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Palaeo-ice streams: an introduction

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Ice streams are narrow fast-flowing zones within ice sheets, and in the case of Antarctica are responsible for draining up to 90% of the mass from the ice sheet. It has been shown that Quaternary ice sheets were profoundly, and arguably catastrophically, influenced by the operation of transitory ice streaming. The palaeo-ice stream that operated through Hudson Strait for example, destabilized the Laurentide Ice Sheet, changed its configuration and thickness, and the resultant iceberg melt cooled North Atlantic waters enough to alter ocean circulation and produce $\sim$4°C flips in climate on abrupt time scales.

It is imperative for palaeo-glaciological reconstructions that we can identify palaeo-ice stream tracks, elucidate the controls on ice-stream activation and functioning, and assess their mass balance effects on ice-sheet dynamics and retreat. Such a process and palaeogeographic knowledge will lead to a better appreciation of the role that ice streams play in determining ice-sheet function and behaviour, and their interaction with ocean circulation and the wider climate system. Our ultimate aim must be to develop this aspect of science such that we can use palaeoglaciology, inclusive of ice streams, to understand how abrupt climate changes have occurred in the past, and use such knowledge to inform predictive modelling of the likely responses of Antarctic and Greenland Ice Sheets to future climate forcing. Now that we recognize the significance of ice streams, the major challenge in glaciology and Quaternary science is to understand where, how and why they do their thing.

Over the past 5 years there has been a strong research drive to find and understand ice streams, both in the contemporary settings of Antarctica and Greenland and for the great palaeo-ice sheets of the last glaciation. To reflect this and bring together knowledge on palaeo-ice streams the INQUA Commission on Glaciation organized the first *Palaeo-Ice Stream International Symposium*, which was held on 17–20 October 2001 at the University of Aarhus in Denmark, hosted by Jan A. Piotrowski with the assistance of David J. A. Evans and Chris D. Clark. Around 70 participants attended and 40 papers and posters were presented. Delegates were from western and eastern Europe, Scandinavia and North America, and importantly they covered the main themes of research activity. Stimulating keynote presentations were provided by Hans Petter Sejrup (University of Bergen) on the *Configuration, history and impact of the Norwegian Channel Ice Stream* and by Don Blankenship (University of Texas at Austin) on *The influence of subglacial geology on ice streaming processes and ice stream evolution in West Antarctica*. For the first time, a diverse set of researchers were brought together, such that interaction occurred between Quaternary scientists working on terrestrial evidence; geophysicists working on investigations of marine signatures; and with numerical modellers investigating the significance of ice streams and the fundamentals of basal ice-stream processes. Both well established and hitherto undiscovered palaeo-ice streams were reported, and with an unprecedented geographic spread including examples from the Laurentide, Cordilleran, Fennoscandian, British-Irish, Antarctic and Greenland ice sheets. After the symposium, a highly informative field trip was led by Flemming Jørgensen, Gunnar Larsen and Jan A. Piotrowski, across the island of Funen, where participants were exposed to the geological and geomorphological expression of a palaeo-ice stream bed and its margin.

A selection of articles from the symposium are published in this special issue, and we hope reflect some of the diversity and interplay between the main themes discussed. Of the well-known and most widely studied palaeo-ice streams, *John Andrews* (University of Colorado) and *Brian MacLean* (Geological Survey of Canada) report on the 'big daddy' of all ice streams and provide a review of the stratigraphy and chronology of the Hudson Strait Ice Stream and how it linked with North Atlantic Heinrich Events. This is the ice stream that started the ball rolling with regard to ice streaming as an important component of the climate system rather than just an interesting glaciological phenomenon. Probably one of the most complete ice-stream records so far documented is reported by *Hans Petter Sejrup* and *colleagues*, whose article reviews the wide range of evidence for the Norwegian Channel Ice Stream. This one has it all, from distal meltwater plumes, a large fan at its terminus fed by debris flows, an ice-stream bed composed of mega-scale glacial lineations, and a wealth of onshore geomorphologic and sedimentary evidence. These invited articles are deliberately of a review type so as to synthesize the large number of other more specific articles describing these important ice streams, as well as adding some further insights and questions for the future.

In an ideal world we would remove a few Antarctic ice streams, enabling us to walk with ease over their beds to examine the geology in detail. This would

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permit a detailed characterization of the sedimentary record produced by ice streaming, which would help us find palaeo examples from elsewhere. Failing this, many researchers have been utilizing published accounts of geophysical and coring investigations of Antarctic ice streams along with their own theorizing and observations of palaeo-ice streams to try and build up a template or landsystem model of what the record of ice streaming should look like. Many of the articles in this volume tackle this issue directly or contribute by describing case studies of individual ice streams. *Colm Ó Cofaigh* and colleagues (Scott Polar Research Institute) review the classical trough mouth fans found at the distal end of ice streams, adding their own observations from swath bathymetric data on the continental shelf of Antarctica. From these they build a conceptual model of continental slope sedimentation in front of palaeo-ice streams. The grounding zone is examined by *Ian Howat* (University of California) and *Eugene Domack* (Hamilton College) using acoustic profiling in the western Ross Sea. This allowed them to refine pre-existing models of grounding zone sedimentation and reconstruct aspects of the history of ice retreat in the Ross Sea since the last glacial maximum. Oscillations of ice-stream margins are examined by *David Evans* (University of Glasgow) and *Colm Ó Cofaigh* (Scott Polar Research Institute) using the case of the Irish Sea Ice Stream. They identify a range of diagnostic landform and glacitectonic criteria that characterize such marginal fluctuations and comment on processes leading to sediment transfer towards the margins. The signature of fast flow within subglacial tills is examined by *Olav Lian* (University of London) and colleagues, where they report that till texture and fabric, stone shape and provenance, stone pavements and glaciotectonic structures can be utilized to distinguish between fast stream and slow sheet, type flow regimes. Taken together, these articles significantly add to our evolving view of the sedimentary imprint that ice streams leave behind.

Ice-stream processes are tackled in a range of articles utilizing numerical modelling and field investigations. A combination of both techniques has been applied to the vexing problem of what causes an ice stream to cease fast flow. *Poul Christoffersen* (Technical University of Denmark) and *Slawek Tulaczyk* (University of California) note a till consolidation profile related to the Baltic Ice Stream (in Denmark) that is reverse to the usual expectation, and hypothesize that this is due to drawdown of cold ice to the ice-stream base that turned off its activity by basal freeze-on. The feasibility is tested by numerical modelling. By bringing together some very detailed field observations and examining clast-compositional data from tills, *Kurt Kjær* (Lund University) and colleagues, reconstruct three glacier advances of the southwest Scandinavian Ice Sheet onto Denmark. They use the degree and nature of erratic dispersal between these three events to distinguish between advances of sheet-flow type and those that were by ice streaming. Furthermore, they use their erratic dispersal data to speculate on the basal processes that operated and permitted ice streaming, inferring that the high dispersal distances (ice-stream phase) reflect the degree of ice-bed coupling. *Knut Stalsberg* (Geological Survey of Norway) and colleagues analyse deposits and landforms on Jæren, southwest Norway attributed to the Norwegian Channel Ice Stream. Glacial lineations with complex internal composition including glaciomarine deposits, glaciofluvial sand and till indicate a low-gradient, fast-moving ice whose high velocity was possibly facilitated by a soft, deforming substratum. *Maris Rattas* (University of Tartu) and *Jan A. Piotrowski* (University of Aarhus) examine the properties of drumlins produced by a small ice stream in Estonia. They demonstrate relationships between drumlin size and till grain size with underlying bedrock permeability, which allows them to comment on likely processes of formation. They argue that drumlin growth was enhanced in areas of relatively well-drained, coarse-grained till within a subglacially deforming bed. Using numerical simulations of Ice Stream C in West Antarctica, *Marion Bougamont* and *Slawek Tulaczyk* (University of California) examine sub-ice stream glacial erosion and transport. This has a central bearing on the long-running controversy over whether subglacial till is transported by viscous or plastic deformation. A problem with plastic deformation has been in explaining the observed high volumes of sediment discharged. The authors argue that this may be reconciled by allowing a bumpy ice base sliding across sediment to plough through the till, facilitating a downstream sediment flux. Two papers deal with ice streams strongly controlled by topographic troughs. *Adrian Hall* (University of Edinburgh) and *Neil Glasser* (University of Wales) describe ice streaming in the mountains of Scotland, and conclude that many ice-stream locations are pre-determined by the location of pre-glacial valley geometries. They arrive at this result by comparing their modelled ice-sheet experiments, which predict zones of cold-based and warm-based ice, with field evidence for these basal regimes. For a still-existing and topographically controlled ice stream, (Jakobshavns Isbrae, Greenland), *Antony Long* and *David Roberts* (University of Durham) use relative sea level data to constrain Late Weichselian retreat of the ice stream and make estimates of the calving rate.

A third and important theme, of course, is in finding and documenting further palaeo-ice streams. Five papers do this, and contribute to enhancing our understanding of what ice-stream geology looks like and try to elucidate what the important processes were. *Michael Houmark-Nielsen* (University of Copenhagen) investigates an 'old' (i.e. pre-deglacial) ice-stream record that cannot be identified by its geomorphological imprint because it was likely erased by later flow events. However, by examining the till stratigraphy, glaciotectonic deformation and dispersal of erratics, he is able to identify the Kattegat Ice Stream which flowed southwards from Norway onto Denmark. Also over Denmark, a younger (deglacial) ice stream has been identified by *Flemming Jørgensen (Vejle Amt)* and *Jan A. Piotrowski* (University of Aarhus). Its route is marked by a drumlin field with an abrupt margin tracking around the island of Funen. This is a part of the Baltic Ice Stream and is the area that participants visited on the post-symposium field excursion. It is argued that fast flow was achieved through a varying (in time and space) alternation between bed deformation, which produced drumlins and basal sliding across a thin-water film. In the Laurentide Ice Sheet a further nine palaeo-ice streams have been identified. *Krister Jansson* and colleagues (Stockholm University) used aerial photographs and satellite images to investigate a complicated area of flow traces that record ice flow from a Quebec dome northwards into Ungava Bay and Hudson Strait. They identify eight small ice-stream imprints that in part overlap each other, indicating considerable dynamism in ice-stream switching. Somehow these ice streams must be related to the Hudson Strait Ice Stream and can only have operated when Hudson Strait was either ice free or was occupied by an ice stream with a low surface profile. Much further west, in the Keewatin dome, *Chris Stokes* (University of Reading) and *Chris Clark* (University of Sheffield) report and describe the characteristics of a major ice stream that played a large part in final deglaciation. Utilizing bedform mapping from satellite images they reconstruct its dimensions and demonstrate that bedform elongation matches with expected ice velocity variation within an ice stream. The Dubawnt Lake Ice Stream has no topographic control on its position and they speculate that it was triggered by ice drawdown into a (known) proglacial lake thus explaining why it occurred in this location.

We hope that this collection of articles will help advance and accelerate future understanding of palaeo-ice streams and that the wider research community will appreciate the significance of ice streams and the variety of pertinent investigative techniques. We have moved from an era where palaeo-ice sheets were thought to have responded in an ordered and predictable pattern of advance and retreat, in harmony with Milankovitch solar forcing, to a situation of ultra-abrupt (10 years!) climate flips in which ice streaming undoubtedly played a part. Many questions remain. Over the coming years we need to evolve a clearer picture of the record that ice streams leave behind, and use this to discover and document further palaeo-ice streams and to critically evaluate previously proposed examples. Once complete, we can tackle the big questions. For example, what role did ice streaming play in rapid terminations at the end of glacial cycles? Given the easy access to palaeo-ice-stream beds in contrast to expensive and limited access to those under contemporary ice sheets, there are excellent opportunities for Quaternary scientists to contribute to the major glaciological challenges of today; working out what 'seeds' an ice stream to initiate, what controls their location, what causes them to suddenly cease fast flow, and how come they flow so fast?

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