Ice sheets viewed from the ocean: the contribution of marine science to understanding modern and past ice sheets

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Over the last two decades, marine science, aided by technological advances in sediment coring, geophysical imaging and remotely operated submersibles, has played a major role in the investigation of contemporary and former ice sheets. Notable advances have been achieved with respect to reconstructing the extent and flow dynamics of the large polar ice sheets and their mid-latitude counterparts during the Quaternary from marine geophysical and geological records of landforms and sediments on glacier-influenced continental margins. Investigations of the deep-sea ice-rafted debris record have demonstrated that catastrophic collapse of large (10^5–10^6 km^2) ice-sheet drainage basins occurred on millennial and shorter time scales and had a major influence on oceanography. In the last few years, increasing emphasis has been placed on understanding physical processes at the ice–ocean interface, particularly at the grounding line, and on determining how these processes affect ice-sheet stability. This remains a major challenge, however, owing to the logistical constraints imposed by working in ice-infested polar waters and ice-shelf cavities. Furthermore, despite advances in reconstructing the Quaternary history of mid- and high-latitude ice sheets, major unanswered questions remain regarding West Antarctic ice-sheet stability, and the long-term offshore history of the East Antarctic and Greenland ice sheets remains poorly constrained. While these are major research frontiers in glaciology, and ones in which marine science has a pivotal role to play, realizing such future advances will require an integrated collaborative approach between oceanographers, glaciologists, marine geologists and numerical modellers.

Keywords: ice sheets; multi-beam swath bathymetry; ice streams; continental margin; glacimarine processes and sediments; ice shelves and marine-terminating outlet glaciers

1. Introduction

Understanding and predicting the response of the large polar ice sheets in Greenland and Antarctica to climate change and their associated contribution to sea-level rise is a key scientific challenge. Many high- and mid-latitude continental margins preserve a record of past ice-sheet growth and decay [1]. During full glacial periods, ice sheets advanced across continental shelves adjacent to terrestrial landmasses, often to the shelf edge, and delivered icebergs, meltwater

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and sediment to the deep ocean. Much of this sediment delivery was associated with ice streams. Ice streams are fast-flowing features that can be several hundred kilometres in length and can flow at speeds of several hundred to several thousand metres per year. They are important because they are responsible for most of the drainage from the large polar ice sheets both today [2] and during past glaciations [3,4], and hence impact directly on ocean circulation and, through this, climate. Understanding the controls on ice-stream flow and, in particular, the processes that occur at the ice–ocean interface is increasingly recognized as being critical to understanding ice-stream dynamics [5,6] and to future estimates of the contribution of polar ice sheets to sea-level rise [7]. Marine science has been central to both the reconstruction of past ice sheets and to the understanding of their contemporary counterparts.

In this paper, I have two aims. First, to review the contribution of marine science to advances in understanding of contemporary and past ice sheets over the last two decades focusing on four major advances in which marine science has been pivotal: (i) reconstruction of past ice-sheet history from the deep-sea ice-rafted debris (IRD) record, (ii) reconstruction of past ice-sheet extent, form and flow from glacial geomorphological and geological data on high- and mid-latitude continental shelves, (iii) the nature of large-scale, glacially influenced sedimentation on continental slopes, and (iv) investigations of ice-shelf grounding lines and oceanographic drivers of outlet glacier retreat. These advances have occurred in tandem with technological developments in marine geophysics and sediment sampling, in particular, multi-beam swath bathymetry, three-dimensional seismics, the use of remotely operated submersibles (ROVs) and autonomous underwater vehicles (AUVs) and improvements in sediment coring and analysis. Second, the paper outlines what are currently considered to be the major scientific glaciological challenges in which the role of marine science is fundamental, and the associated technological challenges that will be necessary to overcome in order to achieve them. These are: (i) to understand the role of the ocean in ice stream and outlet glacier dynamics and, in particular, the interaction of oceanographic and glaciological processes at the ice–ocean interface and (ii) to understand the history of large ice-sheet drainage basins in Greenland and Antarctica. The role of UK science in terms of past advances and future research priorities is highlighted where appropriate, but it is recognized that many of the advances achieved over the last 20 years have involved a wider international research community, perhaps reflecting the necessarily multi-disciplinary approaches required for effective research at the interface between ice sheets and oceans.

2. Marine science and glaciology: looking back over the last 20 years

This section highlights four areas where, over the last two decades, marine science has made a fundamental contribution to advancing our understanding of modern and former ice sheets. As noted above, these advances are intimately associated with technological developments; in particular, the imaging and analysis of seafloor morphology and acoustic stratigraphy, the acquisition and analysis of marine sediment cores and observations of oceanography, seafloor and glacier morphology from remotely operated submersibles.
Prior to the 1990s, understanding of the history of former mid- and high-latitude ice sheets on their marine margins was still at a comparatively early stage in terms of the reconstruction of ice-sheet extent, ice-sheet flow dynamics, timing and rate of retreat. For example, in the case of the last North American, Greenland and British–Irish ice sheets (BIISs), it was recognized that these ice sheets expanded onto continental shelves during the last glacial maximum (LGM), but because of a frequent lack of offshore data from the shelves themselves, the maximum extent of these advances remained largely unresolved with considerable debate centring on whether ice sheets grounded to the shelf edge or some more restricted mid- or inner shelf position. Technological advances since the late 1990s, in particular, the development of multi-beam swath bathymetry systems, have allowed the acquisition of high-resolution, and often spatially extensive, datasets of fjord and continental shelf bathymetry and morphology. Indeed, the routine use of swath bathymetry to map many glaciated continental margins has allowed reconstruction of past ice-sheet extent and flow to be determined over large areas. Conversely, our understanding of glacimarine sedimentary systems, particularly in temperate environments such as Alaskan fjords had already seen major advances prior to the 1990s, notably with respect to the nature of sedimentary processes and resulting deposits, especially those related to meltwater delivery from tidewater glacier margins [8–12].

(a) Investigations of the deep-sea ice-rafted debris record and iceberg-rafting events

Iceberg rafting refers to the transport by icebergs of glacial debris into the ocean. The melting of icebergs through time results in the delivery of this debris to the seafloor as ‘IRD’. It is the principal mechanism by which glacial sediment is delivered to the deep ocean basins beyond the continental shelf edge. The use of IRD as a proxy by the palaeoceanographic community is common and the changing concentrations of IRD in deep-sea sediment cores have been used to infer rapid environmental and oceanographic change at sub-Milankovitch time scales [13]. Central to this research was the identification of six sand-rich layers in deep-sea sediment cores from the North Atlantic. These layers (termed the ‘Heinrich layers’) were deposited from icebergs sourced from the repeated collapse of the Laurentide ice sheet, principally from the Hudson Bay region of Canada and the associated delivery of icebergs into the North Atlantic that accompanied each collapse event (the ‘Heinrich events’) [14–16]. The initial work on the Heinrich layers provided the impetus for an increased focus on the use of IRD as a proxy to reconstruct past oceanographic and ice-sheet change, which led to the recognition of IRD in deep-sea cores related to the other circum-north Atlantic ice sheets [17–21]. While a number of studies have investigated IRD in the Southern Ocean and in Antarctic marine sediments [22–24] there, the IRD signal in some cases appears to be very weak [23,25], and there are conflicting interpretations of the significance of this record with respect to Antarctic ice-sheet stability [24,26]. Hence, unlike in the Northern Hemisphere, IRD abundance alone may not provide a reliable proxy for past ice-sheet collapse in Antarctica.

While many studies have reported on the presence or the absence of IRD within deep-sea cores and from this reconstructed past ice-sheet activity, the interpretation of some of these sediments as IRD has been debated [27], and a
key question remains as to whether these iceberg-rafting events are forced by some internal glaciological mechanism (e.g. the binge-purge theory of MacAyeal [28]) or are related to externally driven climate forcing [17,29]. This has been a matter of considerable debate, and much effort has focused on the correlation (or not) of IRD layers between widely separated deep-sea sediment cores and with other palaeo-environmental proxies [30,31]. The precise mechanisms responsible for driving these iceberg-rafting events, both the Heinrich events themselves and the intervening IRD events are likely to remain a matter of debate for some time to come. This raises a question as to the interpretation of such layers in sediment cores given the prevalence to infer palaeo-environmental and palaeoceanographic change from such sedimentary archives.

In addition to the identification and dating of IRD layers within deep-sea sediment cores, a major development has been in the use of IRD lithology and mineralogy to pinpoint the ice-sheet source(s) responsible for iceberg delivery [13,17,21,32–34]. This approach of ‘IRD finger-printing’ has allowed the various IRD contributions from different ice sheets to be identified, as well as any associated synchronicity to be established. For example, recent studies of deep-sea sediment cores from offshore of the western and northwestern margins of the last BIIS used multiple IRD finger-printing techniques to identify that component of IRD related to the iceberg delivery from the BIIS (figure 1) [35,36]. Most of the IRD in these cores was sourced from adjacent BIIS ice streams, with the exception of the centre of Heinrich layers in which the IRD was related to a Laurentide ice sheet source. These studies demonstrated that major growth of the BIIS occurred after 29 ka BP, and that the ice sheet reached its maximum extent at 24 ka BP followed by rapid retreat shortly thereafter at 23 ka BP.
(b) Reconstruction of past ice sheets on high- and mid-latitude continental shelves

Continental shelves range in width from tens to hundreds of kilometres and are characterized by water depths of typically a few hundred metres. The routine use of multi-beam swath bathymetry for the mapping of high- and mid-latitude shelves, in particular, since the mid-late 1990s, has allowed a detailed picture of their morphology to be acquired. High-latitude glaciated continental shelves in both the Arctic and Antarctica are characterized by relatively deep cross-shelf troughs, separated by intervening shallow banks, that extend from the mouths of fjords draining the hinterland of adjacent landmasses (figure 2) [3,38,39]. The record of glacial landforms and sediments preserved across these shelves and, in particular, within the cross-shelf troughs has enabled the reconstruction of former ice sheets in terms of their extent, flow dynamics and nature of their retreat [4,40–44]. A major development has been the recognition that these shelf troughs acted as the loci for fast-flowing ice streams during glacial maxima.

From swath bathymetric mapping of formerly glaciated continental shelves, it is now recognized that there are a series of characteristic seafloor features, including a range of streamlined subglacial landforms, such as drumlins and mega-scale glacial lineations that formed parallel to ice flow and thus indicate past iceflow direction and dynamics, as well as features that formed transverse to ice flow, such as moraine ridges and grounding-zone accumulations that mark either the maximum extent of grounded ice or recessional positions during deglaciation [1,39,45]. Mega-scale glacial lineations are characterized by amplitudes of less than 5 m, lengths of up to 20 km and widths of a few hundred metres (figure 3). They have been observed widely in cross-shelf bathymetric troughs where they are often formed in soft, deformable, diamictic sediments and, on the basis of their analogy with similar features documented beneath active Antarctic ice streams [47], they are now widely regarded as indicating the former presence of ice streams. Spectacular examples of these features have been recorded from bathymetric troughs in the Arctic and Antarctica [48–51].

In addition, submarine features formed transverse to ice-sheet flow provide information about the position of the ice-sheet margin or grounding line in time and space. The formation of these landforms typically requires ice-marginal or grounding-line stabilization so that sediment build-up can take place, and dated cores from these features allow a chronology of ice-sheet retreat to be established. Grounding-zone wedges, sometimes referred to as ‘till-deltas’, have been identified on seismic records and multi-beam swath bathymetric data on formerly glaciated continental shelves, but have also been associated with modern ice-stream grounding lines in the Siple coast region of West Antarctica [52,53]. They are sedimentary depocentres formed at the transition from grounded to floating ice (figure 4) [52–56]. Moraines are sedimentary ridges orientated parallel to the former ice-sheet edge and mark the maximum ice-sheet extent or successive positions of the ice-sheet margin during deglaciation [4,57]. Impressive examples of these features have recently been imaged from the seas around Ireland and Britain where they have been used to reconstruct the maximum extent of past glaciation and the form and pattern of subsequent ice-sheet retreat [42,58–60]. For example, offshore of northwest Ireland multi-beam swath bathymetric data...
provides the first direct evidence for extensive glaciation of the continental shelf in this region. The major glacial landforms consist of well-developed, nested arcuate moraines that mark the retreat of a former ice-sheet margin(s) across the shelf.

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Figure 3. Mega-scale glacial lineations in Marguerite Trough, Antarctic Peninsula (adapted from Ó Cofaigh et al. [46]).

during regional deglaciation (figure 5) [58,61]. The pattern of the moraines implies that the BIIS underwent major reorganization during shelf deglaciation from a ‘line-source’-type margin that extended along the shelf edge to a more lobate form [42,61].

Recently, the large-scale distribution of glacigenic landform-sediment assemblages as mapped from marine geophysics and outlined above has allowed inferences to be made regarding the overall form and flow of palaeo-ice sheets during full glacial periods as well as the nature of their retreat. For example, mapping of streamlined subglacial landforms for many areas of the continental shelves surrounding the Antarctic ice sheet and offshore of Norway has demonstrated that both the full glacial Antarctic and Fennoscandian ice sheets were characterized by zones of streaming flow concentrated along cross-shelf bathymetric troughs, separated by zones of slower flow on adjacent banks [4,44]. This is consistent with the present day ice-velocity patterns in Greenland and Antarctica as mapped from satellite remote sensing [62,63].

The distribution of these landform-sediment assemblages also provides detailed information on the nature of ice-sheet retreat. Recent work from Antarctica has shown that the style of ice-stream retreat following the LGM was spatially variable between troughs [46]. Three styles of retreat were inferred from marine geophysical records of glacial landform–sediment assemblages within the troughs:
Figure 4. Swath bathymetric and sub-bottom profiler records of grounding-zone wedges from the Antarctic shelf. (a) Sediment scarp (arrowed) marking a palaeo-grounding line formed during the retreat of ice offshore of the Larsen-A Ice Shelf (adapted from Evans et al. [54]). (b) Grounding-zone wedges (GZWs) on continental shelf of the Bellingshausen Sea, west Antarctica (adapted from Ó Cofaigh et al. [46]).

(i) rapid retreat by ice-stream floatation and calving, (ii) episodic retreat between successive grounding-zone positions, and (iii) slow-staggered retreat of grounded ice across the shelf (figure 6). This spatial variation in ice-stream retreat between different bathymetric troughs indicates that Antarctic palaeo-ice streams did not respond uniformly to external forcing during deglaciation following the LGM. Furthermore, the troughs investigated were characterized by reverse bed slopes. This is significant because models of marine ice-stream retreat suggest that it will be inherently unstable where the ice retreats along a reverse (i.e. deepening inland) bed [64–66]. The landform–sediment assemblages and style of retreat of palaeo-ice streams on the Antarctic shelf show that this scenario appears to be more complex and that ice-stream grounding lines can stabilize on reverse bed slopes. Observations from Arctic continental shelves [41] imply that this pattern is not solely limited to Antarctica.

At a smaller scale, the landforms and sediments on high-latitude continental shelves have allowed inferences to be made regarding the nature of subglacial processes operating beneath palaeo-ice sheets and, in particular, palaeo-ice streams. While investigations of the modern subglacial setting provide detailed observations and measurements of subglacial processes, the logistical constraints imposed by the presence of hundreds to thousands of metres of overlying ice necessarily means that those observations are limited in spatial, and often temporal, extent. In contrast, palaeo-ice-stream beds offer ease of access from ships and the possibility to collect data across the whole of the ice-stream

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Figure 5. Submarine moraines recording punctuated gradual retreat of a grounded ice-sheet margin characterized by numerous stillstands. The example shown is from the continental shelf offshore of Donegal Bay, northwest Ireland. (a) Multi-beam swath bathymetric image of arcuate recessional moraines. (b) Cross-sectional profile taken across the nested moraines. Data collected under the auspices of the Irish National Seabed Survey, Geological Survey of Ireland. (Reproduced from Ó Cofaigh et al. [61], copyright © (2012) with permission from Elsevier.)
bed using marine geophysical techniques. Shallow acoustic stratigraphy and sediment facies in cores have been used to investigate the nature of subglacial tills beneath former ice streams and to infer the nature of the processes operating at the ice-bed interface [54,67–69]. These investigations have shown that Antarctic ice streams are often associated with the presence of a thick, soft and porous subglacial till layer that is a product of a combination of subglacial sediment deformation and lodgement [70]. Palaeo-ice-stream beds have also allowed the mapping of the form, type and size of subglacial drainage networks, currently a major focus of research in contemporary glaciology. To this end, swath bathymetric mapping from cross-shelf bathymetric troughs in Antarctica has revealed extensive networks of meltwater channels and basins.
incised into crystalline bedrock [71,72]. Spectacular examples of relict subglacial meltwater features have been recorded, including tunnel channels over 20 km long and several kilometres wide [43,71]. These features provide evidence for the transfer of substantial volumes of meltwater beneath former ice streams, although the assumption that such channels record bank-full conditions and erosion by catastrophic flows [72] may not be correct. Such features could, alternatively, be produced by erosion during successive glacial cycles.

The application of three-dimensional seismic data has made possible the investigation of the form of buried surfaces and has allowed the identification of glacial landforms from earlier, pre-LGM, ice-sheet advances and assessment to be made of how ice-sheet flow has changed spatially and temporally between glaciations. A particular focus for the application of three-dimensional seismic techniques for the investigation of past ice-sheet activity has been the mid-Norwegian and Barents Sea shelves where extensive three-dimensional seismic datasets have been acquired by industry during exploration for hydrocarbons. These datasets have provided detailed information on ice-sheet dynamics and the nature of glacier-influenced sediment delivery across the continental margin [73–76]. On the mid-Norwegian shelf, seismic surveys of the 2.7 Ma Naust Formation has revealed the occurrence of glacial landforms that are common on modern polar continental shelves, including mega-scale glacial lineations and moraines related to pre-LGM glaciations [76]. Streamlined subglacial bedforms preserved on three-dimensional seismic surfaces point to the occurrence of major switches in ice-stream flow trajectory between successive glaciations. As noted by Dowdeswell et al. [76], ice-stream switching in modern and former ice sheets has commonly been regarded a product of internal glaciodynamic changes. The three-dimensional marine seismic data from the mid-Norwegian margin show that switching over longer, 100 kyr time scales may be related to large-scale sediment deposition and physiographic development of the continental margin.

(c) Large-scale glacier-influenced continental slope sedimentation and morphology

Allied to advances in understanding the record of ice-sheet dynamics and glacigenic sedimentation on continental shelves, the last two decades have also seen a major research effort using marine geology and geophysics to investigate glacier-influenced sedimentation on high-latitude continental slopes. Undoubtedly, some of the key advances in this topic have emanated from work carried out in the Polar North Atlantic, especially under the auspices of the ‘Polar North Atlantic Margins’ programme [77]. Successive developments in marine geophysics, initially side-scan sonar (Geological Long Range Inclined Asdic; GLORIA) and then multi-beam swath bathymetry have been used to investigate the morphology and sediment architecture of glacially influenced continental slopes in the Polar North Atlantic and have identified a series of large-scale features characteristic of ice-sheet-influenced continental slope settings.

Large submarine sediment fans have been documented from in front of many cross-shelf bathymetric troughs on high- and mid-latitude glaciated continental margins [78–80]. These ‘trough-mouth fans’ are associated with the former presence of ice streams draining to the shelf edge during past glacial maxima and
delivering glacigenic sediment onto the upper slope [81–83]. They represent major submarine depocentres on glaciated continental margins and are characterized by low gradient slopes (often less than 1°), are $10^4$–$10^5$ km$^2$ in area and can extend from the shelf edge to abyssal depths. Seismic and coring investigations of the sediments that comprise trough-mouth fans show that the major building blocks of these fans are glacigenic debris flows composed of diamictic sediment [81,84,85] (figure 7). Mapping of debris flow distribution on fans from GLORIA long-range side-scan sonar imagery shows that they typically emanate from trough mouths at the shelf break and can extend for over 100 km downslope. Debris flow delivery onto the slope and associated fan progradation are believed to occur during

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Figure 7. Glacigenic debris flows observed on 6.5 kHz GLORIA long-range side-scan sonar imagery from the surface of the Bear Island Fan, Norwegian Svalbard margin (adapted from Taylor et al. [86]).
intervals of maximum ice-sheet extent when ice streams grounded to the shelf edge and delivered unconsolidated glacigenic sediment onto the slope. The debris flows typically occur in ‘packages’ across the fans and are separated by units of hemipelagic sediment that record interglacial or interstadial conditions. Studies have also shown that iceberg rafted and hemipelagic sediments of full glacial age also occur on fans, thus demonstrating spatial variation in sediment delivery and glacimarine sedimentary processes across individual fans during full glacials [86]. In the Polar North Atlantic, large-scale sediment slides have been documented between the fans, and sometimes on them [79,87].

Trough-mouth fans appear to be rarer on the Antarctic margin [80,88], probably reflecting the much steeper gradient of the continental slope, which is often in excess of $5^\circ$ [89]. As a result, sediments delivered from ice streams onto the upper slope rapidly evolve downslope into turbidity currents that effectively bypass the slope and are deposited on the continental rise within sediment drifts [90]. Continental slopes in front of troughs and between them are therefore often characterized by gullies that acted as route ways for sediment bypass from the shelf edge to the base of the slope [91]. In some instances, the surfaces of trough-mouth fans themselves are actually incised by gullies and channels (e.g. Belgica Fan, Bellingshausen Sea, Antarctica). These channels and gullies are clearly erosional and most probably relate to incision by turbidity currents. While they clearly post-date the most recent phase of glacigenic debris flow delivery onto the fans, their relationship to the ice sheet and glacigenic sedimentary processes is still uncertain, with alternative explanations being proposed that range from glacial meltwater sedimentation during deglaciation to post-glacial brine rejection and formation of dense water cascades during sea-ice formation on the adjoining shelf [91].

Large-scale submarine channel systems also characterize some glaciated continental margins [92–94]. In the Labrador Sea, offshore of Hudson Strait, the continental slope is characterized by alternating high to moderate and low-relief imparted by the presence of canyons incising the slope [92]. Low-relief sectors comprise generally shallow (less than 150 m deep) canyons with broad floors. High–moderate-relief sectors comprise deeply incised, narrow canyons between 200 and 500 m in depth. This spatial contrast in slope morphology is thought to represent differences in the processes by which sediment was transferred through ice-sheet outlets of the Laurentide ice sheet and down the continental slope [95]. In the 250 000 km$^2$ Greenland Basin offshore of northeast Greenland, an extensive system of low gradient (less than 1$^\circ$) submarine channels extends for about 300 km from the middle continental slope to the abyssal depths of the basin where they terminate in a series of sandy channel mouth lobes (figure 8) [96–98]. The channels are up to 100 m deep, 4 km wide, and are dominated by mass-wasting deposits in the form of debris flows and turbidity currents, as well as hemipelagic sediments.

(d) Ice-shelf grounding lines and oceanographic drivers of outlet glacier retreat

Ice-shelf cavities and grounding zones (that zone where the grounded ice sheet passes into the floating ice shelf) are some of the most difficult glaciological environments to access logistically and, as a result, our understanding of their
associated oceanographic, glaciological and sedimentary processes remains poorly constrained by direct observation. In the last decade, however, technological developments, especially in ROVs and AUVs, have facilitated a number of studies of these environments. I will firstly outline advances in our understanding of sedimentary processes in these settings, and then move on to discuss more recent investigations that have focused on oceanographic processes and their interaction with the ice sheet.

Understanding of glacimarine sedimentation associated with floating ice shelves remains rudimentary, particularly when compared with that from temperate and sub-polar tidewater glacimarine settings. With few exceptions, it is based largely on inferences from Quaternary sediments from the Antarctic shelf. Existing models of ice-shelf sedimentation highlight a lack of meltwater delivery and emphasize deposition of poorly sorted coarse-grained diamictons (poorly sorted mixture of sand, gravel and mud) along the grounding line, as well as the formation of sediments by rain-out from the base of the ice shelf [54,99–101]. In a ground-breaking study, Powell et al. [102] described the sediments found at the grounding line and beneath the floating ice tongue of Mackay Glacier, a small outlet glacier in East Antarctica. Investigations using an ROV showed that sediments were being deposited predominantly by the squeezing out of diamicton from beneath the grounding line and subsequent remobilization by mass flow (figure 9).
In the last decade, technological advances in the development of AUVs has allowed access to a range of ice–ocean settings, including the cavities of large Antarctic ice shelves, the fronts of marine-terminating outlet glaciers in Greenland and sub-sea-ice investigations [103–105]. The UK has played a central role in this research, perhaps most notably through the design and implementation of the Autosub AUV. Autosub has depth and range ratings of 1.6 km and several hundred kilometres, respectively, and is designed to collect a range of oceanographic and bathymetric data along pre-programmed mission tracks while navigating by dead reckoning relative to the ice shelf or sea-ice base or the seafloor. A notable recent success was the deployment of Autostub beneath the floating ice shelf of Pine Island Glacier, West Antarctica [5]. This ice shelf has been thinning rapidly due to advection of warm ocean water into the ice-shelf cavity. Swath bathymetric data collected by Autosub indicated that the ice stream was...
grounded on a submarine ridge until recently, but has subsequently ungrounded from this bathymetric high and is now retreating into deeper water. Hence, the present thinning and retreat of Pine Island Glacier appears to be part of a longer-term pattern. It is, however, important to note that the observations from this one study constitute 90 per cent of all the data collected from AUV deployments beneath ice shelves [5], underlining the paucity of observations from this environment.

3. Marine science and ice sheets: looking ahead to the next 20 years

(a) Processes at the ice–ocean interface and relationship to glacier dynamics

Recent observations from satellite remote sensing have shown that many of the fast-flowing ice streams and marine-terminating outlet glaciers of the West Antarctic and Greenland ice sheets are accelerating and thinning rapidly, and thus contributing to sea-level rise [106,107]. Estimates of this ‘dynamic thinning’ for the marine-terminating outlet glaciers that drain ice from the interior of the Greenland ice sheet to the surrounding ocean show average thinning rates of $0.84 \text{ m yr}^{-1}$, while in West Antarctica, thinning has exceeded $9 \text{ m yr}^{-1}$ at the grounding lines of some of the ice streams draining into the Amundsen Sea embayment [107]. Although Greenland and Antarctica differ fundamentally in that, for the former, the ice sheet interacts with the oceans via marine-terminating outlet glaciers flowing into fjords, whereas in Antarctica, ice shelves and open shelf circulation are more important, dynamic thinning has nonetheless spread rapidly into the interiors of both ice sheets [107].

The precise mechanisms leading to this dynamic thinning remain poorly understood, although the removal of resistive stresses through the collapse of ice shelves and floating termini appears to be important [108,109]. However, there is an increasing recognition that interaction between the ice and the surrounding ocean may be critical in controlling the glacio-dynamic response. The West Antarctic Ice Sheet (WAIS) is a marine-based ice sheet that is grounded more than 2 km below sea level, and this has resulted in concerns about its stability in the context of warming climate and rising sea level [110]. With the exception of the Antarctic Peninsula, melt owing to atmospheric warming is minimal in Antarctica and the main driver of ice-sheet retreat and thinning appears to be warm ocean water interacting with ice-shelf grounding lines. Recent retreat in the Amundsen Sea sector of WAIS has been linked to the advection of warm circumpolar deep water across the continental shelf to the grounding line [5]. In Greenland, there is growing evidence for the warming of coastal waters and penetration of these waters into fjords coincident with recent dynamic mass loss [111–113]. However, there is considerable spatial and temporal variability in the dynamic response of these marine-terminating outlet glaciers and, crucially, numerical ice-sheet and oceanographic models are still too crude to capture this variability. In particular, the processes by which warm fjord waters are transmitted to the ice front and link to iceberg calving and the resulting dynamic response are poorly understood. Furthermore, observations of dynamic mass loss and associated ocean warming are restricted to the last two decades (the period of satellite observation) and, with few exceptions [114], the longer-term
significance of these dynamic changes are unknown; are they a solely recent phenomenon or are they part of a longer-term pattern related to continued deglaciation?

To date, much of the research on this topic has been discipline based and has focused on either contemporary glacier dynamics [109] or contemporary oceanography [111] or, more rarely, palaeoceanography [114] or palaeo-glaciology [115]. However, in order to make significant progress what is now needed is a collaborative approach integrating research efforts across all these disciplines. The UK is particularly well placed to do this, having the diversity of expertise required within the community. For Antarctica, the forthcoming Natural Environment Research Council Ice Sheet Stability Research initiative includes contemporary oceanographic and glaciological components, with a major research focus on the ocean forcing of WAIS dynamics in the Amundsen Sea sector, although the longer-term geological and palaeoceanographic record are not included in the programme. In Greenland, investigations of the role of oceanography in driving outlet glacier dynamics both past and present, and using these results to inform numerical models for future prediction, represents a key research goal and one in which marine science is absolutely central.

As noted above, ice-shelf cavities, grounding lines and the marine fronts of outlet glaciers are particularly challenging environments in which to collect data due to the severe access difficulties and potential hazards to equipment from, for example, iceberg calving and the narrow, often irregular shape of ice-shelf cavities. Existing observations from these settings are sparse and are predominantly limited to the summer season. However, there is emerging evidence that meaningful estimates of heat transport require measurements over longer periods of time, including the annual cycle [112]. In fjord settings as Greenland, this will require deployment of moorings over multiple seasons, but it presents particular technological challenges for investigations of sub-ice-shelf oceanography. Here, the development of sub-ice moorings and/or perhaps AUV technology in which an AUV is able to undergo periods of ‘hibernation’ between missions might allow the acquisition of longer times series. The UK is well placed to lead such research efforts given its track record in developing AUV technology, most notably Autosub. The continued refinement and development of AUVs that are capable of accessing these remote environments and making oceanographic, sedimentary and bathymetric measurements is therefore a key requirement. An alternative approach is to deploy ROVs through hot water drilled holes (e.g. the US Whillans Ice Stream Subglacial Access Research Drilling project). Other novel approaches, such as tagging marine mammals with instruments capable of oceanographic measurements [116], also have potential, particularly for data collection during the winter season.

As discussed in §2d, our understanding of the sedimentary processes and products at ice-shelf grounding lines and within ice-shelf cavities is rudimentary and is based largely on Quaternary examples. The development of sediment corers or grab samplers, which could be deployed from AUVs, would allow recovery of sub-ice-shelf sediments, and thus provide direct constraints on ice-shelf glacimarine facies models and the longer-term history of grounding-line dynamics. Such direct observations may also help with the development of reliable proxies for palaeoceangraphic interpretation, e.g. circumpolar deep water, although with few exceptions [101], the potential of marine microfauna, particularly
benthic foraminiferal ecology, remains under-used in palaeoceanographic and palaeoglaciological studies from the Antarctic continental shelf. Finally, while much of the interest in ice–ocean interaction centres on how the ocean affects the ice sheet, conversely, we know relatively little about how ice-sheet growth in Antarctica has affected the processes and distribution of bottom water formation.

(b) Investigations of ice-sheet history and glacial processes

(i) Long-term stability of ice-sheet drainage basins

As highlighted above, understanding the long-term pattern of ice-sheet dynamical change is important in order to determine the trajectory of current change and to better constrain numerical models for future prediction. UK marine scientists have played a considerable role in reconstructing the history of the Antarctic ice sheet, and major UK research efforts in the last few years have focused on the Amundsen Sea embayment [45,50,117,118] as well as the continental margins of the Antarctic Peninsula [48,54,67,68,119]. Our understanding of the geomorphological and sedimentary record of ice-sheet advance and retreat in these sectors has been aided by multi-beam swath bathymetry and vibrocoring (notably using the British Geological Survey (BGS) vibrocorer) to recover stiff glacigenic sediments on the continental shelf. However, key challenges remain, for example, with regard to the acquisition of well-dated stratigraphic records of ice-sheet retreat. Carbonate preservation is poor in Antarctic marine sediments owing to dissolution, and, in shallower water, problems of reworking are introduced by iceberg scour. Many investigations of Antarctic marine sediments have relied on radiocarbon dating the more-readily available bulk organic fraction, even though there are problems involved with dating this material, such as uncertainties with corrections for reworked organic carbon and often wide ranges of ages for core tops [120]. Continued improvements to existing dating techniques and the development and refinement of more novel methods, such as palaeo-magnetic intensity dating [121] represent a major challenge but an important one if palaeo-reconstructions of ice-sheet retreat in Antarctica are to provide meaningful estimates of rates of change, particularly at resolutions that are of use to numerical ice-sheet modellers. Clearly, while this is a problem that affects the most recent step change in the ice sheet from the LGM to last deglaciation, it is even more acute for records that are beyond the range of radiocarbon dating.

An allied problem on both Arctic and Antarctic continental shelves is that the recovery of glacial sediments in cores can be poor on account of their often consolidated, coarse-grained and poorly sorted nature. The BGS vibrocoring system (figure 10) allows good recovery of glacial sediments in cores up to 6 m in length, often penetrating back to the LGM. However, recovery of longer core records is difficult, as the performance of piston and gravity corers in recovering coarse, poorly sorted, stiff glacial sediments is typically poor. The BGS rockdrill (15 m recovery) and the German MEBO system (70 m recovery) offer great potential, but have not yet been used widely for the recovery of glacial sediments, and can also induce disturbance of the core sediments. Developments in coring technology are therefore an essential prerequisite for the recovery of long, undisturbed glacigenic sediment cores from polar continental shelves.
Intimately linked with the problems of dating Antarctic marine sediments is the necessity to develop reliable proxies by which we can identify collapse events of WAIS in marine sediments. As noted above, IRD abundance alone may not provide a reliable proxy. More broadly, key unanswered questions remain surrounding the glaciological significance of IRD and whether the associated purging of icebergs is a consequence of an ice-sheet advance and hence a positive mass balance, or represents collapse of a marine-based sector of an ice sheet, and hence a negative mass balance [35]. While in many cases, IRD layers have been inferred to record growth of marine-based ice-sheet margins (and thus a positive mass balance), rapid ice-sheet retreat by calving is likely to deliver an increased flux of IRD to the deep ocean. Discriminating between these contrasting interpretations remains an important avenue for IRD research and will require both high-resolution well-dated records of IRD that can be fingerprinted to individual ice sheets and, ideally, individual ice streams, combined with numerical modelling of both glaciology and oceanography to better understand the mechanisms and inter-relationships between iceberg calving, glacier dynamics and debris release.

As outlined in §2, in the last decade, the use of multi-beam swath bathymetry has allowed the detailed mapping of polar continental shelves and fjords. Seafloor morphology (in effect the shape of the former subglacial bed) is being increasingly recognized as a critical control in retreat dynamics of ice streams, both past and present, and individual outlets may behave differently for the same external forcing [122]. Understanding how bed morphology and other potential controls such as drainage basin size and sediment flux modulate ice-stream retreat is critical, given their potential importance in the future dynamic response of polar ice sheets to climate warming and sea-level rise. Many sectors of the Antarctic
and Greenland shelves, however, remain un-surveyed or have only been surveyed at a reconnaissance level. This is particularly the case around much of the East Antarctic margin.

Surprisingly, our knowledge of the marine record of Greenland ice sheet history is arguably poorer than that for Antarctica, and large areas of the Greenland continental shelf remain un-surveyed without even a rudimentary understanding of seafloor bathymetry and acoustic stratigraphy. This is particularly the case for much of the southwest, northwest and north Greenland shelf. In northeast Greenland, a few marine geophysical studies have recently been carried out [39,123], but they lack ground-truthing by dated sediment cores. Given the current interest in the dynamics of Greenland’s contemporary marine-terminating outlet glaciers and the future contribution of the Greenland ice sheet to sea-level rise, the absence of data on the longer-term record of ice-sheet history from much of the Greenland continental margin represents a major research gap for which marine geology and geophysics will be central. In addition, pre-LGM records of Greenland ice-sheet history are few and hence we cannot answer at present if, for example, major Greenland ice streams were present in earlier full glacial periods prior to the LGM. Long-drill records are therefore important, and in this regard, the large trough-mouth fans along the little-studied Baffin Bay margin west of Greenland represent major targets. In Antarctica, the Amundsen Sea margin remains an important drilling target for the recovery of long-term archives of ice-sheet history and forcing mechanisms for this region of WAIS

(ii) Subglacial and glacimarine processes

Questions also remain regarding subglacial processes; questions which marine geological and geophysical studies are well placed to address. For example, with regard to subglacial hydrology, the length of time it takes to form the large well-developed meltwater drainage systems incised into hard bedrock on the inner Antarctic continental shelf is at present unknown. Are the channels a product of incision by steady-state flows over multiple glacial cycles or are they due to erosion by catastrophic meltwater floods over a much shorter period? Subglacial meltwater channels have not been observed within areas of the bed formed in till. Does this reflect drainage of meltwater through pore spaces in the till by Darcian throughflow, or does it reflect the fact that existing multi-beam systems are, as yet, unable to resolve these kinds of features over the soft bed? These are unanswered questions, but ones which marine science has the potential to answer through acquisition of well-dated core chronologies and increasing improvements in multi-beam systems [124].

Understanding the large-scale sediment architecture and morphology of glacially influenced continental slopes has undergone major advances in the last two decades with the identification of a series of distinctive features related to the past growth and decay of ice sheets and delivery of glacigenic sediment onto the slope. A number of conceptual models have been proposed to explain this variation in sediment architecture and slope morphology. These models variously emphasize shelf width, slope gradient, ice-sheet dynamics and rates of sediment delivery [38,82,89]. However, to date, no one model has successfully managed to explain all the variation or indeed the relative importance, timing and frequency of the associated processes of sediment delivery. Perhaps, the pursuit of a single
model is misplaced and the importance or dominance of different controls varies in both time and space for a given glacier-influenced margin? Answering this question remains a major scientific challenge.

4. Conclusion

Over the last two decades, marine science, aided by technological advances in geophysics, sediment coring, ROVs and AUVs, has played a major role in the investigation of both contemporary and former ice sheets. Significant advances have been achieved in deciphering the record of glaciations on high-latitude continental margins and the associated nature of glacier-influenced sediment delivery. The use of the deep-sea IRD record has allowed reconstruction of the long-term history of past ice-sheet collapse, most notably in the Northern Hemisphere. Increasing sophistication in IRD finger-printing has allowed the IRD to be traced to individual ice sheets and ice-sheet drainage basins. Most recently an emerging recognition that the ocean acts as a driver of ice-sheet dynamics in both Greenland and Antarctica has focused attention on understanding the glaciological and oceanographic processes operating at the ice–ocean interface. However, for both ice sheets, this is still at a relatively early stage and it represents a major research frontier requiring observations of contemporary processes and variability and the reconstruction of their longer-term history. The major challenge will be to record the observations of rapid dynamic changes, both past and present, on scales that are useful to numerical modellers and with which they can use to tune and test models that can then be used for prediction. Such datasets are rare, particularly in Antarctica, where there are considerable problems in obtaining high-resolution well-dated records of ice-sheet retreat, and understanding of forcing mechanisms [101] is often elusive. Advances in this field will require an integrated collaborative approach between oceanographers, glaciologists, marine geologists and numerical modellers.

Despite considerable advances in reconstructing the Quaternary history of mid- and high-latitude ice sheets, major unanswered questions remain regarding WAIS stability, which will probably require improvements in dating and in coring technology to achieve. While sedimentary and geomorphological records of ice-sheet advance and retreat have now been obtained for many sectors of the continental shelf bordering West Antarctica and the Antarctic Peninsula [44] as noted above, associated dating control is often poor or at best sparse, even though temporally well-constrained records are a priority for the effective modelling of grounding-line retreat. The long-term offshore history of the East Antarctic and Greenland ice sheets remains poorly constrained, and there are large sectors of the continental shelves surrounding both ice sheets for where there are no data.

Finally, there is considerable potential for collaboration between academia and industry on the marine geological and geophysical investigation of glaciated continental margins. For example, the Greenland shelf is currently a major area of hydrocarbon exploration with a number of UK companies active in the area. There are therefore possibilities for strong collaboration between academia and industry in this region. In particular, the use of two- and three-dimensional seismics by industry along the Greenland margin represents great potential for
providing longer records of pre-LGM Greenland ice-sheet history. Industry is also interested in seabed properties and morphology (of mutual interest to scientists) for drill rig location and hazard assessment.

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