

Introduction: an *Atlas of Submarine Glacial Landforms*

J. A. DOWDESWELL^{1*}, M. CANALS², M. JAKOBSSON³, B. J. TODD⁴, E. K. DOWDESWELL¹ & K. A. HOGAN⁵

¹*Scott Polar Research Institute, University of Cambridge, Cambridge CB2 1ER, UK*

²*GRC Geociències Marines, Universitat de Barcelona, 08028 Barcelona, Spain*

³*Department of Geological Sciences, Stockholm University, Svante Arrhenius väg 8, 106 91 Stockholm, Sweden*

⁴*Geological Survey of Canada, Natural Resources Canada, PO Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada*

⁵*British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK*

*Corresponding author (e-mail: jd16@cam.ac.uk)

Glacial landforms and sediments exposed sub-aerially have been the subject of description, analysis and interpretation for more than a century (e.g. De Laski 1864; De Geer 1889). Indeed, such features provided important initial observations informing Louis Agassiz's ideas that ice was a key instrument in sculpting the landscape and that glaciers and ice sheets had extended to mid-latitudes during the past, implying that Earth's climate must have changed considerably through time (Agassiz 1840). It is only in the last few decades that attention has begun to focus on the marine evidence for the past growth and decay of ice sheets that is recorded in submarine landforms and sediments preserved on high-latitude continental margins. This interest has been driven, in part, by the recognition that sediments deposited below wave-base are often well preserved in the Quaternary geological record, and may be less subject to erosion and reworking than their terrestrial counterparts. In addition, new marine-geophysical technologies have enabled increasingly high-resolution imaging and penetration of the high-latitude seafloor, most notably using multibeam swath-bathymetric and three-dimensional (3D) seismic-reflection methods, and modern ice-strengthened and ice-breaking research vessels have allowed the effective deployment of these increasingly sophisticated instruments in the often ice-infested waters of the Arctic and Antarctic seas.

The geological record from high-latitude continental margins is now recognized to provide key information on former ice-sheet extent, the direction and nature of past ice flow and dynamics, and a well-preserved window on the detailed form and composition of former ice-sheet beds (e.g. Ottesen *et al.* 2005; Anderson *et al.* 2014; Jakobsson *et al.* 2014). The geometry and distribution of submarine glacial landforms on the seafloor, and the underlying glacial-sedimentary stratigraphic record with which they are associated, is the topic of this volume. The aims and purpose of the *Atlas* are: (1) to provide a comprehensive set of examples of the full range of *individual* submarine glacial landforms and *assemblages* of landforms produced beneath and at the marine margins of glaciers and ice sheets; and (2) to integrate this information over entire fjord-shelf-slope systems across the full climatic range of glacier-influenced marine settings, in order to better understand the morphology and architecture of glacimarine environments. This evidence is used to reconstruct the growth, decay and dynamics of past ice sheets, including those of Quaternary and more ancient ice ages.

The glacimarine environment present and past

Today, the glacier-influenced marine environment includes about 20% of the world's oceans (Fig. 1). Glaciers reach the sea in settings that range from grounded tidewater glaciers at fjord heads in Patagonia and SE Alaska to extensive water bodies beneath the huge floating ice shelves of Antarctica. The lowest latitude in which modern tidewater glaciers occur is in the fjords of Chilean Patagonia at 48° S, where water temperatures may be almost 10°C (e.g. Boyd *et al.* 2008; Dowdeswell & Vásquez 2013). This contrasts with the sub-zero values of the frigid waters

of East Antarctica, noting that normal-salinity ocean water freezes at about −1.8°C. The equatorward limit of ice-influence in modern and past oceans is represented by the presence of ice-rafted debris transported by far-travelled drifting icebergs, and by ploughmarks produced on the seafloor by the erosive action of their keels (Fig. 1) (e.g. Ruddiman 1977; Grousset *et al.* 1993; López-Martínez *et al.* 2011; Hill & Condron 2014).

At the Last Glacial Maximum (LGM) about 18–20 000 years ago, much of mid-latitude North America and western Eurasia was covered by huge ice sheets of about 13 and 5.5×10^6 km², respectively (e.g. Dyke *et al.* 2002; Svendsen *et al.* 2004; England *et al.* 2006; Hughes *et al.* 2016). In addition, the termini of many parts of the ice sheets on Greenland and Antarctica expanded out as far as the continental shelf edge (e.g. Anderson 1999; Anderson *et al.* 2002, 2014; Funder *et al.* 2011; Ó Cofaigh *et al.* 2013; RAISED Consortium 2014). Seafloor ploughmarks produced by the keels of deep-drafted icebergs show that drift took place as far south as Florida in the North Atlantic (Hill & Condron 2014), and glaciers themselves reached the sea west of New Zealand and the British Isles in the two hemispheres (e.g. Suggate & Almond 2005; Clark *et al.* 2012; Bradwell & Stoker 2015; Howe *et al.* 2015). The area of the world's oceans affected by ice and glacimarine sedimentation therefore increased dramatically under full-glacial climatic conditions (Fig. 1).

This shifting pattern of global ice extent, driven by astronomical variations in the Earth's orbit and enhanced by ice-ocean feedback processes (e.g. Hayes *et al.* 1976; Wilson *et al.* 2000; Broecker 2002; Galeotti *et al.* 2016), implies that high-latitude continental margins have been affected by glacier and ice-sheet growth and decay many times over the past few million years. These glacial-interglacial cycles, with a dominant periodicity of about 100 ka, are observed in isotopic records from ice sheets and marine sediments through the Quaternary (e.g. EPICA Community Members 2004; Lowe & Walker 2014). In fact, the inception of ice-sheet growth during the Cenozoic goes back to the Late Miocene in Greenland (e.g. Larsen *et al.* 1994; Solgaard *et al.* 2013) and to the Eocene in Antarctica (e.g. Anderson 1999; Wilson *et al.* 2013), marking the beginning of glacial sediment delivery to the polar seas.

Although the long-term climate of the Earth has been predominantly warmer than that of today, six ice ages, presumably comprising their own glacial-interglacial cycles (e.g. Sutcliffe *et al.* 2000), are present at still longer timescales in the geological record of the past billion years or so (e.g. Hambrey & Harland 1981; Deynoux *et al.* 1994; Arnaud *et al.* 2011). The occurrence of these ancient ice ages, such as those of the Permian, Late Ordovician and Precambrian, is inferred from remnant glacial and glacimarine rocks. Many of these ancient glacial rocks are from old shield regions far from plate margins, but some are also from residual glacimarine continental shelf and slope systems that have avoided subduction at active plate boundaries over timescales of hundreds of millions of years.

Whether glaciers and ice sheets are contemporary, or date from the Quaternary, Cenozoic or more ancient glaciations, the ice will have waxed and waned across continental margins as ice age

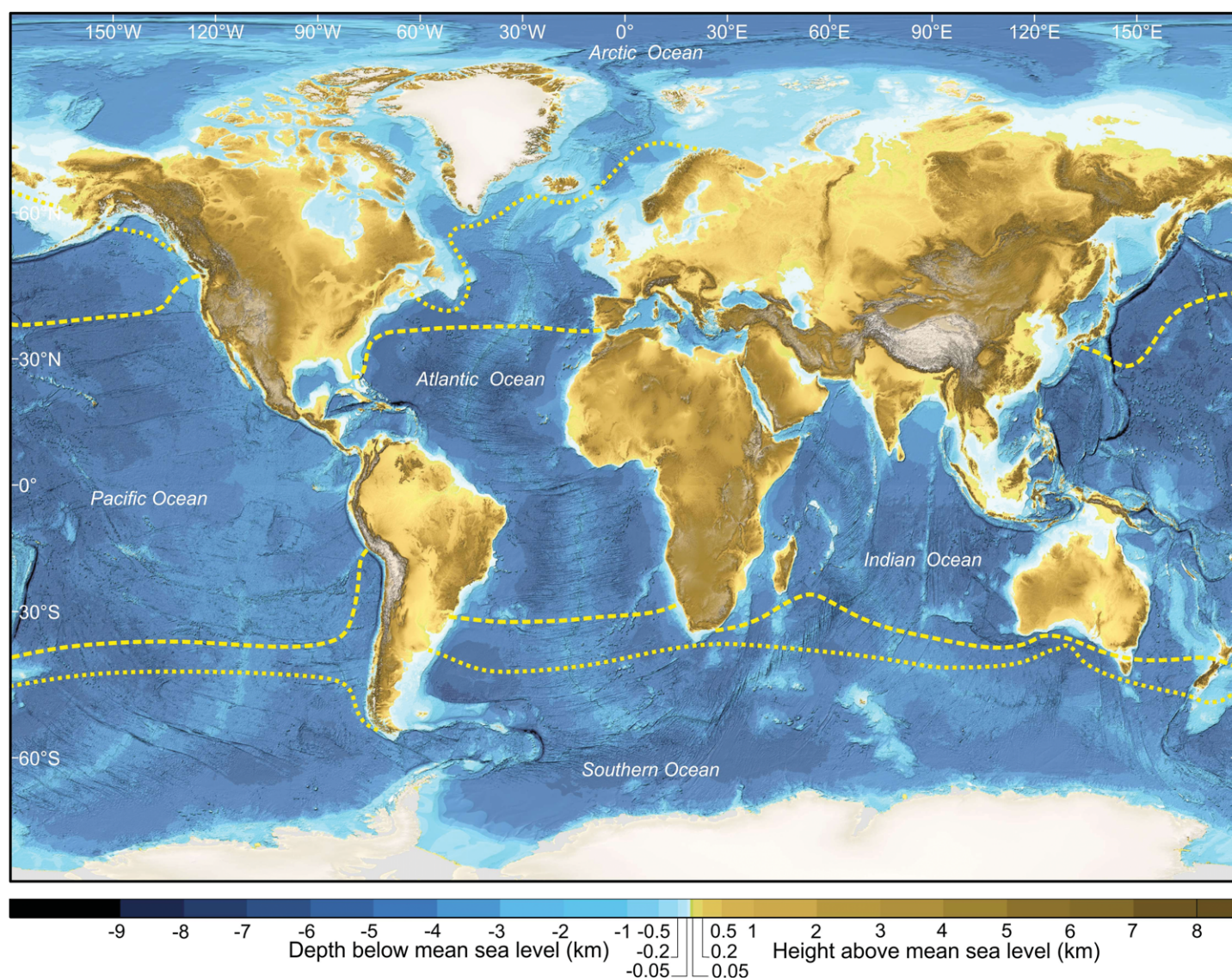


Fig. 1. The global distribution of glaciers and ice sheets and the glacier-influenced, or glacimarine, environment. The approximate modern (yellow dotted line) and Quaternary full-glacial (yellow dashed line) limits of ice-raftering and ice-keel ploughing of the seafloor are shown (modified from Anderson 1983). GEBCO World Map, Gall projection.

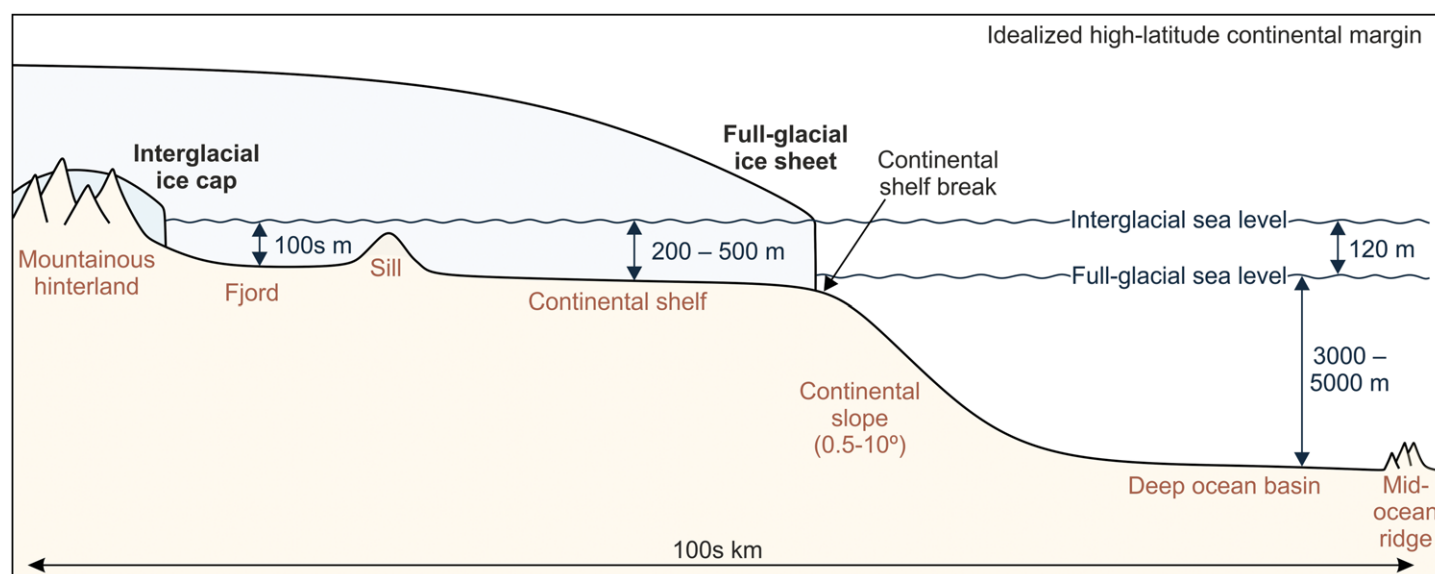


Fig. 2. Characteristic morphology of a high-latitude continental margin including fjord, shelf, slope and deep-ocean settings (modified from Dowdeswell *et al.* 2002). The changing position of ice-sheet termini, which is the focus of glacier-driven sedimentation, is shown for modern interglacial and Quaternary full-glacial times.

climate shifted between colder full-glacial and relatively warmer interglacial periods (Fig. 2). In today's present interglacial, the large, fast-flowing outlet glaciers of the Greenland Ice Sheet terminate at the heads of fjords; even the margins of the Antarctic Ice Sheet do not extend far onto the Antarctic continental shelf. Under full-glacial conditions, however, these ice sheets advanced to the shelf edge, and ice which is at present restricted to the mountains and fjords on the archipelagos of Svalbard and the Russian and Canadian Arctic also thickened and advanced across high-latitude continental shelves (e.g. Svendsen *et al.* 2004; England *et al.* 2006; Hughes *et al.* 2016).

The glacimarine sedimentary system

The significance of glacier and ice-sheet growth and decay for the glacimarine sedimentary system has been huge. Whereas today it is fjord heads that are the predominant focus for ice-proximal sediment delivery everywhere except in East and West Antarctica, and many high-latitude shelf-slope systems are areas of low sediment delivery, the situation under full-glacial conditions was very different. Ice sheets, and the fast-flowing ice streams that preferentially drained them, delivered very large quantities of ice, sediment and meltwater to the shelf edge, providing a high sediment flux to the adjacent continental slope and deep-ocean basin (e.g. Vorren *et al.* 1998; Dowdeswell & Siegert 1999). Many northern high-latitude continental shelves have also experienced shifts from full-glacial erosion and deposition beneath ice sheets to relatively ice-distal marine conditions during interglacials. The focus of sediment delivery from ice masses to the ocean has therefore shifted radically across fjord–shelf–slope–basin continental-margin systems between full-glacial and interglacial periods as ice sheets grew and decayed (Fig. 2) (e.g. Anderson 1999; Dowdeswell *et al.* 2002). In addition, along the length of marine ice-sheet termini, the delivery rate of ice and sediment varies greatly; there is, therefore, the additional distinction between the termini of fast-flowing ice streams and outlet glaciers compared with slow-flowing inter-ice stream areas (e.g. Ottesen & Dowdeswell 2009; Livingstone *et al.* 2012; Klages *et al.* 2013).

The sedimentary record of Quaternary ice sheets is often better preserved in the marine environment than when exposed on land. In sub-aerial settings, deglaciation produces huge amounts of eroding meltwater and the action of river, slope and aeolian processes continues during subsequent interglacials. By contrast, below the erosive action of active waves (often 10–30 m), many high-latitude shelf and slope systems are often hundreds of kilometres from the focus of interglacial sediment delivery from glaciers and rivers and are largely protected from erosion. Exceptions include, for example, reworking by deep-water currents and deep-keeled icebergs, and by slides which have remobilized slope sediments at scales ranging from fjord walls to the continental slope (e.g. Ó Cofaigh *et al.* 2002; Haflidason *et al.* 2004; Vanneste *et al.* 2006; Ottesen & Dowdeswell 2009). In fact, many high-latitude shelves contain an almost unmodified set of subglacial and ice-marginal landforms which have been preserved since ice last retreated between 15 and 10 ka ago and are being buried only slowly in ice-distal low-energy interglacial environments (e.g. Anderson *et al.* 2002; Ottesen *et al.* 2005; Dowdeswell *et al.* 2014). In addition, such landforms often remain recognizable even when draped by metres or more of subsequent sedimentation (e.g. Canals *et al.* 2000).

To illustrate the excellent preservation of seafloor landforms, submarine and sub-aerial glacial landforms produced beneath glaciers that have retreated a few kilometres from a Little Ice Age maximum only about 100 years ago may be compared (Fig. 3). It can be seen that whereas the glacier-derived sediments and landforms on a fjord floor remain largely unaltered (Fig. 3a), the landforms and sediments beyond the modern margin of a terrestrial glacier are being eroded and degraded by fluvial and mass-wasting

processes (Fig. 3b). In addition, the potential for longer-term preservation of submarine landforms in the geological record is far greater, given their likely burial by subsequent glacimarine and normal-marine sedimentation.

Taking this a stage further, the well-preserved subglacial and ice-marginal sediments and landforms on high-latitude shelves provide a very clear window on the process environment at the base of past glaciers and ice sheets at a detailed spatial resolution (e.g. Ottesen & Dowdeswell 2006) and over very large areas (e.g. Dowdeswell *et al.* 2004, 2014). Examples include evidence of the geometry of past subglacial hydrological systems, preserved as eskers and tunnel valleys, which appear to have formed in meltwater-rich environments at the southern margins of former mid-latitude ice sheets (e.g. Kehew *et al.* 2012; Stewart *et al.* 2013; Greenwood *et al.* 2016; Stewart 2016). This information is hard to match from beneath modern ice sheets of several kilometres in thickness, where drill holes, radar and seismic imaging have provided important insights into the contemporary ice–bed interface but are often very limited in terms of spatial resolution and coverage (e.g. Engelhardt *et al.* 1990; Anandakrishnan *et al.* 2007; King *et al.* 2007, 2009; Horgan *et al.* 2013).

Investigating glacimarine environments

It is only over the past few decades that detailed systematic scientific study of the glacier-influenced marine sedimentary record has taken place. The building and availability of research ships with ice-strengthened hulls and ice-breaking capability has allowed the investigation of modern environments infested by icebergs and sea ice. This has gone hand-in-hand with the development of marine-geophysical equipment that has enabled data of a progressively higher resolution to be obtained over increasing areas of the polar seas and right to the margins of modern glaciers and ice sheets. Indeed, the deployment of remotely operated vehicles (ROVs) and, most recently, autonomous underwater vehicles (AUVs), has occasionally allowed views beneath icebergs, sea ice and even under the edges of floating ice shelves, locations too hazardous for research ships (e.g. Powell *et al.* 1996; Nicholls *et al.* 2006; Wadhams *et al.* 2006; Dowdeswell *et al.* 2008; Dutrieux *et al.* 2016). In addition, the development of Global Positioning Systems (GPS) and, later, Differential GPS (DGPS) has also played a critical role in the precise georeferencing of data-acquisition platforms and in data processing through high-quality measurements of changing vessel motion.

The scientific equipment deployed from these marine platforms has also increased in sophistication over the past few decades. Single-beam echo sounders have been augmented by imaging systems in the form of side-scan sonar and, more recently, by multibeam swath-bathymetric systems, which can now produce digital-elevation models of the seafloor at horizontal resolutions that range from a few tens of metres to a few metres or even better, depending on instrument frequency, water depth and platform. Marine seismic-reflection methods have also developed beyond single profiles through marine sediments (conventional 2D seismic-reflection lines) to sets of very closely spaced profiles in the form of 3D seismic-reflection cubes. The analysis of such cubes allows three-dimensional renditions of the sedimentary record and the reconstruction of the morphology of former seafloors laid down through an ice age that are now buried under tens to hundreds of metres of sediment (e.g. Andreassen *et al.* 2004, 2007; Dowdeswell *et al.* 2006, 2007; Dowdeswell & Ottesen 2013; Newton *et al.* 2016). Newly developed seismic methods, such as P-Cable, offer even higher 3D resolution (e.g. Tasianan *et al.* 2016; Vadakkepuliambatta *et al.* 2016). The vertical resolution of shallow sub-bottom profilers and towed systems has also been improved to allow acoustic-stratigraphic details on the scale of a few tens of centimetres to be revealed. These geophysical advances are set alongside the availability of increasing numbers

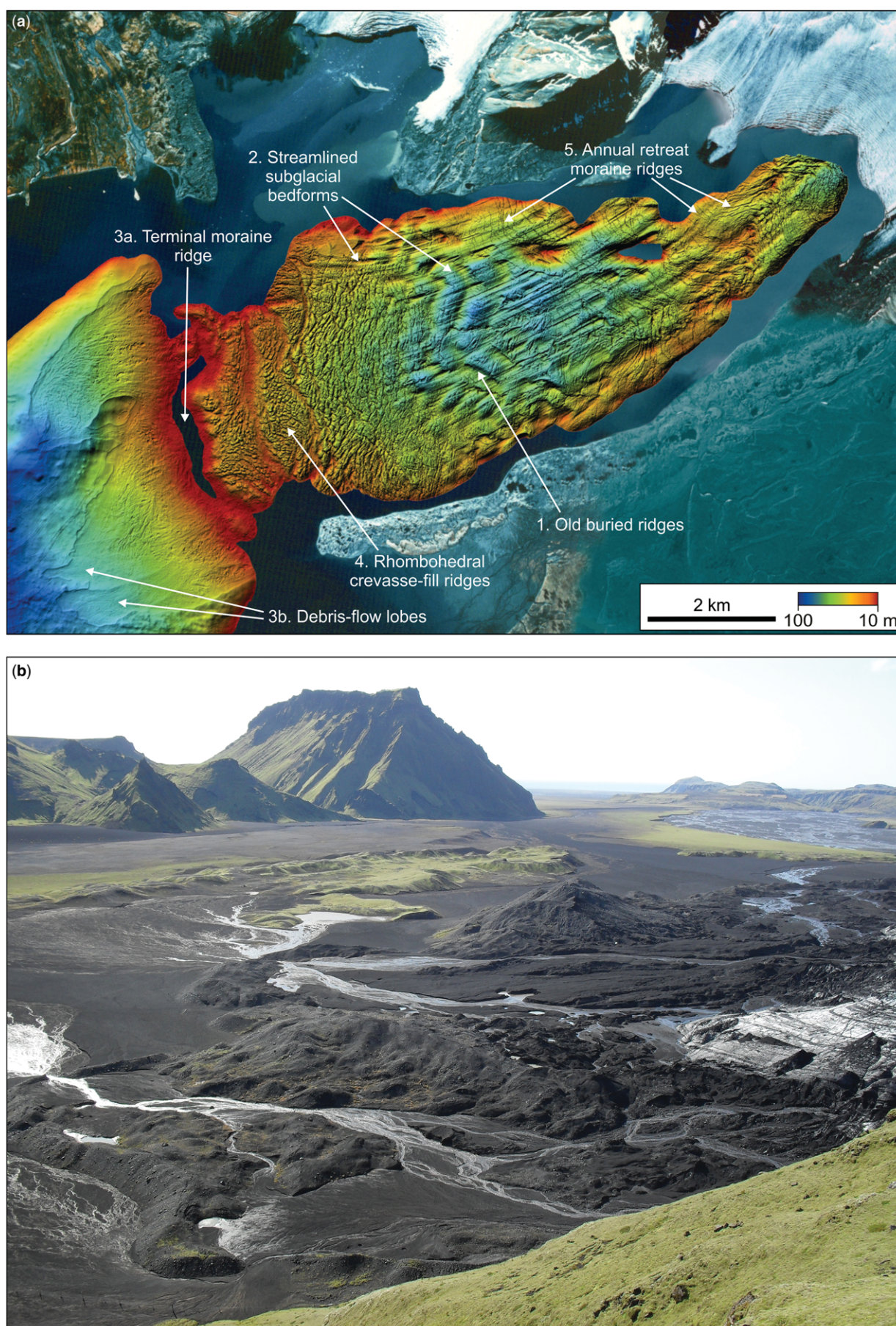


Fig. 3. The varying preservation of glacial landforms in marine and sub-aerial environments after deglaciation less than 100 years ago. **(a)** Multibeam-bathymetric image of the seafloor of Borebukta in western Svalbard, adjacent to two tidewater glaciers. Five types of glacial landform (1, oldest, to 5, youngest) are superimposed, illustrating a very well-preserved assemblage of submarine landforms (modified from Ottesen & Dowdeswell 2006). **(b)** Photograph of the forefield of Kotlujökull, Iceland (courtesy of D.J.A. Evans). The glacier is on the right. Note the erosion of the glacier forefield and moraine ridges by braided meltwater streams.

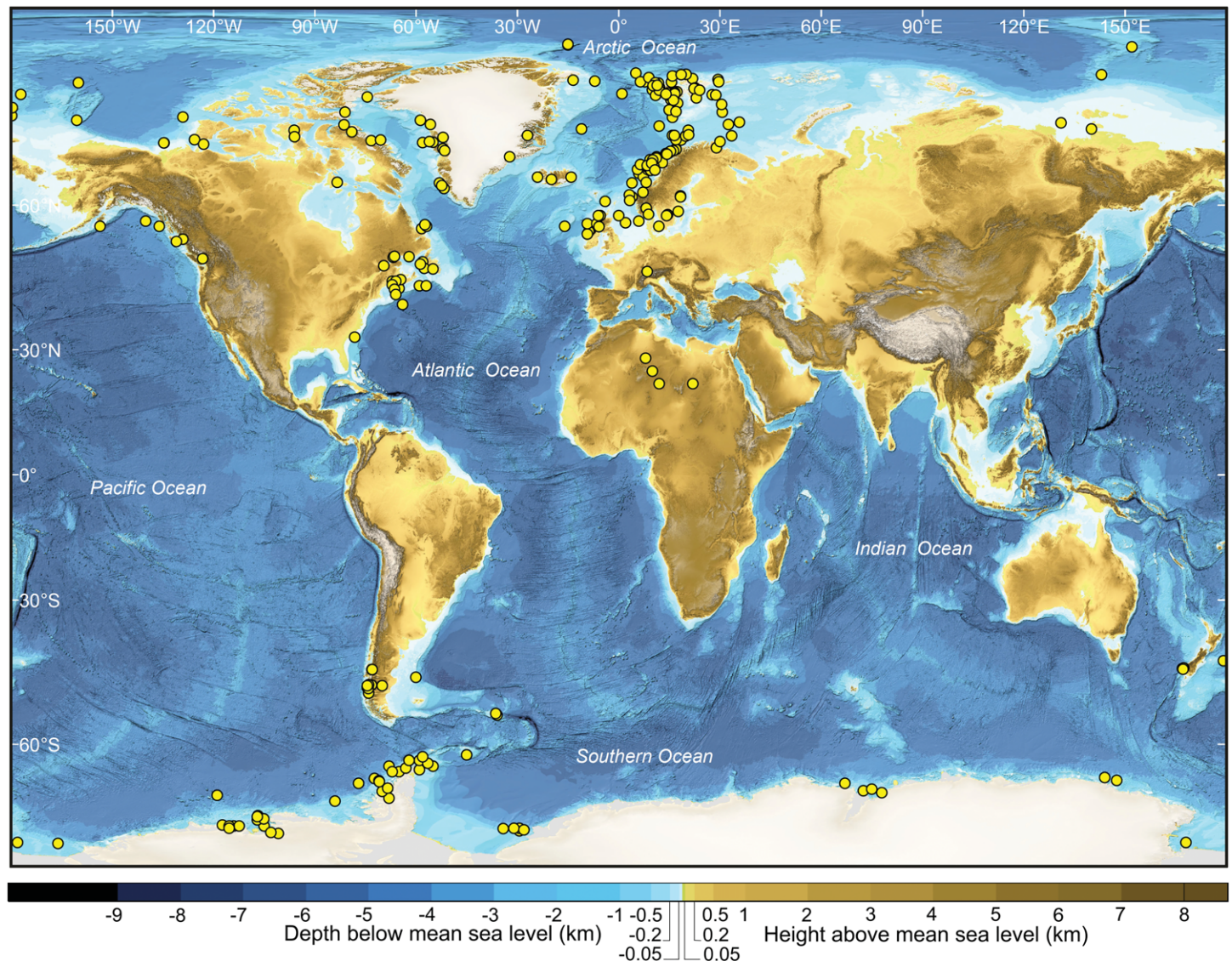


Fig. 4. Map showing the geographical locations of the contributions to the *Atlas of Submarine Glacial Landforms* (yellow dots). GEBCO World Map: Gall projection. Note that the distribution includes Late Ordovician glacial landforms from Northern Africa.

of marine sediment cores from the polar seas, whose sedimentology calibrates geophysical data and informs studies of process, and whose biogenic material is routinely radiocarbon dated to yield chronological control and information on rates of sediment delivery.

More details on the marine-geophysical methods used to obtain both planform information on the morphology of the seafloor, and stratigraphic data on the nature of the underlying sedimentary record, are given in the ‘acoustic methods’ section of this volume (Jakobsson *et al.* 2016).

An Atlas of Submarine Glacial Landforms

Timing

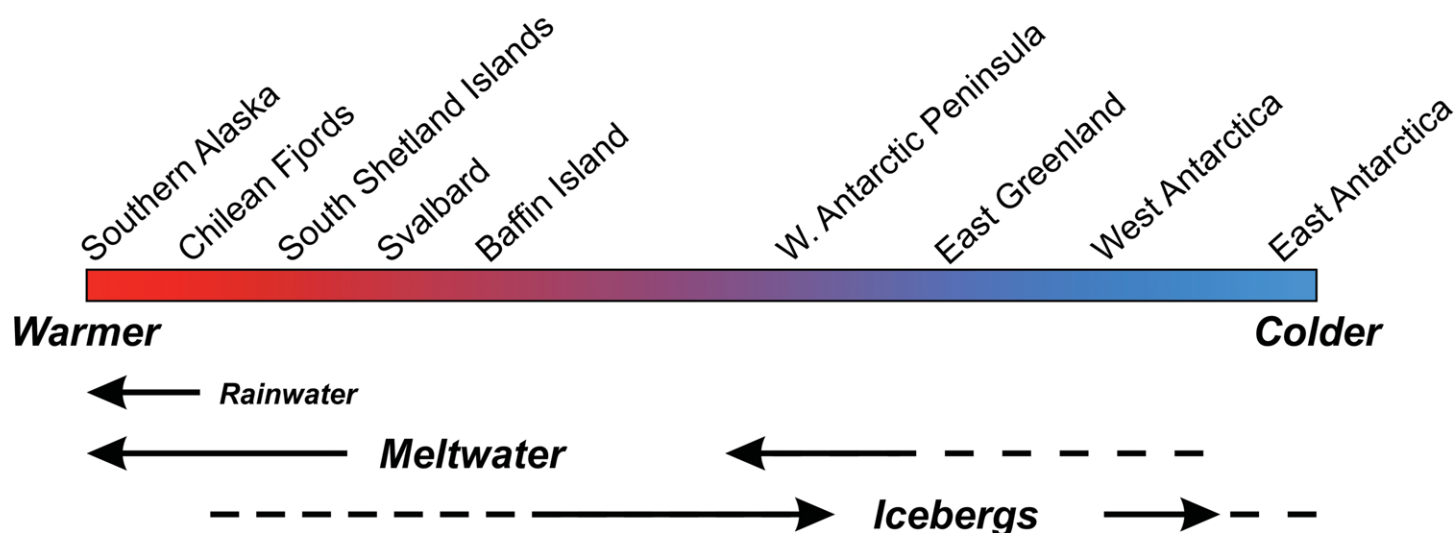
Twenty years ago, the international marine community brought together a first *Atlas of Acoustic Images* of the high-latitude geomarine environment (Davies *et al.* 1997). The present *Atlas of Submarine Glacial Landforms* presents a new attempt to summarize the state of knowledge of these high-latitude glacier-influenced systems, focusing in particular on high-resolution seafloor imagery, derived mainly from multibeam swath-bathymetric and associated acoustic-stratigraphic data. We consider it timely to provide

a compilation of the variety of submarine glacial and related landforms, together with their stratigraphic setting where possible, for several scholarly, technological, environmental and economic reasons. First, new-generation techniques have revolutionized the high-resolution imaging of the modern seafloor over the past decade or so and these instruments have now been deployed widely in the polar seas, providing vast quantities of new data. Secondly, palaeo-shelf surfaces, buried in glacial-sedimentary depocentres, can now be imaged using 3D seismic methods, providing novel insights into sedimentary architecture and past environmental conditions (e.g. Newton *et al.* 2016). Thirdly, it is now widely recognized that the polar regions and their changing ice cover are a key driver of global climate change, enhancing the significance of their understanding (e.g. IPCC 2013). Finally, industry is increasingly interested in understanding the dimensions and architecture of glacial sedimentary depocentres on present and past continental shelves because of the considerable potential of some glacial-sedimentary facies, such as the sand and gravel fill of tunnel valleys, as hydrocarbon reservoirs (e.g. Huuse *et al.* 2012).

Data sources

The geophysical datasets that we include in the *Atlas of Submarine Glacial Landforms* are focused on multibeam swath-bathymetric

(a) Modern, Quaternary interglacial



(b) Quaternary full-glacial

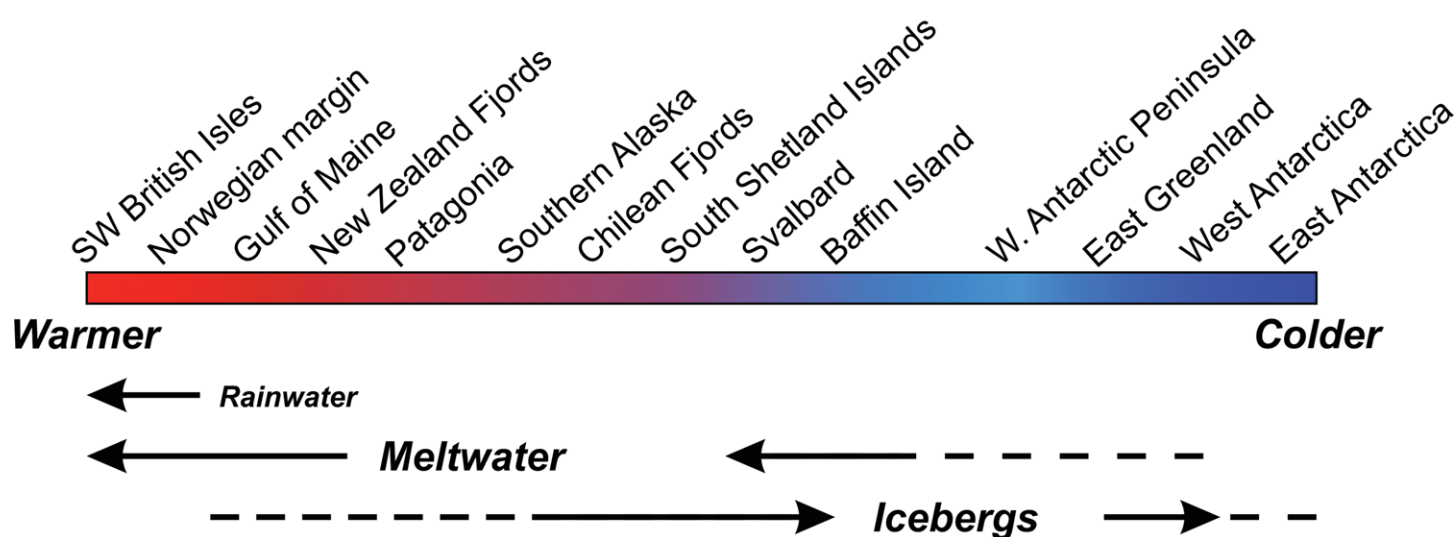


Fig. 5. The climatic continuum of glacier-influenced marine settings for (a) the modern, or Quaternary interglacial Earth, and (b) Quaternary full-glacial conditions (modified from Dowdeswell & Vásquez 2013). Mid-latitude ice sheets grow to reach the sea closer to the equator during full-glacials.

imagery of the high-latitude seafloor. The many multibeam-derived images of submarine glacial geomorphology in the 180 or so papers of the volume are augmented by some older side-scan sonar and merged single-beam echo-sounder (Olex) data (e.g. Laberg & Dowdeswell 2016; Ryan *et al.* 2016; Todd 2016) and, importantly, by relatively recent evidence in the form of buried horizons such as palaeo-shelves derived from the analysis of 3D seismic cubes. Where stratigraphic data are available, the plan-form views of the seafloor and buried surfaces are supported by various acoustic-stratigraphic data to provide cross-sections and long-profiles through the submarine glacial and related landforms. These stratigraphic data range from relatively high-resolution but low-penetration acoustic sub-bottom profiles operating at frequencies of a few kilohertz, through seismic data in the form of relatively high-resolution evidence from, for example, boomer, sparker and water-guns, to the kilometres of penetration of conventional 2D seismic-reflection records and 3D seismic cubes (noting that 3D P-Cable penetrates only some hundreds of metres). Occasionally, use is also made of bottom photographs and sediment-core material to illustrate specific submarine landforms (e.g. Bøe *et al.* 2016; Bradwell & Stoker 2016a).

Geographical coverage

The *Atlas* contains about 180 contributions with a geographical spread that is shown in Figure 4. Examples come from the continuum of ice-influenced marine environments found on Earth today (Fig. 5), from the relatively warm-water fjords of Patagonia (e.g. Dowdeswell *et al.* 2016a) to the frigid water-filled cavity beneath the floating Pine Island Glacier tongue in West Antarctica (e.g. Dutrieux *et al.* 2016). Arctic and Antarctic fjords, shelves and slopes are considered in many contributions (e.g. Bjarnadóttir & Andreassen 2016; Forwick *et al.* 2016; Rebesco *et al.* 2016), and examples from sub-Antarctic islands such as the South Orkneys and South Georgia are also included (e.g. Dickens *et al.* 2016; Graham & Hodgson 2016). The volume also has a temporal reach that includes many Quaternary examples, from the now deglaciated shelves and fjords of the northern mid-latitudes, such as those off-shore of the British Isles and eastern Canada, and in the Baltic (Bradwell & Stoker 2016b; Greenwood *et al.* 2016; Todd *et al.* 2016), to the fjords of New Zealand (Barnes *et al.* 2016a, b) and the continental shelf of Antarctica in the Southern Hemisphere (Amblas & Canals 2016; Klages *et al.* 2016; Simkins *et al.*

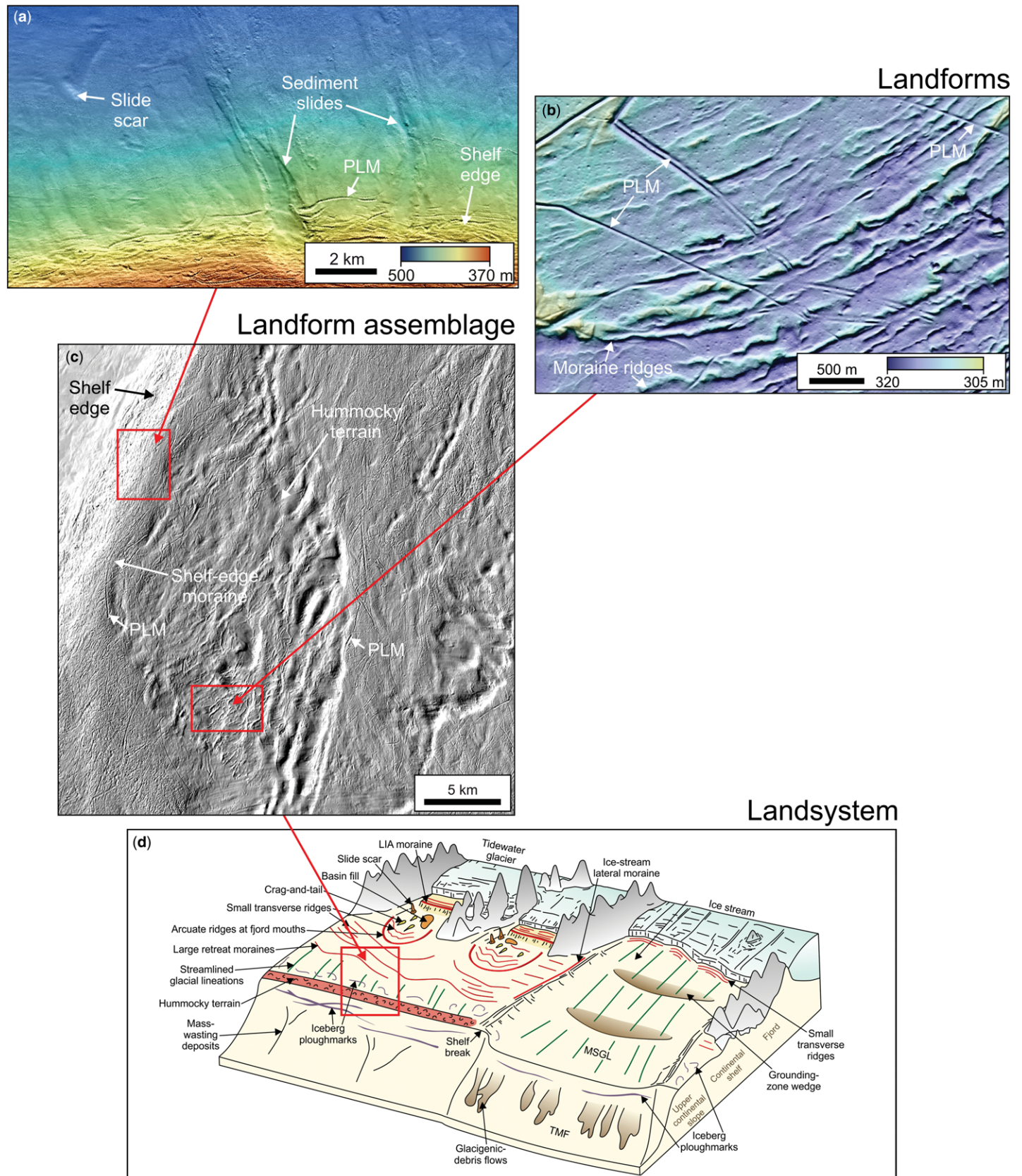


Fig. 6. Illustration of the nested hierarchy of submarine glacial landforms used to organize the contributions in the *Atlas of Submarine Glacial Landforms* (from Dowdeswell *et al.* 2016b). (a, b) Individual landforms: slides, iceberg ploughmarks (PLMs) and moraine ridges. (c) An assemblage of landforms. (d) Fjord–shelf–slope landsystems. LIA, Little Ice Age; MSGL, mega-scale glacial lineations; TMF, trough-mouth fan.

2016). Several examples of subaqueous glacial landforms preserved in glacier-influenced lakes are also included for comparison with the marine environment (e.g. Geirsdóttir *et al.* 2016; Hilbe *et al.* 2016).

Further back in time, 3D seismic-reflection methods allow examples of glacial marine landforms to be drawn not only from the seafloor, encompassing the LGM and subsequent deglaciation where sedimentation rates are low and landforms are not buried by

post-glacial sedimentation, but also from much deeper in the record. Published research using 3D seismic datasets is currently relatively limited, but available cubes collected by industry have allowed some investigations of deeply buried palaeo-shelf surfaces and their landforms, especially in the Quaternary sediments of the Norwegian margin and the North Sea (e.g. Dowdeswell & Ottesen 2016; Ottesen *et al.* 2016; Rise *et al.* 2016; Rydningen *et al.* 2016). Finally, a number of examples of submarine glacial landforms from ancient ice ages are included, in particular from the Late Ordovician rocks of northern Africa, that have been investigated by industry using 3D seismic methods (e.g. Decalf *et al.* 2016), in outcrop (Le Heron 2016) and on satellite imagery (Moreau & Ghienne 2016) where they have been exposed by long-term uplift and subsequent erosion.

In terms of authors, scientists from many countries and institutions have made contributions to the *Atlas*. Almost 250 scientists from universities, government research laboratories and industry in some 20 countries have been involved in the writing and illustrating of the wide range of contributions in the volume.

Structure and organization of the *Atlas*

The *Atlas* begins with this general *introduction* to the glacimarine environment (Section 1), followed by Section 2 on the *acoustic methods* used to acquire seafloor and sub-seafloor imagery.

The bulk of the 180 or so papers in the *Atlas* are organized in terms of their positions on continental margins (Fig. 2) into contributions from: fjords (Section 3), continental shelves and plateaux (Section 4), and the continental slope, rise and deep-sea basins beyond (Section 5). These contributions are further subdivided by their morphological complexity into papers of either two or four pages in length. The two-page contributions focus on *individual* seafloor landforms from glaciated continental margins, and have one page of text that describes and interprets the landform and a second that illustrates it in planform and, where possible, stratigraphically (Sections 3a and 4a). The four-page papers describe and illustrate *assemblages* of submarine glacial landforms and discuss their distribution and genesis (Sections 3b and 4b).

Additional organization of the many individual contributions within each of Sections 3–5 is in terms of either: (1) the process-environment of landform genesis (subglacial, ice-contact/ice-proximal, glacimarine, or reworked by other processes), or (2) the climatic setting in terms of the continuum from relatively mild to very cold glacimarine settings (Fig. 5). Additional ordering takes account of geography (Northern and Southern hemispheres) and timescale (from modern, through the Quaternary, to pre-Quaternary ice ages).

Section 6 of the *Atlas* comprises a further set of eight-page contributions. These papers illustrate, interpret and discuss *whole systems* of submarine landforms, sometimes referred to as *landsystems* (Eyles 1983; Evans 2005), across continental margins. Each glacimarine landsystem includes evidence from fjords together with the adjacent shelf and slope, and concludes with a schematic diagram of the landsystem. The overall approach is that of a nested hierarchy, in which individual submarine glacial landforms sit within landform assemblages that, in turn, provide the building blocks for whole fjord–shelf–slope landsystems (Fig. 6).

These 12 contributions on entire glacimarine landsystems are ordered in terms of the continuum of climatic settings in which glaciers reach the sea today and during the Quaternary in the Northern and Southern hemispheres, respectively (Fig. 5). The environmental continuum extends from relatively mild glacier-influenced environments such as those of the western British Isles and the Gulf of Maine (Bradwell & Stoker 2016b; Todd *et al.* 2016), through the intermediate environments of, for example, Svalbard and the Antarctic Peninsula (Canals *et al.* 2016; Dowdeswell *et al.* 2016b), to the coldest settings of the Arctic Ocean and East Antarctica (Jakobsson 2016; O'Brien *et al.* 2016). The ancient

glacimarine system of Late Ordovician northern Africa (Le Heron 2016) concludes this section of the *Atlas*, noting that it is interpreted as a relatively mild palaeo-glacial setting.

The substantive contributions to the *Atlas* (Sections 3–6) are then brought together in a *concluding* paper (Section 7) which provides a synthesis of the landforms, assemblages and whole-systems presented earlier and discusses the wider significance and application of this knowledge for ice-sheet reconstruction and environmental change.

The *Atlas* is then completed with a *cumulated bibliography*, which combines all the references from the individual contributions in order to make them easy to locate and use, a *glossary of terms* and an *index*.

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