1999) presented a methodology for determining the relative timing of regional ice flows that applies equally well to meltwater flows. We would benefit enormously if customized maps were available of s-forms over areas of former continental glaciation. Unfortunately, we live in times when field mapping is out of favor with national and provincial surveys and compilation of such maps by individuals working in universities will be slow. Nevertheless, even limited mapping is likely to produce wide-reaching results.

There may have been considerable direct effects of meltwater floods on sea level and rates of sea level rise. These may explain or partly explain the rapid sea level rises inferred from coral studies. Also major effects of outburst floods are expected on marine sedimentation in areas around formerly glaciated land masses. Studies on these effects are in their infancy. Underflows of cold, turbid, fresh water into saline oceans must first lose their sediment and then rise to the surface in cold plumes. After mixing during plume ascent, surface water would be brackish and cooler than it was prior to the outburst. Such dramatic effects on ocean surface temperature would have affected climate and future correlation of outburst events and climate fluctuations might well provide insight into climate change during glaciations.

A number of fundamental questions must be answered before the meltwater hypothesis is well founded in observation and theory. Two of these, the source of the meltwater and its catastrophic discharge, have been answered in a global sense. Specific concerns such as the stability of sheet flow remain contentious, though observation of such flows lasting tens of hours makes the theoretical difficulties less critical. On the other hand, flow of meltwater in conduits much wider than the ice is thick has yet to be analyzed mathematically.

The meltwater hypothesis is said to be controversial by some. This view suggests implicitly that the hypothesis is not respectable and the controversy it generates somehow reflects badly on the scientific judgement of its adherents. Others go so far as to condemn the hypothesis outright, but their evidence and logic leave a lot to be desired. There are easily identified factions in this debate, the politics are disheartening, and students who choose to work on outburst flood landforms have been through difficult times. For all this, the hypothesis will stand or fall according to how well it improves our understanding of the real world.

Acknowledgements

NSERC, Canada has funded this research all along and I am grateful for the generous support given to my students and me. I have worked with many people on meltwater forms and sediments and learned a great deal from them. Ed. Shoemaker was special amongst them, a scholar with a remarkable irreverence for establishments, a friend. I thank David Sharp for a typically frank and helpful review and Victor Baker for explaining to me what it is I have been doing over the last 20 years. These two reviewers and Tim Fisher as editor made many constructive suggestions.

References

Aalto, K.R., Aalto, R., Garrison-Laney, C.E., Abramson, H.F., 1999. Tsunami (?) sculpturing of the Pebble Beach wave-cut platform, Crescent City, California. Journal of Geology 107, 607–622.

Allen, J.R.L., 1971. Transverse erosional marks of mud and rock: their physical basis and geological significance. Sedimentary Geology 5, 167–385.

Allen, J.R.L., 1982. Sedimentary structures. Developments in Sedimentology 30B, Vol. 2. Elsevier, Amsterdam, 663pp.

Armstrong, J.E., Tipper, H.W., 1948. Glaciation in north central British Columbia. American Journal of Science 246, 283–310.

Baker, V.R., 1996. The pragmatic roots of American Quaternary Geology and Geomorphology. Geomorphology 16, 197–205.

Baker, V.R., 2000. Let Earth speak!. In: Schneiderman, J.S. (Ed.), The Earth Around Us. Freeman, New York, pp. 358–367.

Beaney, C.L., 1998. The subglacial geomorphology of southeast Alberta: evidence for glacial meltwater erosion. M.Sc. Thesis, University of Alberta, Canada, 131pp.

Beaney, C.L., Shaw, J., 2000. The subglacial geomorphology of southeast Alberta: evidence for subglacial meltwater erosion. Canadian Journal of Earth Sciences 37, 51–61.

Beaney, C.L., Hicks, F.E., 2000. Hydraulic modelling of subglacial tunnel channels, south-east Alberta, Canada. Hydrological Processes 14, 2545–2557.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and Glaciation. Arnold, London, 734pp.

Blanchon, P., Shaw, J., 1995. Reef drowning during the last deglaciation: evidence for catastrophic sea-level rise and ice-sheet collapse. Geology 23, 4–8.

Boulton, G.S., 1974. Processes and patterns of subglacial erosion. In: Coates, D.R. (Ed.), Glacial Geomorphology. State University of New York, Binghampton, pp. 41–87.

Boyce, J.I., Eyles, N., 1991. Drumlins carved by deforming till streams below the Laurentide ice sheet. Geology 19, 787–790.

Brennand, T.A., 1994. Macroforms, large bedforms and rhythmic sedimentary sequences in subglacial eskers, south-central Ontario: implications for esker genesis and meltwater regime. Sedimentary Geology 91, 9–55.

Brennand, T.A., Sharpe, D.R., 1993. Ice sheet dynamics and subglacial meltwater regimes inferred from and sedimentology of glaciofluvial systems: Victoria Island, District of Franklin, Northwest Territories. Canadian Journal of Earth Sciences 30, 928–944.

Brennand, T.A., Shaw, J., Sharpe, D.R., 1995. Regional-scale meltwater erosion and deposition patterns, northern Quebec, Canada. Annals of Glaciology 22, 85–92.

Bryant, E.A., Young, R.W., 1996. Bedrock-sculpturing by tsunami, south coast New South Wales, Australia. Journal of Geology 104, 565–582.

Clark, C.D., 1999. Glaciodynamic context of subglacial bedform generation and preservation. Annals of Glaciology 28, 23–32.

Cox, D., 1979. A diluvial origin for drumlins. Creation Research Society Quarterly 16, 154–162.

Dahl, R., 1965. Plastically sculptured detail forms on rock surfaces in northern Nordland, Norway. Geografiska Annaler 47, 3–140.

Dardis, G.F., 1987. Sedimentology of late-Pleistocene drumlins in south-central Ulster, Northern Ireland. In: Menzies, J., Rose, J. (Eds.), Drumlin Symposium. Balkema, Rotterdam, pp. 215–224.

Dardis, G.F., McCabe, A.M., 1987. Subglacial sheetwash and debris flow deposits in late-Pleistocene drumlins, Northern Ireland. In: Menzies, J., Rose, J. (Eds.), Drumlin Symposium. Balkema, Rotterdam, pp. 225–240.

Dardis, G.F., McCabe, A.M., Mitchell, W.I., 1984. Characteristics and origins of lee-side stratification sequences in late Pleistocene drumlins, Northern Ireland. Earth Surface Processes and Landforms 9, 409–424.

Dzulinski, S., Walton, E.K., 1965. Sedimentary features of flysch and greywacke. Developments in Sedimentology. Elsevier, Amsterdam, 274pp.

Emiliani, C., Roooth, C., Stripp, J.J., 1975. The late wisconsin flood into the Gulf of Mexico. Earth and Planetary Sciences Letters 49, 159–162.

Engelhardt, W. von, Zimmermann, J., 1988. Theory of Earth Science. Cambridge University Press, Cambridge, pp. 381.

Eyles, N., Boyce, J.I., 1998a. Kinematic indicators in fault gouge: tectonic analog for soft-bedded ice sheets. Sedimentary Geology 116, 1–12.

Eyles, N., Boyce, J.I., 1998b. Reply to comments: kinematic indicators in fault gouge: tectonic analog for soft-bedded ice sheets. Sedimentary Geology 123, 157–161.

Eyles, N., Boyce, J.I., Barendregt, R.W., 1999. Hummocky moraine: sedimentary record of stagnant Laurentide Ice Sheet lobes resting on soft beds. Sedimentary Geology 123, 163–174.

Fisher, T.G., Shaw, J., 1992. A depositional model for Rogen moraine, with examples from the Avalon Peninsula, Newfoundland. Canadian Journal of Earth Sciences 29, 669–686.

Fisher, T.G., Spooner, I., 1994. Subglacial meltwater origin and subaerial meltwater modification of drumlins near Morley, Alberta, Canada. Sedimentary Geology 91, 285–298.

Fisher, T.G., Taylor, L.D., 2000. Boulder beds, a product of subglacial outburst flooding, south-central Michigan. Geological Society of America Annual Meeting, Abstracts with Programs 32 (7), p. A116.

Gilbert, G.K., 1886. The inculcation of scientific method by example. Journal of Science 31, 284–299.

Gilbert, G.K., 1896. The origin of hypotheses, illustrated by a discussion of topographic problems. Science 3, 1–13.

Gilbert, R., Shaw, J., 1994. Infered subglacial meltwater origin of lakes on the southern border of the Canadian Shield. Canadian Journal of Earth Sciences 31, 1630–1637.

Gravenor, C.P., 1957. Surficial geology of the Lindsay-Peterborough area, Ontario. Geological Survey of Canada Memoir 288.

Gravenor, C.P., Kupsch, W.O., 1959. Ice disintegration features in western Canada. Journal of Geology 67, 48–64.

Hall, J., 1815. On the revolutions of the earth's surface. Transactions of the Royal Society of Edinburgh 7, 169–212.
Hanvey, P.M., 1987. Sedimentology of lee-side stratification in late-Pleistocene drumlins, north-west Ireland. In: Menzies, J., Rose, J. (Eds.), Drumlin Symposium. Balkema, Rotterdam, pp. 241–253.
Hjulström, P., 1935. Morphological activity of rivers as illustrated by the River Fyris. Bulletin of the Geological Institutes of the University of Uppsala 25, 221–527.
Hoppe, G., 1952. Hummocky moraine regions, with special reference to the interior of norrbotten. Geografiska Annaler 34, 1–72.
Karcz, I., 1973. Reflections on the origin of small scale longitudinal stream-bed scours. In: Morisowa, M. (Ed.), Fluvial Geomorphology. State University of New York, Binghampton, pp. 149–173.
Kennett, J.P., Shackleton, N.J., 1975. Laurentide ice sheet meltwater recorded in Gulf of Mexico deep sea cores. Science 188, 147–150.
Kor, P.S.G., Shaw, J., Sharpe, D.R., 1991. Erosion of bedrock by subglacial meltwater, Georgian Bay, Ontario: a regional view. Canadian Journal of Earth Sciences 28, 623–642.
Kor, P.S.G., Cowell, D.W., 1998. Evidence for catastrophic subglacial meltwater sheetflood events on the Bruce Peninsula, Ontario. Canadian Journal of Earth Sciences 35, 1180–1202.
Leventer, A., Williams, D., Kennet, J.P., 1982. Dynamics of the Laurentide ice sheet during the last glaciation: evidence from the Gulf of Mexico. Earth and Planetary Science Letters 59, 11–17.
Lewis, C.F.M., Blasco, S.M., Cameron, G.D.M., King, E.L., Mayer, L.A., Shaw, J., Todd, B.J., 1996. Were the Ontario and Erie basins swept by catastrophic meltwater flooding? Geological Society of America, Abstracts with Programs, Northeastern Section, p. 76.
Ljungner, E., 1930. Spaltektonik und morphologie der schwedishen Skagerakke-Kust. Teill III. Die erosionformen. Bulletin of the Geological Institutions of the University of Uppsala 25, 255–475.
Munro-Stasiuk, M.J., 1999a. Evidence for water storage and drainage at the base of the Laurentide ice-sheet, south-central Alberta, Canada. Annals of Glaciology 28, 175–180.
Munro-Stasiuk, M.J., 1999b. Geomorphology and sedimentology of hummocky moraine, south-central Alberta. Ph.D. Thesis, University of Alberta, Canada, 230pp.
Munro, M., Shaw, J., 1997. Erosional origin of hummocky terrain in south-central Alberta. Geology 25, 1027–1030.
Murray, E.A., 1988. Subglacial erosion marks in the Kingston, Ontario, Canada Region: their distribution, form and genesis. M. Sc. Thesis, Queen's University, Canada, 177pp.
Normark, W.R., Piper, D.J.W., Hess, G.R., 1979. Distributary channels, sand lobes, and mesotopography of Navy Submarine Fan, California Borderland, with application to ancient fan sediments. Sedimentology 26, 749–774.
Nye, J.F., 1976. Water flow in glaciers: jökulhlaups, tunnels and veins. Journal of Glaciology 17, 181–207.
Ó Cofaigh, C., 1996. Tunnel valley genesis. Progress in Physical Geography 20, 1–19.
Odynsky, W., 1962. Soil zones of Albert, 3rd Edition. Research Council of Alberta Map, scale 1 : 3 000 000.
Pair, D.L., 1997. Thin film, channelized drainage, or sheetfloods beneath a portion of the Laurentide Ice Sheet: an examination of glacial erosion forms, northern New York State. Sedimentary Geology 111, 199–216.
Pollard, A., Wakarini, N., Shaw, J., 1996. Genesis and morphology of erosional shapes associated with turbulent flow over a forward-facing step. In: Ashworth, P.J., Bennett, S.J., Best, J.L., McClelland, S.J. (Eds.), Coherent Flow Structures in Open Channels. Wiley, Chichester, pp. 249–265.
Prest, V.K., 1983. Canada's heritage of glacial features. Geological Survey of Canada, Miscellaneous Report 28, 119pp.
Rains, R.B., Shaw, J., Skoye, K.R., Sjogren, D.B., Kvill, D.R., 1993. Late Wisconsin subglacial megaflood paths in Alberta. Geology 21, 323–326.
Rampton, V.N., 2000. Large-scale effects of subglacial meltwater flow in the southern Slave Province, Northwest territories, Canada. Canadian Journal of Earth Sciences 37, 81–93.
Russell, A.J., Knudsen, O., 1999. Controls on the sedimentology of the November 1996 jökulhlaup deposits, Skeidararsandur, Iceland. Special Publication International Association Sedimentology 28, 315–329.
Sagawaki, T., Harawaka, K., 1997. Erosion of bedrock by subglacial meltwater, Soya Coast, East Antarctica. Geografiska Annaler 79, 223–238.
Sawyer, B., 2000. Drumlins of the Prince George region, British Columbia. M.Sc. Thesis, University of Alberta, Canada, 200pp.
Sharpe, D.R., 1987. The stratified nature of drumlins from Victoria Island and Southern Ontario, Canada. In: Menzies, J., Rose, J. (Eds.), Drumlin Symposium. Balkema, Rotterdam, pp. 185–214.
Sharpe, D.R., Shaw, J., 1989. Erosion of bedrock by subglacial meltwater, Cantley, Quebec. Geological Society of America Bulletin 101, 1011–1020.
Shaw, J., 1983. Drumlin formation related to inverted meltwater erosional marks. Journal of Glaciology 29, 461–479.
Shaw, J., 1988. Subglacial erosional marks, Wilton Creek, Ontario. Canadian Journal of Earth Sciences 25, 1256–1267.
Shaw, J., 1989. Drumlins, subglacial meltwater floods and ocean responses. Geology 17, 853–856.
Shaw, J., 1994. Hairpin erosional marks, horseshoe vortices and subglacial erosion. Sedimentary Geology 91, 269–283.
Shaw, J., 1996. A meltwater model for Laurentide subglacial landscapes. In: McCann, S.B., Ford, D.C. (Eds.), Geomorphology sans frontière. Wiley, Chichester, pp. 182–226.
Shaw, J., Kvill, D., 1984. A glaciofluvial origin for drumlins of the livingstone Lake Area, Saskatchewan. Canadian Journal of Earth Sciences 21, 1442–1459.
Shaw, J., Sharpe, D.R., 1987. Drumlin formation by subglacial meltwater erosion. Canadian Journal of Earth Sciences 24, 2316–2322.
Shaw, J., Gilbert, R., 1990. Evidence for large-scale subglacial meltwater flood events in southern Ontario and northern New York State. Geology 18, 1169–1172.
Shaw, J., Kvill, D., Rains, R.B., 1989. Drumlins and catastrophic subglacial floods. Sedimentary Geology 62, 177–202.
Shaw, J., Faragini, D., Kvill, D.R., Rains, R.B., 2000. The Athabasca fluting field, Alberta, Canada: implications for the formation of large-scale fluting (erosional lineations). Quaternary Science Reviews 19, 959–980.
Shaw, J., Rains, B., Eyton, R., Weissling, L., 1996. Laurentide subglacial outburst floods: landform evidence from digital elevation models. Canadian Journal of Earth Sciences 33, 1154–1168.
Shetsen, I., 1987. Quaternary geology of southern Alberta. Alberta Research Council Map, scale 1 : 500 000.
Shetson, I., 1990. Quaternary geology of central Alberta. Alberta Research Council Map, scale 1 : 500 000.
Shoemaker, E.M., 1991. On the formation of large subglacial lakes. Canadian Journal of Earth Sciences 28, 1975–1981.
Shoemaker, E.M., 1992a. Subglacial floods and the origin of low relief ice sheet lobes. Journal of Glaciology 38, 105–112.
Shoemaker, E.M., 1992b. Water sheet outburst floods from the Laurentide Ice Sheet. Canadian Journal of Earth Sciences 29, 1250–1264.
Shoemaker, E.M., 1994. Reply to comments on 'Subglacial floods and the origins of low-relief ice-sheet lobes' by J.S. Walder. Journal of Glaciology 40, 201–202.
Shoemaker, E.M., 1995. On the meltwater genesis of drumlins. Boreas 24, 3–10.
Shoemaker, E.M., 1999. Subglacial water-sheet floods, drumlins and ice sheet-lobes. Journal of Glaciology 45, 201–213.

Sjogren, D.B., 1994. Geomorphology of the Coronation-Spondin scabland. M.Sc. Thesis, University of Alberta, Canada.

Sjogren, D.B., 1999. Formation of the Viking Moraine, east-central Alberta: geomorphic and sedimentary evidence. Ph.D. Thesis, University of Alberta, Canada, 219pp.

Sjogren, D.B., Rains, R.B., 1995. Glaciofluvial erosional morphology and sediments of the Coronation–Spondin scabland, east-central Alberta. Canadian Journal of Earth Sciences 32, 565–578.

Sjogren, E.C., 1999. Geomorphology of the Tawatinaw area. M.Sc. Thesis, University of Alberta, 112pp.

Skoye, K.R., Eyton, J.R., 1992. Digital analysis of low-relief topography in a Landsat scene in south-central Alberta. Canadian Journal of Remote Sensing 18, 143–150.

Stalker, A. MacS., 1960. Ice-pressed drift forms and associated deposits in Alberta. Geological Survey of Canada, Bulletin 57.

Thelin, G.P., Pike, R.J., 1991. Landforms of the coterminous United States—a digital shaded relief portrayal. United States Geological Survey, Map 1-2206, scale 1 : 3 500 000.

Tinkler, R.J., Stenson, R.E., 1992. Sculpted bedrock forms along the Niagara escarpment, Niagara Peninsula, Ontario. Géographie physique et Quaternaire 46, 195–207.

Walder, J.S., 1994. Comments on 'Subglacial floods and the origin of low relief ice-sheet lobes' by E.M. Shoemaker. Journal of Glaciology 40, 199–200.

Whewell, 1860.

Worsley, P.W., 1997. The 1996 volcanically induced glacial mega flood in Iceland—cause and consequence. Geology Today, November–December, pp. 211–216.

Zelcs, V., Dreimanis, A., 1997. Morphology, internal structure and genesis of the Burtnieks drumlin field Northern Vidzeme, Latvia. Sedimentary Geology 111, 73–90.