Lateral shear-moraines and lateral marginal-moraines of palaeo-ice streams

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ABSTRACT

An understanding of the nature of sedimentation at ice-stream lateral margins is important in reconstructing the dynamics of former ice sheets and modelling the mechanisms by which sediment is transported beneath contemporary ice streams. Theories of the formation of ice-stream lateral moraines (ISLMs) have hitherto been based on a relatively limited number of terrestrial and marine examples. Here, an inventory of ISLMs is compiled from available studies, together with independent analysis of seismic-reflection and bathymetric datasets. The locations and dimensions of 70 ISLMs, alongside a synthesis of their key architectural and geomorphic characteristics, are presented. Two different types of ISLMs are identified. Type 1 ISLMs are up to 3.5 km wide and 60 m thick. They maintain a constant width, thickness and cross-sectional shape along their length. Type 1 ISLMs are interpreted and referred to as ice-stream *lateral shear-moraines* that form subglacially in the shear zone between ice streams and slower-flowing regions of an ice sheet. In contrast, Type 2 ISLMs are up to 50 km wide and 300 m thick. They are only identified close to the shelf break in the marine environment. Type 2 ISLMs exhibit an increase in width and thickness along their length and their distal slopes become steeper in a seaward direction. They contain internal dipping reflections that indicate sediment progradation away from the former ice stream. Type 2 ISLMs are interpreted and referred to as ice-stream *lateral marginal-moraine*s that were formed at the lateral boundary between ice streams and seafloor terrain that was free of grounded ice. We suggest that, using bathymetric images and acoustic profiles, it is possible to differentiate between ice-stream lateral shear-moraines and lateral marginal-moraines in the geological record. This distinction is important for understanding the mechanisms of

sediment transfer beneath ice streams and for making inferences about the conditions that existed beyond the lateral ice-stream margin at the time of lateral-moraine formation: slow-moving ice beyond lateral shear-moraines, and ocean water rather than ice beyond lateral marginal-moraines.

1. INTRODUCTION

1.1 Ice streams and their significance

Fast-flowing ice streams are responsible for draining the majority of mass from the Greenland and Antarctic ice sheets (e.g. Rignot and Kanagaratnam, 2006; Shepherd and Wingham, 2007; Rignot et al., 2008; Pritchard et al., 2012; Shepherd et al., 2012). They exert an important influence on ice-sheet stability; responding dynamically to perturbations over short, sub-decadal time-scales (e.g. Anandakrishnan and Alley, 1997; Joughin et al., 2003), and having the potential to force abrupt climatic change through the rapid delivery of ice and meltwater to their marine margins (e.g. MacAyeal, 1993; Clark, 1994; Stokes et al., 2005). A thorough understanding of the configuration and dynamics of former ice streams, which have been shown to have been spatially and temporally variable (Dowdeswell et al., 2006; Sarkar et al., 2011; Stokes et al., 2016), is needed to develop qualitative models of past ice-stream behaviour and to constrain numerical ice-sheet models and test their quantitative predictions relating to future global sea-level rise. The landforms and sediments that are preserved at the beds of former ice-streams can also provide insights into the processes that are operating currently at the largely inaccessible beds of contemporary ice streams.

A number of diagnostic morphological criteria have been developed to identify the locations of former ice streams. These include subglacially produced elongate and streamlined glacial lineations, abrupt lateral margins and pervasively deformed till (Fig. 1B, F) (Stokes and Clark, 1999, 2001, 2002; Clark and Stokes, 2003). A range of techniques, including aerial and satellite imagery and field observations in the terrestrial environment, and multi-beam swath bathymetry, acoustic profiling and sediment coring in the marine environment, have been used to map and interpret glacigenic landforms and sediments, facilitating the interpretation of former ice-stream locations and dynamics (e.g. Boulton and Clark, 1990; Solheim et al., 1990; Shipp et al., 1999; Stokes and Clark, 1999; Dowdeswell et al., 2002, 2008, 2014; Ottesen et al., 2005a; Bradwell et al., 2008; Evans et al., 2008; Ottesen and Dowdeswell, 2009; Ó Cofaigh et al., 2010; Bradwell and Stoker, 2015). The repeated expansion of ice streams across high- and mid-latitude continental shelves has resulted in the formation of deep bathymetric depressions termed cross-shelf troughs, which typically extend to the shelf break and are bordered laterally by shallower banks (Fig. 1A) (Vorren and Laberg, 1997; Anderson, 1999; Stokes and Clark, 2001; O'Grady and Syvitski, 2002; Batchelor and Dowdeswell, 2014; Dowdeswell et al., 2016).

The frontal terminus of ice-streams is a key site for sediment deposition, given the high flux of ice and debris delivered by these fast-flowing elements of ice sheets. Under full-glacial conditions, ice-streams often terminated in marine waters at trough-mouths at the continental-shelf edge, where they deposited large volumes of mainly diamictic debris. This subglacially-derived sediment often fails on the upper continental slope to form glacigenic debris-flows that are the building blocks of huge trough-mouth fans (e.g. Dowdeswell and Siegert, 1999; Ó Cofaigh et al., 2003; Nygård et al., 2007). In addition, sedimentary depocentres, including moraine ridges, grounding-zone wedges (GZWs) and ice-proximal fans, may build up at the frontal terminus of ice streams during still-stands or re-advances during regional deglaciation (e.g. Powell and Domack, 1995; Powell and Alley, 1997; Bjarnadóttir et al., 2013 Batchelor and Dowdeswell, 2015; Dowdeswell et al., 2015).

The identification of these landforms in the geological record provides information about the dynamics of former ice streams (e.g. Evans et al., 1999, 2008; Shipp et al., 1999; Ottesen et al., 2005a; Mosola and Anderson, 2006; Dowdeswell et al., 2008a; Graham et al., 2009; Jakobsson et al., 2012a; Larter et al., 2012). Moraine ridges and GZWs are orientated transverse to the former ice-flow direction (Fig. 1C and D). Moraine ridges have been suggested to form preferentially at the termini of tidewater glaciers, which have almost unlimited vertical accommodation space at the grounding-zone because it coincides with terminus ice cliffs (King and Fader, 1986; King et al., 1987; Powell and Alley, 1997). By contrast, GZWs are asymmetric sedimentary depocentres which form through subglacial deposition of deforming till at the grounding-zone of marine-terminating ice streams (Fig. 1A and D) (e.g. Powell and Domack, 1995; Powell and Alley, 1997; O’Brien et al., 1999; Ó Cofaigh et al., 2005). They have more subdued relief and higher length: height ratios compared with higher-amplitude moraine ridges. This suggests that GZWs may be formed preferentially by glaciers with termini ending as floating ice shelves, which restrict vertical accommodation space at the grounding-zone (Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015). The point-source deposition of sediment at the mouths of subglacial or englacial meltwater channels can lead to the development of ice-proximal fans at the frontal terminus of tidewater glaciers (Fig. 1A) (Powell, 1984, 1990; Sexton et al., 1992; Lønne, 1995, 1997; Powell and Domack, 1995; Seramur et al., 1997; Dowdeswell et al., 2015).

1.2 Ice-stream lateral moraines

Significant sedimentary depocentres can also build up at the lateral margins of ice streams; these landforms are termed ice-stream lateral moraines (ISLMs) (Fig. 1A and F) (e.g. Dyke and Morris, 1988; Stokes and Clark, 2002). Comparatively little is known about the characteristics and formation of ISLMs compared with landforms that are produced at the frontal termini of ice streams. ISLMs are distinct from the lateral moraines of terrestrial valley glaciers, which are formed mainly through the melt-out of relatively unmodified supraglacial and englacial debris, together with rockfall from adjacent valley walls (Benn and Evans, 2010). In contrast, ISLMs are suggested to be formed subglacially and to be composed predominantly of subglacial till (Dyke and Morris, 1988; Stokes and Clark, 2002).

There are two different categories of ISLMs; ice-stream lateral shear-moraines and ice-stream lateral marginal-moraines. Ice-stream lateral shear-moraines form in the shear zone between fast-flowing ice streams and slower-flowing sections of the ice sheet (Bentley, 1987; Dyke and Morris, 1988; Dyke et al., 1992; Stokes and Clark, 2002; Ottesen et al., 2005a). Ice-stream shear zones are up to several hundred metres wide and are characterised on the ice surface by prominent bands of fractures and crevasses (e.g. Bentley, 1987; Hodge and Doppelhammer, 1996; Bindschadler and Vornberger, 1998). A number of theories have been proposed for the formation of ice-stream lateral shear-moraines (e.g. Stokes and Clark, 2002; Hindmarsh and Stokes, 2008); however, these theories are based on a relatively limited number of observations of these landforms in the geological record. By contrast, ice-stream lateral marginal-moraines form at the lateral boundary between ice streams and terrain that is free of grounded ice. These landforms have received little attention previously and have only been reported from the continental shelf of north Norway (Rydningen et al., 2013).

ISLMs are important geomorphological indicators of palaeo-ice stream activity (Stokes and Clark, 1999, 2002). The identification of ISLMs in the geological record is crucial for reconstructing the locations and dynamics of former ice streams, as well as for allowing inferences to be made about the conditions that persisted beyond the lateral margins of former ice streams (i.e. slow-flowing ice or ice-free terrain). Ice-stream lateral margins play a significant role in the force balance of contemporary ice streams by providing resistance through lateral drag (Echelmeyer et al., 1994; Jackson and Kamb, 1997; Raymond et al., 2001); the flux of ice through an ice stream is therefore extremely sensitive to changes in ice-stream width (e.g. Jamieson et al., 2012). It is important to understand the mechanisms by which ISLMs are formed as this provides information about the processes transporting sediment beneath ice streams and the factors that control the position and stability of ice-stream lateral margins.

In this paper, we present an inventory of ISLMs that is compiled from available accounts that use satellite and aerial imagery from the terrestrial environment, and bathymetric and shallow-acoustic data from formerly glaciated continental shelves. Two-dimensional marine seismic-reflection data and single- and multi-beam bathymetry are also used here to identify previously unreported ISLMs on the continental shelves of Greenland, Svalbard and Norway. The locations of 70 ISLMs are presented, alongside a synthesis of their dimensions, geometry and acoustic character. We discuss the implications of these data in relation to glacial history, ice-stream dynamics and processes of sedimentation beneath ice streams. Throughout the paper, we use the term ISLM when ice-stream lateral shear-moraines and ice-stream lateral marginal-moraines are discussed collectively, or when there is insufficient information to determine the nature of the former ice-stream lateral margin.

2. OBSERVATIONS OF ICE-STREAM LATERAL MORAINES

Elongate ridges of sediment preserved at the lateral margins of former ice streams were first recognised in the terrestrial environment in the 1980s and 1990s (e.g. Dyke and Morris, 1988; Dyke et al., 1992; Punkari, 1995, 1997). The first detailed analysis was provided by Dyke and Morris (1988), who described a 68 km-long curved ridge of till orientated parallel to the former ice-flow direction on Prince of Wales Island, Arctic Canada. The possibility that the ridge was formed at a boundary between an ice stream and ice-free terrain was rejected, and the term ‘lateral shear-moraine’ was introduced to describe ridges of sediment that were interpreted to have formed along the shear zone between fast-flowing ice streams and slower-flowing ice (Dyke and Morris, 1988; Dyke et al., 1992).

Several similar elongate ridges of till, interpreted as lateral shear-moraines formed at the lateral margins of the former M’Clintock Channel Ice Stream, have been identified from aerial and satellite imagery of the neighbouring Victoria and Stefansson islands, Arctic Canada (Hodgson, 1994; Stokes and Clark, 2001, 2002; Storrar and Stokes, 2007; Stokes et al., 2009). A number of discontinuous ice-stream lateral shear-moraines have also been reported from the lateral margins of the Maskwa palaeo-ice stream, western Canadian Prairies (Ross et al., 2009; Ó Cofaigh et al., 2010).

No unequivocal evidence for the existence of terrestrial ISLMs has been reported from outside Canada. However, a 600 m-long ridge of till has been identified in northern Sweden at the former boundary of warm- and cold-based patches of the Scandinavian Ice Sheet (Kleman and Borgström, 1994). Streamlined glacial lineations, interpreted to have been produced beneath the warm-based ice, are orientated at a low angle towards the cold-based ice (Kleman and Borgström, 1994). The ridge of till was therefore suggested to have been formed by ice flow and basal-sediment transport from the warm-based ice towards its lateral margin, where it was folded and stacked up against the thermal boundary (Kleman and Borgström, 1994). However, there is no evidence that this ridge was formed at the lateral margin of a fast-flowing ice stream (Stokes and Clark, 2002).

Elongate, hummocky ridges, which were termed interlobate complexes, have been described from the former lateral margins of terrestrial ice streams in southern Sweden (Punkari, 1995, 1997). Although meltwater may play a role in the formation of ISLMs, the morphology and sedimentology of these ridges, which are sinuous with many tributaries and are composed predominantly of sorted sediment (Punkari, 1997), precludes their interpretation as ISLMs, which are inferred to be curvilinear and composed of subglacial till (Hodgson, 1994; Stokes and Clark, 2002).

A very early description of a possible ISLM in the marine environment was provided by Barnes (1987), who identified an elongate ridge up to 50 m high at the northern lateral margin of the Mertz cross-shelf trough, East Antarctica (Domack et al., 1989; Beaman and Harris, 2003). A comprehensive analysis of marine ISLMs offshore of Svalbard and Norway was presented by Ottesen et al. (2005a), who used bathymetric and acoustic data to identify a number of curvilinear ridges up to 50 m high and 5 km wide from the lateral margins of cross-shelf troughs on these continental shelves. The ridges were interpreted to have formed in the shear zone between ice-stream flow in the troughs and stagnant or slow-flowing ice on the intervening shallow banks (Ottesen et al., 2005a). A number of marine ice-stream lateral shear-moraines have been interpreted subsequently from the high-latitude continental shelves of Svalbard, Norway, the UK and South Georgia (Golledge and Stoker, 2006; Ottesen et al., 2005b, 2007, 2008; Bradwell et al., 2008; Graham et al., 2008; Rydningen et al., 2013).

There is no unequivocal subglacial evidence for the existence of shear-moraines at the lateral margins of contemporary ice streams. However, several features, interpreted as entrained morainic debris, have been identified from radar data at the base of the recently abandoned shear margin of Ice Stream B (now named Whillans Ice Stream), West Antarctica (Clarke et al., 2000). These features have been suggested subsequently to be ice-stream lateral shear-moraines (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008).

Five ice-stream lateral marginal-moraines, interpreted to have been formed at the lateral boundary between ice streams and terrain that was free of grounded ice, have been identified on the Norwegian continental shelf (Rydningen et al., 2013). Similar ridges up to 50 km wide and 200 m thick have been reported from the outer-shelf lateral margins of the Amundsen Gulf and M’Clure Strait troughs in the Canadian Beaufort Sea (Batchelor et al., 2014; Batchelor and Dowdeswell, 2015) and the Pennel and Central Ross Sea troughs in the Ross Sea, West Antarctica (Shipp et al., 1999). These ridges were suggested to have formed by the lateral accretion of sediment at the outermost lateral margins of former ice-streams (Shipp et al., 1999).

3. FORMATION MECHANISMS FOR ICE-STREAM LATERAL SHEAR-MORAINES

A number of methods of formation have been proposed for the source of sediment within ice-stream lateral shear-moraines and to explain the mechanisms by which this sediment is delivered to the lateral margins of ice streams (e.g. Kleman and Borgström, 1994; Clark and Stokes, 2002; Hindmarsh and Stokes, 2008). This discussion is based on the preliminary ideas of Stokes and Clark (2002).

3.1 Differential erosion rates between ice-stream and inter-ice stream locations

As a result of their high ice-flow velocities, ice streams are generally considerably more efficient at eroding their beds compared with slower-flowing inter-ice stream regions of an ice sheet (Alley et al., 1989; Elverhøi et al., 1998). Ice-stream lateral shear-moraines have therefore been suggested to be erosional remnants preserved at the lateral boundaries of ice-streams that have eroded and evacuated sediment from their beds, with the adjacent inter-ice stream areas having remained relatively unmodified by the presence of grounded ice (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). However, this mechanism is unable to explain why lateral moraines are typically higher than the adjacent terrain beyond the ice-stream margin (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008).

3.2 Sediment recycling

The theory of sediment recycling, as proposed by Stokes and Clark (2002), builds upon the concept of differential erosion between ice-stream and inter-ice stream locations. Ice-stream lateral shear-moraines are interpreted to be composed of sediment which has been mined from erosion into the lateral margins of ice-streams, producing topographic steps in till thickness. This sediment is subsequently ‘recycled’ or smeared out and deposited in a downstream direction (Stokes and Clark, 2002). In this theory, the formation of ice-stream lateral shear-moraines is controlled by the availability of thick, unconsolidated sediment at the upstream lateral margins of ice streams; there is no need to invoke a mechanism of transporting sediment from the centre of the ice stream towards its lateral margins (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). This mechanism can account for the existence of ice-stream lateral shear-moraines that are higher than the surrounding terrain, and may also explain the existence of topographic steps in till thickness that have been reported from some ice-stream lateral margins (Stokes and Clark, 2002). However, not all ice-stream lateral shear-moraines are located in association with topographic steps (Hindmarsh and Stokes, 2008).

3.3 Melt-out and deposition of entrained debris

The melt-out and deposition of entrained englacial sediment has been suggested as a feasible method for the formation of ice-stream lateral shear-moraines, given sufficiently long timescales (Hindmarsh and Stokes, 2008). In contrast to the theory of sediment recycling, in which sediment is derived exclusively from the lateral margins of ice streams (Stokes and Clark, 2002), this theory proposes that sediment is sourced from beneath the main trunk of the ice stream through the process of basal freeze-on (Christofferson et al., 2006; Rempel, 2008). The sediment is then concentrated into higher densities in a downstream direction as a result of ice-stream flow convergence (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). Sediment is suggested to be deposited preferentially at the downstream lateral margins of ice streams due to the elevated levels of strain heating and melting that occur in the shear zone (Jacobsen and Raymond, 1998; Schoof, 2004; Hindmarsh and Stokes, 2008). The development of crevasses and longitudinal cavities in the shear zone may allow this sediment to be squeezed upwards, producing ridges of till at the lateral margins of ice streams (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008; Rydningen et al., 2013).

3.4 Lateral advection

The transfer of till to the lateral margins of ice streams by horizontal flow, or lateral advection, has been suggested to play an important role in the formation of ice-stream lateral shear-moraines (e.g. Kleman and Borgström, 1994; Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). A difficulty with this theory is that it requires sediment transfer to occur obliquely to the lateral margins of ice streams. The identification of streamlined glacial lineations orientated obliquely towards a ridge of sediment at the former boundary of warm- and cold-based ice in northern Sweden suggests that compressive flow within warm-based ice can result in the thrusting and folding of subglacial sediment up against a thermal boundary (Kleman and Borgström, 1994). However, no streamlined glacial lineations orientated obliquely to ice-stream lateral shear-moraines have been identified from the beds of former ice streams (e.g. Stokes and Clark, 2002; Ottesen et al., 2005a, 2007; Rydningen et al., 2013).

3.5 Differential erosion rates related to lateral variations in ice-stream velocity

Ice-sheet numerical modelling suggests that it is possible for ice-stream lateral shear-moraines to be formed as a result of differential patterns of till erosion and deposition across an ice stream (Hindmarsh and Stokes, 2008). Differential erosion rates across an ice stream are interpreted to be related to lateral variations in downstream ice-flow velocity; ice-flow velocity is relatively low at ice-stream lateral margins, due to the resistance provided by lateral drag, and increases rapidly away from them, reaching a maximum along the ice-stream central axis (e.g. Whillans et al., 1993; Echelmeyer et al., 1994). In the differential erosion model of Hindmarsh and Stokes (2008), the possibility of sediment being deposited at any point beneath an ice stream is dependent on the ice-flow velocity, which causes erosion and varies laterally across the ice stream, and the local accumulation rate, which causes erosion if it is positive and deposition if it is negative. It is therefore interpreted to be possible for sediment to build up at the relatively slow-flowing lateral margins of ice streams in ablation areas (Hindmarsh and Stokes, 2008).

The differential erosion model of Hindmarsh and Stokes (2008) predicts that ice-stream lateral shear-moraines tens of metres thick and several kilometres wide can be produced over a timescale of about one thousand years. The model also predicts that ice-stream lateral shear-moraines are relatively rarely produced due to a particular set of criteria that are required for their formation; these include a metres-thick layer of unconsolidated sediment, an abrupt lateral transition in ice-flow velocity, and relatively high rates of ice-surface ablation (Hindmarsh and Stokes, 2008).

A difficulty with this theory is that it predicts the movement of sediment that is derived from upstream towards the ice-stream lateral margins in the ablation zone. However, there is currently no evidence of streamlined glacial lineations orientated obliquely towards ice-stream lateral shear-moraines in the geomorphological record. Another difficulty is that some high-latitude Quaternary ice streams may not have had a significant ablation zone under full-glacial conditions, such as is the case for the ice streams that feed the Ross Ice Shelf today.

4. METHODOLOGY

An inventory of ISLMs is presented in Tables 1 and 2 and the geographical locations of the ISLMs are mapped in Figure 2. ISLM locations are compiled from published accounts of aerial and satellite imagery from terrestrial Canada (e.g. Stokes and Clark, 2002; Storrar and Stokes, 2007; Ó Cofaigh et al., 2010) and bathymetric and acoustic data from the continental shelves of Arctic Canada, Greenland, Svalbard, Norway, the UK, South Georgia and Antarctica (e.g. Shipp et al., 1999; Ottesen et al., 2005a, 2007; Rydningen et al., 2013; Arndt et al., 2015).

In addition, independent analysis of bathymetric and acoustic data reveals the locations of a number of marine ISLMs that have not been reported previously (Table 1). ISLMs on the continental shelves of South Greenland, Svalbard and Norway were distinguished using the Olex compilation of single-beam echo-sounder bathymetry data (www.olex.no). Multibeam bathymetry data collected as part of the Norwegian MAREANO programme (www.mareano.no) were also used to identify ISLMs between 65°N and 72°N on the Norwegian margin. All elongate ridges at the margins of cross-shelf troughs were categorised as ISLMs. The horizontal resolution of this bathymetry data is between 5 and several tens of metres. The approximate locations of ISLMs off northwest and northeast Greenland were determined from newly-available two-dimensional (2-D) seismic-reflection data provided by TGS. Although the seismic-reflection data enables the internal acoustic character of ISLMs to be analysed, the horizontal resolution of these data, which is around 50 m, may have precluded the identification of small lateral ridges on the continental shelf of Greenland.

A synthesis of the dimensions, geometry and acoustic character of each ISLM is presented in Table 1. ISLM dimensions were determined from previous descriptions of each landform, together with measurements from any available bathymetric or acoustic-stratigraphic data. In this study, lateral-moraine width was measured at several points along the moraine in an across-trough direction, perpendicular to the inferred former ice-flow direction. Lateral-moraine length was measured in a trough-parallel direction. Some ISLMs occur as discontinuous segments along the lateral margin of a former ice stream (e.g. Stokes and Clark, 2002; Ó Cofaigh et al., 2010; Rydningen et al., 2013). In this study, lateral moraine segments that are separated by a gap greater than 5 km are considered as separate landforms. Several ISLMs were identified solely from seismic-reflection profiles (nos. 19 to 25, 28, 29, 68 and 69 in Tables 1 and 2 and Fig. 2); their trough-parallel lengths are therefore unknown. For ISLMs identified from bathymetric data, thickness refers to the maximum height of the moraine crest above the general level of the seafloor. Where acoustic-stratigraphic data were available, ISLM thickness also includes any portion of the landform which is buried beneath the present-day seafloor.

5. RESULTS

5.1 An inventory of ice-stream lateral moraines

5.1.1 Description

The locations of 70 ISLMs, together with a synthesis of their key physiographic and geological characteristics are presented in Tables 1 and 2 and Figure 2. ISLMs have been identified only occasionally in the terrestrial environment; 8 ISLMs are present on Prince of Wales, Victoria and Stefansson Islands in Arctic Canada (Table 1 and Fig. 2) (e.g. Dyke et al., 1992; Stokes and Clark, 2002), and 10 have been identified from the western Canadian Prairies (Ó Cofaigh et al., 2010).

The majority of ISLMs in our inventory are submarine landforms identified from the high-latitude glacier-influenced marine environment (Fig. 2). ISLMs are reported from one or both lateral margins of a number of cross-shelf troughs that have been interpreted as the former sites of marine-terminating ice streams or fast-flowing outlet glaciers (Dowdeswell et al., 1996; Ó Cofaigh et al., 2003; Batchelor and Dowdeswell, 2014). Our discovery of a number of previously unrecognised ISLMs on the continental shelves of Greenland and Norway (Table 2) suggests that marine ISLMs may be more widespread and/or better preserved than has been inferred previously.

The locations and dimensions of ISLMs on the Svalbard and Norwegian margins are particularly well documented (Table 2 and Fig. 2) (Ottesen et al., 2005a, 2007, 2008, 2016; Rydningen et al., 2013). By contrast, no ISLMs have been reported from the continental shelves of Baffin Island or the Queen Elizabeth Islands (QEI), or at the sides of the large cross-shelf troughs in the northern Barents-Kara Sea (Batchelor and Dowdeswell, 2014). One possible ISLM, the Wee Bankie moraine beyond the Firth of Tay, East Scotland, is identified off the UK (no. 66 in Table 2 and Fig. 2). Although this ridge, which is 6 km wide and at least 60 km long, was previously interpreted as a terminal moraine (Stoker et al., 1985), its position, morphology and composition suggest that it may have been formed at the lateral margin of an ice stream (Golledge and Stoker, 2006).

We have found only three ISLMs described from the Antarctic margin (nos. 68 to 70 in Table 2 and Fig. 2). Ridges of sediment, interpreted as ISLMs, have been identified at the southern lateral margin of Mertz Trough, East Antarctica (Barnes, 1987; Domack et al., 1989; Beaman and Harris, 2003), and at the lateral margins of the Pennel and Central Ross Sea troughs off West Antarctica (Shipp et al., 1999).

The majority of the marine ISLMs presented in our inventory were identified solely from bathymetric maps of the seafloor (e.g. Figs. 3 to 5). Seismic-reflection data, which reveal the configuration of internal reflections within each landform, were available for only 15 or 29% of the marine ISLMs.

5.1.2 Interpretation

The discrepancy between the number of ISLMs identified in the terrestrial and marine environments (18 and 52, respectively) is unlikely to be a consequence of the inferior preservation of ISLMs on land. Although other glacigenic landforms including mega-scale glacial lineations (MSGLs) tend to occur in fields rather than as isolated features, they are only a few metres in relief and have been identified and mapped widely in terrestrial environments (e.g. Clark, 1993; Stokes and Clark, 2001, 2002; Ó Cofaigh et al., 2010). We therefore suggest that the conditions required for the formation of ISLMs are more readily achieved in the marine environment than on land. Unconsolidated sediment, which has been interpreted to be necessary for the development of ISLMs (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008), occurs as thick, prograding sequences on the mid- and outer-shelves of many high-latitude cross-shelf troughs (e.g. Alley et al., 1987; Shipp et al., 1999; Ó Cofaigh et al., 2002) and may encourage the formation of marine ISLMs.

It is also possible that the relative absence of ISLMs from the terrestrial environment is a consequence of the variable position of the lateral margins of terrestrial ice streams. Although there is evidence for the switching of ice-stream flow directions across the continental shelf between full-glacial periods (e.g. Dowdeswell et al., 2006; Sarkar et al., 2011), marine-terminating ice streams are mainly topographically controlled and generally occupy the same cross-shelf trough during successive glaciations (Dowdeswell et al., 1996; Elverhøi et al., 1998; Dowdeswell and Siegert, 1999; Batchelor and Dowdeswell, 2014). By contrast, terrestrial ice streams are not generally controlled to a large extent by bedrock and valley-wall morphology (Bentley, 1987; Stokes and Clark, 1999; Stokes et al., 2016). They may, consequently, be more dynamic and transitory than their marine-terminating counterparts; evidence of former ice-streaming flow in terrestrial environments may, on some occasions, record relatively short-lived surges of an ice stream (Patterson, 1998; Evans et al., 1999, 2008; Margold et al., 2015). ISLMs may take longer to form than other subglacial landforms such as MSGLs (which are typically one to two orders of magnitude smaller in volume than ISLMs; Dowdeswell et al., 2016b) that have been mapped from the bases of numerous terrestrial ice streams (e.g. Clark, 1993; Stokes and Clark, 2001, 2002; Ó Cofaigh et al., 2010) and have been interpreted to be formed over a timescale of decades (King et al., 2009).

Although marine-geophysical data are available from many Antarctic cross-shelf troughs (e.g. Anderson, 1999; Canals et al., 2000; Ó Cofaigh et al., 2002; Dowdeswell et al., 2004; Mosola and Anderson, 2006; Graham et al., 2009; Larter et al., 2012, 2014), only three ISLMs have been identified from the Antarctic margin (nos. 68 to 70 in Table 2 and Figure 2). Marine-terminating palaeo-ice streams in Antarctica certainly had the capacity to transport large volumes of glacigenic sediment to their grounding-zones, as shown by the presence of GZWs with volumes of between ten and several hundred cubic kilometres on the continental shelf (e.g. Larter and Vanneste, 1995; Anderson, 1997; Domack et al., 1998; Ó Cofaigh et al., 2005; Batchelor and Dowdeswell, 2015). Where they are identified in the geological record, Antarctic ISLMs are some of the widest and thickest ISLMs in our inventory (Table 2 and Fig. 6). In addition, it is possible that ISLMs exist beneath the lateral margins of some contemporary Antarctic ice streams (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008).

An important difference between Arctic and Antarctic continental margins is that, whereas the majority of Arctic cross-shelf troughs widen significantly towards the shelf break, often as a result of ice emerging from the constraints of fjords and inter-island channels, Antarctic troughs do not typically exhibit a pronounced seaward increase in width (Livingstone et al., 2012; Batchelor and Dowdeswell, 2014). The relative absence of ISLMs off Antarctica could be related to a lack of ice-flow divergence on the outer continental shelf. Trough widening and ice-flow divergence on the outer-shelf may play a role in the formation of some ISLMs through encouraging the transfer of sediment beneath ice streams towards their outer-shelf lateral margins.

The relative absence of Antarctic ISLMs from our inventory is also probably, in part at least, an artefact of the preferential surveying of trough axes, rather than their lateral margins, where shallower inter-trough banks are often heavily ploughed and reworked by iceberg keels (e.g. Anderson, 1999; Ó Cofaigh et al., 2002, 2005; Jakobsson et al., 2012a). The apparent absence of marine ISLMs from the Baffin Island, QEI and northern Barents-Kara Sea margins may also be related to a lack of high-resolution geophysical data available from these regions.

The relatively fresh, apparently undegraded appearance of ISLMs on seafloor bathymetry (e.g. Figs. 3 to 5) indicates that the majority of the marine ISLMs recorded in Table 2 experienced their most recent phase of formation during the last glaciation or subsequent deglaciation. However, a number of the large marine ISLMs in our inventory (e.g. nos. 19 to 29 in Table 2) are interpreted to be composite landforms that built up over several successive full-glacial periods as ice streams repeatedly reached the same approximate lateral position on the continental shelf.

In summary, we suggest that the availability of unconsolidated sediment on the mid- and outer-shelves of many high-latitude continental margins encourages the formation of ISLMs in the marine environment. ISLMs may also be produced preferentially in the marine environment due to the often dynamic and transitory behaviour of terrestrial ice streams. We interpret the relative absence of ISLMs off Antarctica, as well as on the Baffin Island, QEI and northern Barents-Kara Sea margins, to be mainly a consequence of a lack of data from the lateral margins of cross-shelf troughs in these regions.

5.2 Relative position of ice-stream lateral moraines

5.2.1 Description

All the ISLMs in our inventory are located towards the downstream ends of palaeo-ice streams which had their onset zones from tens to, more usually, hundreds of kilometres further back in the ice-sheet interior. The relatively smooth and often streamlined appearance of the seafloor on bathymetric data, together with acoustic penetration at frequencies of a few kilohertz, suggests that all the marine ISLMs are associated with regions of cross-shelf troughs that possess a sedimentary substrate (Figs. 3 to 5). In some cases, this is further supported by evidence from deeper-penetrating reflection-seismic data (Rydningen et al., 2013; Batchelor et al., 2014).

With the exception of the ISLMs off Antarctica, all the marine ISLMs in our inventory are located at the lateral margins of cross-shelf troughs that exhibit a significant seaward increase in width and contain streamlined glacial lineations that diverge in a seaward direction (Figs. 3 to 5). Streamlined glacial lineations are generally orientated parallel to ISLMs (e.g. Figs. 3B and 4C). An exception is at the northern lateral margin of Trænadjupet, a north Norwegian cross-shelf trough (Fig. 5C), where streamlined glacial lineations appear to be orientated at an oblique angle towards a curvilinear landform that has been interpreted previously as an ISLM (Ottesen et al., 2002, 2005a, b). Some streamlined glacial lineations also appear to be orientated at an oblique angle towards the ISLMs at the lateral margins of the Maskwa palaeo-ice stream in the terrestrial setting of the western Canadian Prairies (Ó Cofaigh et al., 2010).

5.2.2 Interpretation

Although it is difficult to determine the length of a palaeo-ice stream from its geomorphology, analysis of the data in our inventory suggests that ISLMs are only formed at the downstream lateral margins of ice streams. This is in agreement with the theory of differential erosion rates that was proposed by Hindmarsh and Stokes (2008), which predicts that lateral deposition of subglacial sediment can only occur in zones of subglacial mass loss. There is probably also an insufficient supply of unconsolidated sediment and/or an insufficient contrast in ice-flow velocity between the ice stream and the adjacent slower-flowing ice to enable the formation of ISLMs at the upstream lateral margins of many ice streams.

Although the resolution of our bathymetric data is sometimes relatively limited (between 5 and several tens of metres in the horizontal), streamlined glacial lineations are generally observed to be orientated parallel to ISLMs (Figs. 3 to 5). These observations have been interpreted previously to be inconsistent with theories of ISLM formation that invoke the transverse movement of sediment from within an ice stream towards its lateral margins (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). However, streamlined glacial lineations appear to be orientated at an oblique angle towards an ISLM at the outermost northern lateral margin of Trænadjupet (Fig. 5C). Several streamlined glacial lineations are also interpreted to be orientated obliquely towards the lateral margins of the former Maskwa ice stream (Ó Cofaigh et al., 2010). This suggests that some ISLMs may contain a proportion of sediment that was transferred within the ice stream at an oblique angle towards its lateral margins.

In summary, we hypothesise that ISLMs are only formed at the downstream lateral margins of ice streams. The association of marine ISLMs with regions of trough widening and diverging streamlined glacial lineations (Figs. 3 to 5) suggests that ice-stream widening and ice-flow divergence on the outer continental shelf play a role in the formation of some ice-stream lateral moraines.

5.3 Dimensions of ice-stream lateral moraines

5.3.1. Description

Information on ISLM length, in the direction of past ice-flow, is provided for 58 of the ISLMs in Tables 1 and 2 and Figure 2. ISLM lengths range between 2 and 160 km; the modal value is 5 to 10 km and the mean is 28 km (Fig. 6A). Considerable variations in ISLM length are recognised along each continental margin (Fig. 6A). Although only 18 ISLMs have been reported from the terrestrial environment, terrestrial ISLMs appear to have similar lengths to ISLMs identified from formerly-glaciated continental shelves (Fig. 6A).

ISLM width is available for 55 of the recorded ISLMs, and ranges between 200 m and 50 km (Fig. 6B). The majority (76%) of ISLMs are less than 10 km wide. The modal width is 0.5 to 1 km and the mean is 8 km (Fig. 6B). Considerable variations in ISLM width are recognised between the various settings; whereas ISLMs wider than 13 km have not been reported from the terrestrial environment or off Svalbard, Norway, the UK or South Greenland, all of the ISLMs on the northwest and northeast Greenland margins and in the Canadian Beaufort Sea are more than 15 km wide (Fig. 6B).

Sediment thickness data are available for 53 ISLMs. ISLM thicknesses range between 5 and 300 m; the modal thickness is 40 to 50 m and the mean is 74 m (Fig. 6C). All of the ISLMs that have been identified from the terrestrial environment and from the continental shelves of Norway, Svalbard and South Greenland are less than 100 m thick (Fig. 6C), whereas all of the ISLMs off northwest and northeast Greenland and in the Canadian Beaufort Sea are more than 150 m thick.

The scatter plot shown in Figure 7A demonstrates that ISLM width has a moderately strong positive correlation with palaeo-ice stream width. A least-squares regression fit to these data produces a correlation coefficient, R, of 0.53, which is significant at a 99% level of probability. ISLM width is shown to have a strong positive correlation with ISLM thickness (Fig. 7B). A least-squares regression fit to these data gives a correlation coefficient, R, of 0.85, which is significant at a 99% level of probability. In contrast, a relatively weak positive correlation exists between ISLM length and width when all the ISLMs are analysed collectively (R = 0.43: significant at a 99% level of probability) (Fig. 7C). There is no significant correlation between ISLM length and thickness (Fig. 7D).

Cross-profiles were constructed from Olex and MAREANO bathymetry of a number of ISLMs on the South Greenland, Norwegian and Svalbard margins (e.g. Figs. 3 to 5). Five equally spaced measurements of width and thickness were taken across each ISLM. Two types of ISLMs are differentiated: Type 1 ISLMs maintain a constant width and thickness along their length (e.g. Fig. 3B); Type 2 ISLMs exhibit a seaward increase in width and thickness (e.g. Fig. 5).

Type 1 ISLMs are generally identified in fjord, mid-shelf and outer-shelf settings on the Norwegian margin. With the exception of three Type 1 ISLMs at the northern lateral margin of Andfjorden, north Norway (Fig. 3F and G), they are not identified close to or at the shelf break. The terrestrial ISLMs that have been described from Arctic Canada and the western

Canadian Prairies have also been observed to maintain a relatively constant width and thickness along their length (Dyke and Morris, 1988; Stokes and Clark, 2002; Ó Cofaigh et al., 2010) and are therefore categorised as Type 1 ISLMs (Table 1). All of the Type 1 ISLMs are less than 3.5 km wide and between 5 and 60 m thick (Table 1 and Fig. 8). Examples of Type 1 ISLMs include the landforms at the southern lateral margins of Hakjerringdjupet (Fig. 3C to E) and Rebbenesdjupet (Fig. 3A and B) and at the northern and southern lateral margins of Malangsdjupet on the Norwegian margin (Fig. 4A and C).

In contrast, Type 2 ISLMs, which are identified on the South Greenland, Norwegian and Svalbard margins, exhibit a seaward increase in width and thickness and terminate at the shelf break (e.g. Figs. 4 b, d, e and 5). At their landward ends, Type 2 ISLMs are identified as subdued ridges that are associated with changes in the gradient of the slope at the lateral trough margin (Fig. 5). These ridges increase in width and thickness in a seaward direction. With maximum widths of between 1.5 and 13 km, and thicknesses of between 20 and 80 m, Type 2 ISLMs are some of the widest and thickest ISLMs in our inventory (Fig. 8B and C).

Several of the large ISLMs on the northwest and northeast Greenland, Antarctic and Canadian Beaufort Sea margins, which are identified solely from seismic-reflection data, are present on the outermost continental shelf and are up to 50 km wide and 300 m thick. Although it is not possible to determine if these ISLMs exhibit any seaward changes in width or thickness, their dimensions, geometry and position on the outermost shelf suggest that they are probably also Type 2 ISLMs (Table 2 and Fig. 8).

5.3.2. Interpretation

The data on ISLM dimensions and geometry lead us to suggest that two different types of ISLM are preserved in the geological record; Type 1 ISLMs are generally narrower and thinner and do not exhibit a seaward change in dimensions, whereas Type 2 ISLMs are wider and thicker and exhibit a seaward increase in dimensions (Figs. 5 and 9). In addition, Type 2 ISLMs are only observed in the marine record, where they all extend to the shelf break.

The identification of two different types of ISLM explains why ISLM length does not scale strongly with ISLM width or thickness (Fig. 7C and D). Although they exhibit a wide range of lengths, all of the Type 1 ISLMs are less than 3.5 km wide (Figs. 7C, 9A and B). Type 1 ISLMs have relatively high length: width ratios; the majority are between 10:1 and 30:1 (Tables 1 and 2).

In contrast, a strong positive relationship exists between the length and width of Type 2 ISLMs (Fig. 7C) ($R = 0.89$ at a 99% level of probability). Although they have comparable lengths, Type 2 ISLMs reach considerably greater widths than Type 1 ISLMs (Fig. 7C, 9A and B). For example, the Type 1 ISLM at the southern side of Malangsdjupet (Fig. 4A and C) is 15 km long and only 0.7 km wide, whereas the Type 2 ISLM on the outermost shelf beyond Trænabanken is 12 km long and reaches a maximum width of 10 km (Fig. 5C). Type 2 ISLMs therefore exhibit relatively low length: width ratios (typically < 10:1 at their widest point).

ISLMs on the northwest and northeast Greenland and Canadian Beaufort Sea margins are generally wider and thicker than ISLMs that have been described from terrestrial Canada and from the continental shelves of Norway, Svalbard and South Greenland (Fig. 6B and C). It is possible that this pattern is a consequence of the former existence of wider and longer ice streams on the continental shelves of the Canadian Beaufort and north Greenland areas (Fig. 7B), which provided a greater source of sediment to be deposited at ice-stream lateral margins. Several of the ISLMs off northwest and northeast Greenland and the Canadian Beaufort Sea are also interpreted to be composite landforms that built up over several successive full-glacial periods, as their seismic stratigraphy will show (Table 2). In addition, the ISLMs that are recognised off Greenland and Canada are all Type 2 ISLMs, which are shown to be considerably wider than Type 1 landforms.

In summary, we show that two different types of ISLMs are preserved in the geological record. The narrower and more elongate Type 1 ISLMs are identified in terrestrial Canada and on the Norwegian continental shelf (Fig. 3). Type 2 ISLMs, which are wider and display a seaward increase in width and thickness, are observed off Norway, Svalbard, Greenland, Canada and Antarctica (Fig. 4b, d and e). We hypothesise that Type 1 ISLMs are probably also present on the Svalbard, Greenland, Canadian and Antarctic margins, perhaps in inner-shelf settings, but they are not identified at the resolution of seismic-reflection or relatively coarse-resolution bathymetry data.

5.4 Volume of ice-stream lateral moraines

5.4.1 Description

Average volumes were estimated for Type 1 and Type 2 ISLMs from the mean and modal values for length, width and thickness (Fig. 8 and Table 3). Using this method, Type 1 ISLMs have an average volume of between 0.03 and 0.45 km³, depending on whether mean or modal dimensions are used (Table 3). Type 2 ISLMs have a greater average volume of between 10.1 and 23.5 km³ (Table 3).

Average ISLM volumes were also estimated from individual length, width and thickness measurements for those ISLMs for which these data are available (Tables 1 to 3). These values use the maximum thickness and width measurements from Tables 1 and 2, and therefore provide an estimate of the maximum volume of each ISLM. The maximum volume of Type 1 ISLMs is shown to range between 0.002 and 5.78 km³ (Table 3); however, the majority of these landforms have volumes of less than 0.5 km³ (Tables 1 and 2). The maximum volume of Type 2 ISLMs ranges between 0.11 and 1344 km³ (Table 3), with the majority possessing volumes of between 0.5 and 10 km³ (Table 2).

5.4.2 Interpretation

The data shown in Table 3 suggest that the volume of Type 2 ISLMs is generally around two orders of magnitude greater than the volume of Type 1 ISLMs. This is consistent with the greater thicknesses and widths that have been reported for Type 2 ISLMs (Fig. 8).

The majority of Type 2 ISLMs for which length, width and thickness measurements are available have volumes of a few cubic kilometres to tens of cubic kilometres (Table 2). However, one Type 2 ISLM with an estimated volume of more than 1000 km³ has been reported from the southwest lateral margin of Norske Trough off northeast Greenland (no. 27 in Table 2). This is probably not an anomalously large landform; extreme widths and thicknesses have been reported for other Type 2 ISLMs off northeast and northwest Greenland and in the Canadian Beaufort Sea (Table 2), suggesting that other Type 2 ISLMs may have comparable volumes. In addition to their remarkable dimensions, the seismic stratigraphy of these Type 2 ISLMs suggests that they are probably composite features that developed over several successive full-glacial periods.

5.5 Geometry of ice-stream lateral moraines

5.5.1 Description

Terrestrial and marine ISLMs are shown to be linear to curvilinear in plan-form (Dyke and Morris, 1988; Stokes and Clark, 2002; Ottesen et al., 2005a). A number of Type 1 ISLMs occur as discontinuous segments (e.g. Fig. 4A) (Stokes and Clark, 2002; Ó Cofaigh et al., 2010; Rydningen et al., 2013). In contrast, no discontinuous Type 2 ISLMs are recognised from the data. Type 1 ISLMs are generally more elongate compared with Type 2 ISLMs, which have a more equidimensional shape (e.g. Figs. 4B, D, E and 5). Several Type 1 and Type 2 ISLMs occur in sets of two or more parallel or sub-parallel ridges that are spaced 500 m to 4 km apart (e.g. Figs. 3H, 4B, C and 5A).

Type 1 ISLMs maintain a relatively constant cross-sectional shape along their length (e.g. Fig. 3B). They are either relatively symmetrical or have steeper trough-proximal sides. For example, the Type 1 terrestrial ISLMs that have been described from terrestrial Canada are relatively symmetrical in cross-section and do not undergo significant downstream changes in geometry (Dyke and Morris, 1988; Dyke et al., 1992; Stokes et al., 2002; Ó Cofaigh et al., 2010). Similarly, the Type 1 marine ISLM at the southern lateral margin of Rebbenesdjupet, Norway (Fig. 3B) exhibits a steeper trough-proximal slope along its entire length.

In contrast, Type 2 ISLMs undergo a change in cross-sectional shape along their length (e.g. Fig. 5). All of the Type 2 ISLMs exhibit steepening of their trough-distal slope in a seaward direction; this has the effect of making ISLM ridges appear more pronounced on the outermost continental shelf (e.g. Fig. 5). Some Type 2 ISLMs still possess a steeper trough-proximal slope at their downstream end (e.g. Fig. 5A and B), whereas others originate as an asymmetric ridge with a steeper trough-proximal side and transition in a seaward direction into an asymmetric ridge that has a steeper trough-distal side (e.g. Fig. 5C). Although information about seaward changes in cross-sectional geometry is not available for those ISLMs that are identified solely from seismic-reflection data, a number of the ISLMs on the northwest and northeast Greenland, Antarctic and Canadian Beaufort Sea margins exhibit a pronounced asymmetric shape in cross-section, with a steeper trough-distal slope (Figs. 9 and 11) (Shipp et al., 1999; Batchelor et al., 2014).

5.5.2 Interpretation

The difference in plan-view geometry between Type 1 and Type 2 ISLMs is a consequence of the higher length: width ratios of the more elongate Type 1 ISLMs compared with those of Type 2 (Fig. 7C). It has been suggested previously that ice-stream lateral shear-moraines have relatively constrained conditions of formation given their likely subglacial origin; this may explain the deposition of multiple, discontinuous Type 1 ISLM segments along the lateral ice-stream margin (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). Alternatively, the existence of discontinuous ISLM segments may be a result of the dissection of the ridges by post-depositional processes.

Sets of two or more ISLMs on the same side of a trough, orientated sub-parallel to each other and to trough central axes (Fig. 4C), are interpreted to record fluctuations in the position of ice-stream lateral margins. Their relatively fresh appearance on seafloor bathymetry (e.g. Fig. 3E) suggests that sets of ISLMs probably record minor adjustments in ice-stream width that occurred during the last glacial-deglacial cycle. Sets of two or more Type 2 ISLMs, which are only present on the outermost continental shelf, are orientated sub-parallel to each other (e.g. Figs. 4B and 5A). This provides evidence for ice-stream widening and ice-flow divergence close to the shelf break. The absence of sets of ‘recessional’ ISLM ridges from the beds of former ice streams suggests that ISLMs are formed during periods of ice-stream widening rather than during retreat of the ice-stream lateral margin, and/or that lateral ice retreat was relatively rapid.

A number of differences in cross-sectional geometry are also apparent between Type 1 and Type 2 ISLMs. Type 1 ISLMs maintain a constant cross-sectional shape along their length and are either roughly symmetrical or have a steeper ice-proximal side (e.g. Figs. 3A to C and 4C). The steep trough-proximal slope of Type 1 ISLMs is probably a consequence of erosion by fast-flowing ice streams.

In contrast, Type 2 ISLMs exhibit a seaward increase in the steepness of their trough-distal slope that is often accompanied by a corresponding shallowing of the trough-proximal slope (Figs. 4B, D, E and 5). We suggest that this seaward change in geometry is related to a change in the amount of accumulation space that existed beyond the ice-stream lateral margin.

In summary, the two different types of ISLM display significant differences in plan-view and cross-sectional geometry. Type 1 ISLMs have higher length: width ratios compared with Type 2 ISLMs and they often occur as discontinuous segments. Type 1 ISLMs maintain a relatively constant cross-sectional geometry and are either roughly symmetrical or have a steeper ice-proximal side. In contrast, Type 2 ISLMs exhibit a seaward increase in the steepness of their trough-distal slope.

5.6 Acoustic character of ice-stream lateral moraines

5.6.1 Description

Seismic-reflection data are available for 15 of the marine ISLMs in our inventory (Table 2; Figs. 8 and 11). The data reveal that a considerable proportion of some ISLMs is buried beneath the seafloor (e.g. Figs. 4A, 9 and 11). A seismic-reflection profile across the Type 1 ISLM at the southern lateral margin of Malangsdjupet, north Norway (Fig. 4A and B) shows that it contains internal reflections that dip towards the trough and are truncated against the steep trough side (Rydningen et al., 2013).

Newly available seismic-reflection profiles of the northwest and northeast Greenland shelves (Fig. 10A), together with existing accounts of seismic data from the West Antarctic, Norwegian and Canadian Beaufort Sea margins (nos. 19 to 29, 69 and 70 in Table 2 and Fig.

2), reveal that Type 2 ISLMs are characterised by internal reflections that dip away from the former ice stream and towards the adjacent shallow bank (e.g. Figs. 9 and 11) (Shipp et al., 1999; Rydningen et al., 2013; Batchelor et al., 2014; Batchelor and Dowdeswell, 2015). Multiple downlap surfaces are present within a number of Type 2 ISLMs (e.g. Fig. 10B, D, E and 11).

Four of the ISLMs off northwest and northeast Greenland are not categorised as Type 1 or Type 2 ISLMs due to their complex geometries (Table 2). For example, the mid-shelf ISLM at the southern lateral margin of Upernavik Trough, northwest Greenland is characterised by internal reflections that dip towards the trough and are truncated against a steep trough-proximal cliff at its northern end, and by internal reflections that dip away from the trough at its southern end (Fig. 10A and D).

5.6.2 Interpretation

The internal reflections that dip towards the trough within the Type 1 ISLM at the southern lateral margin of Malangsdjupet (Fig. 4A and B) (Rydningen et al., 2013) indicate that the predominant sediment-transfer direction was from the shallow bank towards the trough. This is consistent with relatively slow-flowing ice on the bank feeding into faster-flowing ice in the deeper trough. The truncation of internal reflections against the steep trough-proximal side of this ISLM indicates net erosion of the lateral margin of the trough by the former ice stream (Rydningen et al., 2013).

Seismic-reflection profiles across the lateral margins of former ice streams reveal that, rather than just consisting of a ridge crest, Type 2 ISLMs are large, prograding depocentres that are buried partially beneath the seafloor (Figs. 9 and 11). Internal reflections are shown to dip away from the trough (e.g. Figs. 10B, D, E and 11), indicating sediment progradation and lateral moraine growth through the continued delivery of sediment from an active ice stream in the trough towards the adjacent bank. This is consistent with previous interpretations of large Type 2 ISLMs off West Antarctica and in the Canadian Beaufort Sea, which were suggested to have been formed by the lateral accretion of sediment at the outermost lateral margins of former ice streams (Shipp et al., 1999; Batchelor et al., 2014).

The presence of multiple downlap surfaces on seismic-reflection profiles of several of the Type 2 ISLMs off northwest and northeast Greenland, West Antarctica and the Canadian Beaufort Sea (Figs. 10B, D, E and 11), together with their large widths and thicknesses (Fig. 6B and C), suggests that they are composite features that built up as ice streams repeatedly expanded their lateral margins to the same approximate position during relatively short-lived (century-scale) fluctuations in ice-stream extent (e.g. Hulbe and Fahnestock, 2007) and/or successive full-glacial periods.

Complex ISLMs that show evidence of erosion at their trough-proximal sides and progradation at their trough-distal sides (e.g. Fig. 10D) probably record temporal variations in relative rates of sediment erosion and deposition at ice-stream lateral margins. The complex ISLM shown in Figure 10D is probably a Type 2 ISLM that has been eroded on its trough-proximal side by a subsequent ice-stream advance through Upernavik Trough (Fig. 10A).

Type 2 ISLMs are shown to have similar geometry and acoustic characteristics to GZWs; they have an asymmetric shape with a steeper ice-distal side, dipping internal reflections and multiple downlap surfaces (Figs. 9 and 11) (Alley et al., 1987; Larter and Vanneste, 1995; Powell and Alley, 1997; Dowdeswell and Fugelli, 2012; Batchelor and Dowdeswell, 2015). However, whereas GZWs form through the rapid accumulation of sediment along a line-source at the grounding zone of marine-terminating ice streams and are orientated perpendicular to the former ice-flow direction, Type 2 ISLMs are orientated parallel or oblique to the former ice-flow direction (e.g. Figs. 4 and 5).

In summary, Type 1 ISLMs contain internal reflections that dip towards the trough, suggesting that the sediment transfer direction was predominantly from the shallow bank towards the trough. In contrast, Type 2 ISLMs contain internal reflections that dip away from the trough, indicating that the predominant sediment-transfer direction was from the ice stream in the trough towards the shallow bank. Another difference is that a number of Type 2 ISLMs are interpreted to be composite landforms.

6. DISCUSSION

6.1 Landforms at the lateral margins of palaeo-ice streams

The inventory of ISLMs presented in Tables 1 and 2 and Figure 2 provides a synthesis of the locations and morphological characteristics of 70 terrestrial and marine ISLMs. Two types of ISLMs are differentiated based on their dimensions, geometry and acoustic character, which are summarised in a schematic model in Figure 11.

Type 1 ISLMs maintain a relatively constant width, thickness and cross-sectional geometry along their length (e.g. Fig. 3B). They often consist of multiple, discontinuous segments and do not typically extend to the shelf break (Figs. 3 and 12). Type 1 ISLMs are less than 3.5 km wide and less than 60 m thick (Fig. 8B and C). They are relatively symmetrical or have steeper ice-stream proximal sides in cross-section (Fig. 4A).

Type 1 ISLMs are interpreted as ice-stream lateral shear-moraines that form subglacially in the shear zone between ice streams and slow-flowing ice. This is consistent with previous interpretations of elongate sedimentary ridges of relatively uniform width that have been identified at the lateral margins of former ice streams (e.g. Dyke and Morris, 1988; Dyke et al., 1992; Stokes and Clark, 2002; Storrar and Stokes, 2007; Ó Cofaigh et al., 2010).

In contrast, Type 2 ISLMs exhibit a seaward increase in width and thickness and terminate at the shelf break (Figs. 4, 5 and 12). Their distal slopes also become steeper in a seaward direction (Fig. 5). They are only identified in the marine environment and are up to 50 km wide and 300 m thick (Fig. 8B and C). They are continuous landforms and generally have lower length: width ratios (typically < 10:1) compared with the more elongate Type 1 ISLMs (Figs. 7C and 12). Seismic-reflection data shows that Type 2 ISLMs are characterised by dipping internal reflections that indicate sediment progradation away from the former ice stream (Figs. 9 and 11).

We consider two interpretations for Type 2 ISLMs. First, it is possible that Type 2 ISLMs are also ice-stream lateral *shear-moraine*s; the differences that are observed between Type 1 and Type 2 ISLMs may be simply a result of the location of Type 2 ISLMs on the outermost continental shelf. The seaward increase in width and thickness that is recorded for Type 2 ISLMs could be due to increased rates of ablation, increased ice-stream widths and reduced levels of erosion close to the shelf break. The difficulty with this interpretation is that it does not explain why Type 1 ISLMs do not show any seaward change in dimensions or geometry when they are observed at the lateral margins of former ice streams that exhibited a pronounced downstream increase in width (e.g. Figs. 3A to E and 4A).

An alternative explanation, which we favour, is that Type 2 ISLMs are ice-stream lateral *marginal-moraine*s that were formed at the lateral boundary between ice streams and terrain that was free of grounded ice. Thus, these are not subglacial, but ice-marginal landforms. The gradual seaward changes in dimensions and geometry that are recognised for Type 2 ISLMs suggest that the ice stream may have become progressively unconstrained laterally by adjacent grounded ice as it extended across the continental shelf. It should be stressed that the presence of ice-stream lateral marginal-moraines does not preclude the former existence of grounded slow-flowing ice beyond the lateral margins of the trough. It is possible that the lateral marginal-moraines were produced subsequent to the retreat of slow-flowing ice from the shallow banks whilst an ice stream still operated in the trough. The lack of Type 2 ISLMs from the terrestrial environment (Table 1 and Fig. 2) leads us to infer, provisionally at least in the absence of contradicting terrestrial evidence to date, that these landforms are probably outer-shelf phenomena of marine-terminating ice streams.

6.2 Comparison with other glacial depositional landforms

Knowledge of the volumes of glacigenic landforms is important for understanding the mechanisms by which they are produced and for testing the predictions of numerical ice-sheet models of sediment transportation beneath ice sheets. The estimated volumes of several types of glacier-depositional landforms, shown in Figure 1, are illustrated in Figure 12.

At the smallest scale, MSGLs are typically less than 5 m thick, 100-200 m wide and 1-10 km long (Clark, 1993; Shipp et al., 1999; Canals et al., 2000; Spagnolo et al., 2014); each MSGL ridge therefore has a volume of between ~0.0005 and 0.01 km^3. MSGLs generally occur in groups of ridges across the former ice-stream bed, and have typical spacing of 200-300 m (Spagnolo et al., 2014). This suggests that, on average, there are between 2 and 4 MSGLs per km of ice-stream width, giving a sediment volume of 0.001-0.04 km^3 per km of ice-stream width (Fig. 12).

Small recessional moraines, which are often formed annually, are typically less than 10 m thick, 100 m wide and 10 km long (Lindén and Möller, 2005; Todd et al., 2007), with volumes in the order of 0.001-0.01 km^3. Larger terminal moraine complexes, such as the Skjoldruggen moraine on the mid-Norwegian shelf (Ottesen et al. 2005), can reach volumes of up to a few hundred cubic kilometres (Fig. 12).

GZWs and TMFs are large glacial-sedimentary depocentres that are only identified in the marine environment (Figs. 1 and 12). GZWs are probably formed during grounding-zone still-stands of at least several decades to centuries, and have volumes of between ten and several hundred cubic kilometres (Larter and Vanneste, 1995; Alley et al., 2007; Batchelor and Dowdeswell, 2015). High-latitude TMFs, which build up on the continental slope when full-glacial ice streams deliver large quantities of deformable sediment to the shelf break, have volumes of between 10,000 and 100,000 km³ (Dowdeswell et al., 1997, 2008b; Vorren and Laberg, 1997; Vorren et al, 1998).

The volume of sediment contained within ice-stream lateral shear moraines, which has been estimated at 0.002-6 km³, is of the same order of magnitude as the volume of groups of MSGLs or recessional moraine ridges (Fig. 12). In contrast, ice-stream lateral marginal-moraines typically possess volumes of between 0.5 and 10 km³. Several larger ice-stream lateral marginal-moraines, which are probably composite features formed over several cycles of ice-sheet growth and decay, have volumes greater than 1000 km³. The volumes of ice-stream lateral marginal-moraines are therefore of the same orders of magnitude as the volumes of GZWs (Fig. 12).

6.3 Implications of identifying ice-stream lateral moraines in the geological record

6.3.1 Glacial reconstruction

ISLMs are an important geomorphological indicator of past ice-stream activity (e.g. Stokes and Clark, 1999, 2002; Ottesen et al., 2005a). They mark the location of the lateral margins of former ice streams, from which palaeo-ice stream width can be reconstructed and lateral stability can be inferred.

The differentiation of two different types of ISLM in the geological record (Fig. 11) suggests that it is possible to make inferences about the conditions that existed beyond the lateral margins of former ice streams at the time of lateral-moraine formation. The presence of ice-stream lateral shear-moraines (Type 1) (e.g. Fig. 3) implies that grounded slow-flowing ice existed beyond the lateral ice-stream margin; that is, the ice streams were embedded in slower-flowing ice. In contrast, ice-stream lateral marginal-moraines (Type 2) (e.g. Figs. 4A, D, E and 5) indicate that the terrain beyond the lateral ice-stream margin was free of grounded ice at this time, and probably occupied by seawater

A number of the Type 2 ISLMs in our inventory, which are interpreted as ice-stream lateral *marginal-moraine*s, have been viewed previously as subglacially-formed ice-stream lateral *shear-moraine*s (e.g. 36 – 45 and 62 - 65 in Table 2 and Fig. 2) (Ottesen et al., 2005a, 2007). It is important to differentiate between the two types of ISLMs in order to avoid any implicit assumptions about the glaciological conditions that existed beyond the lateral margins of the ice stream at the time of lateral-moraine formation (i.e. grounded slow-flowing ice or ice-free submerged terrain).

The interpretation of Type 2 ISLMs as ice-stream lateral marginal-moraines is supported by the position of submarine transverse moraines (Fig. 1C) on some shallow inter-ice stream regions of the shelf. For example, a transverse moraine, which has been interpreted previously as a terminal moraine formed by grounded slow-flowing ice during the last glacial maximum (LGM) (Rydningen et al., 2013), is present on the shallow bank beyond the northern outer-shelf lateral margin of the palaeo-ice stream that occupied Malangsdjupet cross-shelf trough (Fig. 4A and B). The location of the transverse moraine ridge corresponds with the point at which the Type 2 ISLM originates on the outer-shelf, suggesting that the outermost few kilometres of the shallow bank was free of grounded ice at the time of lateral-moraine formation. Similarly, transverse moraine ridges on the shallow bank beyond the southern lateral margin of the Norwegian Channel are present immediately landward of a large Type 2 ISLM (Fig. 5B).

It is possible that narrow enclaves of the outer-shelf beyond the lateral margins of palaeo-ice streams remained free of grounded ice during the LGM. Indeed, some reconstructions of the Eurasian Ice Sheet on the Norwegian and Svalbard margins depict small ice-free regions of the continental shelf beyond the outermost lateral margins of palaeo-ice streams (e.g. Ottesen et al., 2007; Rydningen et al., 2013). The absence of grounded ice from these outermost inter-ice stream regions may have been influenced by the topography of the shelf. In contrast to cross-shelf troughs, which generally have landward-dipping seafloor gradients, inter-ice stream regions of the shelf typically have relatively flat or seaward-dipping slopes (e.g. Fig. 10A), meaning that grounded ice may have had to advance into progressively deeper water.

It is possible that grounded slow-flowing ice extended to the shelf break in these inter-ice stream regions, prior to the formation of the ice-stream lateral marginal-moraines. The transverse moraines that have been identified beyond Malangsdjupet and the Norwegian Channel (Figs. 4A, B and 5B) (Rydningen et al., 2013) may therefore be recessional features. Uncertainty about the extent of former ice sheets in inter-ice stream locations is compounded by the grounding of deep-keeled icebergs in seafloor sediments, which often rework or remove geomorphological evidence of past glacial activity from shallow banks (e.g. Dowdeswell et al., 1993; Larter et al., 2012; Jakobsson et al., 2012a)

The ability to infer the presence or absence of grounded, slow-flowing ice adjacent to a former ice stream has implications for our understanding of palaeo-ice stream stability. Composite ice-stream lateral marginal-moraines can be identified from relatively coarse-resolution (grid-cell size 500 m) IBCAO bathymetry data (e.g. Fig. 10A) (Jakobsson et al., 2012b) and may be considered part of the broad-scale architecture of formerly-glaciated continental margins. The development of these large, prograding depocentres along the outermost lateral margins of marine-terminating ice streams may have provided a stabilising or buttressing effect upon the ice stream as it extended beyond of the confines of grounded slower-flowing ice on adjacent shallow banks.

6.3.2 Formation mechanisms

Based on the data in our inventory, we suggest that ice-stream lateral shear-moraines (Type 1) are unlikely to be formed solely by differential erosion rates between ice stream and inter-ice stream locations or by the recycling of sediment derived from erosion into the upstream lateral margins of ice streams (Stokes and Clark, 2002). We suggest that ice-stream lateral shear-moraines are formed subglacially through the preferential accumulation of sediment at the downstream lateral margins of ice streams (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008). Ice-stream lateral shear-moraines lack the internal dipping reflections and external geometry that is indicative of ice-marginal sediment progradation away from the former ice stream. Sediment that is deposited subglacially in the lateral shear zone may be prevented from prograding onto the adjacent shallow bank due to the presence of grounded slow-flowing ice, which restricts the accommodation space at the ice-stream lateral margin. The presence of grounded ice adjacent to the ice stream lateral margin may also restrict the degree of ice-stream flow divergence that can occur on the mid- to outer-shelf, limiting the amount of transverse sediment motion that takes place beneath the ice stream.

The preferential accumulation of sediment at ice-stream lateral margins may be linked to high rates of ablation due to strain heating and subglacial melting in the shear zone (Hindmarsh and Stokes, 2008). With melt rates of up to 5 m per year (van der Wal et al., 2012), ice-surface melting can provide several orders of magnitude more meltwater to the bed compared with subglacial sources (Dowdeswell et al., In Press). However, geothermal heating and strain heating can produce significant quantities of basal meltwater under certain conditions, including at hotspots of geothermal energy and when strain heating is focused at the lateral margins of fast-flowing ice streams (Dowdeswell et al., 2015, 2016). Numerical ice-sheet modelling suggests that frictional heating in the shear zone can produce basal melt rates of 90 to 180 mm per year, assuming that all the available heat was used for melting (Golledge et al., 2014; Dowdeswell et al., 2016).

Numerical modelling results also suggest that thicker ice beneath the downstream central axis of ice streams forces subglacial water towards the downstream lateral margins of ice streams along a water-pressure gradient, which is controlled by basal and ice-surface topography and subglacial water pressures (Dowdeswell et al., 2015). Lower water discharges have been modelled for the upstream lateral margins of ice streams, where thicker ice within adjacent inter-ice stream areas forces water towards regions of faster ice flow (Dowdeswell et al., 2015). This may explain why ice-stream lateral shear-moraines are not produced at the upstream lateral margins of ice streams.

The formation of ice-stream lateral marginal-moraines (Type 2) has received little attention previously. The size and internal-reflection configuration of these landforms (e.g. Figs. 8 – 11) suggest that that they are unlikely to be formed solely by the preferential deposition of sediment derived from the lateral margins of ice streams. The large ridges of sediment at the lateral margins of cross-shelf troughs in the Ross Sea, West Antarctica (nos. 68 and 69 in Table 2 and Fig. 2), which we interpret as ice-stream lateral marginal-moraines, were suggested by Shipp et al. (1999) to have been formed by the lateral accretion of sediment. This idea is supported by our observation of dipping internal reflections within similar landforms offshore of Greenland and the Canadian Arctic islands (e.g. Figs. 9 and 11), which indicate sediment progradation through the continued delivery of sediment from an active ice stream in the trough towards the adjacent bank.

All the ice-stream lateral marginal-moraines in our inventory are present in areas of former ice-stream flow divergence on the outer-shelf (e.g. Figs. 4, 5, 9 and 11). It is possible that the process of ice-flow divergence encourages the transfer of sediment beneath ice streams towards their outer-shelf lateral margins. We suggest that ice-stream lateral marginal-moraines are somewhat similar to GZWs in their mode of formation. Whereas GZWs are formed by the ice-flow parallel delivery of sediment to the grounding-zone, lateral marginal-moraines may be produced when sediment is delivered to the ice-stream lateral margin at an oblique angle to the ice-flow direction. One difficulty with this explanation is that we do not generally observe streamlined glacial lineations at an oblique angle to ice-stream lateral marginal-moraines. It is possible that the sediment-transfer direction is not as strongly coupled to the ice-flow direction as has been assumed previously (e.g. Hindmarsh and Stokes, 2008). Alternatively, the glacial lineations preserved on the seafloor may not reveal the direction of ice flow at the time of lateral-moraine formation.

7. SUMMARY AND CONCLUSIONS

We have presented an inventory of ISLMs that is compiled from available terrestrial and marine datasets, alongside independent analysis of seismic-reflection and bathymetric data from high-latitude margins (Tables 1 and 2). The locations of 70 ISLMs are shown, together with a synthesis of their dimensions, geometry and acoustic character (Tables 1 and 2, Fig. 2). ISLMs may be formed preferentially in the marine environment due to the availability of unconsolidated sediment on mid- and outer-shelves.

Two different types of ISLMs are identified from the geological record, differentiated by their dimensions, geometry and acoustic character. These characteristics are summarised in a schematic model in Figure 11. Type 1 ISLMs maintain a relatively constant width, thickness and cross-sectional shape along their length, and often occur as discontinuous segments (e.g. Figs. 3 and 4C). They are less than 3.5 km wide and less than 60 m thick (Fig. 8B and C).

Type 1 ISLMs are relatively symmetrical or have steeper ice-stream proximal sides in cross-section. Type 1 ISLMs are interpreted as ice-stream *lateral shear-moraines* that form subglacially in the shear zone between ice streams and slow-flowing ice (e.g. Dyke and Morris, 1988; Dyke et al., 1992; Stokes and Clark, 2002). Order of magnitude calculations suggest that these landforms have volumes of between 0.002 and 6 km^3 (Table 3), which is similar to the volumes of groups of MSGLs and recessional moraine ridges (Fig. 12). Ice-stream lateral shear-moraines probably take longer to form than MSGLs, which have been interpreted to be formed over a timescale of decades (King et al., 2009).

In contrast, Type 2 ISLMs, which are only identified in the marine environment, exhibit a seaward increase in width and thickness (Figs. 4, 5 and 12). Their distal slopes also become steeper in a seaward direction (Fig. 5). At up to 50 km wide and 300 m thick, Type 2 ISLMs are generally wider and thicker than Type 1 ISLMs (Fig. 8). Seismic-reflection data reveal that Type 2 ISLMs are characterised by internal reflections that dip away from the trough (e.g. Figs. 9B, D, E and 11), indicating sediment progradation and lateral moraine growth through the continued delivery of sediment from an active ice stream in the trough. The identification of multiple downlap surfaces (Figs. 9 and 11) suggests that some Type 2 ISLMs are composite features that built up over a number of successive ice-stream advances. Type 2 ISLMs are interpreted as ice-stream *lateral marginal-moraines* that were formed at the outer-shelf lateral boundary between marine-terminating ice streams and terrain that was free of grounded ice at the time of lateral-moraine formation. Ice-stream lateral marginal-moraines typically possess volumes of between 0.5 and 10 km^3; however, several larger landforms may have volumes greater than 1000 km^3. The volumes of ice-stream lateral marginal-moraines are therefore of the same order of magnitude as GZWs, and generally at least two orders of magnitude greater than the volumes of ice-stream lateral shear-moraines (Fig. 12).

Ice-stream lateral shear-moraines (Type 1) are interpreted to be formed subglacially by the preferential accumulation of sediment at the downstream lateral margins of ice streams. Sediment accumulation in these regions may be linked to high rates of meltwater production due to strain heating in the shear zone between fast and slower-flowing ice. In contrast, we suggest that ice-stream lateral marginal-moraines (Type 2) are produced by the oblique transfer of sediment beneath ice streams towards their lateral margins, which is encouraged by ice-flow divergence on the outermost continental shelf. Ice-stream lateral marginal-moraines may have provided a stabilising or buttressing effect upon full-glacial marine-terminating ice streams as they extended beyond of the confines of grounded slower-flowing ice on adjacent shallow banks.

Our identification of a number of previously unrecognised ISLMs on the continental shelves of Greenland and Norway (Table 2) suggests that marine ISLMs may be more widespread and/or better preserved than has been recognised previously. It is important to differentiate between ice-stream lateral shear-moraines and lateral marginal-moraines in the geological record in order to avoid any implicit assumptions about their mechanism of formation or the glaciological and marine conditions that existed beyond the lateral ice-stream margin at the time of lateral-moraine formation.

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FIGURE CAPTIONS

Table 1. The dimensions and characteristics of terrestrial ice-stream lateral moraines, as determined from available accounts utilizing aerial and satellite imagery.

Table 2. The dimensions and characteristics of marine ice-stream lateral moraines, as determined from available accounts of bathymetric and acoustic data, and independent analysis of 2-D seismic-reflection data, provided by TGS, and Olex and MAREANO bathymetry data. The locations of the ice-stream lateral moraines are shown in Fig. 2.

Table 3. The dimensions of Type 1 and Type 2 ice-stream lateral moraines, as calculated from the data shown in Figure 8 and Tables 1 and 2.

Fig. 1. (a) Typical ice-stream landform assemblage produced by fast, ice-stream flow on a continental margin (adapted from Ottesen and Dowdeswell, 2009). (b) Plan-view of streamlined glacial lineations in Borebukta, Spitsbergen (78°24´N, 14°14´E) (adapted from Dowdeswell and Ottesen, 2016a). (c) Plan-view of transverse retreat moraines in inner Van Keulenfjorden, Spitsbergen (78°29´N, 16°2´E) (adapted from Dowdeswell and Ottesen, 2016a). (d) Plan-view of a grounding-zone wedge (GZW) in Vestfjorden, North Norway (67°30´N, 13°E) (adapted from Dowdeswell and Ottesen, 2016b). (e) Oblique view of the Bear Island trough-mouth fan and superimposed glacigenic debris-flows on the Barents Sea margin (73°N, 13°E) (adapted from Laberg and Dowdeswell, 2016). (f) Plan-view of an ice stream lateral shear-moraine in Rebbenesdjupet, North Norway (70°N, 17°30´E) (from MAREANO seafloor bathymetry). White arrows show former ice-flow directions.

Fig. 2. Maps showing the approximate locations of ice-stream lateral moraines, as determined from available studies of satellite, bathymetric and acoustic data, overlying IBCAO bathymetry (Jakobsson et al., 2012b) in the Arctic and IBCSO bathymetry (Arndt et al., 2013) for Antarctica. Red circles are approximate locations of ISLMs. Black lines delimit cross-shelf troughs from which ISLMs have been reported. The numbers refer to the corresponding ISLM and references in Tables 1 and 2. (a) ISLM locations in the Canadian Arctic. AG = Amundsen Gulf; MS = M'Clure Strait; PWI = Prince of Wales Island; SI = Stefansson Island. (b) ISLMs in the western Canadian Prairies. (c) ISLM locations off Greenland. (d) ISLM locations off Svalbard and north Norway. (e) ISLM locations off

Norway. (f) ISLM locations off south Norway and the UK. (g) ISLM location off South Georgia (SG). (h) ISLM locations off Antarctica.

Fig. 3. Multibeam bathymetric images of Type 1 ISLMs on the Norwegian shelf (from MAREANO seafloor bathymetry). Dashed white lines are streamlined glacial lineations. Dotted white lines are GZWs. (a) Rebbenesdjupet cross-shelf trough, north Norway. (b) Close-up of the lateral moraine at the southern lateral margin of Rebbenesdjupet (no. 51 in Table 2 and Fig. 2). (c) Håkjerringdjupet cross-shelf trough, north Norway. (d) Close-up of lateral moraines at the southern outer-shelf lateral margin of Håkjerringdjupet (nos. 49 and 50 in Table 2 and Fig. 2). (e) Close-up of lateral moraine at the southern mid-shelf lateral margin of Håkjerringdjupet (no. 48 in Table 2 and Fig. 2). (f) Andfjorden cross-shelf trough, north Norway. (g) Close-up of three lateral moraines at the northern lateral margin of Andfjorden (nos. 57 to 59 in Table 2 and Fig. 2).

Fig. 4. Multibeam bathymetric images of ISLMs. Dashed white lines are streamlined glacial lineations. Dotted white lines are GZWs. (a) Malangsdjupet cross-shelf trough (from MAREANO seafloor bathymetry). Inset: Seismic-reflection profile adapted from Rydningen et al. (2013). (b) Close-up of two Type 2 ISLMs at the northern lateral margin of Malangsdjupet (nos. 52 and 53 in Table 2 and Fig. 2). (c) Close-up of two Type 1 ISLMs at the southern lateral margin of Malangsdjupet (nos. 55 and 56 in Table 2 and Fig. 2). (d) Olex seafloor bathymetry and cross-profile of a Type 2 ISLM at the northern lateral margin of Holsteinsborg cross-shelf trough, south Greenland (no. 30 in Table 2 and Fig. 2). (e) Olex seafloor bathymetry and cross-profile of a Type 2 ISLM at the northern lateral margin of Bellsund, western Svalbard margin (no. 43 in Table 2 and Fig. 2).

Fig. 5. Multibeam bathymetric images and cross-profiles of Type 2 ISLMs (from Olex seafloor bathymetry), showing how Type 2 ISLMs undergo a seaward change in dimensions and geometry. Dashed white lines are streamlined glacial lineations. (a) Two Type 2 ISLMs at the eastern lateral margin of Godthaab cross-shelf trough, south Greenland (nos. 32 and 33 in Table 2 and Fig. 2). (b) Type 2 ISLM at the western lateral margin of the Norwegian Channel cross-shelf trough, south Norway (no. 65 in Table 2 and Fig. 2). (c) Type 2 ISLMs at the northern and southern lateral margins of Trænadjupet cross-shelf trough and beyond Trænabanken, Norway (nos. 62 to 64 in Table 2 and Fig. 2).

Fig. 6. Histograms of ISLM dimensions, coloured by margin, as determined from available accounts of ISLMs (Tables 1 and 2). (a) ISLM lengths. (b) ISLM maximum widths. (c) ISLM maximum thicknesses.

Fig. 7. ISLM dimensions, coloured by margin, as determined from available accounts of ISLMs (Tables 1 and 2). (a) Scatter-plot with linear regression of the relationship between ISLM maximum width and cross-shelf trough width, coloured by margin. (b) Scatter-plot and linear regression of the relationship between ISLM width and thickness. (c) Scatter-plot and linear regression of the relationship between ISLM length and width. Green and red circles show ISLMs that have been interpreted as Type 1 and Type 2, respectively. The black regression line is for Type 1 and Type 2 landforms considered together (d) Scatter-plot of the relationship between ISLM length and thickness. ISLM no. 27 off Northeast Greenland is excluded from (b) and (c) due to its extreme dimensions.

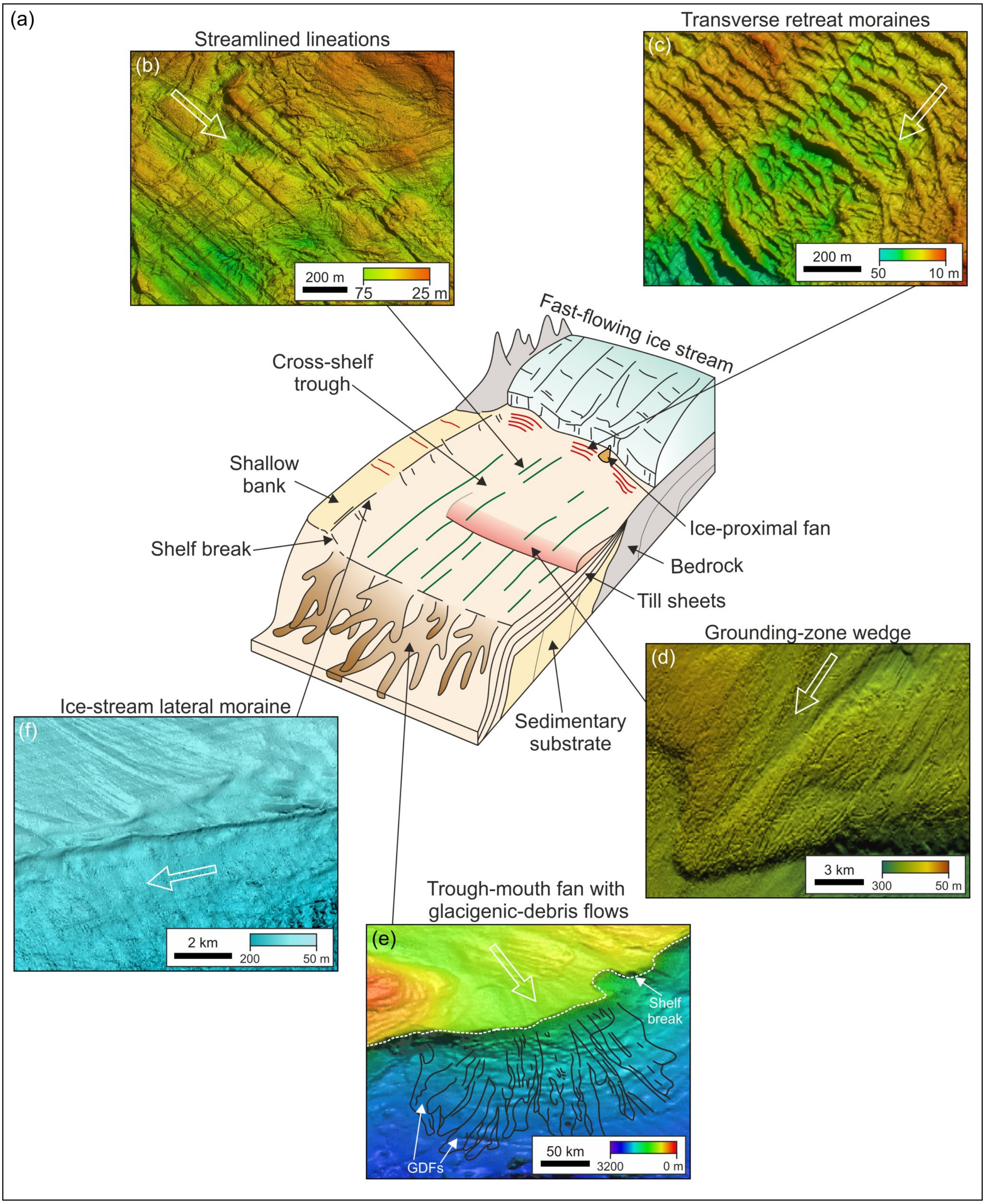
Fig. 8. Histograms of ISLM dimensions coloured by ISLM type. (a) ISLM length. (b) ISLM width. (c) ISLM thickness.

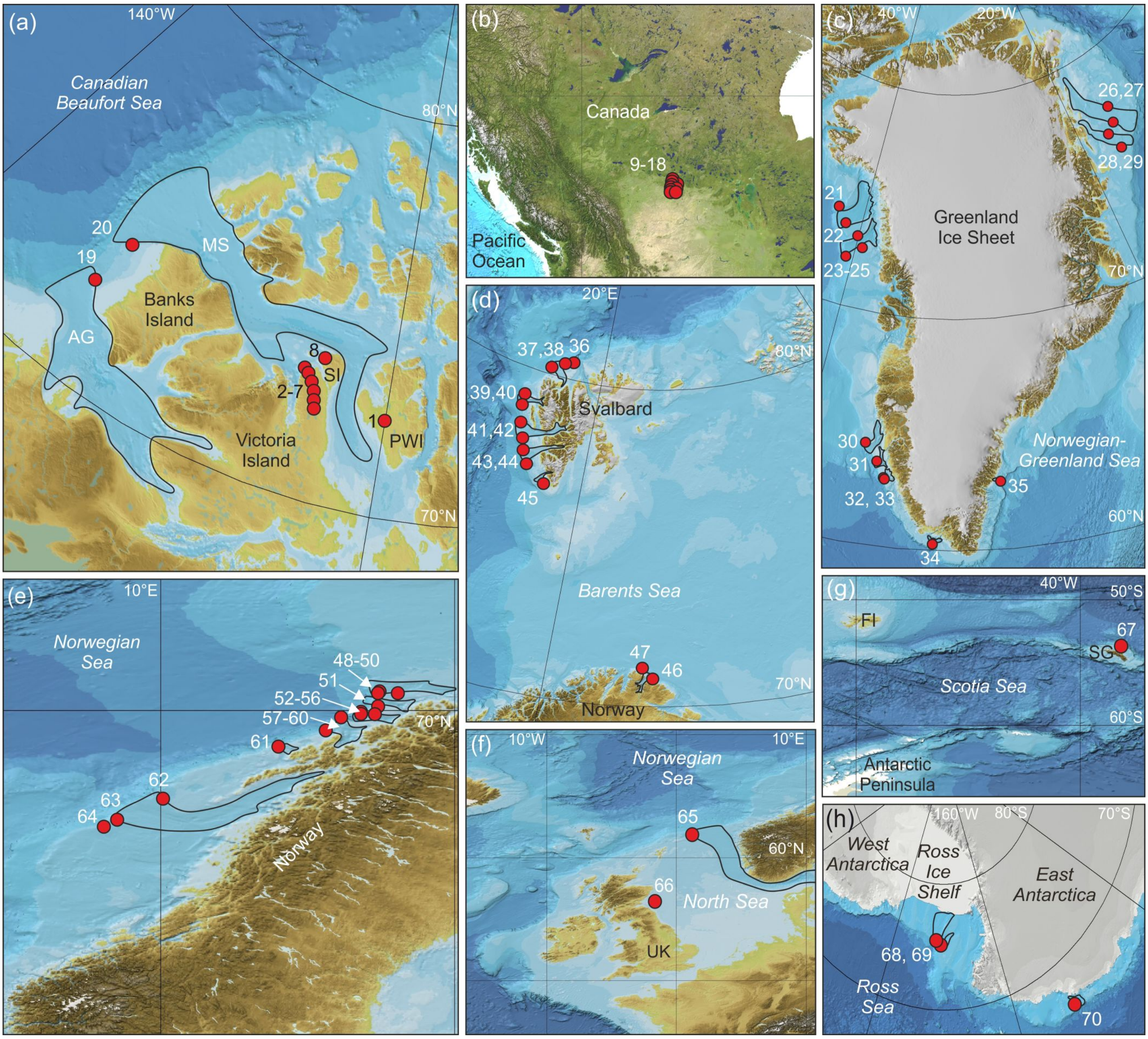
Fig. 9. Examples of ISLMs on seismic-reflection profiles from the Canadian Beaufort Sea margin (adapted from Batchelor et al., 2014). (a) Location of profiles shown in (b) and (c). (b) Type 2 ISLM at the southern lateral margin of M'Clure Strait (no. 20 in Table 2 and Fig. 2). VE = 37. (c) Type 2 ISLM at the northern lateral margin of Amundsen Gulf (no. 19 in Table 2 and Fig. 2). VE = 26.

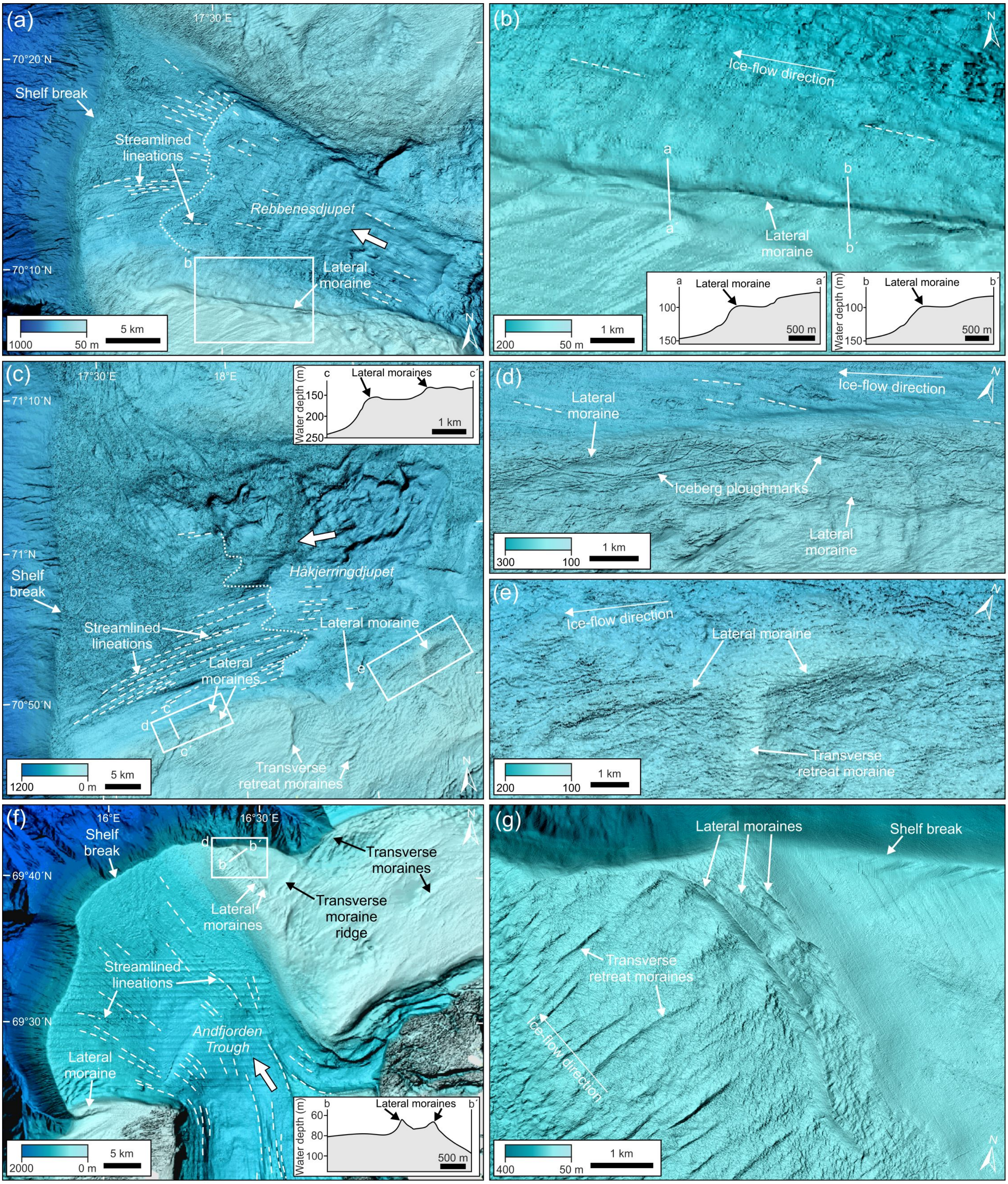
Fig. 10. Examples of ISLMs on seismic-reflection profiles from the Northwest Greenland margin. (a) Location of profiles shown in (b) to (e). Black arrows are lateral moraines. (b) Type 2 ISLM at the northern lateral margin of Melville Trough (no. 21 in Table 2 and Fig. 2). VE = 6. (c) Type 2 ISLM at the southern lateral margin of Melville Trough (no. 22 in Table 2 and Fig. 2). VE = 8. (d) ISLM with complex geometry at the southern lateral margin of Upernavik Trough (no. 24 in Table 2 and Fig. 2). VE = 9. (e) Type 2 ISLM at the southern lateral margin of Upernavik Trough (no. 25 in Table 2 and Fig. 2). VE = 8. Seismic-reflection data in (b) to (e) are provided by TGS. A velocity of 1500 m/s was used to calculate the approximate vertical exaggeration (VE).

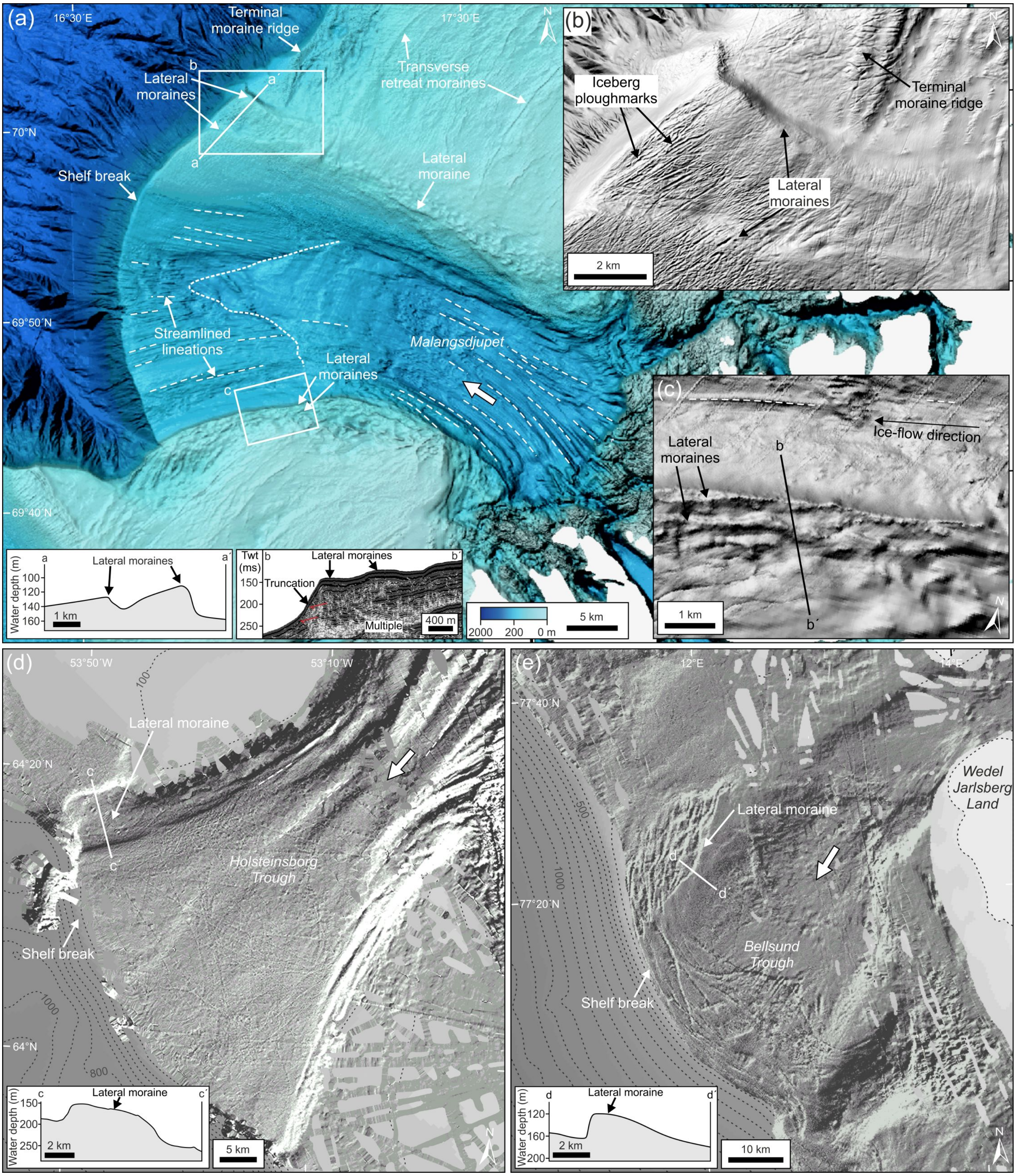
Fig. 11. Schematic model of landforms preserved at the lateral margin of marine-terminating palaeo-ice streams. GZW = grounding-zone wedge. Type 2 ISLMs are suggested to only be produced by marine-terminating ice streams. Type 1 ISLMs are formed by marine and terrestrial ice streams.

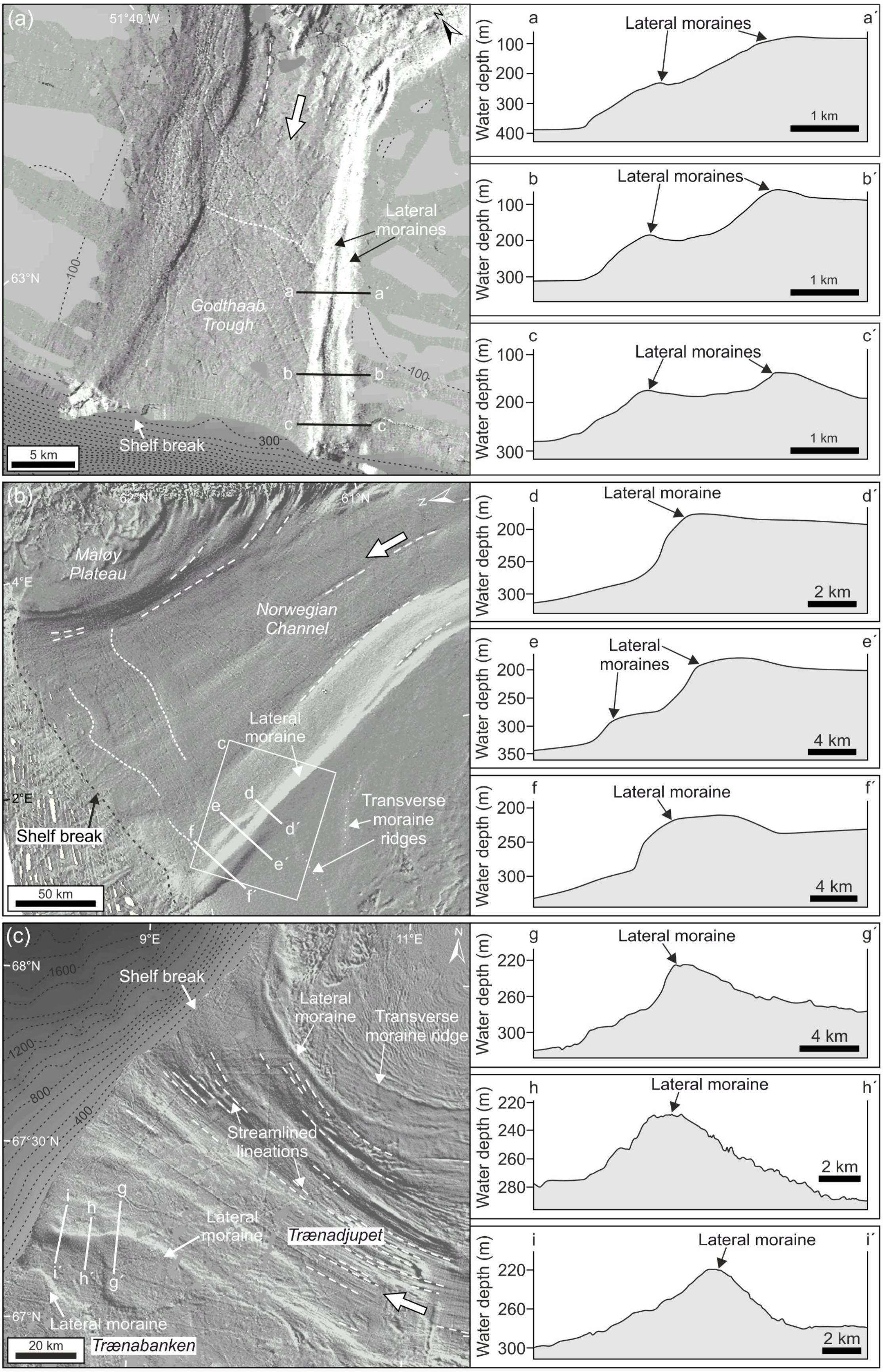
Fig. 12. Diagram showing the range of estimated volumes for a variety of glacial depositional landforms. Note the logarithmic scale. GZWs = grounding-zone wedges; MSGLs = mega-scale glacial lineations. White arrow is former ice-flow direction.

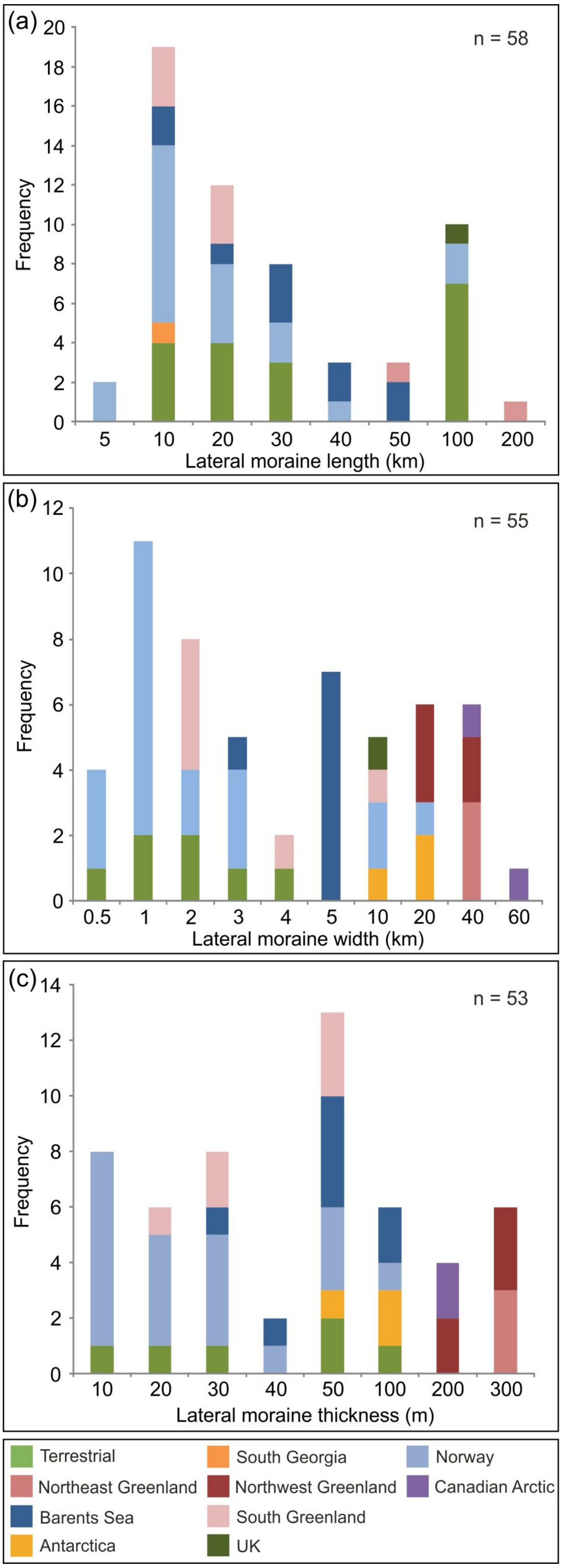

(a)
Streamlined lineations
(b)
200 m
75
25 m
Transverse retreat moraines
(c)
200 m
50
10 m
Fast-flowing ice stream
Cross-shelf trough
Shallow bank
Shelf break
Ice-proximal fan
Bedrock
Till sheets
Sedimentary substrate
Grounding-zone wedge
(d)
3 km
300
50 m
Ice-stream lateral moraine
(f)
2 km
200
50 m
Trough-mouth fan with glacigenic-debris flows
(e)
Shelf break
GDFs
50 km
3200
0 m

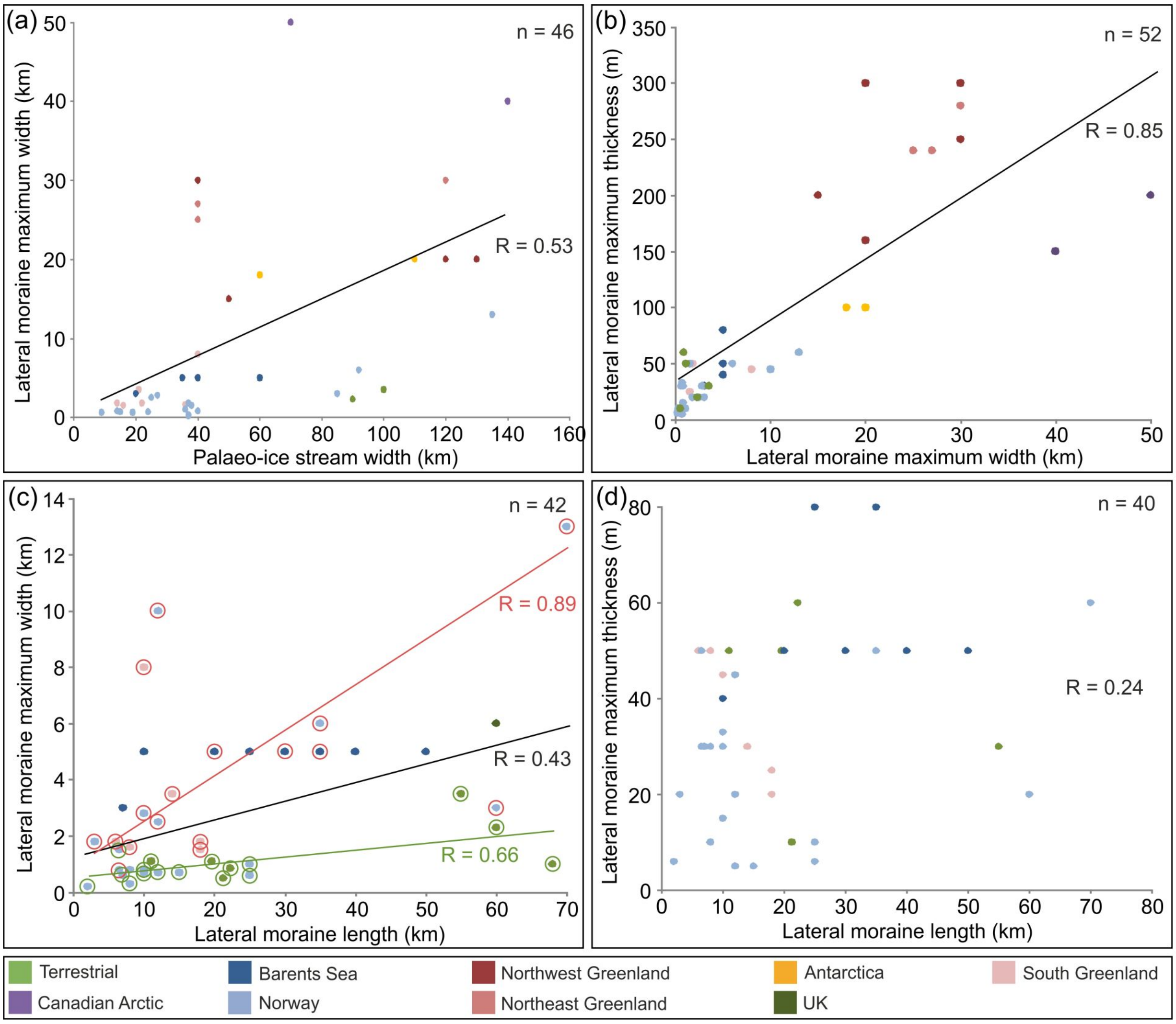

(a)
140°W
Canadian Beaufort Sea
80°N
20
MS
19
Banks Island
AG
8
SI
2-7
1
PWI
Victoria Island
70°N
(b)
Canada
9-18
Pacific Ocean
(c)
40°W
20°W
26,27
28,29
21
22
23-25
Greenland Ice Sheet
70°N
30
31
32, 33
Norwegian-Greenland Sea
35
60°N
34
(d)
20°E
80°N
37,38
36
39,40
Svalbard
41,42
43,44
45
Barents Sea
47
46
70°N
Norway
(e)
10°E
Norwegian Sea
48-50
51
52-56
57-60
70°N
61
62
63
64
Norway
(f)
10°W
10°E
Norwegian Sea
65
60°N
66
North Sea
UK
(g)
40°W
50°S
FI
67
SG
Scotia Sea
60°S
Antarctic Peninsula
(h)
160°W
80°S
70°S
West Antarctica
Ross Ice Shelf
East Antarctica
68, 69
Ross Sea
70

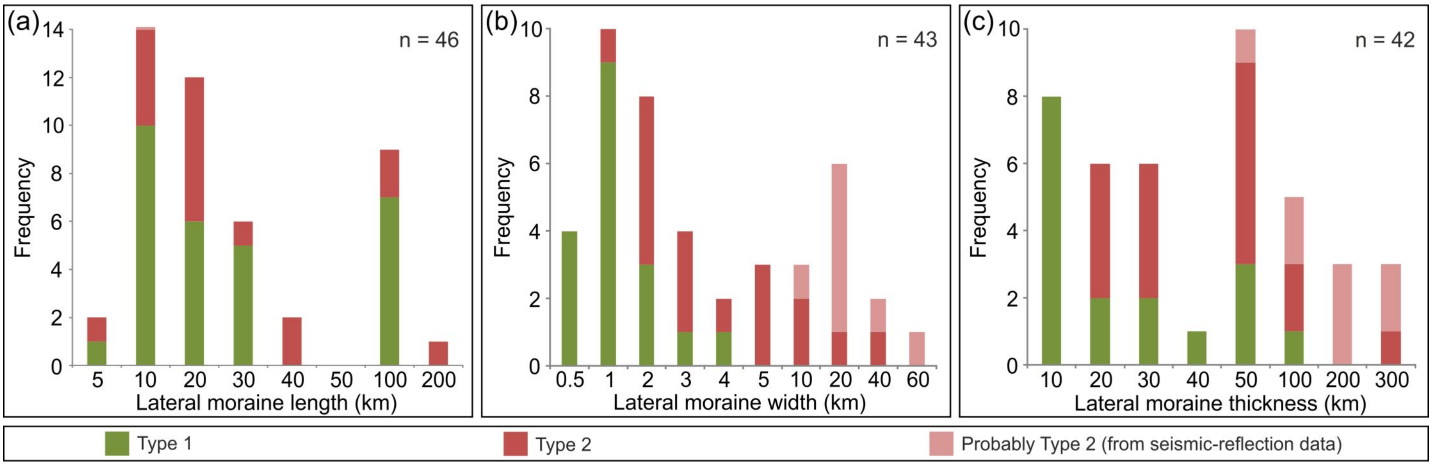

(a)
17°30´E
70°20´N
Shelf break
Streamlined lineations
Rebbenesdjupet
70°10´N
b
Lateral moraine
1000
50 m
5 km
N
(b)
N
Ice-flow direction
a
a´
b
b´
Lateral moraine
200
50 m
1 km
a
Lateral moraine
a´
100
150
500 m
b
Lateral moraine
b´
Water depth (m)
100
150
500 m
(c)
17°30´E
18°E
71°10´N
c
Lateral moraines
c´
Water depth (m)
150
200
250
1 km
71°N
Shelf break
Håkjerringdjupet
Streamlined lineations
Lateral moraines
Lateral moraine
e
d
c
c´
70°50´N
Transverse retreat moraines
1200
0 m
5 km
N
(d)
Ice-flow direction
N
Lateral moraine
Iceberg ploughmarks
Lateral moraine
300
100
1 km
(e)
N
Ice-flow direction
Lateral moraine
Transverse retreat moraine
200
100
1 km
(f)
16°E
16°30´E
N
Shelf break
d
b´
b
Transverse moraines
69°40´N
Lateral moraines
Transverse moraine ridge
Streamlined lineations
69°30´N
Andfjorden Trough
Lateral moraine
b
Lateral moraines
b´
Water depth (m)
60
80
100
500 m
2000
0 m
5 km
(g)
Lateral moraines
Shelf break
Transverse retreat moraines
Ice-flow direction
400
50 m
1 km
N

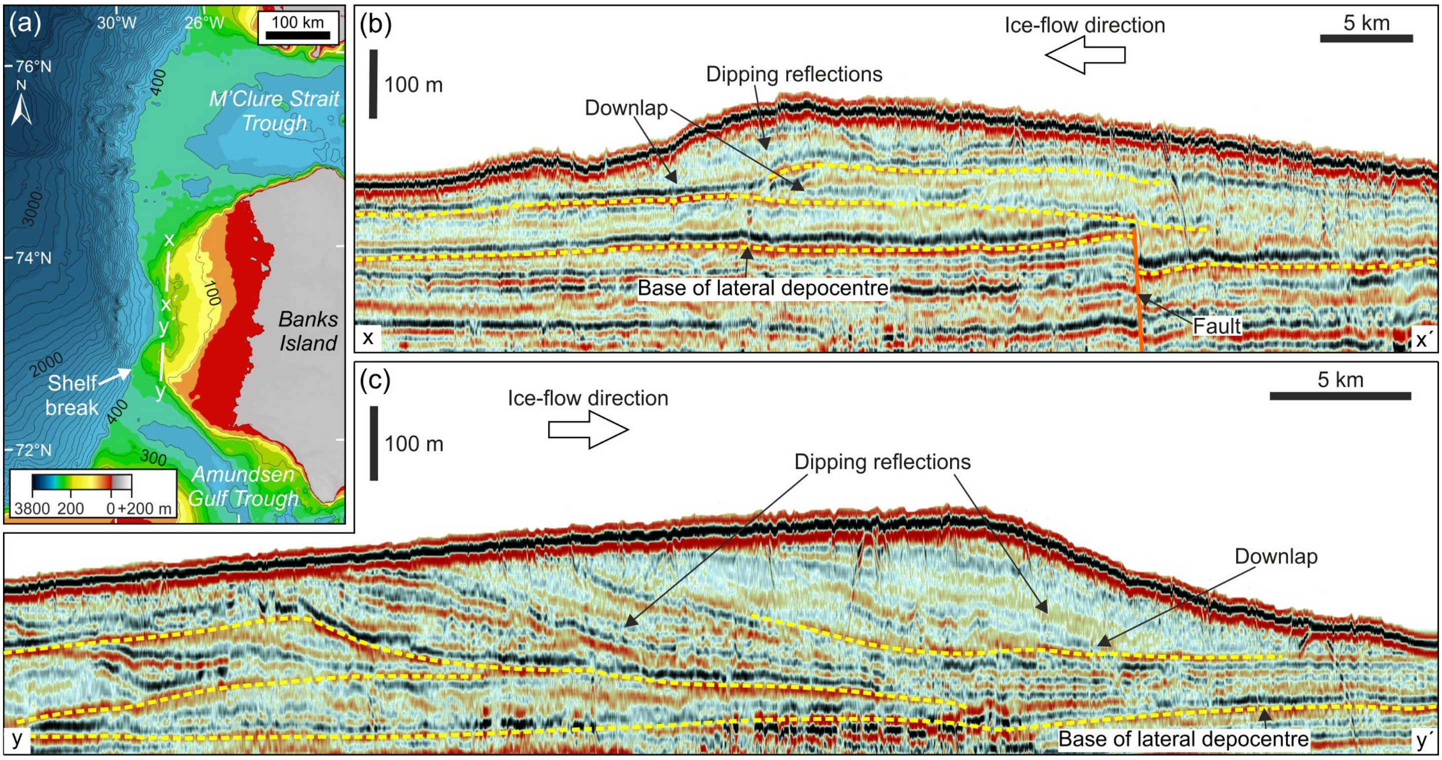

(a)
16°30´E
17°30´E
Terminal moraine ridge
Transverse retreat moraines
b
a´
Lateral moraines
a
70°N
Shelf break
Lateral moraine
Streamlined lineations
69°50´N
Malangsdjupet
c
Lateral moraines
69°40´N
a
Lateral moraines
a´
Water depth (m)
100
120
140
160
1 km
Twt (ms)
b
Lateral moraines
b´
150
200
250
Truncation
Multiple
400 m
2000
200
0 m
5 km
(b)
Iceberg ploughmarks
Terminal moraine ridge
Lateral moraines
2 km
(c)
Ice-flow direction
Lateral moraines
b
b´
1 km
N
(d)
53°50´W
53°10´W
100
Lateral moraine
64°20´N
c
c´
Holsteinsborg Trough
Shelf break
1000
800
64°N
c
Lateral moraine
c´
Water depth (m)
150
200
250
2 km
5 km
(e)
12°E
14°E
77°40´N
Wedel Jarlsberg Land
500
Lateral moraine
d
d´
1000
77°20´N
Bellsund Trough
Shelf break
d
Lateral moraine
d´
Water depth (m)
120
160
200
2 km
10 km

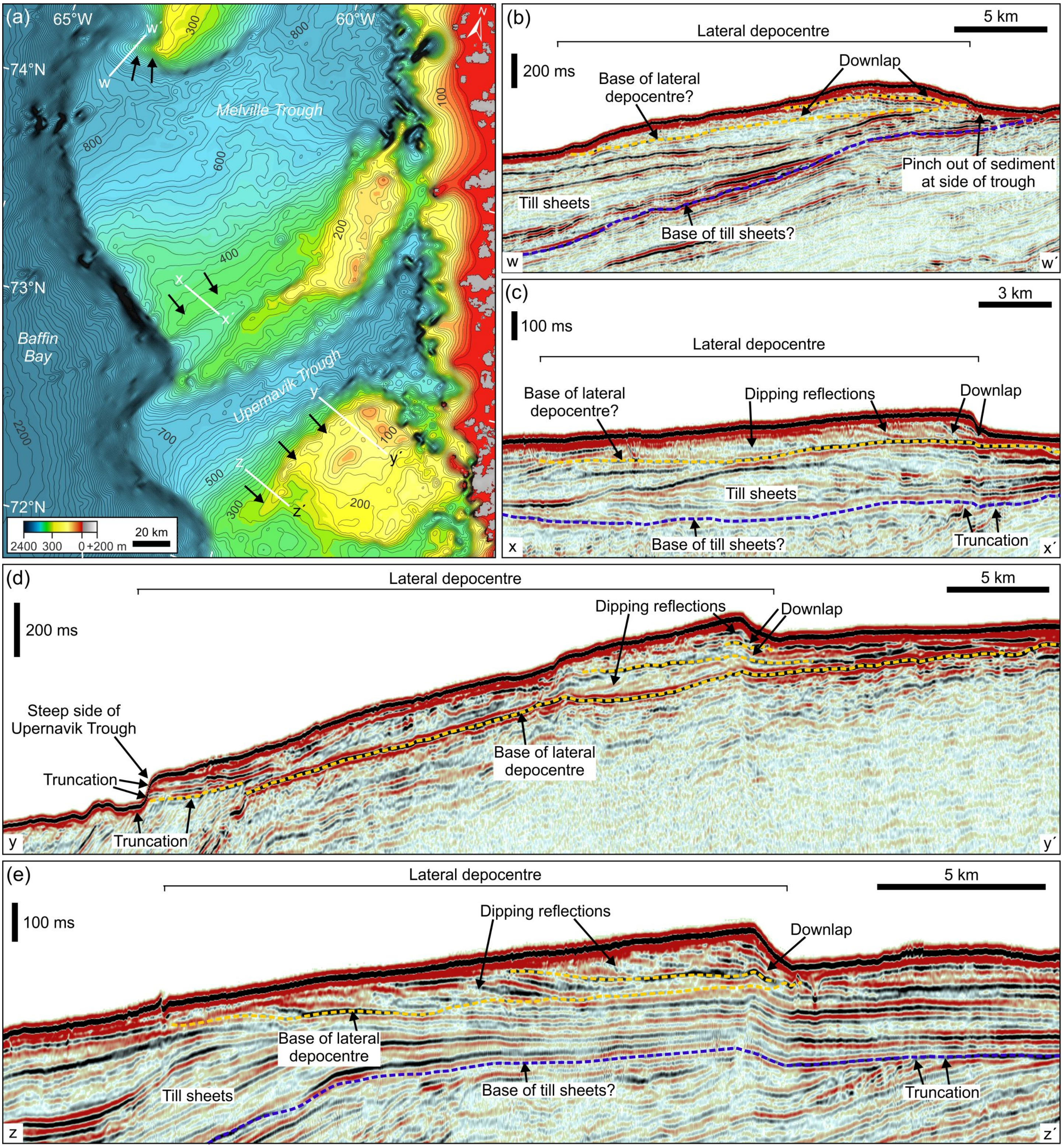

(a)
51°40´W
63°N
100
Lateral moraines
a
a´
Godthaab Trough
b
b´
c
c´
100
300
Shelf break
5 km
a
a´
Lateral moraines
Water depth (m)
100
200
300
400
1 km
b
b´
Lateral moraines
100
200
300
1 km
c
c´
Lateral moraines
100
200
300
1 km
(b)
62°N
61°N
4°E
Måløy Plateau
Norwegian Channel
Lateral moraine
c
d
d´
e
e´
f
f´
2°E
Shelf break
Transverse moraine ridges
50 km
d
d´
Lateral moraine
200
250
300
2 km
e
e´
Lateral moraines
200
250
300
350
4 km
f
f´
Lateral moraine
200
250
300
4 km
(c)
9°E
11°E
68°N
1600
1200
800
400
67°30´N
67°N
Shelf break
Lateral moraine
Transverse moraine ridge
Streamlined lineations
Lateral moraine
Trænadjupet
i
h
g
i´
h´
g´
Lateral moraine
Trænabanken
20 km
g
g´
Lateral moraine
220
260
300
4 km
h
h´
Lateral moraine
220
240
260
280
2 km
i
i´
Lateral moraine
220
260
300
2 km

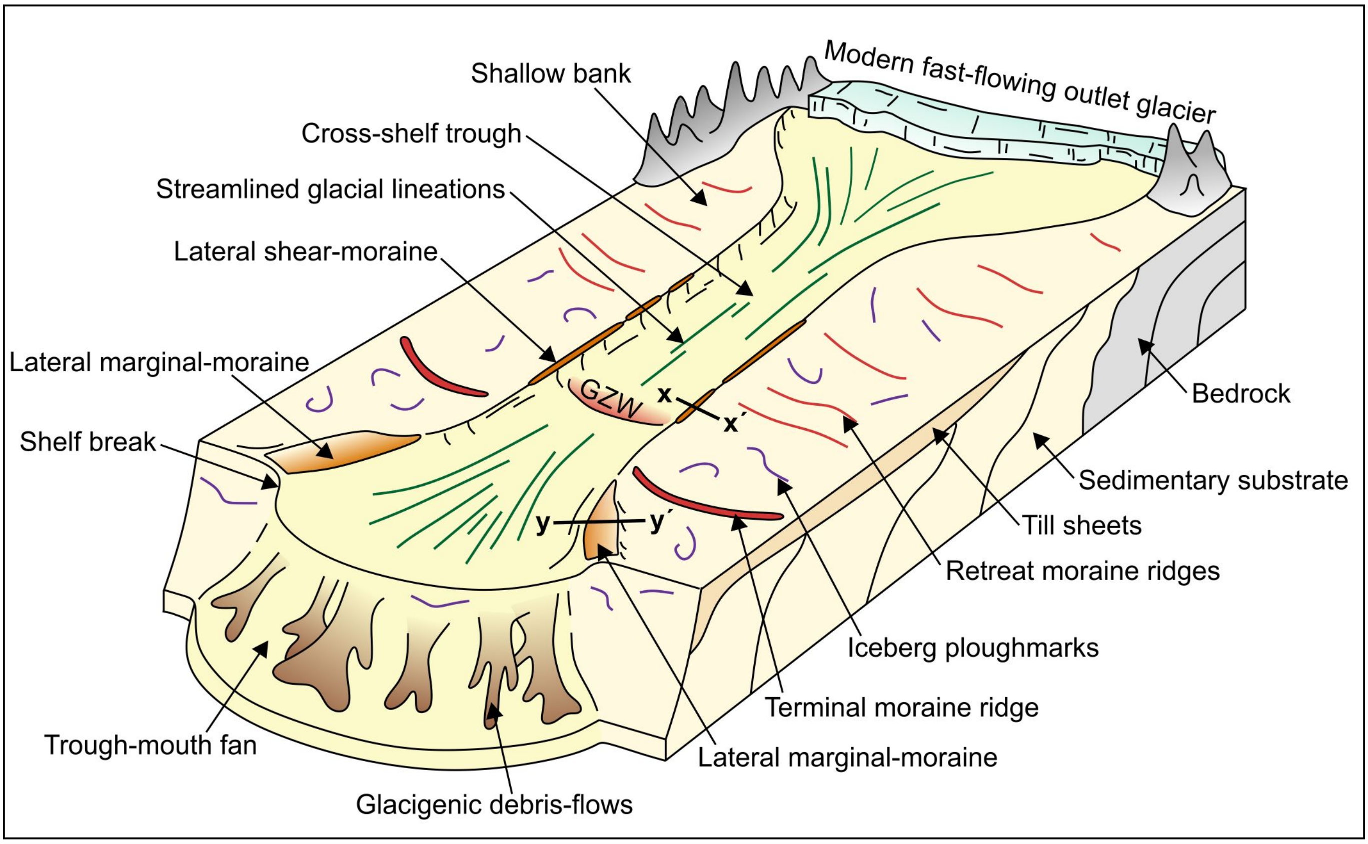

(a)
n = 58
Frequency
0
2
4
6
8
10
12
14
16
18
20
5
10
20
30
40
50
100
200
Lateral moraine length (km)
(b)
n = 55
Frequency
0
2
4
6
8
10
12
0.5
1
2
3
4
5
10
20
40
60
Lateral moraine width (km)
(c)
n = 53
Frequency
0
2
4
6
8
10
12
14
10
20
30
40
50
100
200
300
Lateral moraine thickness (m)
Terrestrial
South Georgia
Norway
Northeast Greenland
Northwest Greenland
Canadian Arctic
Barents Sea
South Greenland
Antarctica
UK

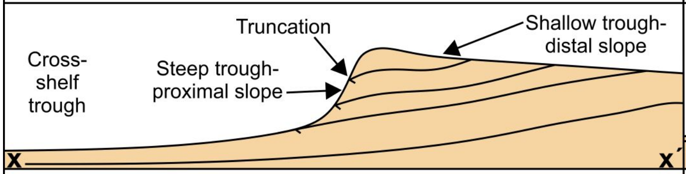
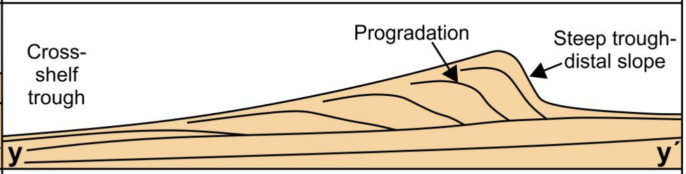

(a)
n = 46
R = 0.53
Lateral moraine maximum width (km)
Palaeo-ice stream width (km)
0
10
20
30
40
50
0
20
40
60
80
100
120
140
160
(b)
n = 52
R = 0.85
Lateral moraine maximum thickness (m)
Lateral moraine maximum width (km)
0
50
100
150
200
250
300
350
0
10
20
30
40
50
(c)
n = 42
R = 0.89
R = 0.43
R = 0.66
Lateral moraine maximum width (km)
Lateral moraine length (km)
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
(d)
n = 40
R = 0.24
Lateral moraine maximum thickness (m)
Lateral moraine length (km)
0
20
40
60
80
0
10
20
30
40
50
60
70
80
Terrestrial
Barents Sea
Northwest Greenland
Antarctica
South Greenland
Canadian Arctic
Norway
Northeast Greenland
UK

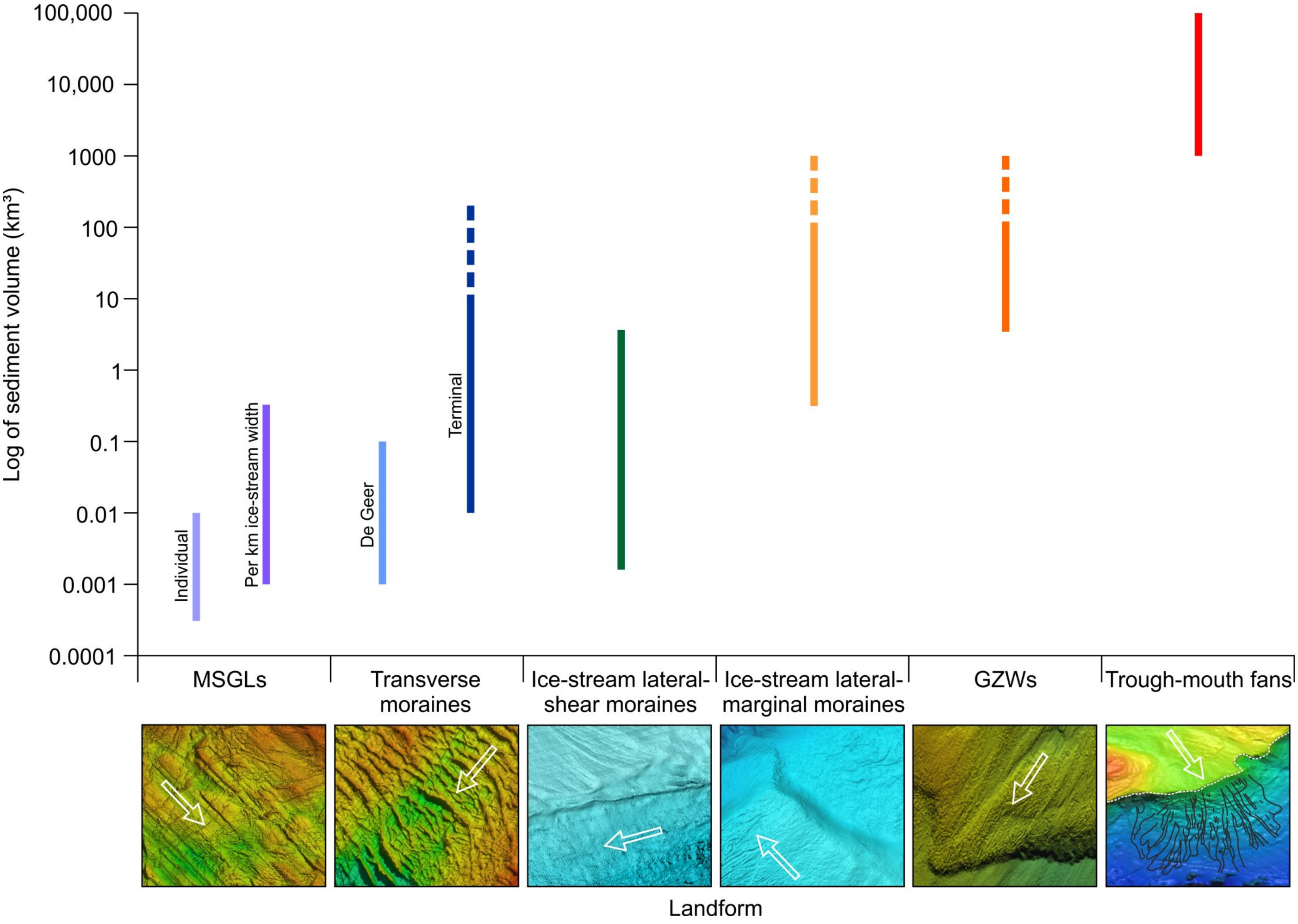

(a)
n = 46
Frequency
0
2
4
6
8
10
12
14
5
10
20
30
40
50
100
200
Lateral moraine length (km)
(b)
n = 43
Frequency
0
2
4
6
8
10
0.5
1
2
3
4
5
10
20
40
60
Lateral moraine width (km)
(c)
n = 42
Frequency
0
2
4
6
8
10
10
20
30
40
50
100
200
300
Lateral moraine thickness (km)
Type 1
Type 2
Probably Type 2 (from seismic-reflection data)


(a)
30°W
26°W
100 km
76°N
N
400
M'Clure Strait Trough
3000
74°N
x
x´
y
y´
100
Banks Island
2000
Shelf break
400
72°N
300
Amundsen Gulf Trough
3800 200 0 +200 m
(b)
Ice-flow direction
5 km
100 m
Dipping reflections
Downlap
Base of lateral depocentre
Fault
x
x´
(c)
Ice-flow direction
5 km
100 m
Dipping reflections
Downlap
Base of lateral depocentre
y
y´


(a)
65°W
60°W
w´
w
74°N
73°N
72°N
Melville Trough
Upernavik Trough
Baffin Bay
300
800
100
600
400
200
700
500
2200
x
x´
y
y´
z
z´
2400 300 0 +200 m
20 km
(b)
Lateral depocentre
5 km
200 ms
Base of lateral depocentre?
Downlap
Pinch out of sediment at side of trough
Till sheets
Base of till sheets?
w
w´
(c)
3 km
100 ms
Lateral depocentre
Base of lateral depocentre?
Dipping reflections
Downlap
Till sheets
Base of till sheets?
Truncation
x
x´
(d)
Lateral depocentre
5 km
200 ms
Dipping reflections
Downlap
Steep side of Upernavik Trough
Truncation
Base of lateral depocentre
Truncation
y
y´
(e)
Lateral depocentre
5 km
100 ms
Dipping reflections
Downlap
Base of lateral depocentre
Till sheets
Base of till sheets?
Truncation
z
z´



Type 1: Ice-stream lateral shear-moraine	Type 2: Ice-stream lateral marginal-moraine
	
Location: Terrestrial and marine, mid- to outer-shelf	**Location:** Marine, outer-shelf to shelf break
Dimensions: 0.5-3.5 km wide, <60 m thick High length: width ratios Do not exhibit changes in dimensions in a seaward direction	**Dimensions:** 1.5-50 km wide, <300 m thick Low length: width ratios Become higher and wider in a seaward direction
Plan-view geometry: Linear to curvilinear	**Plan-view geometry:** Linear to curvilinear
Cross-section: Symmetrical or asymmetrical with steeper trough-proximal slope	**Cross-section:** Distal slope becomes steeper in seaward direction, often asymmetrical with steeper trough-distal slope
Acoustic character: Internal reflections dip towards the trough and are truncated at the trough-proximal side	**Acoustic character:** Prograding internal reflections dip away from trough
Interpretation: Formed subglacially in the shear zone between fast-flowing ice streams and slower-flowing ice. Formed in terrestrial and marine environments	**Interpretation:** Formed at the boundary between ice streams and terrain that is free of grounded ice. Probably submarine landforms


Log of sediment volume (km³)
100,000
10,000
1000
100
10
1
0.1
0.01
0.001
0.0001
Individual
Per km ice-stream width
De Geer
Terminal
MSGLs
Transverse moraines
Ice-stream lateral-shear moraines
Ice-stream lateral-marginal moraines
GZWs
Trough-mouth fans
Landform