



PERGAMON

Quaternary International 90 (2002) 1–4



Preface

The role of outburst floods and glacial meltwater in subglacial and proglacial landform genesis

The role of subglacial meltwater in shaping the glacial landscape has been a topic of considerable discussion in recent years. To explore this subject, a special session entitled “Subglacial processes: a review of past and recent findings” was convened at the joint Canadian Quaternary Association (CANQUA) and Canadian Geomorphology Research Group (CGRG) meeting in August 1999 in Calgary, Alberta. Most of the papers in this volume were presented at this special session.

Modern glacier studies provide an understanding of processes that, depending on the scale of the study, are applicable to paleo-ice sheet reconstructions. Studies of modern glaciers have produced useful analogs of Pleistocene glacial processes, such as small-scale flute formation, ice-marginal sedimentation, and thrust-moraine formation. However, we have no modern analogs for large-scale (10–100 km wide), subglacial meltwater floods that some have suggested were responsible for forming large suites of associated glacial landforms such as drumlins, mega-flutings and ribbed moraines, which dominate the glacial landscapes of the Northern Hemisphere (Shaw et al., 1989; Fisher and Shaw, 1992; Rains et al., 1993). Although we can use the Greenland and Antarctic Ice Sheets as analogs, our understanding of their subglacial conditions is presently based on a few drill holes and geophysical data, plus attempts to model their behavior. In contrast, the subglacial terrain of the extinct Pleistocene ice sheets is preserved throughout large areas of the Northern Hemisphere.

The papers in this volume contribute to our understanding of subglacial processes by interpreting large-scale landforms and sediment assemblages left by the Laurentide Ice Sheet, that in most cases require large flows of meltwater to form them. However, the lack of a modern analog does not mean that catastrophic floods could not have occurred during the Pleistocene beneath mid-latitude ice sheets. Only recently have glacier surges, jökulhlaups and ice-dammed failures become known in the modern world, with their details and related processes still poorly understood. Rare events, however, are now known to have produced some

Pleistocene landscapes, for example the formation of large channels in the interior plains of North America (Kehew and Lord, 1987) and the Channeled Scabland of Washington state (Bretz, 1969; Baker, 1973) both of which formed by the failure of glacier dams and the release of stored meltwater.

A common thread in the papers of this volume is that some glacial landscapes may have formed by huge subglacial floods in days or weeks near the end of the last glacial maximum. If correct, then the Earth's climate must progress through an entire glacial cycle to create the conditions required to form these landscapes. From a uniformitarian viewpoint, the time scale is very large (~100 ka), the processes are relatively simple (fluvial erosion that can be modeled in a flume [Shepherd and Schumm, 1974]), and catastrophic floods are an expected result. By recognizing that the past may be a key to the future, ephemeral, subglacial catastrophic floods caused by the drainage of large lakes may have been an integral component of the glacial system for which there are no modern analogs.

Subglacial meltwater flow has been described from modern glaciers and reconstructed mid-latitude paleo-ice sheets. Subglacial meltwater flow can occur in channels (R or N channels), tunnel valleys and in more dispersed ways such as porewater flow, thin films, and in linked-cavity or braided canal networks (Benn and Evans, 1998). Papers in this volume describe landforms produced by flow in both discrete channels and dispersed systems. Cross-cutting relationships between tunnel channels and sediments (Fisher and Taylor, 2002), fluting fields (Beany and Shaw, 2000; Munro-Stasiuk and Shaw, 2002), and transverse bedforms, (Beany and Shaw, 2000; Beaney, 2002) suggest that distributed sheetflows evolved into discrete tunnel channel flows, and in some cases (Fisher and Taylor, 2002; Sjogren et al., 2002) to esker formation in R channels.

The first paper in the volume, by Shaw (2002), introduces and reviews the subglacial meltwater hypothesis for glacial landform development, which he and others have developed over the past 20 years. This

hypothesis invokes large subglacial sheetflows to explain drumlins, Rogen (ribbed) moraine, hummocky terrain, tunnel channels and scoured bedrock surfaces (S-forms). The meltwater hypothesis has been used to explain drumlin formation in northern Saskatchewan as a glaciofluvial cavity infilling at glacier bases. Since then, it has been used to explain streamlined bedrock surfaces with erosional marks as well as drumlins composed of bedrock and a variety of glacial and non-glacial sediment. The hypothesis proposes that turbulent, sediment charged sheetflows sculpted bedrock and sediment surfaces and the drumlins are remnants of a more extensive stratigraphy. Shaw and coworkers have also explored the impact such floods may have had on extraglacial environments including the oceans. Abrupt releases of subglacial meltwater may have resulted in rapid rises in sea level, changes in ocean stratification and sea surface temperatures, which in turn may have impacted climate at the end of the Pleistocene. Shaw recounts the history of the subglacial meltwater hypothesis, summarizing field evidence, hypothesis generation, and analog validation.

Four papers focus on tunnel channel genesis. Cutler et al. (2002) present sedimentological evidence from outwash fans at the mouths of tunnel channels to reconstruct outburst floods along the western margin of the Green Bay lobe in Wisconsin. They describe massive boulder deposits containing clasts up to 2 m in average diameter that may have been transported as traction carpets at the base of a turbulent flow with a discharge of at least several hundred m^3s^{-1} . The authors discuss a variety of meltwater sources for the flow and conclude that the most likely source was a subglacial reservoir behind a frozen ice margin (Cutler et al., 2000).

The next paper is by Sjögren et al. (2002), who describe different types of tunnel channels and different stages in tunnel channel formation in east-central Alberta and south-central Michigan. They postulate three types of channels, representing successive development stages: aligned trains of depressions (Type 1); crenulated or beaded channels (Type 2); and channels with sharply defined margins but with some constrictions and expansions (Type 3). After demonstrating that these forms are likely subglacial in origin, Sjögren et al., discuss morphological analogs produced in flumes, proglacial floodways such as the Channeled Scabland, and modern fluvial environments. They describe the subglacial roughness elements that produced macro-turbulent eddies that may have initiated the tunnel channels. Importantly, this paper illustrates that tunnel channels are glaciofluvial in origin, may be preserved in varying degrees of development, may not at first be recognized as tunnel channels, and many circular closed depressions within them are large potholes that could be confused with kettles.

Rains et al. (2002) describe three tunnel channels in the Porcupine Hills of southwestern Alberta. The convex-upward long profiles of these channels are interpreted as evidence for pressurized subglacial meltwater flows beneath about 200–400 m of ice near the periphery of the Laurentide Ice Sheet. The tunnel channels are discussed in the context of large, late-glacial subglacial meltwater flows that swept over much of southern Alberta (Rains et al., 1993; Shaw, 1996). Broad sheetflows supplied the water that carved the channels. Rains et al. suggest that Paleocene sand-stone and shale bedrock eroded during channel formation was transported towards the Gulf of Mexico by the Milk-Missouri-Mississippi River system.

The fourth paper on tunnel channels, by Beany (2002), describes an anabranching tunnel channel network in southeastern Alberta that dissects a preglacial drainage divide. The channels are up to 100 m deep, 5 km wide, and have convex-up longitudinal profiles. The convex profiles and the lack of a sediment fill, other than thin Holocene alluvium, leads Beany to conclude that the channels are not ice-marginal features. She discusses various hypotheses for tunnel channels, including differential glacial erosion and steady-state erosion by migrating R-channels (Boulton and Hindmarsh, 1987), and concludes that subglacial meltwater flow is required for their formation. She points out that, in contrast to tunnel channels in Wisconsin (Clayton et al., 1999; Cutler et al., 2002) but like the Porcupine Hills tunnel channels of Rains et al. (2002), no outwash fans or moraine systems occur at the distal end of the channels.

The papers by Beany (2002), Rains et al. (2002), and Sjögren et al. (2002) briefly mention that the channelized meltwater flows they invoke may have been part of a larger distributed sheetflow that produced streamlined fluting and transverse bedforms. The sixth paper in the volume, by Munro-Stasiuk and Shaw (2002), hypothesizes a 50-km-wide sheetflow to explain the fluted terrain of the Blackspring Ridge flute field in south-central Alberta. The flutes are up to 15 km long and are composed of bedrock and preglacial sand and gravel, with some granite erratics on the surface. The flutes are interpreted as meltwater erosional landforms because they consist of undisturbed sediment and bedrock, have boulder lags, and are similar in form to classic water-sculpted flute marks.

The last paper in the volume, by Fisher and Taylor (2002), describes extensive inter-till boulder gravel deposits in south-central Michigan. A stratigraphic sequence consisting of basal till overlain by sand and gravel, boulder gravel, and patchy glaciolacustrine sediment, which in turn is capped by supraglacial melt-out till and/or debris flows is found in numerous pits within a small area. Clast lithology analysis

indicates a change in lithology up-section that mimics the change in bedrock lithology up-ice of the study area. These lithology data, together with the interpretation that the lower till is 'basal' and the upper till is 'supraglacial', suggest that the deposits record a single ice advance, and that the inter-till boulder gravel was deposited by a subglacial meltwater sheetflow 15 km wide.

Two criticisms of the meltwater flood hypothesis center on the enormous reservoirs required to produce the floods and the depositional sites of the eroded sediment. Large subglacial lakes were discovered in Antarctica 30 years ago (Oswald and Robin, 1973), and recently more subglacial lakes have been identified (Dowdeswell and Siegert, 1999). Siegert and Bamber (2000) suggest that these lakes occur at the head of ice streams. Munro-Stasiuk (2000) has recently documented subglacial glaciolacustrine sediment within preglacial valleys in southern Alberta, and Shoemaker (1999) suggests that basins of the Great Lakes acted as subglacial reservoirs. Research into paleo-subglacial reservoirs is needed to test and advance the meltwater hypothesis.

The second line of criticism relates to the locations of sediment and bedrock eroded by subglacial meltwater in forming drumlins, some Rogen (ribbed) moraine, hummocky terrain and tunnel channels. If meltwater sculpted these forms, then large quantities of sediment were deposited somewhere. Shaw (1996) and Shaw et al. (1996) suggest that the coarse gravel in the Mississippi fan in the Gulf of Mexico is evidence for subglacial meltwater floods from the Laurentide Ice Sheet. However work is needed on other possible sediment repositories, and distinguishing between subglacial floods and proglacial-lake floods in the sedimentary record. Research in areas down flow (water or ice) of erosional landforms may elucidate the origin of subglacial landforms (by meltwater, ice, deforming bed, or a combination thereof) and hence, lead to a better understanding of subglacial processes.

In conclusion, the papers in this volume present evidence that subglacial meltwater floods played an important role in shaping the landscape of glaciated North America. Hopefully, they will stimulate future studies that test and refine the meltwater hypothesis.

This volume is dedicated to the memory of E.M. Shoemaker. We thank the following persons for their reviews of papers submitted for publication in this volume: Victor Baker, Lee Clayton, Robert Gilbert, Mark Johnson, Alan Kehew, Andrew Kozlowski, Grahame Larsen, Gaywood Matile, Jan Piotrowski, David Sharpe, Martin Siegert, David Sugden, Harvey Thorleifson, and William Warren.

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