Submarine Glacial Landforms

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Abstract The development of a range of geophysical imaging techniques, including multi-beam swath bathymetry and shallow-acoustic profiling, has enabled the identification and interpretation of submarine glacial landforms on and beneath the seafloor of formerly-glaciated continental margins. The analysis of these landforms provides information about past ice-sheet dynamic behaviour and the mechanisms by which sediment is eroded, transported and deposited by ice sheets. Submarine glacial landforms can be categorised into subglacial, ice-marginal and glacimarine features. The majority of subglacially produced landforms, including mega-scale glacial lineations and drumlins, are elongate features that are orientated parallel to the direction of former ice flow. In contrast, ice-marginal landforms, including moraines and grounding-zone wedges, are orientated transverse to the former ice-flow direction. Ice-marginal landforms reveal the positions of still-stands or minor re-advances in the grounding-zone during general ice-sheet retreat. Glacimarine landform associations include ploughmarks that are formed by the grounding of iceberg keels on the seafloor, and smooth basin-fill sediments produced by suspension settling of material derived from meltwater plumes. The typical distribution of glacial landforms on formerly glaciated continental margins is illustrated using the case study of the Norwegian continental shelf and slope. The locations of former fast-flowing ice streams are associated with deep cross-shelf troughs that contain elongate subglacial landforms. Major glacial-sedimentary depocentres or trough-mouth fans are typically present on the continental slope beyond trough mouths. In contrast, relatively shallow inter-ice stream banks on the continental shelf are characterised by transverse moraine ridges and widespread iceberg ploughmarks.

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1 Introduction

Ice sheets expanded across the continental shelf beyond mid- and high-latitude land masses on many occasions during the glacial-interglacial cycles of the Quaternary (e.g. Svendsen et al. 1999; Dyke et al. 2002). The advance and retreat of ice across these margins has resulted in the formation of distinctive assemblages of subglacial, ice-marginal and glacimarine landforms (Table 1). Whereas subaerial erosion and human activity have led to a fragmented record of glacial activity on land, glacial landforms are often well preserved in the marine environment, where they can be identified within deglaciated fjords and on the continental shelf and slope (e.g. Solheim et al. 1990; Shipp et al. 1999; Dowdeswell et al. 2002; Ottesen et al. 2005; Larter et al. 2012).

The interpretation of submarine glacial landforms has been made possible by the advent of geophysical imaging techniques. The morphology of the seafloor was initially investigated using single-beam echo sounders, which acquired a line of seafloor depth soundings beneath the ship (e.g. Damuth 1978). Technological improvements in the past few decades have facilitated the use of, first, side-scan sonar and then multi-beam echo sounders to map wide regions of the seafloor, whilst shallow-acoustic and 2-D seismic-reflection profiles enabled the initial recognition of older landforms on buried horizons. More recently, 3-D seismic reflection surveys have been used to interpret the submarine glacial landform record with high temporal and spatial resolution (e.g. Dowdeswell et al. 2006).

The analysis of submarine glacial landforms facilitates reconstructions of the configuration and dynamics of past glaciers and ice sheets. Understanding past rates of change is also important information against which to assess model predictions of future responses of the Greenland and Antarctic ice sheets to climatic change (Stokes et al. 2016). A key focus within ice-sheet reconstruction is the identification of the sites of former ice streams, which are relatively narrow corridors of fast-flowing ice set within slower-flowing regions of an ice sheet (Bentley 1987; Dowdeswell and Siegert 1999; Whillans et al. 2001). Ice streams respond dynamically to perturbations over short, sub-decadal, time-scales (e.g. Anandakrishnan and Alley 1997; Joughin et al. 2003) and also have the potential to force abrupt climatic change through the rapid delivery of ice and meltwater to the marine ice-sheet margin (e.g. MacAyeal 1993; Clark 1994).

Erosion of the continental shelf by fast-flowing ice streams has resulted in the formation of deep bathymetric depressions termed cross-shelf troughs, which are bordered by shallower banks (Vorren and Laberg 1997; Dowdeswell and Siegert 1999; Batchelor and Dowdeswell 2014). Cross-shelf troughs typically contain assemblages of glacial landforms that are indicative of fast, ice-streaming flow, including subglacially produced elongate and streamlined landforms and pervasively deformed till (e.g. Stokes and Clark 2001; Shipp et al. 1999; Ó Cofaigh et al. 2002; Dowdeswell et al. 2004a). Prograding sedimentary depocentres, known as trough-mouth fans, typically develop on the continental slope seaward of cross-shelf troughs that have experienced high rates of sediment delivery to the

Table 1 List of studies covering the environments and landforms discussed in this chapter

Environment	Landform	References
Subglacial	Mega-scale glacial lineations	Stokes and Clark (1999, 2002); Ó Cofaigh et al. (2002); Dowdeswell et al. (2004a); Ottesen et al. (2005, 2007)
	Flutes and drumlins	Shipp et al. (1999); Wellner et al. (2001); Ó Cofaigh et al. (2002)
	Crag-and-tails	Ottesen et al. (2005); Ó Cofaigh et al. (2013)
	Ice-moulded bedrock	Wellner et al. (2001); Dowdeswell et al. (2014)
	Hill-hole pairs	Sættem (1990); Ottesen et al. (2005); Dowdeswell et al. (2010)
	Crevasse-fill ridges	Solheim (1991); Boulton et al. (1996); Ottesen and Dowdeswell (2006), Ottesen et al. (2008)
	Tunnel valleys (glacifluvial)	Ó Cofaigh (1996); Praeg (2003)
	Eskers (glacifluvial)	Ottesen and Dowdeswell (2006); Ottesen et al. (2008)
Ice-marginal	Terminal and recessional moraine ridges	Powell (1983); Seramur et al. (1997); Vorren and Plassen (2002); Ottesen et al. (2005); Bradwell et al. (2008)
	Hummocky-terrain belts	Ottesen and Dowdeswell (2009); Elvenes and Dowdeswell (2016)
	Small retreat moraines	Boulton (1986); Shipp et al. (2002); Ottesen and Dowdeswell (2006); Todd et al. (2007)
	Grounding-zone wedges	Anderson (1997); Powell and Alley (1997); Ó Cofaigh et al. (2005); Dowdeswell and Fugelli (2012); Batchelor and Dowdeswell (2015)
	Ice-proximal fans	Powell (1990); Lønne (1995); Powell and Domack (1995); Dowdeswell et al. (2015)
	Ice-stream lateral shear-zone moraines	Stokes and Clark (2002); Ottesen et al. (2005, 2008)
	Ice-stream lateral marginal-moraines	Rydningen et al. (2013); Batchelor and Dowdeswell (2016)
	Trough-mouth fan	Vorren et al. (1988); King et al. (1996); Dowdeswell et al. (1998); Laberg et al. (2000)
Glacimarine	Iceberg and sea-ice keel ploughmarks	Woodworth-Lynas et al. (1991); Dowdeswell et al. (1993); Mertz et al. (2008)
	Smooth basin-fill from meltwater plumes	Cowan and Powell (1990); Cai et al. (1997); Ó Cofaigh and Dowdeswell (2001)
Marine	Wave and current features	Howe and Pudsey (1999); Garçia et al. (2012)
	Mass movement events	Laberg and Vorren (1993); Vanneste et al. (2006); Piper et al. (2012)

shelf edge over successive full-glacial periods (Dowdeswell et al. 1996; Elverhøi et al. 1998; Dowdeswell and Siegert 1999). The glacial landforms that are preserved on the intervening shallower banks are characteristic of slower-flowing ice (e.g. Ottesen and Dowdeswell 2009).

In this chapter, we describe the submarine glacial landforms that have been identified on mid- to high-latitude continental margins (Figs. 1, 2, 3, 4, 5 and Table 1). The typical distribution of these landforms within cross-shelf troughs and on shallower banks is illustrated using the example of the formerly-glaciated Norwegian margin (Figs. 6 and 7).

2 Landforms Produced in Different Glacial-Process Environments

2.1 Subglacial Landforms

The majority of subglacially produced landforms, including mega-scale glacial lineations (MSGLs), flutes, drumlins, crag-and-tails and ice-moulded bedrock, are streamlined in the direction of ice flow (Fig. 1 and Table 1) and can therefore be used to infer former ice-flow patterns. Hill-hole pairs, crevasse-fill ridges and glacifluvial tunnel valleys and eskers (Fig. 2) are also formed subglacially.

2.1.1 Mega-Scale Glacial Lineations and Other Streamlined Subglacial Landforms

MSGLs (Fig. 1a, b) are elongate sedimentary ridges that have typical lengths of up to a few tens of kilometres, widths of a few hundred metres and amplitudes of a few metres (Stokes and Clark 2002). They have high elongation (length:width) ratios of greater than 10:1, and generally occur in groups of parallel to sub-parallel ridges that have regular spacing of a few hundred metres (Clark 1993; Stokes and Clark 2002; Spagnolo et al. 2014). MSGLs have been recognised on the seafloor of a number of formerly glaciated continental margins, where they are typically identified within cross-shelf troughs (Elverhøi et al. 1995; Shipp et al. 1999; Ó Cofaigh et al. 2002; Ottesen et al. 2005; Dowdeswell et al. 2014). Sub-bottom acoustic profiles (e.g. Fig. 5a) and sediment cores show that MSGLs are formed within an acoustically-transparent structureless diamict of low shear strength, which is interpreted as subglacial deformation till (e.g. Dowdeswell et al. 2004a).

The close association of MSGLs with cross-shelf troughs and areas of deformable sediment has led to these features being considered diagnostic of grounded, fast-flowing ice within ice streams (e.g. Stokes and Clark 2002; Dowdeswell et al. 2004a; Evans et al. 2005). This interpretation is supported by the identification of MSGLs forming beneath modern active ice streams in West Antarctica (King et al. 2009).

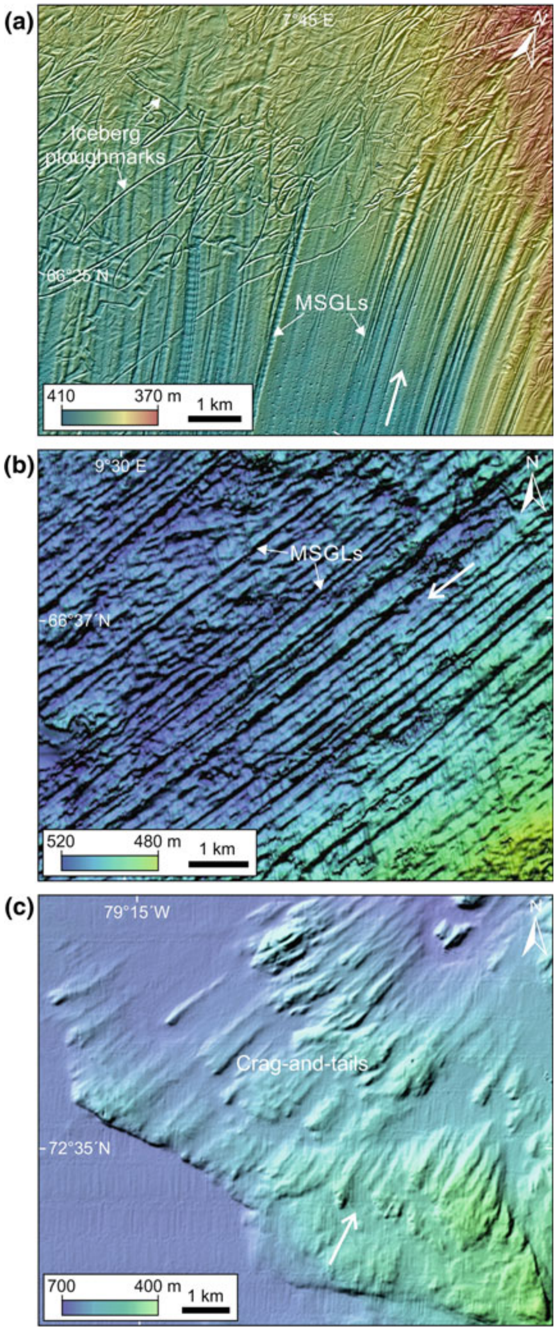

Fig. 1 Examples of subglacially produced streamlined submarine landforms. *White arrows* show former ice-flow directions. **a** Seafloor mega-scale glacial lineations (*MSGLs*) overprinted by iceberg ploughmarks on the Norwegian continental shelf. **b** MSGLs on a buried surface around 100 m deep on the mid-Norwegian margin (adapted from Dowdeswell et al. 2006). **c** Seafloor crag-and-tail features in Eclipse Sound, Baffin Island, Arctic Canada (adapted from Dowdeswell et al. 2016)

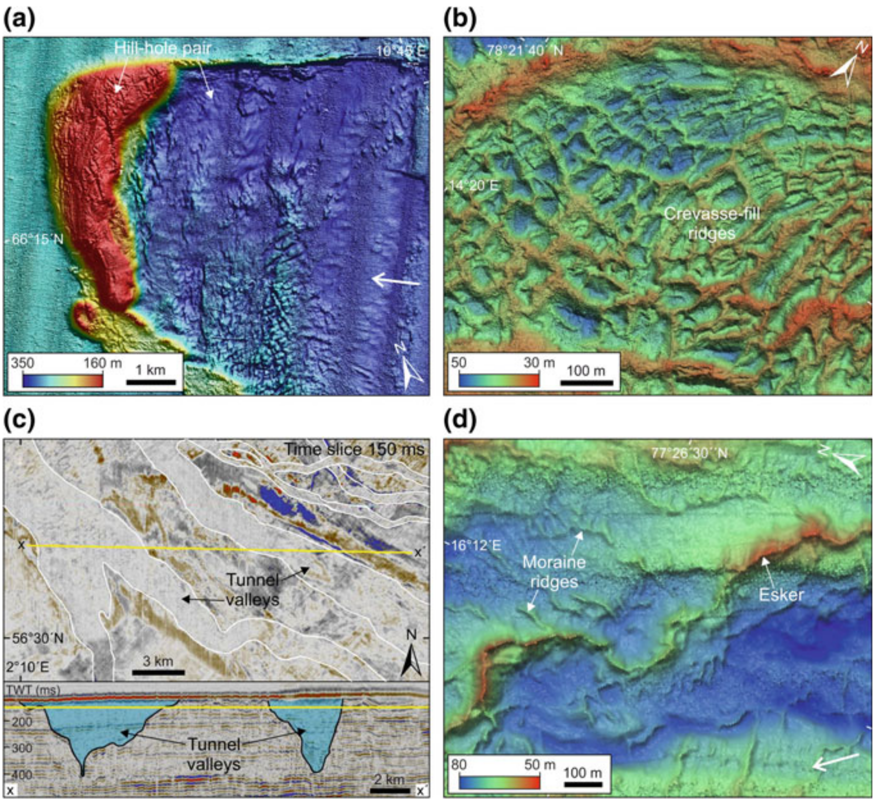

Fig. 2 Examples of subglacially produced, non-streamlined landforms. **a** Seafloor hill-hole pair on the Norwegian margin. **b** Crevasse-fill ridges on the seafloor of Borebukta, Isfjorden, Spitsbergen. **c** Upper time slice of 3D seismic-reflection data, showing a network of tunnel valleys in the North Sea. Lower seismic cross-profile of tunnel valleys in the North Sea. **d** Sinuous esker on the seafloor of Van Keulenfjorden, Spitsbergen

There is currently no consensus regarding the process by which MSGLs are formed. Some theories invoke a predominantly erosional mechanism, by which MSGLs are produced by the ploughing action of basal ice keels across a sedimentary substrate (Clark et al. 2003), whilst others advocate a constructional process involving downflow attenuation by pervasive subglacial sediment deformation (Boulton and Hindmarsh 1987; Clark 1993). The observation that MSGLs tend towards a relatively consistent spacing, size and shape has been interpreted as evidence that some type of instability, possibly involving a film of water at the ice-sediment interface, may be involved in their formation (Fowler 2010).

Although the majority of submarine MSGLs have been recognised on or close to the seafloor, the analysis of 3-D seismic-reflection data facilitates the identification of landforms, including MSGLs, on older surfaces that are buried within the

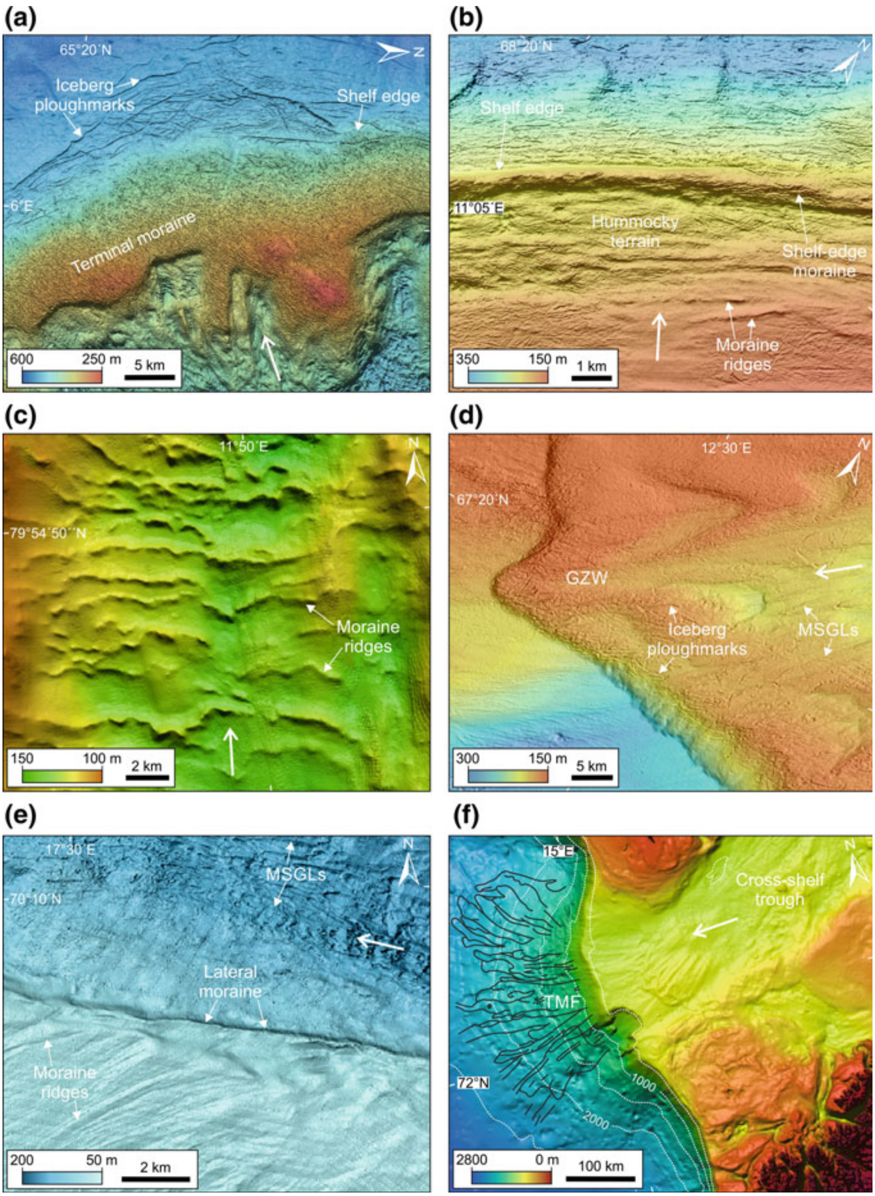

Fig. 3 Examples of submarine ice-marginal landforms. *White arrows* show former ice-flow directions. **a** The Skjoldryggen terminal moraine on the mid-Norwegian shelf. **b** A shelf-edge moraine and a belt of hummocky terrain close to the shelf edge of Røstbanken, west of the Lofoten Islands, Norway. **c** Series of small moraine ridges in Raudfjorden, northwest Spitsbergen. **d** Grounding-zone wedge (*GZW*) in Vestfjorden, south of the Lofoten Islands, Norway. **e** Lateral-moraine ridge at the southern lateral margin of Rebbenesdjupet, northern Norway. **f** Trough-mouth fan (*TMF*) at the mouth of Bear Island cross-shelf trough, Barents Sea. *Black lines* show seafloor glacigenic debris-flows (adapted from Taylor et al. 2002a)

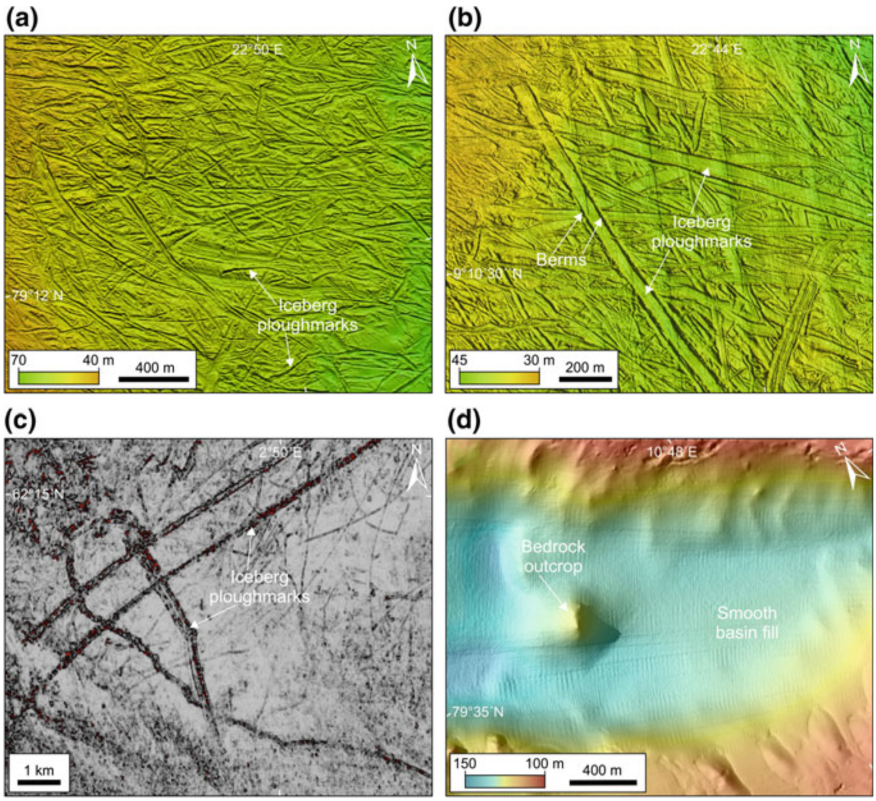

Fig. 4 Examples of glacimarine landforms. **a** Narrow linear to curvilinear iceberg ploughmarks on the seafloor outside Bråsvellbreen, eastern Svalbard. **b** Wide iceberg ploughmarks with raised berms on the seafloor of Bråsvellbreen, eastern Svalbard. **c** Iceberg ploughmarks on a buried surface around 100 m deep in the northern North Sea. **d** Bathymetric image of smooth basin-fill sediments in Magdalenefjorden, northwest Spitsbergen

sub-seafloor stratigraphy (e.g. Fig. 1b). The identification of MSGLs on palaeo-shelves provides direct evidence for the former presence of grounded, fast-flowing ice and can be used to infer palaeo-ice stream flow directions (e.g. Dowdeswell et al. 2006).

Whereas MSGLs represent the end-point of a spectrum of elongate subglacial landforms (Clark 1993), ice-flow parallel ridges with lower elongation ratios, such as flutes and drumlins, are also identified in association with relatively fast-flowing ice (e.g. Shipp et al. 1999; Wellner et al. 2001; Ó Cofaigh et al. 2002; Ottesen et al. 2005). Groups of parallel to subparallel flutes and drumlins have been identified on the seafloor of formerly glaciated fjords and continental shelves, where they are interpreted to indicate relatively fast ice flow within outlet glaciers or ice streams

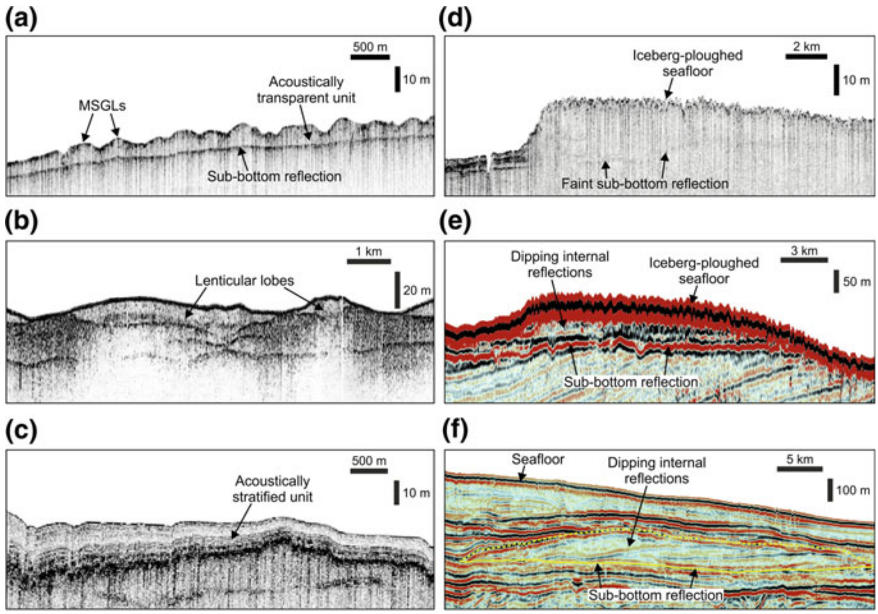

Fig. 5 Examples of the internal acoustic character of glacially-influenced landforms. **a**–**d** show TOPAS sub-bottom profiles (3.5 kHz), whereas **e**–**f** show seismic-reflection profiles. **a** Mega-scale glacial lineations (*MSGLs*) formed within acoustically transparent sediment in Marguerite Bay, Antarctic Peninsula (Reprinted from Ó Cofaigh et al. 2005, with permission from Elsevier)—past ice flow is towards the reader. **b** Cross-section through acoustically transparent glacigenic debris-flow lobes on the Bear Island trough-mouth fan, Barents Sea (Reprinted from Taylor et al. 2002b, with permission from Elsevier). **c** Acoustically stratified basin-fill sediment in the Uummannaq cross-shelf trough, West Greenland. **d** Long-profile of a grounding-zone wedge (*GZW*) in the Uummannaq cross-shelf trough, West Greenland. **c** and **d** are adapted from Dowdeswell et al. (2014). **e** Long-profile of a grounding-zone wedge (*GZW*) off West Greenland. **f** Long-profile of a grounding-zone wedge on a buried surface around 150 deep in Amundsen Gulf, Arctic Canada. **e** and **f** are adapted from Batchelor and Dowdeswell (2015)

(e.g. Solheim and Elverhøi 1997). Drumlins can be differentiated by their distinctive shape, with blunt up-glacier or stoss sides and tapered down-flow or lee sides, and have been interpreted to indicate former zones of ice acceleration (Shipp et al. 1999; Wellner et al. 2001).

Erosional subglacial landforms include streamlined crag-and-tails, which consist of an outcrop of bedrock with a tapering ridge of glacial sediment deposited on the lee side of the obstacle, and ice-moulded bedrock (Table 1 and Fig. 1c). These features are formed by the action of relatively fast-flowing ice and have been identified within fjords and on inner-continental shelves in areas where outcrops of bedrock are exposed on the seafloor (e.g. Fig. 1c) (Wellner et al. 2001; Dowdeswell et al. 2014).

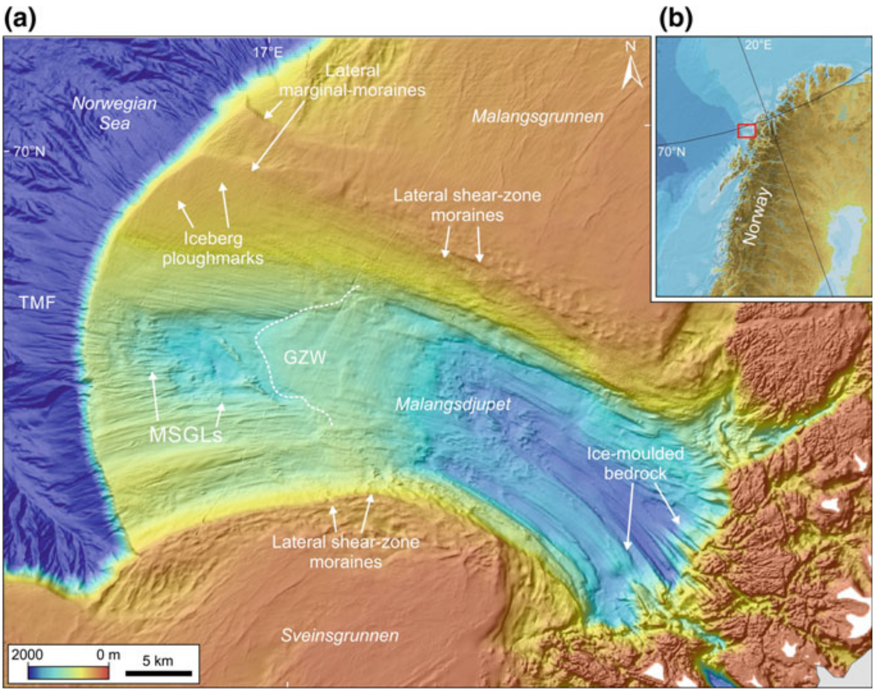

Fig. 6 **a** Bathymetric image of the seafloor of Malangsdjupet cross-shelf trough on the north Norwegian margin, illustrating the typical submarine architecture and landforms that are produced by a fast-flowing ice stream. The locations of ice-moulded bedrock, mega-scale glacial lineations (*MSGLs*), a grounding-zone wedge (*GZW*), ice-stream lateral shear-zone moraines, iceberg ploughmarks and a trough-mouth fan (*TMF*) are shown. The image is provided by the MAREANO project. **b** Location map (*red box*; map from IBCAO v. 3.0)

2.1.2 Hill-Hole Pairs

Hill-hole pairs are subglacially produced glacitectonic landforms that consist of a topographic depression or hole located up-glacier of a positive-relief arcuate hill of similar size (e.g. Fig. 2a). The former direction of ice flow is indicated by the orientation of the hill-hole axis. Individual hill-hole pairs have been identified on relatively shallow submarine banks off Norway and Svalbard (e.g. Sættem 1990; Ottesen et al. 2005; Dowdeswell et al. 2010), whilst an assemblage of several tens of pairs has been reported from the Arendal Terrace on the southern Norwegian margin (Ottesen et al. 2005; Rise et al. 2016). The formation of these landforms is suggested to involve the freezing-on of slabs of sediment at the ice-sheet base and the subsequent melting and release of this sediment in a downstream direction (Ottesen et al. 2005). Hill-hole pairs are therefore interpreted to be produced beneath relatively slow-flowing and probably thin ice, which facilitates the basal freeze-on of sediment.

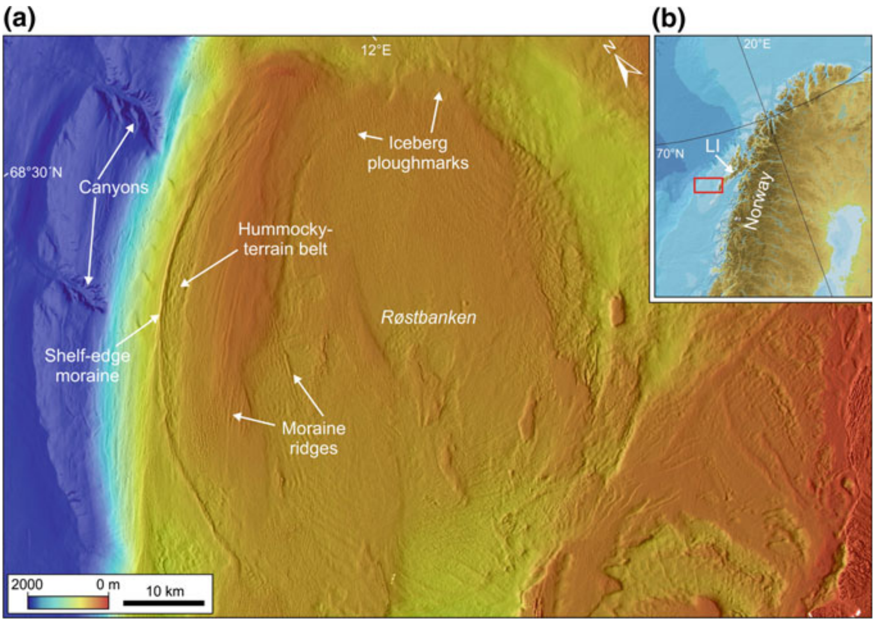

Fig. 7 **a** Bathymetric image of the seafloor of Røstbanken, west of the Lofoten Islands, Norway, illustrating the typical submarine architecture and submarine landforms that are produced by slow-flowing ice. The locations of a shelf-edge moraine, a hummocky-terrain belt, recessional moraine ridges, iceberg ploughmarks and submarine canyons are shown. The image is provided by the MAREANO project. **b** Location map (*red box*; map from IBCAO v. 3.0). *LI* is Lofoten Islands

2.1.3 Crevasse-Fill Ridges

Crevasse-fill ridges are non-orientated subglacial landforms that have a distinctive rhombohedral pattern consisting of a series of intersecting ridges a few metres high (Fig. 2b). They have been identified on the forefields of surging terrestrial glaciers (Sharp 1985; Evans and Rea 1999) and on the seafloor beyond the marine margins of several surge-type glaciers in Svalbard (Boulton et al. 1996; Ottesen et al. 2008). The ridges are interpreted to be produced during the post-surge ice stagnation phase by the squeezing of soft, deformable sediment into basal crevasses. These crevasses are formed at the glacier bed during the preceding active phase of the surge cycle.

2.1.4 Subglacial Glacifluvial Landforms

Tunnel valleys and eskers are produced by the flow of subglacial meltwater (Table 1). They reveal the former pattern of meltwater drainage and are usually aligned parallel or sub-parallel to the direction of former ice flow.

Tunnel valleys are meltwater channels that have cut down beneath the ice into the underlying substrate (Boyd et al. 1988; Ó Cofaigh 1996). They can reach widths of several kilometres and depths of up to around 400 m. Extensive networks of buried tunnel valleys have been identified on seismic-reflection profiles of the North Sea (e.g. Fig. 2c), where they record the pathways of subglacial meltwater beneath the former Eurasian Ice Sheet over a number of successive glaciations (e.g. Praeg 2003).

Conversely, eskers are sedimentary casts of supraglacial, englacial or subglacial meltwater channels (Warren and Ashley 1994). The majority of preserved eskers were formed subglacially by the sedimentary infilling of channels incised upwards into the base of the ice (known as 'R' channels; Röthlisberger 1972). Eskers are straight to sinuous in plan-form (Fig. 2d) and are composed of glacifluvial sand and gravel. Eskers up to a few tens of metres high and 2 km wide have been identified on the seafloor of a number of Spitsbergen fjords, in the Baltic Sea, and in Hudson Bay, Canada (Ottesen et al. 2008; Dowdeswell and Ottesen 2016; Greenwood et al. 2016). The formation of eskers may reflect either the synchronous configuration of the hydrological system during high-magnitude drainage events, or the time-transgressive deposition of short esker segments beneath a retreating ice margin linked to normal intra-annual changes in meltwater discharge (Boulton and Hindmarsh 1987; Ó Cofaigh 1996).

2.2 Ice-Marginal Landforms

Ice-marginal landforms (Fig. 3) are produced during deglacial still-stands or re-advances of the ice margin. They can provide information about the former configuration of an ice mass and the style and relative speed of ice retreat (e.g. Dowdeswell et al. 2008).

2.2.1 Moraine Ridges

Moraine ridges (Fig. 3a–c) are formed transverse to ice-flow direction along a line source at the grounding zone, which is the point at which the ice-sheet base ceases to be in contact with the underlying substrate. Submarine moraines can be categorised into large terminal and recessional moraine ridges, hummocky-terrain belts and small retreat moraines (Fig. 3a–c).

Terminal and recessional moraines can reach several tens of metres thick and several kilometres wide in the former ice-flow direction (e.g. Sexton et al. 1992; Seramur et al. 1997; Ottesen and Dowdeswell 2009). They form through a combination of processes, including sediment lodgement and deformation, meltwater deposition, melt-out of basal and englacial debris, and squeezing and pushing of sediment from beneath the ice (Powell and Domack 1995; Powell and Alley 1997). Terminal and recessional moraines have been identified within high-latitude fjords in both hemispheres (e.g. Powell 1983; Dowdeswell and Vasquez 2013) and are widespread on the continental shelves of Norway, Svalbard and Britain and Ireland (Elverhøi et al. 1983; Powell and Domack 2002; Vorren and Plassen 2002; Ottesen et al. 2005, 2007; Bradwell et al. 2008; Rydningen et al. 2013).

Submarine moraines are probably formed mainly at the margins of tidewater glaciers, which have unrestricted vertical accommodation space for the development of a high-amplitude ridge at the grounding zone (Powell and Alley 1997). They may be formed preferentially at the grounding zone of relatively slow-flowing regions of an ice sheet, as evidenced by their widespread occurrence on shallow, inter-trough areas of the continental shelf (Dowdeswell and Elverhøi 2002; Ottesen et al. 2005, 2007; Ottesen and Dowdeswell 2009). The Skjoldryggen moraine on the mid-Norwegian margin (Fig. 3a) provides an example of a large terminal-moraine ridge. Although this moraine is located in a region that has experienced high rates of sediment delivery during the last three glaciations (Rise et al. 2005), it is interpreted to have formed at times when fast ice flow and rapid sediment delivery to the shelf edge may have ceased (Ottesen et al. 2005).

Submarine hummocky-terrain belts have a distinctive morphology of irregular crests and depressions with amplitude of 5–20 m (Fig. 3b) (Ottesen and Dowdeswell 2009; Elvenes and Dowdeswell 2016). The crests are typically asymmetric with steeper ice-distal faces. Well-defined belts of hummocky terrain up to 6 km wide have been identified extending for tens of kilometres along the outermost continental shelf beyond inter-trough banks off north Norway and northwest Svalbard (Fig. 3b) (Ottesen and Dowdeswell 2009; Elvenes and Dowdeswell 2016). The formation of belts of hummocky-terrain, which have also been termed 'lift-off moraine', has been suggested to be linked to buoyancy-related tidal effects that cause small-scale variations in the position of the grounding zone (Elvenes and Dowdeswell 2016). This process has been observed beneath modern ice-shelf grounding zones (Bindschadler et al. 2003; Gudmundsson 2006).

Small retreat moraines, which are often referred to as De Geer moraines (Lindén and Möller 2005), are typically a few metres high and up to a few hundred metres wide (e.g. Fig. 3c). They are usually identified in assemblages of tens to hundreds of relatively evenly spaced sub-parallel ridges. Small transverse ridges, interpreted as retreat moraines, have been identified on the seafloor of shallow inter-trough regions of the shelf, as well as within cross-shelf troughs and high-latitude fjords (Boulton 1986; Ottesen et al. 2005; Mosola and Anderson 2006; Ottesen and Dowdeswell 2006, 2009; Todd et al. 2007; Ó Cofaigh et al. 2008). In contrast with larger terminal and recessional moraines (Fig. 3a), which probably build-up during grounding-zone still-stands of at least decades to centuries, small moraine ridges (Fig. 3c) are produced by the delivery and ice pushing of sediment during short-lived still-stands or re-advances of a grounded ice margin during overall retreat (Boulton et al. 1996; Ottesen and Dowdeswell 2009). They therefore indicate the relatively slow retreat of grounded ice (Dowdeswell et al. 2008). Although confirmation by dated sediment cores is relatively rare, small retreat moraines are often formed annually, with minor re-advances taking place as a result of the suppression of iceberg calving by sea-ice buttressing during winter months (Boulton 1986; Dowdeswell et al. 2008; Ó Cofaigh et al. 2008).

2.2.2 Grounding-Zone Wedges

Grounding-zone wedges (GZWs) are asymmetric sedimentary depocentres which form predominantly through the rapid accumulation of subglacial sediment at the grounding zone of marine-terminating ice sheets (Fig. 3d) (e.g. Powell and Alley 1997). GZWs are typically 15–100 m thick and less than 15 km long in the along-flow direction (Dowdeswell and Fugelli 2012; Batchelor and Dowdeswell 2015). They can be differentiated by their relatively subdued geometry compared with higher amplitude moraine ridges (Fig. 3a, d). Whereas submarine moraines probably develop preferentially at tidewater ice cliffs, GZWs have been suggested to form mainly where floating ice shelves constrain vertical accommodation space immediately beyond the grounding zone (Dowdeswell and Fugelli 2012; Batchelor and Dowdeswell 2015).

A large number of GZWs have been described from formerly-glaciated continental margins, where they are identified within major fjord systems and cross-shelf troughs (e.g. Anderson 1997; Powell and Alley 1997; Ó Cofaigh et al. 2005; Mosola and Anderson 2006; Ottesen et al. 2007; Larter et al. 2012). The association of GZWs with cross-shelf troughs and fjords suggests that high rates of sediment delivery to the grounding zone of a fast-flowing ice stream or outlet glacier is required for GZW formation. The presence of GZWs in the geological record indicates an episodic style of ice-stream retreat in which rapid retreat of the grounding zone is punctuated by still-stands of at least decades to centuries (Dowdeswell et al. 2008; Ó Cofaigh et al. 2008; Batchelor and Dowdeswell 2015). Many high-latitude GZWs occur at vertical or lateral pinning points in the shelf topography, which encourage grounding-zone stabilisation through increasing basal and lateral drag (Joughin et al. 2004; Ottesen et al. 2007).

Seismic-reflection profiles reveal that a number of GZWs contain seaward-dipping reflections, which indicate sediment progradation and wedge growth through the continued delivery of basal sediment (Fig. 5e and f) (Larter and Vanneste 1995). Although the majority of GZWs have been recognised on or close to the seafloor and were probably formed during the last deglaciation, a number of buried GZWs, interpreted to have been formed during earlier Quaternary glaciations, have been identified from seismic-reflection profiles of the Greenland and West Antarctic margins (Dowdeswell and Fugelli 2012; Gohl et al. 2013; Batchelor and Dowdeswell, 2015). Possible GZWs have also been identified in the Late Ordovician glacial sediments of North Africa (Decalf et al. 2016).

2.2.3 Ice-Proximal Fans

Ice-proximal fans are point-source depocentres that develop at the mouths of subglacial meltwater channels at the ice-sheet grounding zone (e.g. Powell 1990; Powell and Domack 1995). The formation of ice-proximal fans is therefore dependent on the availability of surface-derived meltwater and the existence of a channelised meltwater network beneath the ice sheet (Powell 1990; Siegert and Dowdeswell 2002).

Ice-proximal fans up to a few tens of metres thick have been identified on the seafloor of fjords in Alaska, Norway and Svalbard, where they mark the former locations of relatively stable grounding-zone positions (Powell 1990; Lønne 1995; Seramur et al. 1997; Dowdeswell et al. 2015). The absence of large ice-proximal fans on formerly glaciated continental shelves is probably a consequence of the highly-variable position of the ice-sheet grounding zone (Dowdeswell et al. 2015). Advancing ice sheets overrun and remove evidence of sediment delivered to the mouths of subglacial meltwater channels, whilst the majority of ice-margin still-stands during deglaciation are probably of insufficient duration to enable the development of large fans unless sediment delivery is very rapid.

2.2.4 Lateral Moraines

Submarine glacial landforms can also develop at the lateral margins of fast-flowing ice streams. Ice-stream lateral marginal-moraines build up at the lateral boundary between ice streams and terrain that is free of grounded ice, whilst ice-stream lateral shear-moraines form in the shear zone between ice streams and slower-flowing regions of the ice sheet (Stokes and Clark 2002; Batchelor and Dowdeswell 2016). Ice-stream lateral shear-moraines are orientated parallel to the former ice-flow direction (e.g. Fig. 3e) and their formation is probably linked to the high stress gradient in the shear zone at the boundary between fast- and slow-flowing ice (e.g. Bentley 1987). They are linear to curvilinear in plan-form and are typically a few tens of metres high and less than a few kilometres wide (Stokes and Clark 2002). Ice-stream lateral shear-moraines have been identified at one or both lateral margins of cross-shelf troughs off Norway and Svalbard, where they have been interpreted to define the lateral boundaries of former ice streams (Ottesen et al. 2005, 2008; Rydningen et al. 2013). Although ice-stream lateral shear-moraines are an important geomorphological indicator of past ice-stream activity, they are not always present in the geological record and may require relatively constrained conditions to form (Stokes and Clark 2002; Hindmarsh and Stokes 2008).

2.2.5 Trough-Mouth Fans

Trough-mouth fans (TMFs) are major glacial-sedimentary depocentres that build up on the continental slope beyond fast-flowing ice streams (Fig. 3f). TMFs are formed when large volumes of deformable sediment are delivered to the shelf edge by ice streams over successive full-glacial periods. This sediment is often remobilised on the upper continental slope to form glacigenic debris-flows (GDFs) (Alley et al. 1989; Laberg et al. 2000). TMFs have volumes of up to several hundred thousand cubic kilometres and are identified on bathymetric maps of the seafloor by a distinctive outward bulging of slope contours beyond the trough-mouth, indicating shelf progradation (Fig. 3f) (Dowdeswell et al. 1996, 1998; Ó Cofaigh et al. 2005). These sedimentary depocentres contain a record of past glacial history and can provide information about long-term sediment delivery and ice-stream dynamics (Dowdeswell et al. 1996, 2006; Vorren and Laberg 1997; Dowdeswell and Siegert 1999; Ó Cofaigh et al. 2003).

TMFs composed predominantly of stacked acoustically-transparent lenses representing GDFs from episodes of cross-shelf glaciation (Figs. 3f and 5c) have been identified on the continental slope beyond many high-latitude cross-shelf troughs (Vorren et al. 1988; Laberg and Vorren 1995; Dowdeswell et al. 1996; King et al. 1996; Vorren and Laberg 1997; Ó Cofaigh et al. 2003; Batchelor and Dowdeswell 2014). However, the slope beyond former ice streams can also be characterised by channel and gully systems or mass transfer deposits resulting from slope failure (e.g. Dowdeswell et al. 1996, 2004b; Laberg and Vorren 2000; Ó Cofaigh et al. 2003; Piper et al. 2012). TMF development is encouraged by high debris flux, limited contour-current erosion of the slope and a relatively low (generally <4°) upper-slope gradient, which enables GDFs to accumulate on the upper-slope (Ó Cofaigh et al. 2003).

2.3 *Glacimarine Landforms*

Whereas terrestrial sections of an ice sheet lose mass through surface melting and run-off, and, rarely, sublimation, marine-terminating ice sheets additionally lose mass through iceberg calving and the melt-out of basal and englacial debris from icebergs, ice cliffs and floating ice shelves. The processes associated with mass loss by iceberg and meltwater production lead to the formation of distinctive glacimarine landforms and sediments.

2.3.1 Iceberg Ploughmarks

Iceberg ploughmarks (e.g. Fig. 4a–c) are linear to curvilinear depressions produced by the grounding of iceberg keels in seafloor sediments (Woodworth-Lynas et al. 1991; Dowdeswell et al. 1993). They have typical depths of a few metres to tens of metres and widths of up to several hundred metres, and many have distinctive raised berms a few metres high on either side of a central depression (Fig. 4b).

Linear to curvilinear depressions, interpreted as iceberg ploughmarks, are widespread on the seafloor of mid- and high-latitude continental margins in present-day water depths down to at least 500 m (e.g. Woodworth-Lynas et al. 1991; Dowdeswell et al. 1993; Metz et al. 2008). They are particularly common on relatively shallow inter-trough banks, where they are often responsible for the erosion and reworking of older subglacial and ice-marginal landforms and sediments. Some wide iceberg ploughmarks are probably formed by the grounding of tabular icebergs on the seafloor, whereas parallel to subparallel sets of ploughmarks may be produced by single large icebergs with multiple keels or by the keels of several icebergs that were trapped within multi-year sea ice, providing a uniform pattern of iceberg drift.

Whereas the majority of seafloor iceberg ploughmarks were probably formed during the last glacial-deglacial cycle, iceberg ploughmarks produced during earlier stages of the Quaternary can be identified from 3-D seismic-reflection data (e.g. Fig. 4c). Buried iceberg ploughmarks preserved on palaeo-shelf surfaces indicate the expansion of ice sheets beyond the coastline and provide information about palaeo-oceanographic conditions (e.g. Syvitski et al. 1996; Dowdeswell and Ottesen 2013).

2.3.2 Smooth Basin Fill from Meltwater Plumes

The discharge of sediment-laden meltwater from conduits at the grounding zone produces turbid jets of sediment-water mixtures, which typically transform into buoyant plumes in seawater (e.g. Powell 1990; Mugford and Dowdeswell 2011). The suspension settling of material derived from meltwater plumes provides a significant source of sediment in some glacimarine environments (e.g. Cowan and Powell 1990; Dowdeswell et al. 1998; Ó Cofaigh and Dowdeswell 2001). Sand and coarse silt are typically deposited within a few kilometres of the grounding zone, whereas finer-grained material is transported in plumes for greater distances. The rain-out of sediment through the water column results in the formation of a blanket of acoustically transparent to stratified basin-fill sediment on the seafloor (Cai et al. 1997), which has a smooth appearance on bathymetric images (Fig. 4d). These sediments often have a strong cyclical signature manifested as acoustic lamination as a result of variations in glacial meltwater discharge and the position of the ice margin (Fig. 5c).

Suspension settling occurs at present in high-latitude fjords and was a significant process in some shelf and slope settings during the Quaternary (e.g. Domack 1990; Dowdeswell et al. 1996, 2000). High rates of deglacial and post-glacial meltwater-derived sedimentation in temperate and subpolar glacimarine environments can lead to the burial of submarine glacial landforms (Elverhøi et al. 1983; Cowan and Powell 1990; Cai et al. 1997; Dowdeswell and Vasquez 2013). Suspension setting is less significant on polar continental margins, such as off Greenland and Antarctica, where there are lower rates of glacimarine sedimentation and ice mass is lost predominantly through iceberg calving rather than meltwater runoff (e.g. Dowdeswell et al. 1993, 1996).

2.4 Marine Landforms

Marine processes, including the action of waves and currents, and mass movement events such as submarine slides (Table 1) can result in the burial and reworking of submarine glacial landforms. Current and wave action can modify glacial landforms on relatively shallow areas of the seafloor (e.g. Howe and Pudsey 1999), whilst submarine slides with lengths of up to several kilometres take place as a result of the failure of glacial sediments on steep fjord walls (e.g. Ottesen and Dowdeswell 2009; Forwick et al. 2010). Larger submarine slides with volumes of up to several tens of thousand cubic kilometres have been recognised on the continental slope beyond cross-shelf troughs and shallower banks in both hemispheres (e.g. Laberg and Vorren 1993, 2000; Hjelstuen et al. 2005; Piper et al. 2012). Slope failure on high-latitude continental margins can occur as a consequence of the build-up of excess pore pressure in fine-grained sediment as a result of rapid sedimentation during full-glacial periods, contour-current erosion of the lower slope under inter-glacial conditions, and tectonic activity and gas-hydrate disassociation (e.g. Mosher et al. 1994; Laberg and Vorren 2000; Mienert 2004).

3 Glacial Landforms on the Norwegian Margin: A Case Study

The typical distribution of glacial landforms on formerly-glaciated continental margins is illustrated using the case study of the Norwegian continental shelf and slope (Figs. 6 and 7).

3.1 Landforms in Cross-Shelf Troughs

The large-scale architecture and submarine glacial landforms that are typically produced by fast-flowing ice streams are shown by the Malangsdjupet cross-shelf trough on the north Norwegian margin (Fig. 6). Malangsdjupet has been interpreted to have been occupied by a marine-terminating ice stream during a number of Quaternary full-glacial periods, including during the Last Glacial Maximum (LGM) around 20 ka ago (Ottesen et al. 2005, 2008; Rydningen et al. 2013).

The trough is around 50 km long and has a maximum width and depth of 30 and 400 m, respectively (Fig. 6). Malangsdjupet has characteristic cross-shelf trough geometry, with over-deepened inner-shelf basins extending from fjords, well-defined lateral margins and an increasing width towards the shelf edge (Stokes and Clark 2001) (Fig. 6). It has a landward-dipping seafloor, which is probably a result of repeated erosion of the inner-shelf by ice over successive glaciations. Bathymetric data show a seaward change in the roughness of the seafloor, which corresponds with a transition from outcrops of crystalline bedrock on the inner-shelf to a sedimentary substrate on the mid- and outer-shelf (Fig. 6). The continental slope beyond the trough displays the progradational architecture and outward bulging upper-slope contours that are typical of glacial-sedimentary depocentres or TMFs (Dowdeswell et al. 1998; Ó Cofaigh et al. 2005). Malangsdjupet TMF has been interpreted to have been built up on the slope from around 1.5 million years ago, when fast-flowing ice streams started delivering large quantities of deformable sediment to the Norwegian continental margin over successive full-glacial periods (Rise et al. 2005; Rydningen et al. 2016).

Several types of submarine glacial landform are preserved on the seafloor of Malangsdjupet; these include subglacially produced ice-moulded bedrock and MSGLs, ice-marginal GZWs and lateral moraines, and iceberg ploughmarks (Fig. 6) (Vorren and Plassen 2002; Ottesen et al. 2005, 2008; Rydningen et al. 2013). These landforms record the extent and dynamics of the ice stream in the trough during the last glacial-deglacial cycle.

Ice-moulded bedrock and MSGLs were produced subglacially during ice-stream advance and reveal former ice-flow directions. Ice-moulded bedrock on the inner-shelf shows that the ice emerged from the fjords and converged in the central trunk of the trough (Fig. 6). MSGLs with lengths of several kilometres are present on the mid- and outer-shelf, indicating that grounded, fast-flowing ice extended to the shelf edge during the LGM.

An ice-marginal GZW is present on the mid-shelf of Malangsdjupet (Fig. 6). This depocentre, which spans most of the trough width and is at least 20 km long in the ice-flow direction, was produced during a still-stand in the grounding-zone position of at least decades to centuries during ice-stream retreat. The presence of a mid-shelf GZW and preserved outer-shelf MSGLs suggest that the ice stream experienced an episodic style of retreat (Dowdeswell et al. 2008), with ice probably retreating relatively rapidly from the shelf edge to the GZW position on the mid-shelf.

Ice-stream lateral shear-zone moraines a few metres high are present along both lateral margins of Malangsdjupet (Fig. 6). These landforms delimit the former lateral boundaries between the ice stream in the trough and slower-flowing ice on the adjacent banks (Fig. 6). Ice-stream lateral marginal-moraines are also present at the northern outermost lateral margin of the trough, where they probably record the former boundary between the ice stream and terrain that was free of grounded ice during lateral-moraine formation (Rydningen et al. 2016; Batchelor and Dowdeswell 2016).

A number of linear to curvilinear iceberg ploughmarks are present at the northern margin of Malangsdjupet in water depths of between 100 and 200 m (Fig. 6). They record the drift tracks of deep-keeled icebergs that were produced during regional deglaciation. Iceberg ploughmarks are generally absent from the seafloor of the rest of the trough, which suggests that these regions were deeper than the maximum iceberg-keel depth. The relatively fresh appearance of glacial landforms on bathymetric images of the seafloor suggests that there is only a thin veneer of glacimarine sediments draping the shelf and slope off northern Norway. Accumulations of smooth basin-fill sediments derived from meltwater plumes are probably present in inner-shelf basins between bedrock outcrops and in the more ice-proximal fjords (e.g. Elverhøi et al. 1983).

3.2 Landforms on Inter-Trough Banks

The inter-trough bank of Røstbanken beyond Lofoten on the Norwegian margin illustrates the typical architecture and glacial landforms that are produced by relatively slow-flowing regions of an ice sheet (Fig. 7). Slow-moving ice is interpreted to have expanded to the shelf edge beyond Røstbanken during the LGM as well as probably also during a number of earlier Quaternary full-glacial periods (Ottesen et al. 2005).

Slow-flowing ice is relatively passive; it does not typically cause considerable erosion of the continental shelf or deliver large volumes of deformable sediment to the shelf edge. Røstbanken therefore lacks the erosional cross-shelf trough and depositional TMF architecture that is characteristic of former ice-stream locations. Røstbanken has water depths of between 100 and 200 m and there is no evidence of a significant glacial-sedimentary depocentre on the upper continental slope (Fig. 7). The slope beyond the bank is instead characterised by small-scale mass-wasting features and submarine canyons.

Subglacially produced streamlined landforms that indicate the direction of former ice flow are largely absent from Røstbanken. By contrast, the bank is dominated by ice-marginal moraines that are orientated transverse to the former ice-flow direction (Fig. 7). A terminal-moraine ridge is present at the shelf edge, marking the maximum extent of grounded ice during the LGM (Ottesen et al. 2005). A several kilometre-wide belt of hummocky terrain, which was probably produced by tidally-related variations in the position of the grounding zone (Ottesen and Dowdeswell 2009), is also present on the outermost shelf (Fig. 7). The mid- and outer-shelf of Røstbanken is dominated by a number of recessional-moraine ridges that are a few tens of metres wide in the former ice-flow direction (Fig. 7). These ridges mark the former positions of still-stands or minor re-advances in the grounding zone and indicate the relatively slow retreat of grounded ice across the bank (Dowdeswell et al. 2008). Røstbanken is heavily scoured by linear to curvilinear depressions, which are interpreted to have been produced by the keels of icebergs ploughing into sediments on the relatively shallow seafloor (Fig. 7).

3.3 Landsystem Models for Fast- and Slow-Flowing Ice

The submarine glacier-influenced landforms described from Malangsdjupet and Røstbanken (Figs. 6 and 7) can be combined into schematic landsystem models for fast- and slow-flowing ice on formerly-glaciated continental margins (Fig. 8) (e.g. Ottesen et al. 2005, 2007; Ó Cofaigh et al. 2005; Ottesen and Dowdeswell 2009).

The locations of former ice streams can be identified by deep (typically >300 m) cross-shelf troughs that are formed by fast-flowing ice over successive full-glacial periods. In contrast, the former locations of slower-flowing, relatively passive ice are typically characterised by shallower banks (Fig. 8). Whereas large TMFs often

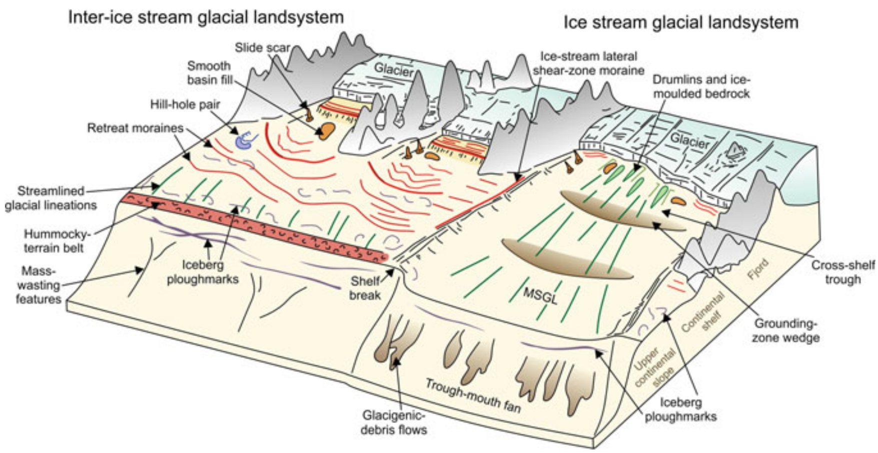

Fig. 8 Summary schematic landsystem models of the submarine landforms on the seafloor of inter-ice stream shallow banks and cross-shelf troughs formerly occupied by fast-flowing ice streams (adapted from Ottesen and Dowdeswell 2009)

develop beyond cross-shelf troughs, lower rates of sediment delivery to the shelf edge beyond inter-ice stream regions of the ice sheet preclude the development of major glacial-sedimentary depocentres in these locations.

A key feature of the ice-stream glacial landform-assemblage model is the presence of elongate streamlined landforms, such as MSGLs, that are orientated parallel to the former ice-flow direction (Fig. 8) (Stokes and Clark 2002; Ó Cofaigh et al. 2002). GZWs record the positions of still-stands in the grounding zone during deglaciation and indicate an episodic style of ice-stream retreat through the trough.

By contrast, the inter-ice stream glacial landform-assemblage model is dominated by ice-marginal landforms, such as moraine and hummocky-terrain belts, which are orientated transverse to the former ice-flow direction (Ottesen and Dowdeswell 2009). Groups of parallel to subparallel moraine-ridges provide evidence for the slow retreat of grounded ice across the bank (Dowdeswell et al. 2008). Some inter-ice stream locations contain glacitectonically formed hill-hole pairs that indicate the direction of past ice flow (Ottesen and Dowdeswell 2009). Ice-stream lateral shear-moraines are orientated parallel to the former ice-flow direction and delimit the lateral boundary between fast- and slow-flowing ice (Fig. 8) (Stokes and Clark 2002).

Iceberg ploughmarks have been identified on the seafloor of inter-trough banks, cross-shelf troughs and the upper continental slope (e.g. Woodworth-Lynas et al. 1991; Dowdeswell et al. 1993). They are most widespread on inter-trough banks that are the former locations of slow-flowing ice, as a result of the shallower seafloor in these locations (Fig. 8).

4 Future Research Objectives

Recent developments in geophysical imaging techniques have enabled the identification and interpretation of glacial landforms in a wide range of submarine environments. There are, however, three key areas in which future research may be directed.

First, there is a need for increased data coverage of formerly glaciated continental margins. Some offshore areas, such as the Norwegian margin and the western Barents Sea, have been the focus of extensive seafloor mapping programmes and subsurface investigations, facilitating detailed reconstructions of past ice-sheet configurations and dynamics (e.g. Ottesen et al. 2005, 2007; Andreassen et al. 2014). However, comparatively little is known about other formerly glaciated regions, such as the Kara Sea in the Russian Arctic and parts of the Queen Elizabeth Islands in the Canadian Arctic, where data collection has historically been hampered by sea ice.

Secondly, higher-resolution data of the seafloor and the subsurface are needed to capture complexity in ice-sheet behaviour, with a particular focus on dynamic behaviour of ice streams during the last deglaciation. Geophysical surveys have revealed that the geological record is more complex than previously envisaged, both in terms of the changing dynamics of individual sectors of former ice sheets, and the assemblages of submarine glacial landforms that are produced (e.g. Greenwood et al. 2012).

Finally, increased chronological control, derived from the dating of material within sediment cores, is needed to establish the timing of ice-sheet advances and retreats and to better constrain the rates of formation of submarine glacial landforms.

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