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An introduction to glaciated margins: the sedimentary and geophysical archive

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Abstract: A glaciated margin is a continental margin that has been occupied by a large ice mass, such that glacial processes and slope processes conspire to produce a thick sedimentary record. Ice masses take an active role in sculpting, redistributing and reorganizing the sediment that they erode on the continental shelf, and act as a supply route to large fan systems (e.g. trough mouth fans, submarine fans) on the continental slope and continental rise. To many researchers, the term ‘glaciated margin’ is synonymous with modern day areas fringing Antarctica and the Arctic shelf systems, yet the geological record contains ancient examples ranging in age from Precambrian to Cenozoic. In the pre-Pleistocene record, there is a tendency for the configuration of the tectonic plates to become increasingly obscure with age. For instance, in the Neoproterozoic record, not everyone agrees on the location of rift margins and some fundamental continental boundaries remain unclear. Given these issues, this introductory paper has two simple aims: (1) to provide a brief commentary of relevant Geological Society publications on glaciated margins, with the landmark papers highlighted and (2) to explain the contents of this volume.

Glaciated margins occur in modern and ancient high-latitude settings and record the growth and recession of ice masses over continental shelves, slopes and rises. They are commonly assumed to be passive continental margins with a glacial overprint, but can equally encompass more active tectonic settings such as rift basins. The processes of ice sheet sculpting (to produce characteristic subglacial bedforms), sediment erosion and transport, and widespread and extensive sediment deposition (most spectacularly on continental slopes) all play a part. Such margins are of widespread interest to an interdisciplinary group of earth scientists. These range from geomorphologists and geophysicists focused on using subglacial landforms to produce ice sheet reconstructions, geologists with similar goals using sediment architecture, and to those interested in resource prospecting, notably hydrocarbon exploration. This volume aims to showcase a cross-section of research on glaciated margins from the very ancient (Cryogenian) to the present day. The hope is that through the long lens of the geological record, research on modern glaciated margins can take lessons from the ancient record and vice versa.

Background

Glaciated margins and the Geological Society of London: setting the scene

The Geological Society of London has a tradition of publishing landmark volumes on what we can describe as ‘glaciated margins science’. As a rapidly evolving research field, a brief introduction such as this cannot endeavour to provide a thorough review of all noteworthy publications in the wider literature, but it is fitting and appropriate to consider important

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volumes from the Geological Society of London Publishing House. Twelve years on from *Glacimarine Environments: Processes and Sediments* (Dowdeswell & Scourse 1990), the Geological Society, London, Special Publication 203 focused on the topic of *Glacier-Influenced Sedimentation on High-Latitude Continental Margins* (Dowdeswell & Ó Cofaigh 2002). This volume showcased several fundamental aspects of northern and southern hemisphere Quaternary and modern margins. In terms of sedimentology, these were: (1) the architecture of glacially fed slopes and, in particular, trough mouth fan (TMF) architecture (O'Grady & Syvitski 2002; Dowdeswell *et al.* 2002; Taylor *et al.* 2002); (2) the processes of mass wasting contributing to the development of TMFs (Elverhøi *et al.* 2002; Talling *et al.* 2002; Ó Cofaigh *et al.* 2002); (3) glacio-marine sedimentology in general (Hambrey *et al.* 2002; Davison & Stoker 2002; Evans *et al.* 2002; Vaughn Barrie & Conway 2002; Jaeger 2002; Powell & Cooper 2002; Andrews & Principato 2002; Wilson & Austin 2002; Woodward *et al.* 2002); and (4) geomorphology, which included spectacular images of sub-ice stream lineations from the Ross Sea, Antarctica (Shipp *et al.* 2002) and the mid-Norwegian continental margin (Ottesen *et al.* 2002), with three-dimensional seismic data revealing evidence of glacial lineations within buried sediment packages of Pleistocene age (Rafaelsen *et al.* 2002). The oldest glacial deposits described in that volume were Late Oligocene (*c.* 28.5–23.8 Ma; Hambrey *et al.* 2002).

Between Special Publication 203 and the present book, three other volumes have been published by the Geological Society of London pertaining to glaciated margins and shelves. The first of these, Special Publication 354, was edited by Martini *et al.* (2011) and was titled *Ice-Marginal and Periglacial Processes and Sediments*. Two papers in that volume, namely Lønne & Nemec (2011) and Keller *et al.* (2011), are of particular relevance to this book. Lønne & Nemec (2011) discuss the occurrence of, and interpretations for, end-moraines in tide water glaciers, whereas Keller *et al.* (2011) provide descriptions and interpretations of the Wajid Sandstone of SW Saudi Arabia – the latter correlative with the papers by **Tofaif *et al.* (2018)**, **Melvin (2018)**, **Hirst & Khatatneh (2018)** and, in part, by **Dietrich *et al.* (2018)** in the present volume.

The following year, Special Publication 368 entitled *Glaciogenic Reservoirs and Hydrocarbon Systems* was published, edited by Huuse *et al.* (2012). Without explicitly doing so, almost every chapter in that book was relevant to some aspect of glaciated margin science, in spite of the deliberately applied focus to oil and gas exploration. On Pleistocene margins, Moreau *et al.* (2012) delivered a seminal article on characterizing glaciogenic deposits using seismic data, with extensive and impressive mapping of tunnel valley networks. These enigmatic meltwater systems, commonly exhibiting unusual thalwegs suggesting an origin through subglacial meltwater incision, were given thorough treatment by van der Vegt *et al.* (2012). The tunnel valley theme continued with Andersen *et al.* (2012) describing Danish systems within the North Sea, Kristensen & Huuse (2012) describing multi-phase incision and infilling of these channels, Stewart *et al.* (2012) documenting multi-generational North Sea examples and Buckley (2012) documenting evidence for Early Pleistocene ice sheets in the North Sea. In the older record, Fielding *et al.* (2012) published an example of Cenozoic shelf architecture for glacio-marine sediments in McMurdo Sound, Antarctica. Looking back through geological time, the papers of Hirst (2012), Lang *et al.* (2012), Girard *et al.* (2012) and Douillet *et al.* (2012) all offered new data on the Late Ordovician glacial shelf record. These data from Algeria (Hirst 2012; Lang *et al.* 2012), Libya (Girard *et al.* 2012) and Jordan (Douillet *et al.* 2012) are of great value to readers of the present volume interested by the papers of **Dietrich *et al.* (2018)**, **Tofaif *et al.* (2018)**, **Hirst & Khatatneh (2018)** and **Melvin (2018)**. In a similar vein, the papers by Martin *et al.* (2012) and Bache *et al.* (2012) will be of interest to readers of **Horan *et al.* (2018)**, as they deal with aspects of the Late Paleozoic Ice Age.

The most recent contribution to glaciated margins science to be published by the Geological Society of London is the formidable Memoir 46, entitled *Atlas of Submarine Glacial Landforms.* This volume (Dowdeswell *et al.* 2016) contains a great wealth of data on northern and southern hemisphere case studies, focusing on the interpretation of geophysical data from modern marine glacial environments. The current volume does not seek to duplicate these earlier publications, but instead builds upon this previous research by presenting fundamental new data on extant glaciated margins, expanding the remit of glaciated margins research to older, deep-time examples (i.e. pre-Quaternary). This is achieved by featuring glaciated margins ranging from Cryogenian (*c.* 720 Ma), via the Late Ordovician (at *c.* 443 Ma) to the Early Permian (*c.* 299 Ma) in age. Thus the present volume provides the first attempt to capture snapshots of glaciated margins throughout the full range of geological time, with the exception of the Mesozoic era (because no glaciated margin of this age has been described).

Contents

Cryogenian glaciated margins

Little has been written about glaciated margins in the Cryogenian, which is to some extent surprising as glaciation in the Cryogenian is thought to share a

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close association with the fragmentation and rifting of the supercontinent of Rodinia (e.g. Eyles & Januszczak 2004). However, other researchers (e.g. Li *et al.* 2013) strongly disagree that there is such a link, stating that 'there is no clear association between continental rifting and the distribution of glacial strata, contradicting models that restrict glacial influence to regions of continental uplift'. Nevertheless, the glacial origins of the 'Sturtian' diamictite sections in the northern part of the Flinders Ranges of South Australia is well established, with this sequence revealing a depositional history on a steep slope, probably associated with a rift margin (Young & Gostin 1988, 1989, 1990, 1991). This sequence is considered to provide evidence of the first TMF within the Cryogenian record (Le Heron *et al.* 2014). Similarly, exceptionally well-exposed sections through the Chuos Formation in Namibia (Lechte *et al.* 2018) and Kingston Peak Formation in Death Valley (**Le Heron *et al.* 2018**) provide further evidence for the close association between rifting and Cryogenian glaciation, and provide a considerable amount of detail regarding the evolution of these past glaciated margins.

In Namibia, **Lechte *et al.* (2018)** demonstrate that diamictites and ironstones are interbedded, with no transition between these facies, a typical characteristic of Snowball Earth deposits of older Cryogenian age (Spence *et al.* 2016; Hoffman *et al.* 2017). Unlike other models that implicate rift processes to explain iron formation associated with glaciation, **Lechte *et al.* (2018)** envisage oxygenated fluids (e.g. sea brines) as a way to explain these unusual facies at an ancient glaciated margin, with ice margin fluctuation explaining how iron-rich deposits are then worked into the diamictites.

In the Death Valley area of the USA, **Le Heron *et al.* (2018)** review the issues associated with a mixed glacial and tectonic influence in producing a highly heterogeneous diamictite-rich succession. Noting dramatic variations in thickness, the occurrence of different numbers of submarine landslide deposits (olistostromes) in different outcrop belts, and no obvious consistent or predictable stratigraphic architecture, they question which Neoproterozoic outcrop belt is truly the most representative. This is an important issue for global correlation. They explain the regional differences by diachronous extensional faulting of the rifting glaciated margin during Cryogenian times.

Paleozoic glaciated margins

A trio of papers by **Melvin (2018)**, **Tofaif *et al.* (2018)** and **Hirst & Khatatneh (2018)** provide detailed insights into the Late Ordovician glacial shelf and margin record of Arabia. These papers provide much needed data on the Arabian plate because most (although not all) research in the last 15–20 years has focused on the extensively exposed (and until recently comparatively easy of access) Saharan outcrops. **Melvin (2018)** provides a detailed and thorough analysis of deformed, diamictite-rich strata, which are extensively exposed over wide areas of the Arabian Peninsula, both at outcrop in Saudi Arabia and in core datasets acquired in both hydrocarbon and water exploration. This paper characterizes the suite of subglacial deformation structures that developed as ice sheets advanced to the palaeoshelf margin beyond the present Persian Gulf, providing criteria for their recognition.

The other two papers on the Late Ordovician record focus on meltwater-related processes in both proximal and distal parts of the Arabian glaciated margin. **Tofaif *et al.* (2018)** provide the first detailed description and interpretation of cross-cutting palaeovalley features in the Tabuk area, NW Saudi Arabia. Remarkable palaeovalleys, tens of kilometres long and hundreds of metres wide, are filled almost entirely with sandstone and contain little that the Quaternary glacial geologist would recognize as glaciogenic sediments. Nevertheless, vestiges of striated pavements and convincing striated clasts are described, which allow the proposition of a glaciogenic origin for these valleys cut under increased hydrostatic pressure (e.g. van der Vegt *et al.* 2012). The features are in many ways similar to those previously described by Douillet *et al.* (2012) from a valley system in neighbouring Jordan.

Continuing with this meltwater theme, **Hirst & Khatatneh (2018)** provide a new depositional model for the distal glaciated margin of Jordan. Their paper is the most applied of the Late Ordovician trilogy, considering how well differentiated sandstone intervals were deposited in the context of reservoir potential in petroleum exploration. By contrast with **Tofaif *et al.* (2018)**, **Hirst & Khatatneh (2018)** describe comparatively unconfined systems of stacked subaqueous fans of much greater lateral extent than the tunnel valleys.

Cenozoic glaciated margins

Five papers in the present volume pertain to Cenozoic records of glaciated margins, namely those of **Passchier *et al.* (2018)**, **Gales *et al.* (2018)**, **Anderson *et al.* (2018)**, **Dietrich *et al.* (2018)** and **Lajeunesse *et al.* (2018)**. **Passchier *et al.* (2018)** deliver a multidisciplinary approach to understanding the sedimentary record of Wilkes Land, a passive continental margin in East Antarctica. They develop a sequence stratigraphic model that elucidates some of the background processes operating at high-latitude margins, even where ice sheets are absent. These processes include a stronger Coriolis effect on sediment distribution patterns, greater seasonality

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and suppressed tidal activity. In conjunction with the presence of ice sheets, a different suite of sequence stratigraphic models is been identified as being necessary to understand the depositional processes active on such margins. Beyond the physical sedimentology, **Passchier *et al.* (2018)** integrate major and trace element data into their analyses, with the variation in both Ba and Si being particularly useful in identifying sedimentary rhythms.

Gales *et al.* (2018) provide an original and highly useful comparison between TMFs located within both Arctic and Antarctic continental margin settings, comparing and contrasting the processes involved in the build-up of such fans in both hemispheres. By incorporating newly acquired data from 76 gravity cores across six drill sites recovered from the outer shelf and upper slope settings of TMFs with published data, they were able to demonstrate that Antarctic TMFs differ significantly from their Arctic counterparts. The Antarctic TMFs were found to be built-up from glaciogenic debris flows and shelf diamictons that are considerably coarser grained than the Arctic examples due to variations in runoff and river discharge between the two hemispheres.

Anderson *et al.* (2018) take a marine geophysical approach to understanding the record of Antarctic Ice Sheet development. These workers argue for the establishment of isolated ice caps on palaeohighs during the Late Oligocene, followed by a phase of basin fill. They propose that a more subdued bathymetry persisted in the eastern as opposed to the western Ross Sea. As cooling progressed from the mid-Miocene onwards, ice sheet expansion across the continental shelves was assisted by the funnelling of ice streams by cross-shelf troughs, most particularly in West Antarctica.

Major new insights into the glaciated margin architecture along the northern shore of the Gulf of St Lawrence are made in two closely related papers by **Lajeunesse *et al.* (2018)** and **Dietrich *et al.* (2018)** by combining detailed outcrop observations with shallow marine bathymetry data. In the only paper that explicitly links systems of completely different ages (Quaternary and Ordovician, *c.* 440 myr apart), **Dietrich *et al.* (2018)** compare and contrast the architecture of deglacial sedimentary systems using traditional outcrop logging and sedimentary facies analysis. They also document the architectural development of shelf margin delta systems and consider the role of isostatic rebound in their generation and modification. **Lajeunesse *et al.* (2018)** document the geomorphology and development of Late Wisconsian age grounding zone wedges using new swath bathymetric and seismic data along the northern shore of the Gulf of St Lawrence to demonstrate that they were constructed in response to three distinct phases of ice margin stabilization during overall retreat.

Summary

The final paper in the volume, by **Dowdeswell *et al.* (2019)**, considers different approaches to both modern and ancient margins and how an integrated approach is necessary to explain all the observed variations. Glaciated margin science is a rapidly progressing field and this volume captures a cross-section of approaches to both modern and ancient systems. Notably, in addition to new insights in modern northern and southern hemisphere systems, this volume adds considerably to our knowledge of glaciated margins throughout geological time by documenting Cryogenian, Ordovician and Late Paleozoic examples. Only by integrating observations between modern, recent and truly ancient examples – and embracing a range of approaches spanning marine geophysical approaches to outcrop sedimentology – can the full spectrum of variation in glaciated margin architecture be appreciated.

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