The glacier-influenced marine record on high-latitude continental margins: synergies between modern, Quaternary and ancient evidence

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Abstract: Major glaciations or “ice ages” are known to have affected the Earth’s surface over the past three billion years. The best preserved records of these glaciations are often found in high-latitude continental margin settings where sediment has been delivered to, and then accumulated at, the edge of the ice sheet in thick glacier-influenced marine sequences. The composition and geometry of these deposits and the related assemblages of glacial landforms provide a wealth of information about the environmental setting during successive cycles of glaciation and deglaciation, including ice-dynamic and oceanographic processes. Here, we discuss modern (present day), Quaternary (last 2.6 Myr) and ancient (last 1 Gyr) high-latitude continental margin settings and then contrast the methodologies used and glacier-influenced deposits and landforms most often identified for each time period. We use examples from the literature to identify synergies, as well as to note differences, between studies of glacier-influenced sediments from ancient to modern environments.

During the last full-glacial period, about 20,000 year ago, there is evidence to show that the great ice sheets of Antarctica and Greenland extended to the edges of high-latitude continental shelves around much of their circumference (e.g. Funder *et al.* 2011; RAISED Consortium 2014) (Fig. 1). Large mid-latitude ice sheets also developed over much of northern North America and western Eurasia (e.g. Dyke *et al.* 2002; Svendsen *et al.* 2004), and many mountain-glacier systems, such as those of the Himalayas, Andes and North American Cordillera, expanded greatly (Ehlers et al., 2011). As a consequence, global sea-level was lowered by about 120-134 m relative to today (e.g. Fairbanks 1989; Lambeck et al. 2014), and the ocean area affected by icebergs and sea ice grew to about twice its present size (Fig. 1). A number of similar full-glacial episodes, separated by interglacials, took place over the whole Quaternary (2.6 Myr to present).

Further back in geological time, there have been six major Ice Ages during the past billion years of Earth history and, where palaeo-glacial deposits have avoided destruction at plate boundaries, remnants of these ancient glaciations are preserved (e.g. Hambrey & Harland 1981; Eyles 1993).

Today, the marine termini of glaciers and ice sheets, and the fjords and continental shelves beyond, are locations where the processes and rates of sediment delivery and deposition to the marine environment can be observed directly (e.g. Syvitksi & Shaw 1995; Forwick et al. 2010). Although it is more difficult to use geophysical techniques through ice than water, subglacial sediments and landforms currently being produced beneath modern fast-flowing ice streams and ice shelves have also been observed at a few sites using seismic and over-snow radar methods (e.g. King *et al*. 2009; Smith & Murray 2009; Jezek *et al*. 2011; Horgan *et al*. 2013, 2017; Bingham *et al*. 2017). However, the excellent preservation of glacial sediments deposited on continental margins during the Last Glacial Maximum (LGM) and subsequent deglaciation, which are now submarine, means that high-latitude continental margins provide a rich area for investigations of the stratigraphy and morphology of late Quaternary subglacial, ice-marginal and glacimarine sediments in which the depositional setting is relatively well-constrained (Dowdeswell *et al*. 2016). By contrast, although ancient, pre-Quaternary glacier-influenced marine sediments, where preserved, are sometimes exposed on land and are therefore open to detailed field inspection, the topographic and environmental setting in which they were deposited is usually difficult to reconstruct (e.g. Eyles & Januszczak 2004).

Here, we consider modern, Quaternary and ancient glacier-influenced marine sediments in the context of how each can contribute to the understanding of the processes of glacimarine sedimentation and the stratigraphy, sedimentology and geomorphology of these deposits. We use examples from the literature on modern, Quaternary and ancient glaciations to highlight the different techniques currently used to study glacimarine sediments, and to explore whether synergies or links can be made between modern and ancient glacimarine processes and settings.

The glacimarine system

Glacier-influenced marine, or glacimarine environments include all those parts of the Earth's oceans and seafloor that are affected by ice. A complex series of glaciological, oceanographic and sedimentary processes interact to produce the sedimentary record of past ice-sheet extent and flow (Fig. 2). Sediments are entrained beneath glaciers and ice sheets, and are transported by ice flow to the ice-ocean interface. Direct melting, meltwater discharge, and iceberg calving from the marine termini of glaciers and ice sheets, together with a contribution from the delivery of deforming basal sediments to the grounding line (e.g. Alley *et al*. 1987; Anandakrishnan *et* *al.* 2007), then release debris into the marine environment. In addition, glacial-meltwater fed proglacial streams may also supply sediment to the glacimarine system. Where meltwater is present and sorting takes place, coarser debris may be deposited in ice-proximal fans and submarine moraine ridges or banks (e.g. Dowdeswell *et al.* 2015), with the finer fraction raining out more slowing from turbid plumes of suspended sediment at rates that decrease with increasing distance from the glacier source (e.g. Syvikski 1989; Powell 1990; Mugford & Dowdeswell 2011). Icebergs, by contrast, are capable of transporting debris of all grain sizes over distances that range from a few kilometres to a few thousand kilometres from the calving ice front, releasing sediment along their drift-tracks as they melt at a rate controlled by their size, drift velocity and ocean temperature (e.g. Weeks & Campbell 1973; Gilbert 1990; Dowdeswell *et al.* 1994; Mugford & Dowdeswell 2010).

There are three components to the glacier-influenced marine system: subglacial, ice-marginal and ice-distal marine settings (Dowdeswell *et al.* 2016). Subglacial environments, affected by both deposition and erosion at the bed of glaciers and ice sheets, become glacimarine when ice sheets retreat across continental shelves and fjords, allowing ice to be replaced by ocean water. This is the typical situation on modern Arctic and Antarctic shelves, where exposed subglacial sediments now lie beneath waters that are often several hundred metres in depth and are often covered by a thin veneer of subsequent deglacial to Holocene sedimentation (Fig. 3). Ice-marginal sediments are being produced today at the grounding zones of ice sheets and glaciers, including within ice-shelf basal cavities; they have been imaged using seismic-reflection methods (e.g. Horgan *et al.* 2013, 2017) and investigated directly using, for example, autonomous and tethered underwater vehicles deployed close to contemporary tidewater glaciers and under floating ice shelves (e.g. Dowdeswell *et al.* 2008a; Davies *et al.* 2017). Further offshore, drifting icebergs and sea-ice floes release debris of all grain sizes as they melt, fragment and overturn, and also rework the sedimentary seafloor where their keels make contact with and plough through it (e.g. Gilbert 1990; Woodworth-Lynas *et al.* 1991).

Today, these glacimarine settings range from the ice-proximal grounding-zone and adjacent cavities beneath ice shelves, and the ice-ocean interface at tidewater glacier termini, to the most ice-distal marine locations reached by far-travelled drifting icebergs. Such glacier-influenced environments include about 20% of the modern global seafloor (Fig. 1). The limits reached by icebergs in the modern ocean are generally controlled by iceberg dimensions and, especially, by water temperature through its influence on iceberg melting (Weeks & Campbell 1973). Thus, offshore of eastern North America, for example, icebergs derived mainly from West Greenland circulate anticlockwise around Baffin Bay, with the largest finally melting as far south as the

Grand Banks of Newfoundland – an area that represents the southern limit of cold Arctic water today.

During Quaternary full-glacial conditions, icebergs were able to drift much farther equatorward as the polar front and associated cold water in the Northern Hemisphere was displaced as far south as about 40°N (Ruddiman 1977). The area of the Earth's oceans affected by glacimarine processes approximately doubled at the LGM (Fig. 1). Evidence for this full-glacial expansion of the glacimarine system is provided, for example, by the changing limit of iceberg-rafted debris recorded in sediments on the North Atlantic seafloor (e.g. Ruddiman 1977) and the presence of seafloor ploughmarks produced by the grounding of deep-keeled icebergs on continental shelves as far equatorward as Florida and northern Argentina (Hall & Condron 2014; López-Martínez *et al.* 2011). As deglaciation from the LGM took place, vast areas of high-latitude shelves were also exposed, revealing the sedimentary imprint of subglacial activity. These submarine glacial sediments and landforms often remain well preserved and only thinly draped by subsequent Holocene sedimentation. Successive glacial-interglacial cycles over the past few million years have generated major sedimentary wedges, including huge trough-mouth fans, that have built out high-latitude continental shelves into deep-ocean waters (e.g. Cooper et al. 1991, 2008; Vorren & Laberg, 1997; Rise *et al.* 2005; Ottesen *et al.* 2010). These wedges, which can be a kilometre or more in thickness, contain sediments produced during multiple glacial cycles, and palaeo-shelf and slope sediments and landforms can be imaged using 2- and 3-dimensional (2D & 3D) seismic-reflection methods (e.g. Andreassen *et al.* 2004; Dowdeswell *et al.* 2007; Montelli *et al.* 2017, 2018).

Further back in geological time, a series of pre-Quaternary glaciations is recorded in much more fragmented form in the rock record (e.g. Hambrey & Harland 1981; Eyles 1993). Ancient glacimarine sediments are most clearly identified by the presence of outsized clasts, interpreted as iceberg-rafted dropstones (e.g. Gilbert 1990), in fine-grained and sometimes laminated marine sediments. Much of the glacimarine record of ancient glaciations has, however, been lost by ocean-basin closure at destructive plate margins at timescales of hundreds of millions of years (e.g. Eyles 1983). Even so, where palaeo-continental shelf and slope sediments initially formed at high-latitudes are preserved, they are sometimes accessible above sea level due to mountain-building and other long-term tectonic processes. This is especially important in parts of the modern globe that are sparsely vegetated, and such outcrops are therefore available for straightforward examination. Examples include the Late Ordovician (458-443 Myr) rocks of the Northern Sahara (e.g. Le Heron 2016), and Permian (299-252 Myr) sediments in the

Transantarctic Mountains (e.g. Koch & Isbell 2013) and the South African Kalahari Desert (e.g. Eyles 1993).

Modern glacimarine settings

An obvious advantage of investigating glacimarine sediments and landforms in modern polar shelves and fjords is that the wider topographic and environmental setting in which they are produced today can be observed directly. In addition, the processes forming the sediments and landforms, and their rates of operation, can often be either observed directly or inferred with reasonable confidence (e.g. Clarke 2005). Thus, the interpretation of the depositional environments within which modern glacimarine sediments form is relatively straightforward.

On the other hand, since such sediments are forming either subglacially, ice-marginally or beneath cold ocean waters where the ice-hazard is often significant, direct observation through ice or water hundreds and sometimes thousands of metres in thickness is problematic. Beneath modern glaciers and ice sheets, the ice-bed interface is of prime significance for both ice flow and sedimentary processes. However, while MHz-frequency radar systems are capable of measuring ice thickness through thousands of metres of ice (e.g. Dowdeswell & Evans 2004), they do not penetrate the glacier bed and provide little information on the nature of the substrate beyond whether water is present or not (e.g. in the form of subglacial lakes; Siegert, 2000). Lower frequency reflection-seismic surveys acquired on the ice surface, by contrast, do penetrate into subglacial sediments, but such investigations are very expensive and relatively few datasets are available (e.g. Alley *et al.* 1986; Blankenship *et al.* 1996; Smith & Murray 2009; Hofstede *et al.* 2018). They do, nonetheless, provide the bulk of existing information about the modern ice-bed interface, including the grounding zone beneath ice shelves (e.g. Christianson *et al.* 2016) and its sedimentary properties.

A small number of sediment cores have also been retrieved from boreholes through glaciers and ice sheets, providing limited data on subglacial debris, its water content and mechanical properties (e.g. Engelhardt *et al.* 1990, Kinslake *et al.* 2018). Hot-water drilling and sediment sampling through the floating tongue of Pine Island Glacier, for example, has also allowed dynamic ice-stream changes over the past 70 years or so to be inferred from the marine-sedimentary record (Smith *et al.* 2017). This is significant, as it begins to bridge the gap between the time-frames typical of sediment cores (centuries to millennia) and direct modern observations (a few decades at most).

The retreat of many glaciers and ice sheets over the past century or so, and especially of those ending in ocean waters, has exposed recently deglaciated areas of the seafloor. This has yielded quasi-modern marine-geophysical and -geological evidence on the form and properties of formerly subglacial environments. These recently exposed submarine sediments and landforms have been investigated using multibeam echo-sounding, bottom cameras, shallow sub-bottom profiling and sediment sampling (e.g. Bøe *et al*. 2009; Flink *et al*. 2015). Seafloor features down to the scale of large boulders and minor ridges can be imaged by high-frequency multibeam systems when data are gridded at a metre to a few metres in horizontal resolution (Jakobsson *et al*. 2016). In addition, bottom cameras acquiring both still and video images allow very detailed mapping, albeit over fairly restricted areas. Garcia *et al*. (2016) provided a detailed example from within a kilometre or so of the modern terminus of a tidewater glacier grounded in an Antarctic Peninsula fjord, where Remotely Operated Vehicle (ROV) deployments of cameras and a multibeam echo-sounder have produced sub-metre scale resolution of ice-marginal and subglacial sediments exposed by ice retreat in the past few decades (Fig. 4). ROVs have also been used occasionally to photograph submarine vertical sections, similar to those exposed on land, such as that on the exposed flank of a large sediment drift west of the Antarctic Peninsula (Larter *et al*. 2016).

Sub-bottom profilers, operating at kHz-frequencies (Jakobsson *et al*. 2016), provide high-resolution shallow acoustic stratigraphy, calibrated by the analysis of the physical, biological, mechanical and geochemical properties of sediment cores which are usually a few metres in length at most. What is generally missing in modern glacier-influenced marine environments, however, is the ability to observe and log sedimentary sections in detail; core-calibrated acoustic stratigraphy is only a limited substitute for this. Nonetheless, where many cores have been collected in a given area, an approach using stratigraphic and sedimentary-facies correlations, similar to studies of ancient glacial rocks where limited terrestrial outcrops are linked together, has provided useful insights. Examples include the reconstruction of past ice-shelf extent and meltwater influence in Pine Island Bay, West Antarctica (e.g. Kirshner *et al*. 2012; Witus *et al*. 2014).

The Quaternary glacimarine record

The glacier-influenced sediments and landforms deposited during the LGM and subsequent regional deglacial retreat from the shelf edge represent the most recent imprint of glacial activity on most high-latitude continental shelf and slope systems. Only in Antarctica do significant ice-sheet termini remain in such inner-shelf locations today. Unlike modern polar environments, the ice dynamics of these late Quaternary ice sheets cannot be observed directly, but can instead be inferred from the sediments and landforms (Dowdeswell *et al*. 2016). For example, streamlined mega-scale glacial lineations (MSGLs) (e.g. Clark 1993; Canals *et al.* 2000; Dowdeswell *et al.* 2004; Ó Cofaigh *et al.* 2005; Spagnolo *et al.* 2014) have been observed forming beneath modern ice streams (King *et al.* 2009; Smith & Murray 2009). This landform has, therefore, been used to map past ice-stream locations and flow-paths on deglaciated shelves where well-preserved submarine landforms are present (e.g. Ottesen *et al.* 2005; Andreassen *et al.* 2016; Graham *et al.* 2016; Livingstone *et al.* 2016). In the same way, clusters of transverse-to-flow moraine ridges forming at the margins of modern tidewater glaciers by ice-push processes (e.g. Boulton 1986; Ottesen & Dowdeswell 2006; Ottesen *et al.* 2017) allow the inference of a similar grounded-ice setting for submarine features formed during slow ice retreat across parts of the Antarctic, eastern Canadian and Svalbard shelves during regional deglaciation from the LGM (e.g. Todd *et al.* 2007; Dowdeswell *et al.* 2008b; Ottesen & Dowdeswell 2009).

Taking this a stage further, observations of deglacial submarine landforms, and the inferences derived from them about past ice-sheet processes, can also be of relevance in understanding possible future ice-sheet dynamics. A recent study of deep iceberg ploughmarks in Pine Island Bay, West Antarctica, provided the first observational evidence in support of a past ice-cliff failure mechanism of mass loss that could lead to rapid iceberg calving from the modern West Antarctic Ice Sheet (Wise *et al.* 2017). This marine ice-cliff instability process of rapid ice-sheet mass loss had previously only been considered theoretically, but is clearly of importance in numerical-model predictions of future ice-sheet change (Bassis & Walker 2012; Pollard *et al.* 2015).

The sedimentary products of continental-shelf glaciations through earlier Quaternary full-glacial periods of ice-sheet growth have been buried and in some cases eroded or reworked by the action of subsequent glacial episodes (e.g. Dowdeswell *et al.* 2007). This makes the LGM unique in the Quaternary, given that the sediments and landforms produced by this latest episode of ice-sheet advance and retreat have not been overridden by subsequent ice advance or, in many cases, buried deeply by later interglacial sedimentation. Thus, the submarine landforms of this last great period of ice-sheet growth and decay are uniquely well preserved, assuming they have remained below wave-base erosion. Other processes of reworking have also affected much of high-latitude shelf areas since the LGM, however. The ploughing action of iceberg keels represents the most significant agent of reworking, and it is estimated that at least half of the Greenland continental shelf, especially that shallower than 450-500 m, has been affected badly by this process to the point where submarine glacial landforms on shallow banks between cross-shelf troughs have been largely obliterated (e.g. Brett & Zarudski 1979; Dowdeswell *et al.* 1993, 2014).

Where they have survived subsequent erosion, the sediments and landforms of older, pre-LGM Quaternary glaciations are present in the stratigraphy of the major sedimentary wedges and trough-mouth fans found on high-latitude margins (e.g. Vorren & Laberg 1997; Dowdeswell *et al.* 2007; Montelli *et al.* 2017, 2018). The classical clinoform horizons observed on seismic records in many such locations represent former shelf-slope systems nested one above the other and prograding outwards from the adjacent coast (e.g. Cooper *et al.* 1991; Fig. 5). The buried slope elements of these past submarine surfaces are usually preserved, since erosion by subsequent ice advances does not generally reach into the deeper water beyond the continental shelf break and even the deepest-keeled icebergs affect only the uppermost continental slope (e.g. Kuijpers *et al.* 2007). By contrast, shelf sediments from many former glaciations have been removed by subglacial erosion, a process that is demonstrated through the truncation of many clinoform topsets or palaeo-shelves and the preservation of foresets or palaeo-slopes (Fig. 5; Dowdeswell *et al.* 2007). Inspection of the seismic stratigraphy of a number of high-latitude margins shows, however, that some palaeo-shelves remain, presumably because of a combination of less erosive and/or shorter duration full-glacial conditions, together with higher levels of subsistence and sea-level rise during some glacial and deglacial periods.

The relatively recent availability of 3D seismic datasets from glaciated margins allows the morphology of these former shelf and slope surfaces to be examined in some detail. This is because, unlike the single-transect records of conventional 2D seismic-reflection data, the individual vertical sections making up 3D seismic data are located so close together that reflectors can be traced horizontally to reconstruct palaeo-surfaces (Jakobsson *et al.* 2016). Once horizons such as the buried seafloor have been reconstructed, the landforms on them can be analysed in a similar way to LGM and modern datasets. This has allowed the identification and mapping of individual glacial landforms and assemblages of landforms through many Quaternary glaciations (Fig. 6). For example, on the mid-Norwegian margin, 31 former continental-slope surfaces and 17 outer-shelf surfaces have been mapped and analysed from the kilometre or so thick Quaternary sedimentary wedge (Montelli *et al*., 2017). The smaller number of preserved shelves is a result of glacial erosion during subsequent ice advances to the shelf edge. Subglacially formed MSGLs and channels, ice-marginal grounding-zone wedges (GZWs), and glacimarine iceberg ploughmarks are among the landforms observed from 3D seismic datasets (e.g. Graham *et al.* 2007; Stewart & Lonergan 2011; Montelli *et al.* 2017). The presence of iceberg ploughmarks buried deeply within 3D seismic records of early Quaternary sediments is an important indicator that the sediment package has a glacial imprint and demonstrates that ice sheets grew to reach marine waters even very early in the Quaternary (e.g. Kuhlmann & Wong 2008; Dowdeswell & Ottesen 2013; Rea *et al*. 2018).

The strategic drilling of long sediment cores of tens to hundreds of metres in length, acquired through the International Ocean Discovery Program (formerly the Deep Sea Drilling Project and Ocean Drilling Program) and several other consortia, together with industrial well logs, allows at least some calibration of Quaternary seismic stratigraphy with detailed sedimentology, biostratigraphy and chronological control. Examples include the detailed sedimentology of Prydz Bay, offshore of the Lambert-Amery ice sheet-ice shelf system in East Antarctica (e.g. Hambrey *et al*. 1991), and the glacial and related sequences of the past 13 million years or so in McMurdo Sound recording long-term ice-sheet growth and decay in the Ross Sea sector (e.g. Powell *et al*. 2001; McKay *et al*. 2009).

In addition, LGM and deglacial sediments have sometimes been exposed above sea level by ice unloading and isostatic rebound. This takes place where isostatic rebound has outpaced deglacial sea-level rise, leading to a relative sea-level fall locally. This occurs typically where glacimarine sediments were formed in shallow coastal waters. Examples include the sedimentology of raised glacimarine deltas and morainal banks formed at the margins of the Irish sector of late Quaternary British Ice Sheet (e.g. McCabe & Eyles 1988; McCabe & Ó Cofaigh 1995). A clear advantage in the investigations of such raised marine deposits is their accessibility and the possibility of examining and logging sedimentary sections in detail (Fig. 7). The deeper and further offshore the site of initial deposition, the less likely glacimarine sediments and landforms are to become emergent.

The glacimarine record from ancient Ice Ages

Compared with modern and Quaternary glacier-influenced sediments, a major difficulty with the interpretation of ancient sequences, even assuming they have been identified as of unequivocal glacial origin (e.g. Hambrey & Harland 1981; Eyles 1993), is the lack of a clear topographic and environmental setting. Thus, sometimes not even the locations of basins and mountains are easy to reconstruct, and the palaeo-climatic setting may also be difficult to establish. As an example, it is relatively easy to work out the likely direction of ice flow in the Quaternary Fennoscandian ice sheet because we know where the mountains are in that region. Ice builds up here due to colder temperatures and flows outwards to the sea. If the position and elevation of the mountains was largely unknown, as in many pre-Quaternary Ice Ages, even the direction of past ice flow becomes difficult to establish, with classic indicators of flow directions (e.g. striations, clast fabrics, facies geometries) being bolstered by “far-field” glacimarine evidence (e.g. dropstone provenance, debris-flow deposit geometries) (e.g. Visser et al. 1997; Isbell et al. 2008).

Conversely, however, once ancient glacimarine deposits have been identified as such, the fact they are often exposed in outcrop is a major advantage. Their sedimentology and stratigraphy is often exposed in terrestrial sections that are extensive vertically and horizontally, allowing facies relationships, contacts and sedimentology to be examined in great detail (Eyles *et al*. 1983) (Fig. 8). By contrast, modern and Quaternary workers are restricted mainly to acoustic stratigraphies calibrated occasionally by sediment cores only a few metres long, except where uplift has led to subaerial exposure (Fig. 7). For example, very detailed sedimentological logging of well exposed ice-proximal fans, grounding-zone sediments, and proglacial debrites and turbidites, together with more fine-grained ice-distal glacimarine sediments, has taken place in the Late Ordovician rocks of the northern Sahara (e.g. Le Heron *et al*. 2007; Hirst 2012; Dowdeswell *et al*. 2015; Dietrich *et al*. 2018). Similar detailed logging has revealed the anatomy of glacimarine ice-contact fans in the Permian rocks of Antarctica (Koch & Isbell 2013). Such fine-scale direct observations are seldom possible in modern glacimarine settings, and only occasional enabled in Quaternary examples formed in relatively shallow water through uplift above sea level.

In addition, where outcrops of ancient glacigenic rock are exposed at the surface, and are sub-horizontal in orientation and not obscured by vegetation, field observation and even satellite imagery can occasionally be used to identify and map ancient glacial landforms. An excellent example is from satellite imagery of an exposed Late Ordovician palaeo-surface straddling the Libya/Algeria border in North Africa (Moreau *et al*. 2005). This dataset covers an area of hundreds of square kilometres, within which linear features interpreted as MSGLs imply the presence of a former fast-flowing ice stream. Likewise, a spectacular and regionally extensive late Paleozoic palaeo-surface in the Enneddi-Bourkou Plateau in Chad exposes belts of MSGLs, interpreted as a suite of palaeo-ice streams that drained Carboniferous-Permian (359-252 Myr) ice sheets (Le Heron 2018) (Fig. 8A).

A clear example of using a combination of detailed outcrop mapping and satellite observations together is the reconstruction of likely ice-flow directions, dynamics and depocentres associated with the former ice sheet draining seaward along a 4,000 km-long margin from the Late Ordovician Saharan ice sheet (Le Heron & Craig 2008). A system of eight cross-shelf troughs, likely occupied by fast-flowing ice streams, was identified together with major meltwater-channel complexes and retreat ridges marking grounding-zones during regional deglaciation. This information is, in turn, important for hydrocarbons exploration in these glacial rocks, where the spacing of sedimentary depocentres in former cross-shelf troughs, and sandstone bodies linked to ice-sheet grounding zones, is of particular importance (Le Heron & Craig 2008). Such a wide-ranging reconstruction of an ancient ice-sheet system would not have been possible without a combination of outcrop-scale mapping over a very wide area, combined with information derived from both field, aerial-photographic and satellite observations of large-scale glacial landforms acquired over many years (e.g. Hirst *et al*. 2002; Ghienne *et al*. 2003; Moreau *et al*. 2005; Le Heron *et al*. 2006).

One of the simplest and most obvious areas in which ancient glacial deposits allow special insight into past meltwater processes is the analysis of tunnel valleys. In particular, the Late Ordovician record of North Africa yields multiple examples of these large channels across several countries (e.g. Mauritania - Ghienne & Deynoux 1998; Morocco - Le Heron 2007, Clerc *et al*. 2013, Ravier *et al*. 2014; Algeria - Deschamps *et al*. 2013; Libya - Moreau 2011; Jordan - Douillet *et al*. 2012; Saudi Arabia - Tofaif *et al*. 2018). In each of these examples, tunnel valleys are expressed as cliff-forming sections (Fig. 8B), where the predominantly sandy but complex fill stands proud of inter-channel sediment, which typically comprise less resistant mudstone. The phenomenon of resistant channel-fill areas is common and allows the analysis of ice-sheet scale phenomena at multiple study locations, and for the fill style of tunnel valleys produced by the same ice sheet to be compared and contrasted in detail.

In other areas, and in spite of common landscape features (e.g. MSGLs, tunnel valleys), ancient records such as that of the Late Ordovician show significant departure from their modern and Quaternary counterparts. The starkest example of the difference is in the composition of the sediments. Many Late Ordovician glacial records are dominated by sandstones, rather than diamictites, and, in isolation, these sandstones might simply record deposition from sustained supercritical flows (Ghienne *et al*. 2010; Girard *et al*. 2012). Diamictites with classic features such as striated clasts (Fig. 8C) may be an easily identified symbol of ancient glacier-influenced marine deposits, but their presence is arguably less important for recognising a glacial context than phenomena such as striated pavements and dropstones (Fig. 8D) in shelf deposits. In other ancient glacial records, such as the Cryogenian (720-635 Myr) in general, diamictites are far more typical (e.g. Hoffman *et al*. 2017). The same applies to the Late Paleozoic Ice Age, which in spite of regional differences, is dominated by a record of diamictite deposition (Isbell *et al*. 2008).

Under the microscope, ancient diamictites compare broadly to modern and Quaternary equivalents. Techniques developed by Quaternary scientists, such as micromorphology (Phillips *et al*. 2011; van der Meer & Menzies 2011), are particularly revealing (Fig. 8E). In many examples, thin-section analysis plays an integral part in distinguishing the effects of tectonic overprint (fractures, cleavage, pressure dissolution), and provides vital clues as to whether diamictites are deposited by direct glacial processes or mass-transport processes (Busfield & Le Heron 2018). In terms of diamictite fabric, Fleming *et al.* (2013) applied the Anisotropy of Magnetic Susceptibility (AMS) to Quaternary (Norfolk) glacial sediments. It was found that this non-invasive technique sheds light on heterogeneity in otherwise structureless deposits, allowing fabrics such as shear planes to be identified. In the absence of other evidence, the technique can be used to infer palaeo-ice sheet flow directions, but it must be used cautiously in the ancient record if detrital remnant magnetism is reset by heating, which can be easily accomplished with changes in the geothermal gradient (e.g. by burial) in ancient glacier-influenced marine rocks. It is difficult, however, to extract useful geotechnical data relating to subglacial processes from the ancient rock record.

Conclusions

There is clear complementarity between investigations of modern, Quaternary and ancient glacier-influenced marine sediments. Glacial and related marine processes can be observed operating in modern high-latitude environments, and linked directly to the production of sediments and landforms. However, modern glacial deposits are often difficult to sample and examine in detail due to their location beneath ice or water and to ice hazards ranging from large icebergs and glacier-terminal collapse to the extreme isolation of sub-ice-shelf grounding-zones at the head of extensive water-filled cavities.

By contrast, it is really only though 3D seismic datasets and occasional deep drilling that high-quality imaging of buried glacial landforms and sedimentological analysis can take place as depth of burial increases through the Quaternary. The deposits produced by the last great ice sheets, and during deglaciation from the LGM over the past 15,000 years as ice retreated back across high-latitude shelves, hold many of the best-preserved landforms and sedimentary depocentres, including subglacial sequences that are hard to investigate beneath several kilometres of modern glacier ice.

In more ancient glacier-influenced marine sedimentary systems, a primary difficulty is to understand the broad-scale topographic and environmental setting. Indeed, once identified, investigated and understood, it is often the glacial sedimentary record itself that provides insights into palaeo-environments (e.g. Koch & Isbell 2013). Importantly though, it is arguably in ancient glacial rocks, where exposed in long horizontal and vertical sections, that we can best extract the detailed sedimentology and facies relationships in glacimarine sediments, especially those formed in relatively deep fjord and shelf waters – sediments formed in relatively deep water during Quaternary glaciations are unlikely to have been uplifted to subaerial locations by isostatic rebound. By contrast, direct sampling of modern and Quaternary glacimarine sequences is mainly through suites of cores, which are inevitably spaced relatively widely and correlated using acoustic profiles.

In conclusion, clear synergies exist between the investigation of modern, Quaternary and ancient glacier-influenced marine sediments, in part because each is studied using a different, but sometimes overlapping, set of geophysical and geological tools of varying resolution (Fig. 9). Thus, direct and detailed logging of such sediments is often simplest in ancient, exposed sections, along with raised Quaternary deposits, whereas the process environment may only be studied directly in modern polar regions. In addition, the topographic and environmental setting, and the time over which glacimarine deposition takes place, is best observed in modern and late Quaternary environments rather than ancient ones. It is, therefore, clearly advantageous for glacial geologists to work with and to understand modern, Quaternary and more ancient glacier-influenced marine depositional systems, because each provides a differing but complementary set of observations and inferences about the sedimentary processes and deposits that are produced on high-latitude continental margins.

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Figure Captions

Fig. 1. The extent of glaciers and ice sheets today and at the Last Glacial Maximum (LGM) and the ocean areas affected by glacimarine processes and sedimentation at these times (modified from Anderson 1983; Dowdeswell *et al*. 2016).

Fig. 2. The complex interaction of glaciological, oceanographic and sedimentary processes that operate in glacier-influenced marine environments (modified from Dowdeswell 1987).

Fig. 3. The morphology of an idealized high-latitude continental margin across which ice sheets have grown and decayed during the Quaternary (modified from Dowdeswell *et al*. 2002).

Fig. 4. ROV-acquired multibeam bathymetry and bottom photographs from Blind Bay, Bourgeois Fjord, Antarctica. A: Location of Bourgeois Fjord on the western Antarctic Peninsula. B: High-resolution multibeam bathymetry from inner Blind Bay showing asymmetric moraine ridges interpreted to have formed during neoglacial readvances of Forel Glacier at the head of the fjord. Small white arrows point out subtle glacial lineations. C: Multibeam bathymetry over “finger-like” arcuate asymmetric ridges in outer Blind Bay. Black arrows indicate glacial lineations; depth colour-scale also applies to B. D: Bottom photograph of a ridge crest composed of unsorted boulder-sized clasts in a mud matrix. The red dots are 20 cm apart.

Fig. 5. A: Interpreted 2D seismic profile of the late Pliocene and Pleistocene glacier-influenced marine Naust sequence from the mid-Norwegian shelf showing prograded clinoforms (some truncated). B: Interpretation of the same seismic profile as in A. Modified from Rise *et al*. (2005).

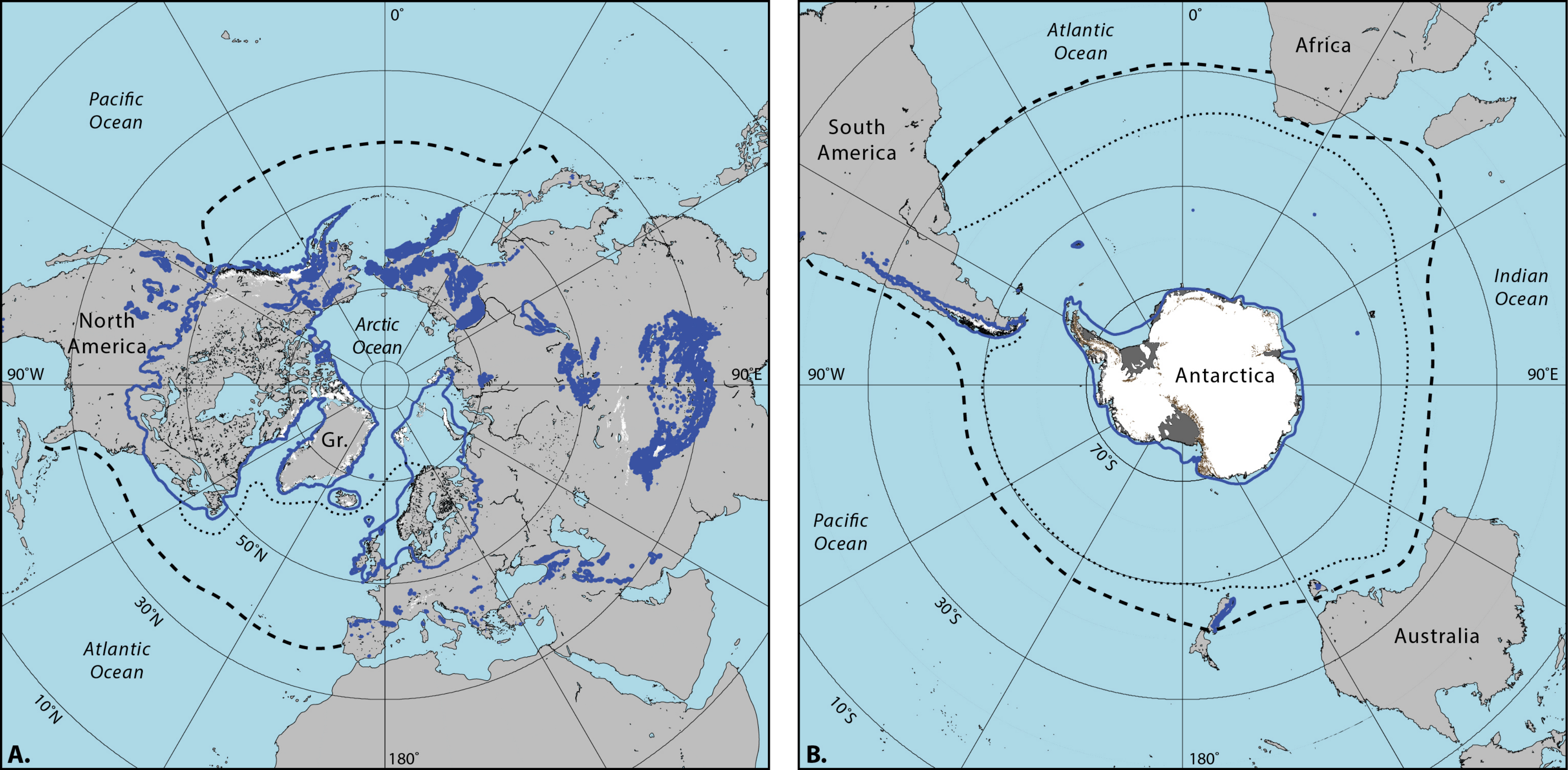
Fig. 6. A selection of buried Quaternary glacial landforms mapped from 3D seismic cubes in the Naust sequence from the mid-Norwegian shelf. A: Curved MSGLs mapped from the base S unit (Fig. 5B). B: A buried channel-fan complex on the frontal continental slope from the base T unit (Fig. 5B). C: Glacitectonic features (hill-hole pairs, rafts) within the S unit (Fig. 5B). Modified from Montelli et al. (2017).

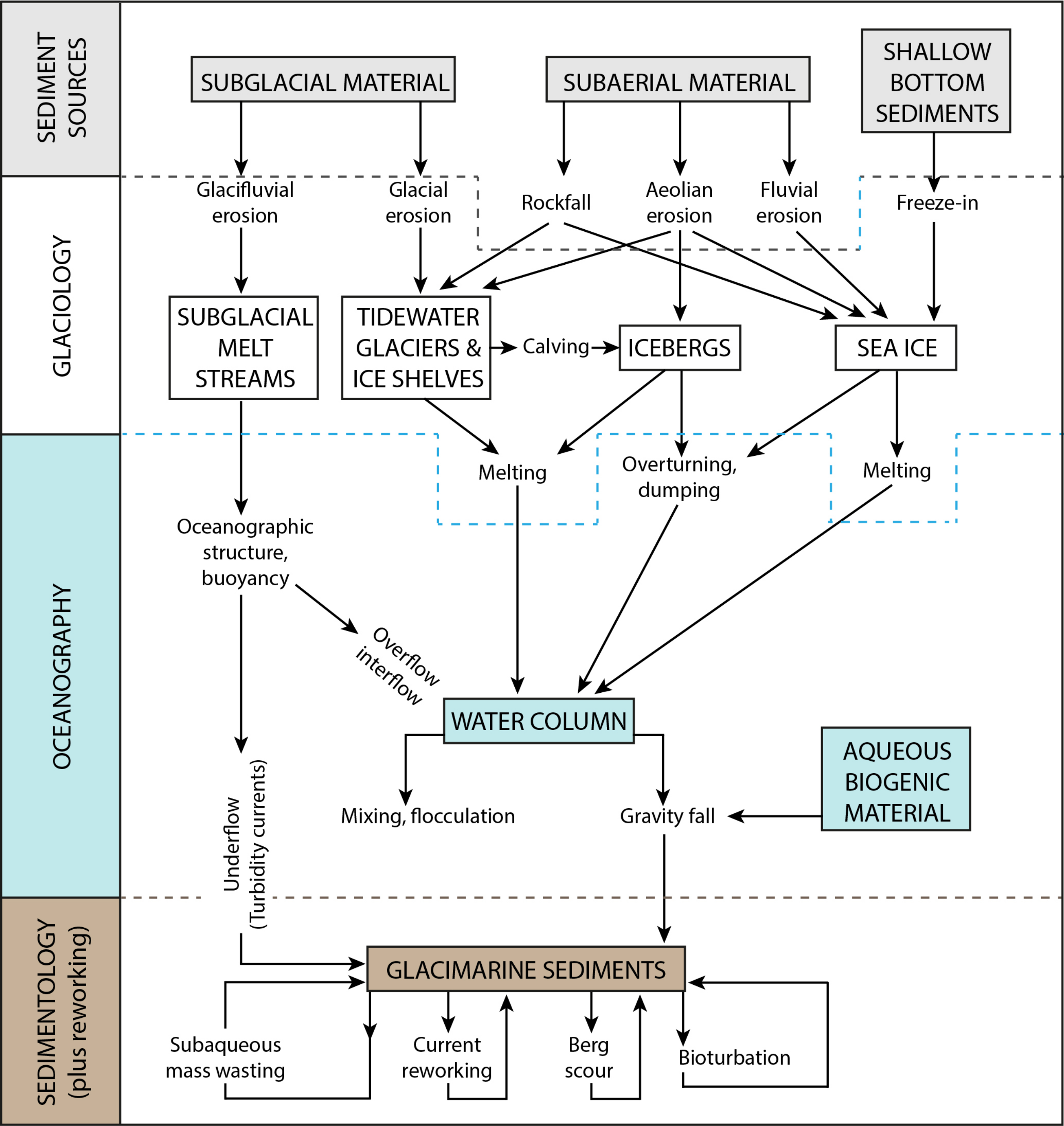
Fig. 7. Subaqueous fan deposited below the local marine limit about 8.5 kyr BP during regional deglaciation and now exposed above sea level due to glacier-isostatic rebound in Phillips Inlet, northwest Ellesmere Island, Arctic Canada. The former glacier margin and subglacial meltwater stream mouth were located towards the left. The clinoforms (white dashed) are composed of interbedded gravels, sands and rhythmites with dropstones and units of cohesionless debris-flow deposits. (Photograph courtesy of D.J.A. Evans).

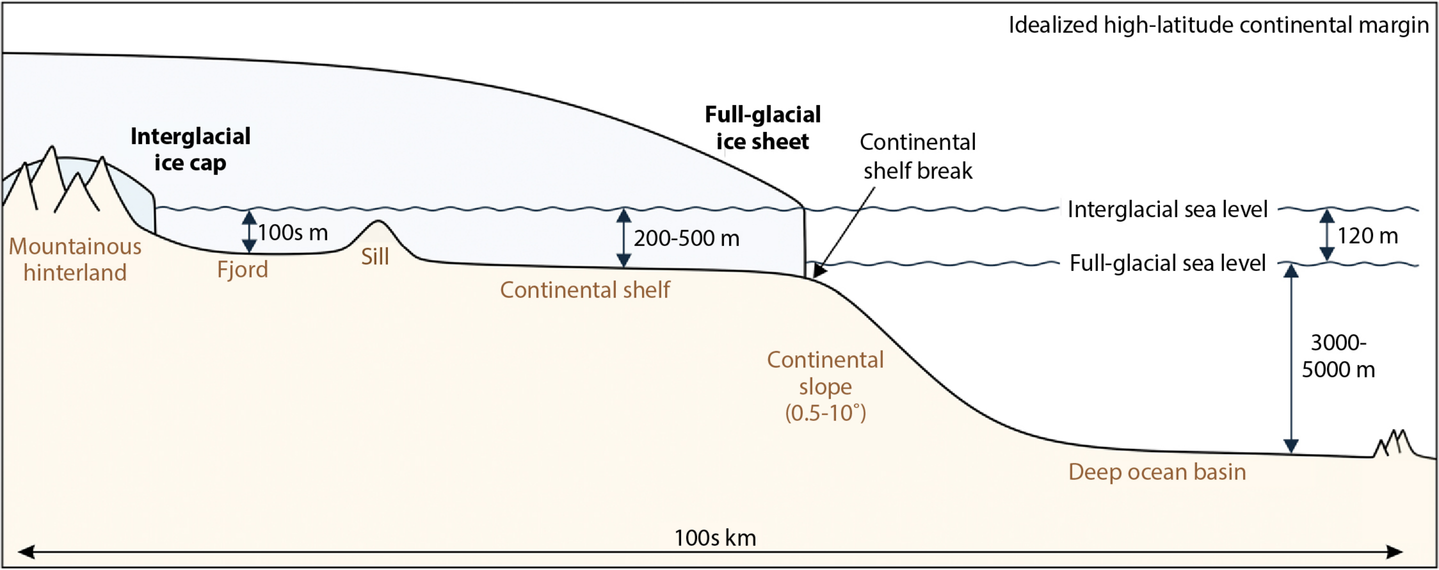
Fig. 8. Features at a range of scales from ancient glaciated-margin systems. A: Exhumed late Paleozoic land surface from northern Chad, central Sahara, displaying suites of palaeo-ice stream tracks (from Le Heron 2018). B: Example of a Late Ordovician tunnel valley in the

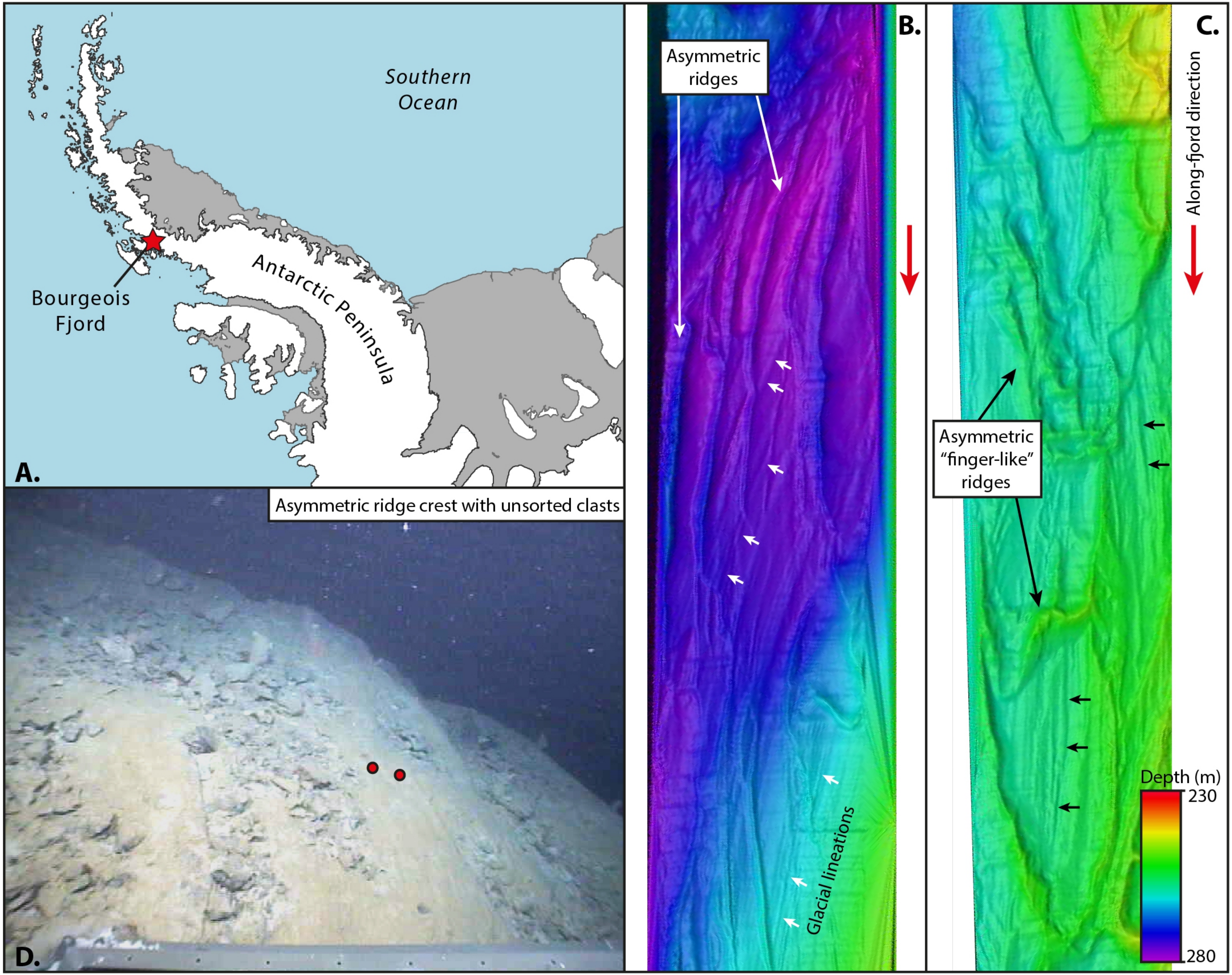
central Sahara (southern Libya) (from Le Heron 2016). One of the highly unusual aspects of this record by comparison to Quaternary and modern glaciated margins systems is the comparative lack of diamictite: the incision shown in the photograph is filled with coarse sandstone. C: A more typical example of glacimarine sediment from the ancient record: the Dwyka Formation near Nieuwoutville, Northern Cape Province, South Africa. D: Example of a dropstone in probable Ediacaran glacial deposits, central China. E: The ancient glacial record under the microscope. This thin section and interpretation are from the Chuos Formation (Cryogenian) of Nambia. From Busfield and Le Heron (2018). Photos B and C: D.P. Le Heron.

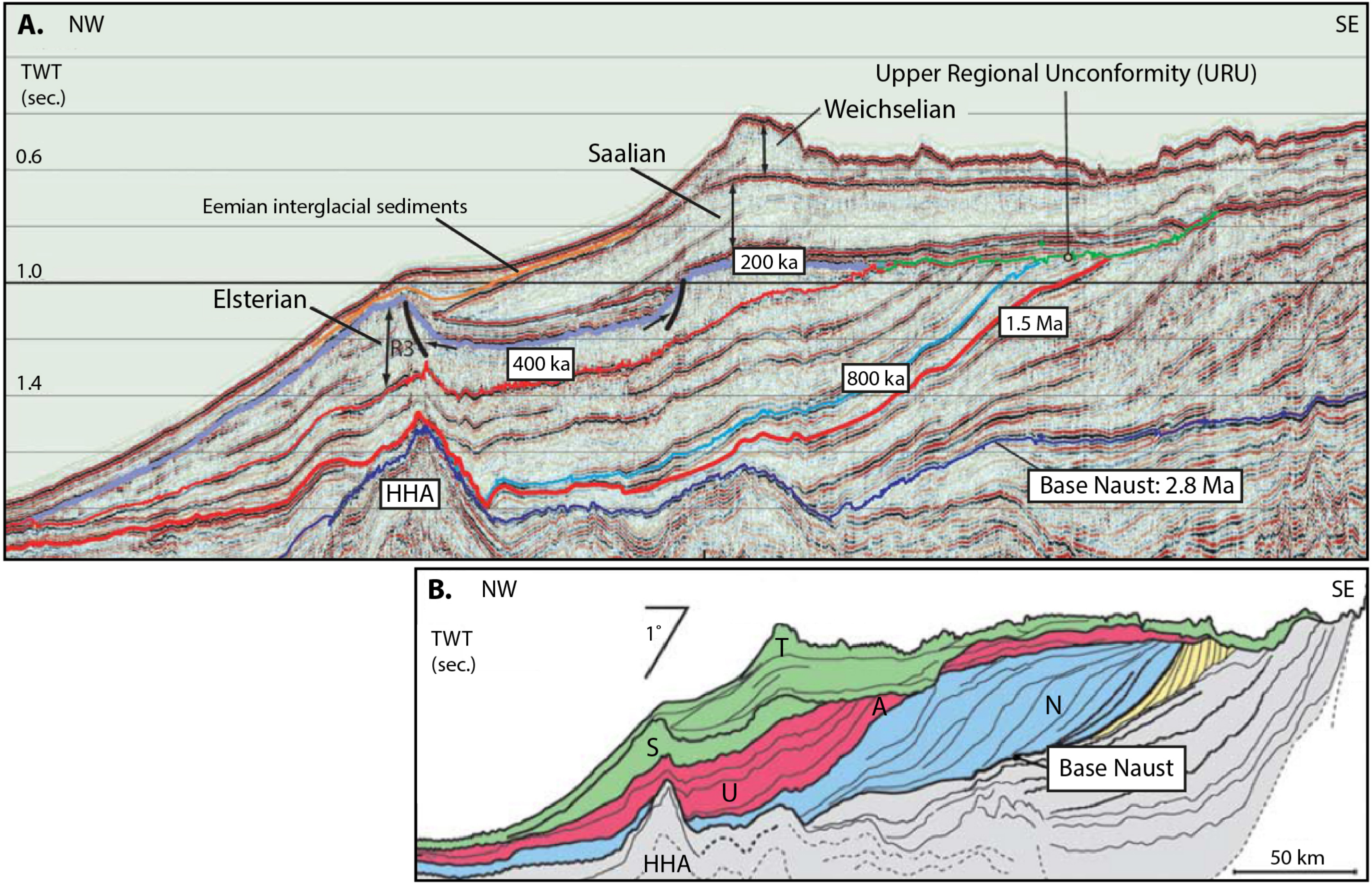
Fig. 9. Schematic flow chart linking methodologies used to investigate glacier-influenced deposits and landforms from modern, last glacial, Quaternary and ancient glacial settings. The brown text indicates methodologies employed for deposits from all time periods whereas the blue text indicates methodologies that can only be used for modern or last glacial settings.

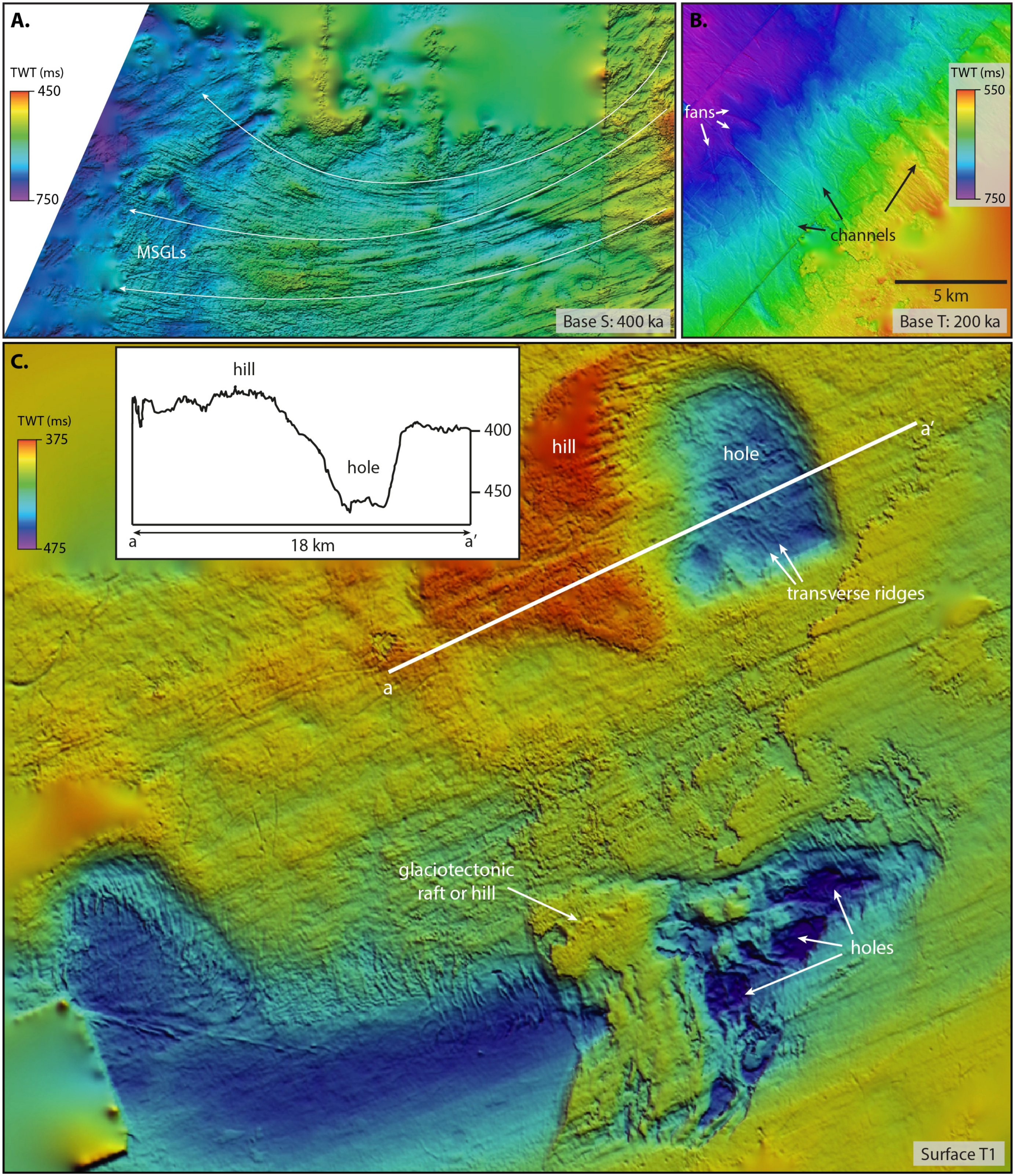

A.
0°
180°
90°W
90°E
10°N
30°N
50°N
Pacific Ocean
Atlantic Ocean
Arctic Ocean
North America
Gr.
B.
0°
180°
90°W
90°E
10°S
30°S
70°S
Atlantic Ocean
Pacific Ocean
Indian Ocean
South America
Africa
Antarctica
Australia

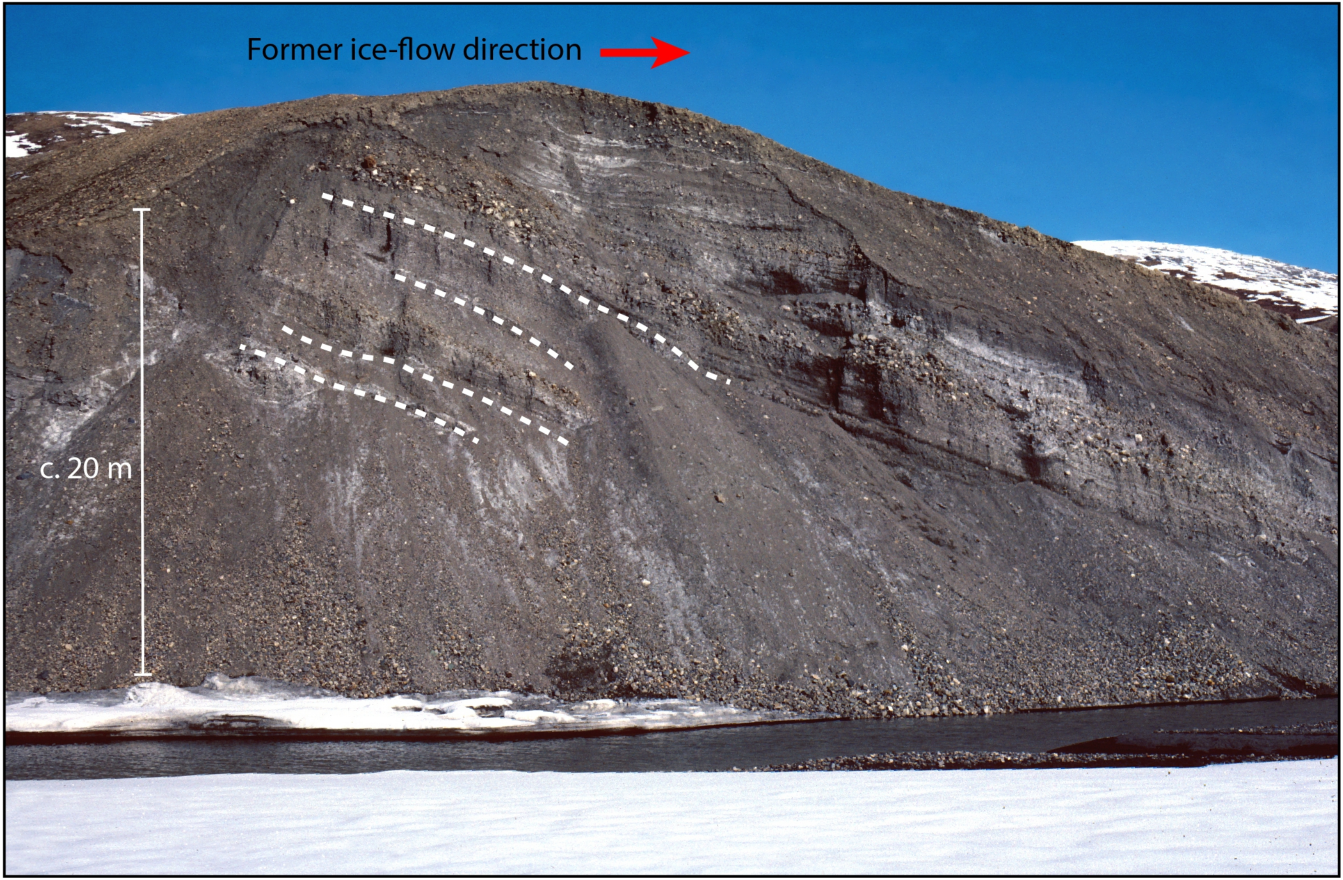

SEDIMENT SOURCES
GLACIOLOGY
OCEANOGRAPHY
SEDIMENTOLOGY (plus reworking)
SUBGLACIAL MATERIAL
SUBAERIAL MATERIAL
SHALLOW BOTTOM SEDIMENTS
Glacifluvial erosion
Glacial erosion
Rockfall
Aeolian erosion
Fluvial erosion
Freeze-in
SUBGLACIAL MELT STREAMS
TIDEWATER GLACIERS & ICE SHELVES
Calving
ICEBERGS
SEA ICE
Melting
Overturning, dumping
Melting
Oceanographic structure, buoyancy
Overflow interflow
WATER COLUMN
Underflow (Turbidity currents)
Mixing, flocculation
Gravity fall
AQUEOUS BIOGENIC MATERIAL
GLACIMARINE SEDIMENTS
Subaqueous mass wasting
Current reworking
Berg scour
Bioturbation

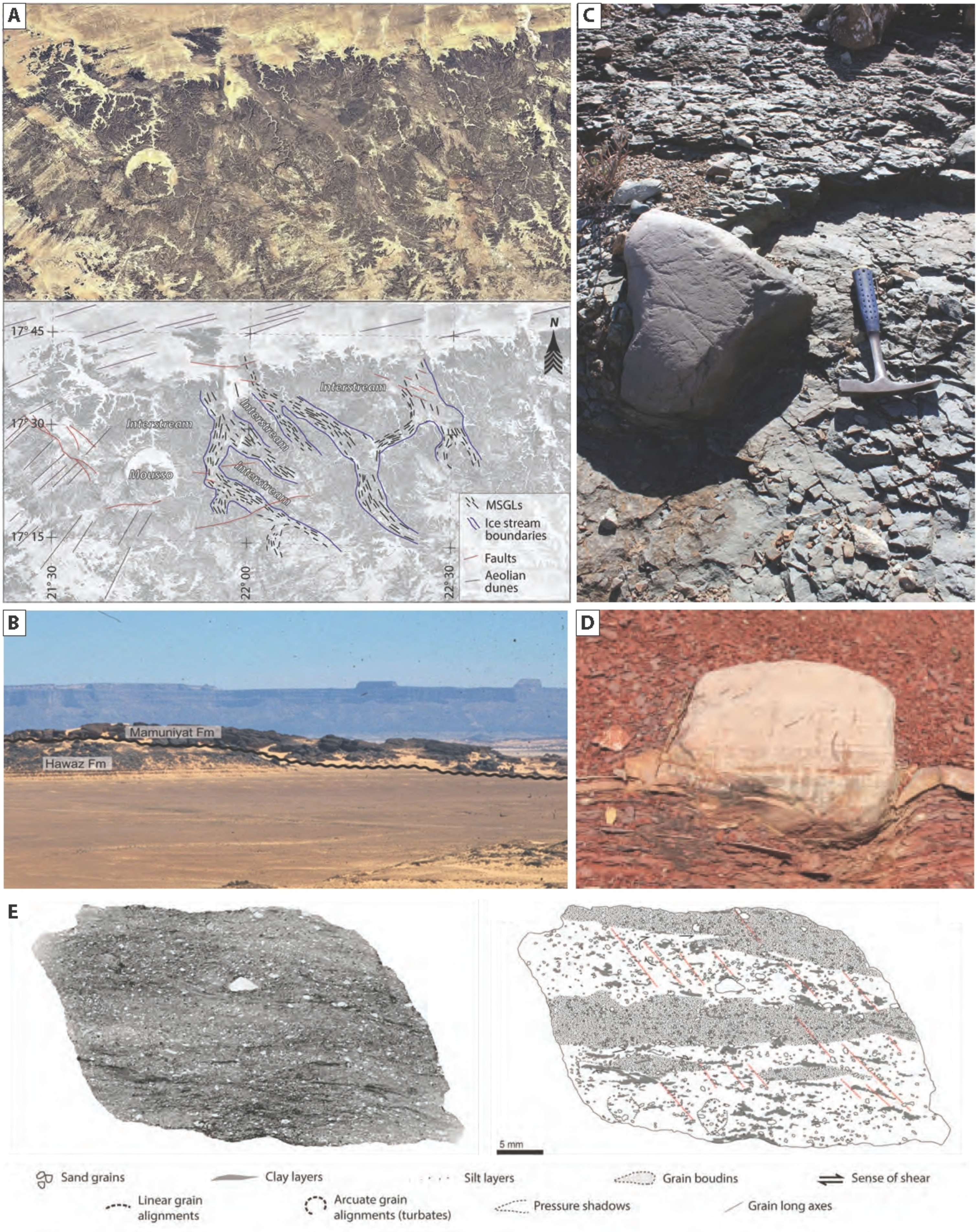

Idealized high-latitude continental margin
Interglacial ice cap
Full-glacial ice sheet
Continental shelf break
Interglacial sea level
Full-glacial sea level
120 m
100s m
200-500 m
Mountainous hinterland
Fjord
Sill
Continental shelf
Continental slope (0.5-10°)
3000-5000 m
Deep ocean basin
100s km

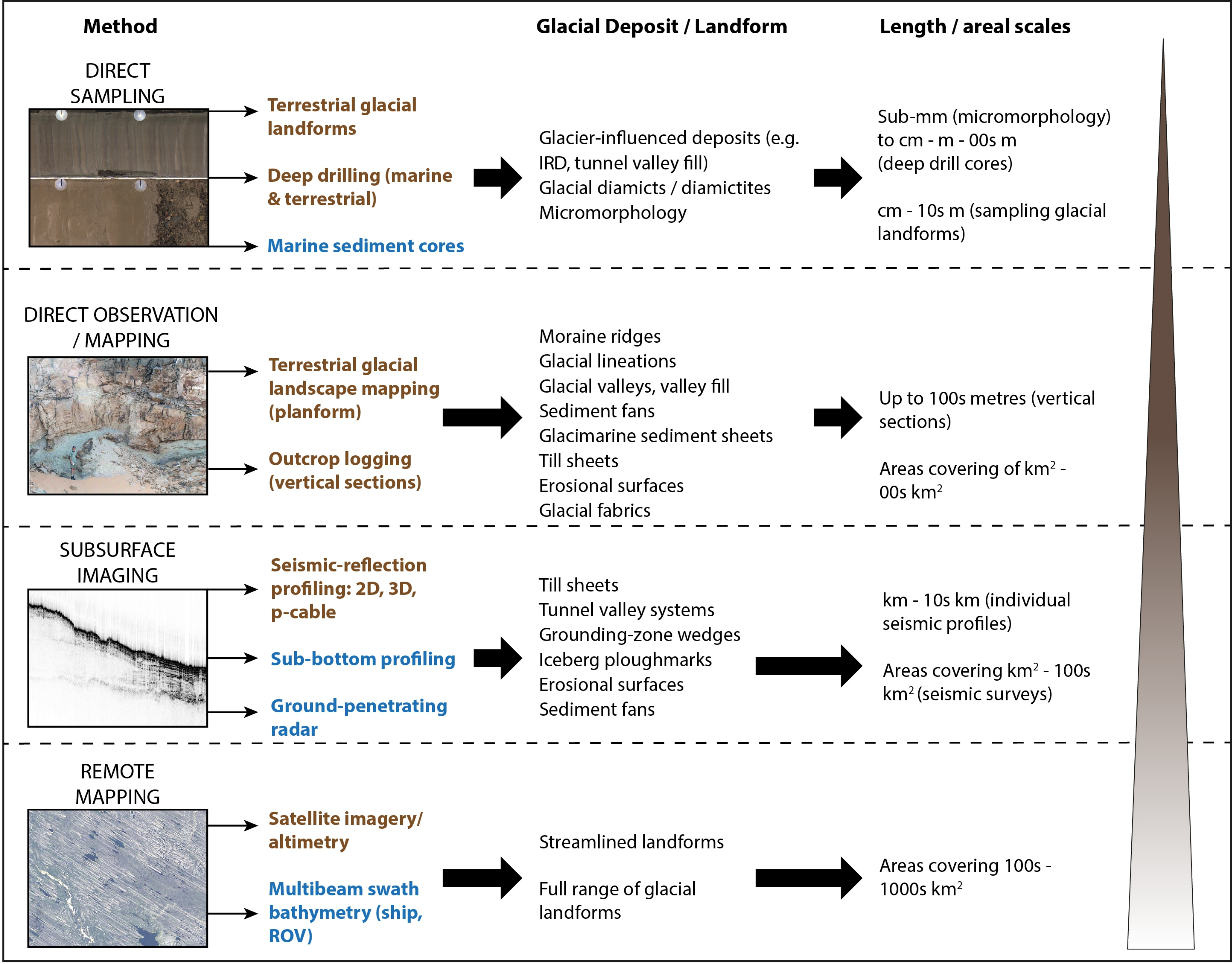

Southern Ocean
Antarctic Peninsula
Bourgeois Fjord
A.
Asymmetric ridges
B.
Glacial lineations
C.
Along-fjord direction
Asymmetric "finger-like" ridges
Depth (m)
230
280
Asymmetric ridge crest with unsorted clasts
D.


A.
NW
SE
TWT (sec.)
0.6
1.0
1.4
Upper Regional Unconformity (URU)
Weichselian
Saalian
Eemian interglacial sediments
200 ka
Elsterian
R3
400 ka
1.5 Ma
800 ka
HHA
Base Naust: 2.8 Ma
B.
NW
SE
TWT (sec.)
1°
T
S
A
N
U
Base Naust
HHA
50 km


A.
TWT (ms)
450
750
MSGLs
Base S: 400 ka
B.
fans
channels
TWT (ms)
550
750
5 km
Base T: 200 ka
C.
TWT (ms)
375
475
hill
hole
400
450
a
18 km
a′
hill
hole
a′
a
transverse ridges
glaciotectonic raft or hill
holes
Surface T1


Former ice-flow direction
c. 20 m


A
17° 45
17° 30
17° 15
21° 30
22° 00
22° 30
N
Interstream
Interstream
Interstream
Interstream
Mousso
MSGLs
Ice stream boundaries
Faults
Aeolian dunes
C
B
Mamuniyat Fm
Hawaz Fm
D
E
5 mm
Sand grains
Clay layers
Silt layers
Grain boudins
Sense of shear
Linear grain alignments
Arcuate grain alignments (turbates)
Pressure shadows
Grain long axes


Method
Glacial Deposit / Landform
Length / areal scales
DIRECT SAMPLING
Terrestrial glacial landforms
Deep drilling (marine & terrestrial)
Marine sediment cores
Glacier-influenced deposits (e.g. IRD, tunnel valley fill)
Glacial diamicts / diamictites
Micromorphology
Sub-mm (micromorphology) to cm - m - 00s m (deep drill cores)
cm - 10s m (sampling glacial landforms)
DIRECT OBSERVATION / MAPPING
Terrestrial glacial landscape mapping (planform)
Outcrop logging (vertical sections)
Moraine ridges
Glacial lineations
Glacial valleys, valley fill
Sediment fans
Glacimarine sediment sheets
Till sheets
Erosional surfaces
Glacial fabrics
Up to 100s metres (vertical sections)
Areas covering of km^2 - 00s km^2
SUBSURFACE IMAGING
Seismic-reflection profiling: 2D, 3D, p-cable
Sub-bottom profiling
Ground-penetrating radar
Till sheets
Tunnel valley systems
Grounding-zone wedges
Iceberg ploughmarks
Erosional surfaces
Sediment fans
km - 10s km (individual seismic profiles)
Areas covering km^2 - 100s km^2 (seismic surveys)
REMOTE MAPPING
Satellite imagery/ altimetry
Multibeam swath bathymetry (ship, ROV)
Streamlined landforms
Full range of glacial landforms
Areas covering 100s - 1000s km^2