The seismic architecture and geometry of grounding-zone wedges formed at the marine margins of past ice sheets

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ABSTRACT

Grounding-zone wedges form where halts of decades to centuries during ice-sheet retreat across polar shelves allow sediment buildup at the grounding zone through delivery of deforming basal debris from fast-flowing ice streams. Thirty grounding-zone wedges were identified on two-dimensional seismic-reflection profiles across the continental shelves of NE and NW Greenland. Grounding-zone wedges close to the seafloor are probably of late Weichselian age; others are on paleoshelves, buried beneath thick prograding glacial sediments. Several Greenland-shelf grounding-zone wedges occur on topographic highs that provide stabilizing pinning points in relatively shallow water. Grounding-zone wedges are asymmetric in the ice-flow direction with steeper ice-distal sides. Typical grounding-zone wedges are approximately 5–20 km long and 50–100 m thick, with a lateral width of several tens of kilometers. Forty grounding-zone wedges from the Greenland, Norwegian, and Antarctica margins show considerable variability about these values. Grounding-zone wedge dimensions are controlled by sediment flux, the duration of halts in ice retreat, subice cavity shape, and ice-stream width. Low-angle ice-shelf cavity roofs immediately beyond the grounding-zone probably restrict vertical accommodation space, preventing formation of high-amplitude ridges. Grounding-zone wedges are mainly transparent or chaotic on seismic profiles, probably resulting from delivery of diamictic debris. Offlapping reflectors represent progradation into an ice-roofed cavity. Reflector truncations of grounding-zone wedge bases indicate erosion during initiation. Channels are present within some grounding-zone wedges; meltwater flow is under high pressure, and V-shaped incisions suggest high-energy flow. Channels are not ubiquitous within Greenland grounding-zone wedges and may represent nonsteady meltwater release, perhaps through lake drainage. Where ice-sheet mass loss is dominated by meltwater runoff, grounding-zone wedges probably contain more sorted sediment than those from Greenland. Simple models of grounding-zone wedge architecture are presented. Grounding-zone wedges indicate episodic rather than catastrophic ice-sheet retreat and are a mechanism for ice-shelf stabilization because wedge growth counteracts collapse induced by ice-sheet thinning and sea-level rise.

INTRODUCTION

Today, the Antarctic and Greenland ice sheets have extensive marine margins, and many smaller ice caps and glaciers also terminate in fjord waters. The ice-ocean interface around the modern Antarctic Ice Sheet, for example, is over 30,000 km long (Drewry et al., 1982). During full-glacial periods, when large Quaternary ice sheets extended to the edge of high-latitude continental shelves in many areas, the length of the ice-ocean interface was even greater (e.g., Anderson, 1999; Elverhøi et al., 1998; Svendsen et al., 2004). The grounding line, or more properly the grounding zone, of glaciers and ice sheets is where their marine margins cease to be in contact with the seafloor (Fig. 1A). This zone can be either where ice loses contact with the bed but extends often tens to hundreds of kilometers further offshore, fed by flow from the ice-sheet interior (an ice-shelf margin), or at the ice-sheet terminus (a tidewater glacier margin).

The grounding zone of ice sheets is important both glaciologically and geologically. Mass is lost through iceberg production and melting, with the latter taking place at both ice cliffs marking the marine ice-sheet margin (e.g., Josberger and Martin, 1981; Rignot et al., 2010) and at the base if the ice sheet becomes ungrounded as an ice shelf and is exposed to ocean water (e.g., Jenkins and Doake, 1991; Rignot et al., 2001; Rignot and Jacobs, 2002). During the environmental oscillations of the Quaternary and, presumably, earlier glaciations, the location of the grounding zone of ice sheets has responded sensitively to climatically induced changes in ice thickness and sea level (e.g., Alley et al., 2007). In addition, where fast-flowing ice streams and outlet glaciers are present, the grounding-zone is a major focus for sediment delivery as a line-source at the marine margins of ice sheets. Diamictic subglacial debris is transferred across the grounding zone from deforming sedimentary beds (e.g., Alley et al., 1986, 1989; Anandakrishnan et al., 2007). Subglacial meltwater channels, where present at the ice margin, may also provide point sources of sorted sediments to the grounding zone (e.g., Powell, 1990; Mugford and Dowdeswell, 2011). Additional sediment is released by the melting of basal debris-rich ice immediately beyond the grounding zone (Alley et al., 2007).

The sedimentary depocenters, or grounding-zone wedges (Powell and Domack, 1995; Anderson, 1999), formed by these processes of rapid sediment delivery to the ice-ocean interface, are up to 10^3 km^2 in area and 10^3 km^3 in volume (e.g., Shipp et al., 1999; McMullen et al., 2006; Ottesen et al., 2005a, 2005b). Grounding-zone wedges are important indicators of past ice-sheet dynamics in the geological record and allow former positions of the grounding zone to be identified and sometimes dated, with implications for the style and rate of ice-sheet flow and retreat (e.g., Shipp et al., 1999, 2002; Anderson et al., 2002; Mosola and Anderson, 2006; Dowdeswell et al., 2008a; Ó Cofaigh et al., 2008). This information, in turn, provides independent geological evidence against which the predictions of time-dependent numerical ice-sheet models can be tested (Dowdeswell et al., 2008a). The plan-view morphology and seismic cross sections for a typical grounding-zone wedge are shown in Figures 1B–1D. Some grounding-zone wedges for which high-resolution swath-bathymetric images are available show streamlined sedimentary lineations on their upper surfaces

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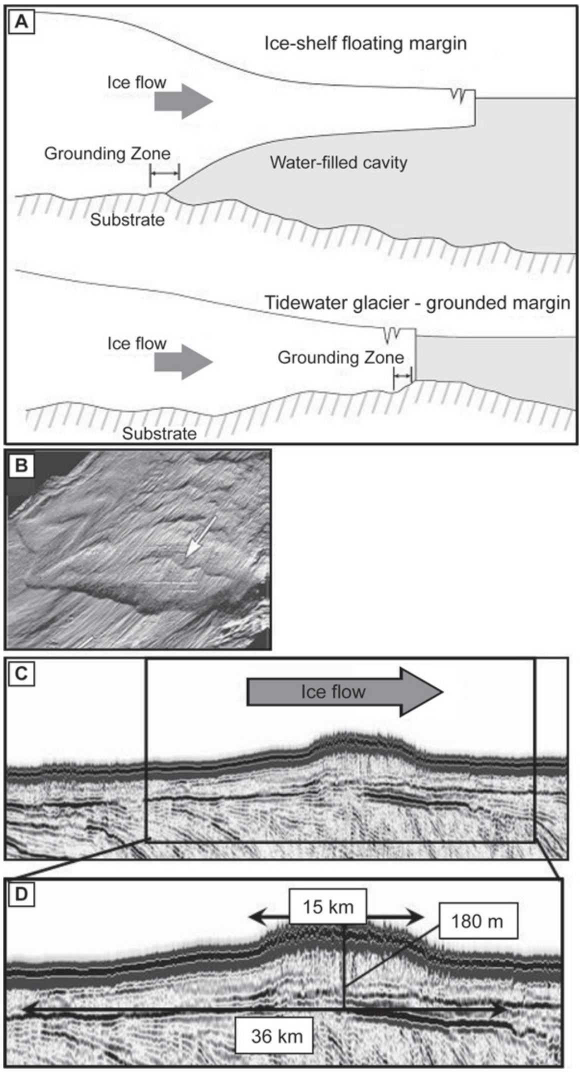

Figure 1. (A) Schematic diagram of the position of grounding-zone wedges (GZW) at the margins of ice sheets with floating and grounded termini. Note the vertical exaggeration. (B) Swath-bathymetric image showing plan view of grounding-zone wedges in Vestfjorden, Norway (67°20′N, 12°45′E; modified from Dowdeswell et al., 2008a). Note the glacially streamlined landforms overridden by the grounding-zone wedge and also superimposed upon its surface. Arrow shows direction of past ice flow. The image is 60 km across. (C) Grounding-zone wedge above dipping reflectors on the prograding continental shelf of NE Greenland. NW-SE seismic-reflection profile down the approximate center of Norske Trough. (D) Enlargement of the grounding-zone wedges in C. Seismic lines are courtesy of TGS-NOPEC.

(Fig. 1B). This demonstrates, importantly, that grounding-zone wedges are formed beneath actively fast-flowing ice, which streamlines their surface in the direction of ice flow and provides a relatively high rate of sediment delivery to the ice margin.

In this paper, we describe and interpret the seismic stratigraphy and morphology of ice-sheet grounding-zone wedges. Our examples come from the continental shelves of Greenland (Fig. 2), although it is not our aim in this paper to use grounding-zone wedges to reconstruct the history of the Greenland Ice Sheet; instead, we focus on the architecture of the grounding-zone wedges themselves, which has been little studied previously using seismic records. We examine the internal structure and dimensions of over 30 grounding-zone wedges offshore of NW and NE Greenland and then compare them with the geometry of examples from other Arctic and Antarctic shelves. We then present simple schematic models of grounding-zone wedge seismic architecture and inferred sedimentary structure. The implications of the geometry and distribution of grounding-zone wedges for past ice-sheet form and flow are also discussed.

GLACIOLOGICAL AND QUATERNARY GEOLOGICAL BACKGROUND

Ice Flotation and the Grounding Zone

The grounding zone of ice sheets is the point at which ice starts to float and becomes separated or "ungrounded" from the sediment or rock bed beneath it (Fig. 1A). The term "grounding zone" is preferred to grounding line, since there is likely to be a time-dependent component to the precise location at which flotation begins that is controlled by short-term variations in forcing factors such as tides (Bindschadler et al., 2003; Gudmundsson, 2007; Murray et al., 2007). In addition, given that the seafloor of continental shelves is often of very low gradient, only small changes in buoyancy are needed to shift the position of grounding by tens or even hundreds of meters. We refer to the grounding zone of ice sheets throughout the remainder of this paper.

The grounding zone is, of course, three dimensional and extends along the ice margin until truncated by the bedrock walls of fjords or the mountain ranges that mark the margins of major marine embayments. Thus, the grounding zone can extend hundreds of kilometers laterally in the case of the huge ice shelves of modern Antarctica (e.g., Drewry et al., 1982), and up to several tens of kilometers for the major outlet glaciers of the Greenland Ice Sheet (e.g., Rignot and Kanagaratnam, 2006) and the open-marine margins of large Arctic ice caps (e.g., Dowdeswell, 1986; Dowdeswell et al., 2008b). It is, however, the grounding zone in front of fast-flowing ice streams and outlet glaciers with which we are principally concerned, because this is where ice and sediment fluxes are greatest. Huge trough-mouth fans containing 10^4 km^3 of sediment grow at the prograding edges of high-latitude continental shelves during full-glacial conditions (e.g., Vorren and Laberg, 1997; Vorren et al., 1998; Dowdeswell et al., 1997, 2008c) and grounding-zone wedges of 10^2 to 10^3 km^3 form on the shelf itself during temporary halts in deglacial ice retreat (e.g., Anderson, 1999; Dowdeswell et al., 2008a).

The water depth (h_w) needed for flotation of ice of a given thickness (h_i) is linked to the density difference between water (ρ_w) and ice (ρ_i), where $h_w = (\rho_i/\rho_w)h_i$. Thus, ice margins (ρ_i of 910 kg m^{-3}) will float in normal-salinity ocean water (ρ_w of 1035 kg m^{-3}) when water depth exceeds ~88% of ice thickness. Where floating ice shelves (sometimes known as "ice tongues" if constrained by fjord walls or protruding as linear features beyond the coastline) are present, the grounding zone can lie beneath hundreds to a thousand or more meters of ice with a water-filled cavity of several hundred meters depth extending tens to several hundreds of kilometers to the calving front of a floating ice shelf (e.g., Jenkins and Doake, 1991; Mayer et al., 2000). Where floating ice is not present beyond the ice margin, the grounding zone is at the base of the terminal ice cliffs of tidewater glaciers. Thus, grounding zones exist at ice-sheet margins irrespective of whether a floating ice shelf is present beyond this point or not; however, we consider it likely that grounding-zone wedges are normally formed in an ice-shelf setting where a water-filled and low-gradient ice-roofed cavity is present, which restricts vertical accommodation space and, hence, the formation of morainal banks or ridges (Fig. 1A).

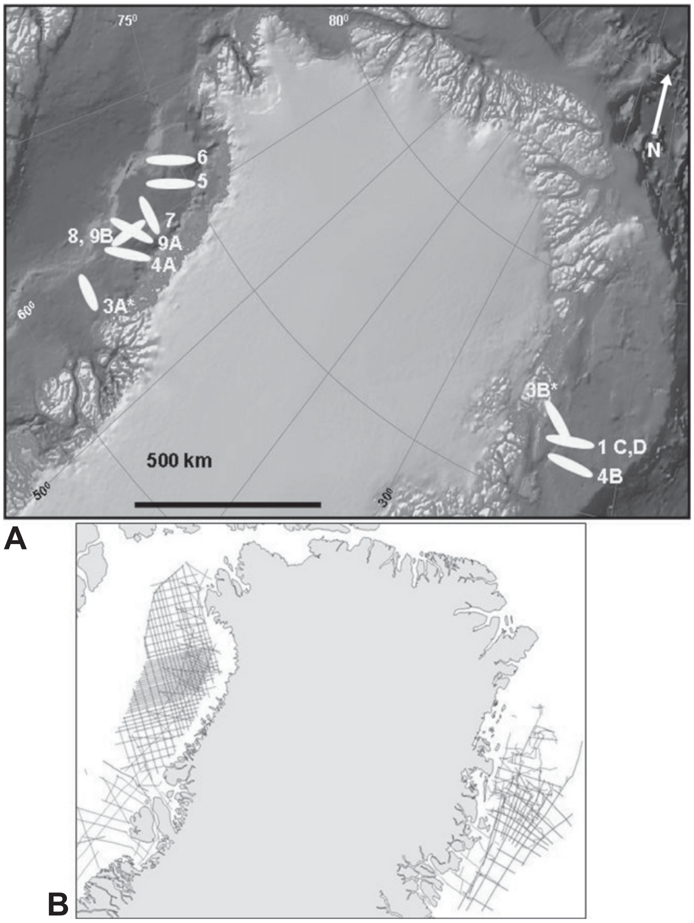

Figure 2. Location maps. (A) The bathymetry of the continental shelves offshore of Greenland with approximate locations of seismic sections shown. Numbers refer to figure numbers in this paper. Those sections marked * represent deeply buried grounding-zone wedges. (B) Seismic database for the Greenland shelf (courtesy of TGS-NOPEC, the Geological Survey of Denmark and Greenland [GEUS], and Nunaoil).

Very few direct observations of grounding zones have been made, given their inaccessibility, although cameras mounted on remotely operated vehicles have imaged the grounding zones of a few Arctic tidewater glaciers (Dowdeswell and Powell, 1996) and that beneath the floating tongue of Mackay Glacier in Antarctica (Powell et al., 1996). Soft, diamictic till has been observed emerging from the grounding zone of Mackay Glacier, together with sediment redeposition as low-angle debris flows and rubble ridges.

Shelf Geometry and Late Quaternary History of Greenland

The continental shelves of NW and NE Greenland are typically several hundred kilometers wide, with water depths usually of several hundred meters (Fig. 2A). The shelf break is generally between water depths of 400 and 600 m. Modern shelf geometry is represented by relatively deep cross-shelf troughs separated by shallower banks (Fig. 2A). The troughs were probably incised during late Pliocene–Pleistocene ice advances. This is a morphology typical of many high-latitude shelves that have been inundated by advancing ice sheets, often on multiple occasions during the past few million years (e.g., Anderson, 1999; Ottesen et al., 2005a).

Grounding-zone wedges are present at or close to the surface of the present continental shelves around Greenland, were deposited during stillstands in ice-sheet retreat from the Last Glacial Maximum (LGM) ~20,000 yr ago, and are buried beneath tens to more than 1000 m of prograding sediments produced by growth and decay of the former Greenland Ice Sheet (e.g., Nielsen et al., 2005; Berger and Jokat, 2008, 2009). The glacial interval is made up of multiple distinctive units associated with ice-sheet advance and retreat; sediments are notably less thick on parts of the Greenland inner shelf, however, where substantial uplift and erosion have taken place. A unified stratigraphy is difficult to establish for the marine sediments offshore of Greenland, and no attempt has been made to tie surfaces across troughs cut into shelf sediments in this study, which is focused on a specific set of landforms, grounding-zone wedges, rather than on regional mapping. The geology demonstrates the complexity of glacial surfaces; some horizons probably represent reworked material, whereas others represent preserved surfaces of varying age (e.g., Dowdeswell et al., 2007). The ages of the sequences mapped are also poorly constrained, and the chronology is not well established due to lack of seismic calibration points.

It should be noted that, until recently, it was thought that ice did not extend across the continental shelves of NW and NE Greenland during the Weichselian glaciations (Funder and Hansen, 1996), and no major glacier-produced trough-mouth fans were reported from these areas. Newly acquired swath-bathymetric data, imaging subglacially produced megascale glacial lineations and ice-contact transverse ridges, have demonstrated that ice did advance across the continental shelves west and east of Greenland at the LGM (e.g., Evans et al., 2002, 2009; Winkelmann et al., 2010; Dowdeswell et al., 2010). The presence of many grounding-zone wedges on the shelves of NE and NW Greenland, produced during stillstands in ice retreat, also confirms that ice extended across these shelves during several glacial cycles of the Quaternary. Similar submarine morphological evidence has been used to infer the presence of grounded ice on the often extensive continental shelves fringing the Eurasian Arctic and Antarctica during the late Quaternary (e.g., Ottesen et al., 2005a; Evans et al., 2005, 2006; Mosola and Anderson, 2006; Andreassen et al., 2008; Graham et al., 2010).

SEISMIC ARCHITECTURE OF GROUNDING-ZONE WEDGES ON GREENLAND SHELVES

Seismic-Reflection Data from the Greenland Shelves

Two-dimensional (2-D) seismic-reflection data are used in this study. They are derived from a large number of track lines across the extensive, up to 250-km-wide, continental shelves of NW and NE Greenland (Fig. 2). More than 40,000 km of seismic data were examined, but only a selection of seismic sections is shown to illustrate the key architectural elements observed in the grounding-zone wedges. The location of each grounding-zone wedge illustrated here is shown in Figure 2A, along with an indication of whether it is a surface or near-surface landform or buried within the Quaternary sediments. Due to restrictions on the use of industrial data, the exact locations and identification numbers of the seismic lines, and details of the acquisition parameters and streamer arrays, are not included.

Only the upper part of the seismic records, typically less than 1 s in two-way traveltime, was investigated. This is normally sufficient to cover the glacier-influenced Pliocene and Pleistocene parts of the sedimentary record offshore of Greenland. The quality of the seismic data is variable, although much is of very high resolution (Figs. 1C–1D and 3); a hard seabed or near-seabed reflector caused by glacial loading in the Pleistocene results in multiples on some of the seismic sections. In the absence of well control, the seismic data are phase-rotated to yield a positive-amplitude zero-phase wavelet at the seabed, and an increase in acoustic impedance therefore yields positive seismic amplitudes.

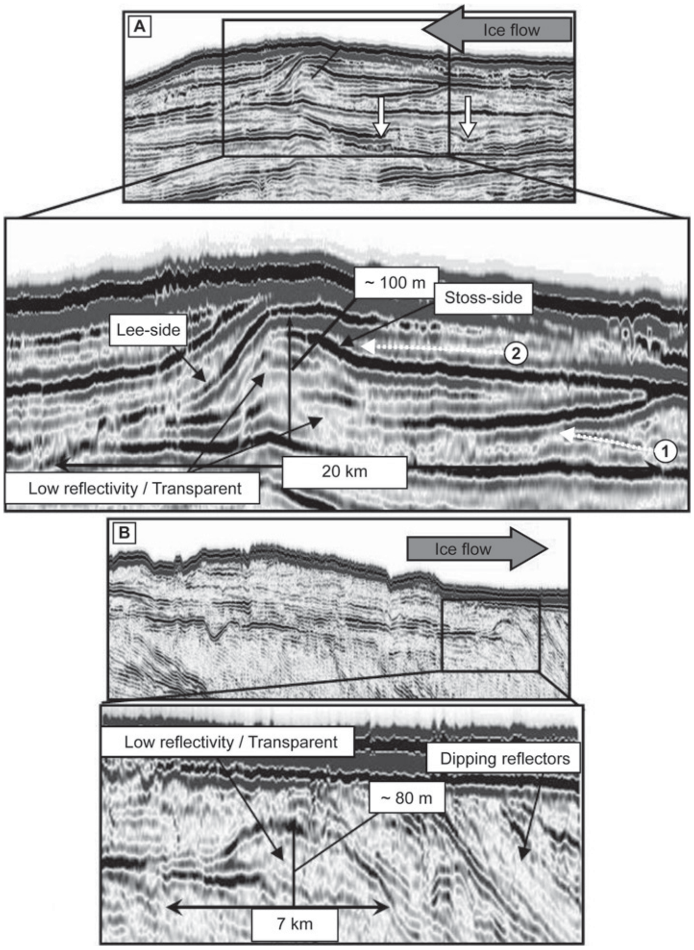

Figure 3. Seismic-reflection data showing examples of buried grounding-zone wedges on the Greenland shelf, with close-ups to show internal detail. (A) NW Greenland. Below the grounding-zone wedge, note arrows pointing to incisions probably related to an older glacial advance toward the reader, indicating switching in the ice-flow direction between glaciations. (B) NE Greenland. Note the dipping reflectors indicating shelf progradation since grounding-zone wedges deposition. Numbers (white, circled): 1—downlap, 2—onlap. Seismic lines are courtesy of TGS-NOPEC.

Geometry of Grounding-Zone Wedges

There is a lack of systematic investigations of the seismic architecture and dimensions of grounding-zone wedges on high-latitude continental shelves, although individual wedges have been illustrated and discussed in a number of studies of Arctic and Antarctic shelves (e.g., Anderson, 1999; Ottesen et al., 2005a; Mosola and Anderson, 2006; McMullen et al., 2006). Anderson (1999) described several grounding-zone wedges on Antarctic shelves that had a massive, layered, or chaotic seismic-reflection pattern and low-angle seaward-dipping foresets that downlapped onto glacial erosion surfaces.

We identified more than 30 major grounding-zone wedges from the examination of an extensive grid of seismic-reflection profiles on the NE and NW Greenland shelves (Fig. 2). Some wedges are found close to the present seafloor, and are likely to be of late Weichselian age (Figs. 1C–1D). Other wedges are located on paleoshelf surfaces, buried beneath tens to hundreds of meters of prograding and predominantly glacier-derived sediments within the glacial sequence deposited around Greenland over the past few million years (Fig. 3) (e.g., Larsen et al., 1994; Berger and Jokat, 2009).

Grounding-zone wedges are positive topographic features within the seismic stratigraphy (Fig. 3). When present at or close to the seafloor, they are identified as subdued ridges in seismic profiles and swath-bathymetric imagery (Figs. 1B–1D). Given that major grounding-zone wedges are typically tens of meters thick and tens of kilometers long in the direction of past ice flow, it should be emphasized that, whereas they may appear as relatively pronounced topographic features on vertically exaggerated seismic lines, they are usually two to three orders of magnitude longer than they are thick. This is why they can sometimes have only limited topographic expression in swath-bathymetric data sets, even when formed in unburied late Weichselian sediments.

The Greenland grounding-zone wedges have a characteristically asymmetric shape in the direction of ice flow or dip direction, with relatively steeper mean ice-distal or lee-side slopes of between 1.8° and ~4° (Figs. 3A and 4). The ice-proximal or stoss side tends to be less steep at between 0.3° and 0.7°. Grounding-zone wedges reported from other Arctic and Antarctic shelves have a similar asymmetric shape in long profile, with a relatively steeper ice-distal face and a more attenuated ice-proximal slope (e.g., Anderson, 1999; Heroy and Anderson, 2005; Mosola and Anderson, 2006). This asymmetry is an important characteristic in the recognition of grounding-zone wedges in seismic records.

Finally, it is observed that several grounding-zone wedges on the Greenland shelf, buried or surficial, occur above topographic highs or crests in the underlying regional bathymetry

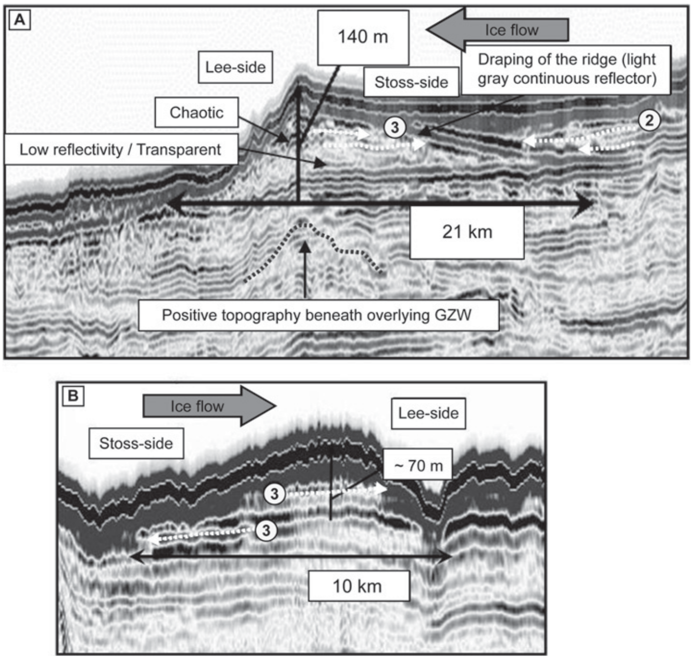

Figure 4. The asymmetric shape of grounding-zone wedges in the direction of past ice flow, with a characteristically steeper ice-distal side, illustrated with seismic-reflection records from the Greenland shelf. (A) NW Greenland shelf. Note that this grounding-zone wedge (GZW) is located on top of a bathymetric high (black arrow and black stippled line). (B) NE Greenland shelf. Numbers (white, circled): 2—onlap, 3—truncation. Seismic lines are courtesy of TGS-NOPEC.

(Figs. 4A and 5). This is expected, given that the rate of mass loss from the marine margins of ice sheets through iceberg production and the migration of the grounding zone of ice shelves is linked closely to buoyancy considerations (e.g., Benn et al., 2007; Schoof, 2007). Topographic highs, therefore, provide pinning points in relatively shallower water, where ice sheets often undergo stillstands during longer-term retreat. This phenomenon has been observed in many fjord and shelf settings during recent ice retreat (e.g., Venteris, 1999) and has also been reconstructed in numerical ice-sheet models predicting the time-dependent behavior of former ice sheets (e.g., Dowdeswell and Siegert, 1999).

Internal Structure of Grounding-Zone Wedges: Description

The internal structure of grounding-zone wedges has seldom been commented on previously (e.g., Anderson, 1999; Mosola and Anderson, 2006), in part due to the limited resolution of earlier seismic data. The high resolution of seismic records from the Greenland margin allows detailed description of the acoustic pattern in the wedges, including architectural elements and internal reflectors, which have been resolved before only rarely. From the complexity of reflector types observed (Fig. 6), it is clear that sedimentation within many grounding-zone wedges is probably a result of several phases of depositional activity, and that some grounding-zone wedges may be composites developed in several stages. This implies that the process regime which produces grounding-zone wedges is not uniform throughout the period of deposition, which may be decades to centuries (Alley et al., 2007; Anandakrishnan et al., 2007; Dowdeswell et al., 2008a).

We identified several seismic patterns and reflectors from seismic-reflection profiles through over 30 grounding-zone wedges on the Greenland margin; they include the following features. (1) The interiors of many grounding-zone wedges typically show a low-reflectivity, transparent, and sometimes chaotic acoustic pattern (Figs. 3, 4, 5, and 6). (2) Offlapping and apparently prograding reflectors are present that appear to build ice distally or seaward (labeled 4 in Fig. 7). Terminations are sometimes visible in association with these progradations (labeled 3 in Fig. 7). (3) Some grounding-zone wedge internal reflectors show downlap (labeled 3 in Figs. 6 and 8) and onlap terminations (labeled 2 in Figs. 6 and 8). Onlap is also seen immediately above some grounding-zone wedges, onto their ice-proximal or stoss sides (labeled 2 in Figs. 3A and 4A). (4) Truncation of seismic reflectors is sometimes present within the wedges (labeled 3 in Figs. 6B and 8). Truncation is also observed immediately below (labeled 3 in Fig. 3B) or on the lee side of some grounding-zone wedges (labeled 3 in Fig. 7). (5) A continuous reflector is usually present at the upper surface of grounding-zone wedges (Fig. 8). (6) There is evidence of channel-like features with onlapping reflectors and V-shaped incisions within some grounding-zone wedges; importantly, the positions of these features do not necessarily

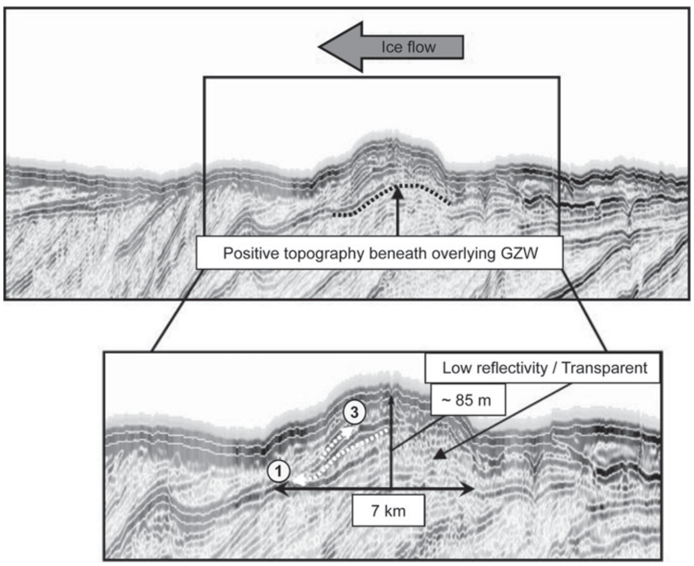

Figure 5. Grounding-zone wedge (GZW) formed above a bathymetric high (black arrow and black stippled line) on the NW Greenland continental shelf. Numbers (white, circled): 1—downlap, 3—truncation. Seismic line is courtesy of TGS-NOPEC.

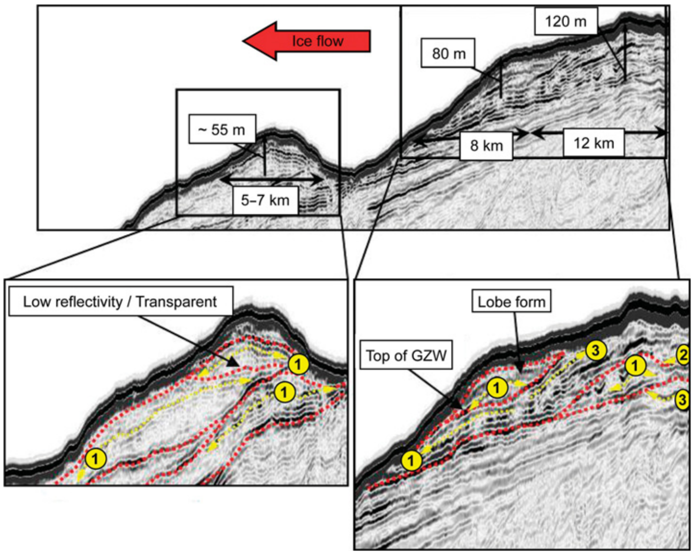

Figure 6. An example of multiple phases in the deposition of large composite grounding-zone wedges, where similar features are superimposed one on another. Numbers (yellow, circled): 1—downlap, 2—onlap, 3—truncation. Seismic line is courtesy of TGS-NOPEC.

coincide with low points in the local topography (Fig. 8). Channel-like features are most easily identified when seismic cross sections or strike lines are examined (Fig. 8).

Internal Structure of Grounding-Zone Wedges: Interpretation

Little is known about the processes operating at the grounding zones of ice sheets, because such modern environments are very difficult to observe directly (Powell et al., 1996; Anandakrishnan et al., 2007). The interpretations that follow therefore reflect both the apparent complexity of the grounding-zone system (e.g., Fig. 8) and our lack of direct information from modern analogs. This, in turn, makes our seismic data of particular significance in aiding the understanding of the formation of grounding-zone wedges.

The low seismic reflectivity of the predominantly glacial debris making up the bulk of grounding-zone wedges indicates a transparent and sometimes chaotic sediment package with a lack of internal reflectors (Figs. 3, 4, 5, and 6). A chaotic internal seismic signature has also been reported for several Antarctic grounding-zone wedges (e.g., Anderson, 1999; Heroy and Anderson, 2005; Mosola and Anderson, 2006) and in sediments deposited immediately beneath the terminus of an Alaskan tidewater glacier (Cai et al., 1997). The low reflectivity represented by the transparent or chaotic seismic pattern is probably a result of the delivery of unsorted diamictic debris derived from the deformable layer that has been reported from beneath a number of modern and Quaternary ice streams (e.g., Alley et al., 1986; Blankenship et al., 1987; Smith, 1997; Powell et al., 1996; Dowdeswell et al., 2004; Anandakrishnan et al., 2007). It is this diamictic layer, and its deformation when subglacial water pressure is high and dilatancy occurs, that is both the main debris source to grounding-zone wedges and that accounts for the high velocities observed in many fast-flowing modern ice streams and outlet glaciers (e.g., Alley et al., 1986; Anandakrishnan et al., 2007). Relative transparency and a lack of internal reflectors may also imply reworking and minor deformation of sediments during short-term perturbations in the precise position of the grounding zone.

Offlapping seismic reflectors are interpreted to represent progradation within grounding-zone wedges (Fig. 7); the set of offlapping reflectors in Figure 7 suggests seaward migration of at least 8 km. Such prograding reflectors imply that accommodation space is present. Sediment delivery presumably takes place into an ice-roofed cavity at the ice-distal margin of a grounding-zone wedge and allows it to build horizontally seaward, whereas a low-gradient ice-shelf base roofing the cavity is likely to restrict vertical development.

Downlapping reflectors within a grounding-zone wedge (Figs. 6 and 8) probably represent phases of sedimentation during minor ice retreat or oscillations at the wedge location. Downlap on the ice-distal side of grounding-zone wedges could be linked to phases of sediment failure, with the degree of failure depending on the relative steepness of the ice-distal side of the grounding-zone wedge (Fig. 6). Internal grounding-zone wedge reflectors downlapping onto a glacial unconformity have also been reported from Antarctic grounding-zone wedges (Anderson, 1999; Mosola and Anderson, 2006). The lobe of sediment above the grounding-zone wedge in Figure 6B may represent sediment from a post retreat slope failure of the ice-distal side of the grounding-zone wedge.

Evidence of truncation of reflectors indicates erosion within a grounding-zone wedge, suggesting that minor glacial readvances or thickening of the overlying ice may induce erosion of the upper grounding-zone wedge surface prior to final ice retreat and abandonment (Fig. 6B). Truncations are also observed at the base of and within grounding-zone wedges (Fig. 8). Those at the base are inferred to represent erosion at the time of grounding-zone wedge initiation, whereas some internal truncations may be a result of sediment deformation by changes in ice-sheet marginal loading and, hence, the imposed stress field. These events are presumably related to minor fluctuations in grounding-zone position and buoyancy. Fluvial activity related to meltwater flow could also cause local erosion, indicated by truncations within the grounding-zone wedges at the base of channel features (Fig. 8). Subsequent buildup of the grounding-zone wedges with acoustically transparent or chaotic debris then represents continuing deposition of diamictic material supplied from the deforming subglacial zone upstream of the wedge (Figs. 3 and 4).

Onlapping reflectors, which are found on the ice-proximal or stoss side of grounding-zone wedges, indicate that wedges are positive topographic features during later sedimentation. They are probably related to deposition of fine-grained and sorted glacimarine sediment after ice retreat from the grounding-zone wedge, given that the sediments tend to drape the stoss side of the features (Figs. 3A and 4A).

Although channel-like forms have only very rarely been reported in association with grounding-zone wedges (McMullen et al., 2006), there is compelling evidence in our high-resolution seismic records that erosional channels are present within some grounding-zone wedges from the Greenland margin (Fig. 8). It is important to note that the incisions are not only seen at the base of some sediment-infill units within grounding-zone wedges, but also within some thicker wedge deposits. The features are not topographically controlled, implying that meltwater flow is at a high water pressure within confined subglacial channel systems (Röthlis-

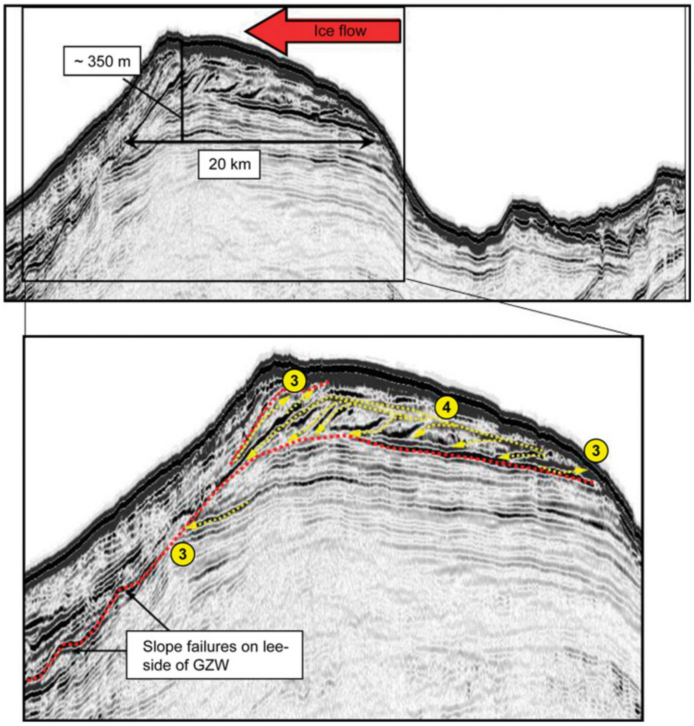

Figure 7. Seismic architectural elements (red stippled lines) and internal reflectors (yellow stippled lines and labeled 3 and 4) within a grounding-zone wedge (GZW) on the NW Greenland shelf. Note that ice advance subsequent to deposition of the grounding-zone wedge has cut a new trough that truncates the older sediments on the landward side of the grounding-zone wedge. Numbers (yellow, circled): 3—truncation, 4—offlap. Seismic line is courtesy of TGS-NOPEC.

berger, 1972; Shreve, 1972). The V-shaped incisions into underlying sediments suggest high energy and erosional capacity in the meltwater flow. The channels are likely to be filled with meltwater-transported sorted debris deposited during the waning stages of water flow.

Channel-like features do not seem to be ubiquitous within the grounding-zone wedges we observed from the Greenland shelf and may, therefore, represent nonsteady meltwater release events during temporary halts in retreat rather than steady flow from a surface-meltwater source. In modern ice-sheet environments, the sudden drainage of surface lakes to the bed has been observed in Greenland (Zwally et al., 2002; Das et al., 2008), along with the episodic drainage of water between linked subglacial lakes in Antarctica (Wingham et al., 2006; Fricker et al., 2007); both would provide high-magnitude water-flow events. The deeper and broader incisions at the base of each phase of grounding-zone wedge buildup may be formed by a combination of glacial erosive processes and confined-flow meltwater erosion; these channel forms are several kilometers wide in our seismic data (Fig. 8). The brighter-amplitude, onlapping reflectors in channels may be indicative of coarser-grained sediment infill.

SIMPLE SCHEMATIC MODELS OF GROUNDING-ZONE WEDGES

The predominantly glacier-derived sediments within which grounding-zone wedges are located usually comprise major prograding successions hundreds of meters thick within which paleoshelves are sometimes preserved from erosion by subsequent ice advance (Dowdeswell et al., 2007). The debris comes mainly from a single dominant sediment source in the form of a glacial trough, which is filled with fast-flowing ice overlying a deforming sedimentary bed. Given that grounding-zone wedge formation during stillstands in ice-sheet retreat probably takes decades to centuries (Alley et al., 2007; Anandakrishnan et al., 2007; Dowdeswell et al., 2008a), the source region and flow direction are usually relatively stable over the period of deposition. Although there is evidence of major shifts in the location of ice-stream flow at the longer time scale of one glaciation to the next in the geological record of the Norwegian margin (Dowdeswell et al., 2006), this would not affect the deposition of individual grounding-zone wedges.

The architectural elements, reflectors, and stratal terminations observed in grounding-zone wedges from the Greenland shelf are summarized in Figure 9. The model includes both long-profile and cross-sectional (i.e., dip and strike) views of idealized grounding-zone wedges; it is based on the seismic characteristics illustrated in the seismic-reflection records from the Greenland margin (Fig. 9). The characteristic asymmetry in the long profile of grounding-zone wedges is also captured in Figure 9A. It should be remembered that most grounding-zone wedges are tens of meters thick and typically tens of kilometers in length, i.e., two to three orders of magnitude longer than they are thick; the schematic models therefore contain considerable vertical exaggeration. Note, too, that multiple phases of sediment infill are implied, based on the reflectors and architectural elements observed on seismic records (intervals between red dotted lines on Fig. 8).

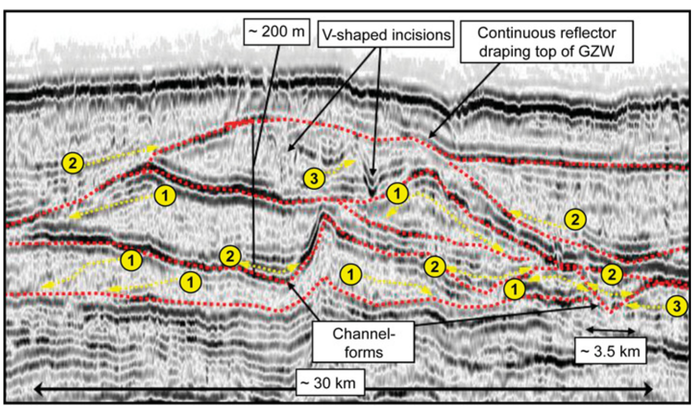

Figure 8. Seismic architectural elements (red stippled lines) and seismic-reflection patterns (yellow arrows) in a grounding-zone wedge (GZW) from NW Greenland. Section across grounding-zone wedge with ice movement toward the reader. Numbers (yellow, circled): 1—downlap, 2—onlap, 3—truncation. Seismic line is courtesy of TGS-NOPEC.

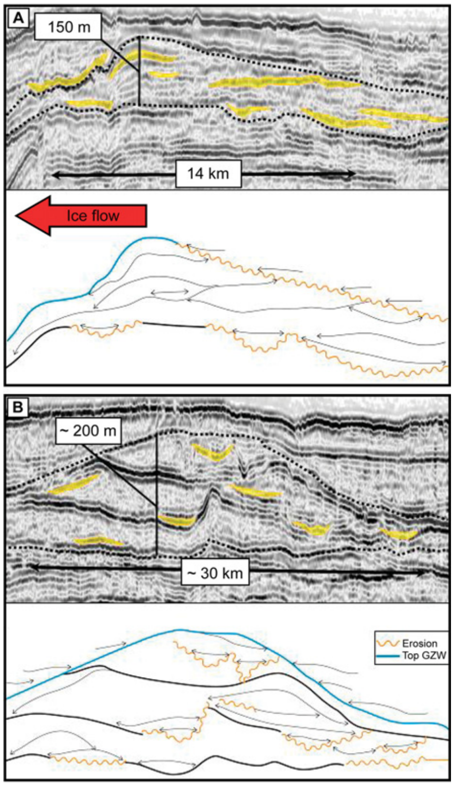

Figure 9. Seismic-reflection data and simple models of grounding-zone wedges from seismic records of stratal geometry and major seismic-architectural elements in grounding-zone wedges from the Greenland shelf. (A) Long profile and (B) cross profile (ice movement is toward the reader). Inferred sedimentary characteristics of the grounding-zone wedges are based on the seismic facies, reflectors, and their amplitude anomalies observed from the Greenland shelf. Black stippled lines—outline of grounding-zone wedges. Yellow—sand-to-gravel–dominated deposits. Observed seismic signatures are highly variable, but sands are generally inferred to display brightening in the seismic data. Thin black lines with arrows—stratal terminations marked by onlap or downlap. Seismic lines are courtesy of TGS-NOPEC.

It is likely that, with increasing depth of burial, and also where seismic data have been collected on land rather than in the marine environment, the resolution of the records will decrease. This means that grounding-zone wedges buried hundreds of meters beneath Quaternary glacial sediments and those from, for example, ancient and indurated glacial deposits now on land (e.g., Le Heron and Craig, 2008) are likely to be less well resolved or blurred on seismic records relative to many of the late Quaternary examples we have shown from the Greenland margin. Thus, as the resolution of seismic records decreases, grounding-zone wedges will be identified most easily by their gross asymmetric form, with their internal acoustic structure becoming progressively less easy to resolve.

Grounding-zone wedges are likely to contain mainly diamictic debris derived from subglacial sediments, and this probably accounts for the semitransparent or chaotic appearance of many grounding-zone wedges on seismic records. Where high-resolution seismic data are available, however, the internal structure of grounding-zone wedges is shown to be more complex than simply a subdued diamictic ridge with an asymmetric long profile (Fig. 9). Internal reflectors suggest seaward wedge growth by progradation that may lead to debris flows and turbidity currents on the steeper lee face of the wedges, which are indicated by the downlapping of reflectors. These processes may, in turn, induce sediment sorting of the mainly diamictic material delivered to the wedge from up-glacier, leading to the deposition of relatively coarse-grained sediment in the ice-distal part of the wedge, which fines with distance into the marine cavity beyond. We indicate the possible locations of sand and gravel on the seismic sections in Figure 9; systematic coring of a grounding-zone wedge exposed close to the surface of a modern high-latitude shelf would allow testing of this model.

In addition, channels and incisions are sometimes observed in the wedges, indicating that meltwater is not only present under pressure within the diamict itself, but can also form subglacial channels that will deliver sediments derived from the glacier bed, which are sorted during transport, to point sources on the wedge front face. The channels are also likely to backfill with coarse-grained sorted debris during waning flows.

On the ice-proximal side of the wedges, truncations indicate phases of erosion that are probably linked to small shifts in ice thickness and buoyancy during wedge growth. Onlapping onto the landward side of grounding-zone wedges probably indicates infill by glacimarine sedimentary processes delivering predominantly fine-grained debris from turbid meltwater plumes after ice retreat (e.g., Powell, 1990; Mugford and Dowdeswell, 2011); this sediment is likely to be composed of upward-fining sorted debris as the wedge becomes increasingly distal from the sediment source at the retreating grounding zone. Thus, not only does the buildup of wedges appear complex over the decades or longer they take to form, but the architectural variability within grounding-zone wedges also suggests that their sedimentology and internal structure will reflect this complexity and that sorted as well as diamictic material is likely to be present within and immediately beyond their margins. The internal details of individual sedimentary packages making up grounding-zone wedges will depend on fluctuations in sediment-delivery rate, buoyancy, meltwater discharge events during formation, and also on the shape of the seawater-filled cavity at their distal margin.

Although most modern and Quaternary grounding-zone wedges are difficult to sample directly due to their position on and beneath the seafloor of continental shelves and fjords, some depocenters formed at the margins of retreating tidewater glaciers and now exposed by isostatic rebound above sea level may provide partial analogs for their internal structure and sedimentology. Detailed description of the sediments deposited in the Mona Ridge in southern Norway by Lønne et al. (2001), for example, shows a suite of sedimentary facies somewhat similar to those inferred here for grounding-zone wedges. The ridge sediments include a diamictic core, internal deformation and truncation of sedimentary units, ice-distal turbidites, sorted and channelized fluvioglacial debris, and coarse, sandy fans. A clear difference from grounding-zone wedges, however, is that the Mona Ridge is a high-amplitude landform, presumably formed at the margins of a tidewater glacier where upward growth was unconstrained by an overlying ice shelf. It should be remembered that the slope of the ice-shelf base close to the grounding zone is likely to be very low (e.g., Bindschadler, 1993; Corr et al., 2001); this is why vertical accommodation space is limited. In addition, both full-glacial and deglacial conditions in southern Norway would have allowed significant surface-meltwater production, which would have been routed to the glacier bed. This environmental setting would have provided a much stronger fluvioglacial component of channels and sorted sediments than the much colder full-glacial and deglacial conditions prevalent in High Arctic and Antarctic locations where mass loss by iceberg production dominates over meltwater runoff (Siegert and Dowdeswell, 2002).

Where there are multiple halts during ice-sheet retreat, and grounding-zone wedges are therefore relatively closely spaced on paleoshelves, low-amplitude basins may form between them. This would restrict the seaward extent of debris flows and turbidity currents originating from the ice-distal side of a grounding-zone wedge, allowing the buildup of turbidite sediments between the wedges and perhaps on the lee side of the older wedge at the seaward margin of a basin. Similar process environments and sedimentary settings on glacier-influenced shelves during deglaciation may be represented by the sedimentary succession cored by the Cape Roberts drilling project in the McMurdo Sound area of Antarctica (Powell and Cooper, 2002) and by parts of the Late Ordovician glacial succession in the Illizi Basin of Algeria (Hirst et al., 2002).

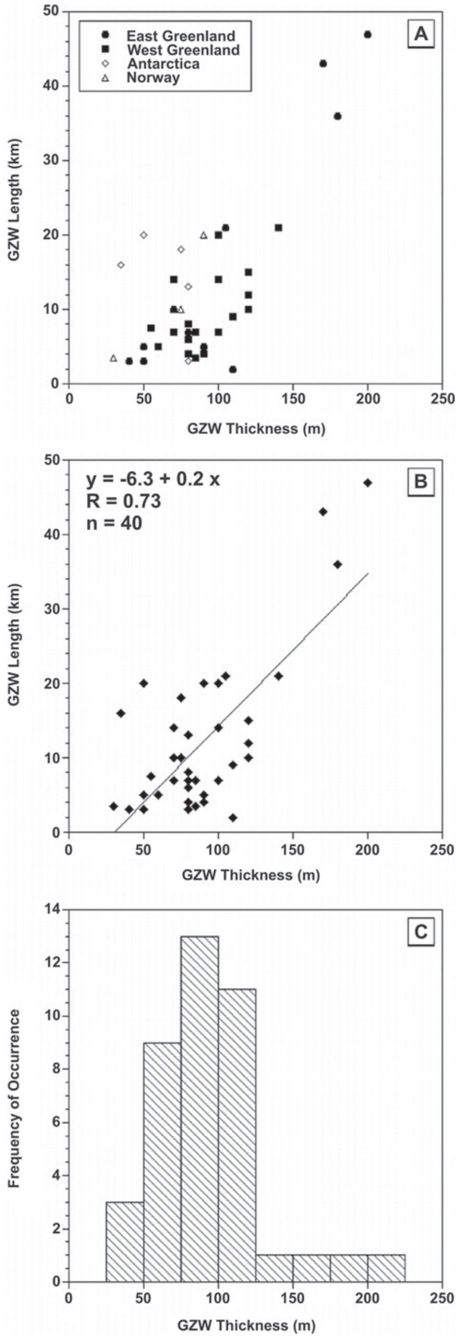

Figure 10. Plots of grounding-zone wedge (GZW) morphology. (A) Scatter plot of grounding-zone wedge thickness and length data from high-latitude continental shelves east and west of Greenland (this paper), west of Norway and the Barents Sea, and around Antarctica (Anderson, 1999; Heroy and Anderson, 2005; Ottesen et al., 2005b, 2008; Mosola and Anderson, 2006; Graham et al., 2010; Rebesco et al., 2011). (B) Scatter plot with linear regression of the relationship between grounding-zone wedge thickness and length for all data. (C) Histogram of grounding-zone wedge thickness for all data. Note that, for the Greenland data, two-way traveltime is converted to sediment thickness using a sound-wave velocity of 2 km s^{-1}, given that there are insufficient data to make specific local corrections for each grounding-zone wedge.

GROUNDING-ZONE WEDGE DIMENSIONS ON HIGH-LATITUDE CONTINENTAL SHELVES

Although grounding-zone wedges have been reported from a number of locations on Arctic and Antarctic continental shelves (e.g., Anderson, 1999; Ottesen et al., 2005a, 2005b; Mosola and Anderson, 2006), there has been no systematic quantification of their dimensions. We now report on the sediment thickness, length in the direction of former ice flow, and ice-marginal width of a number of grounding-zone wedges from high-latitude margins, including about 30 from our Greenland margin data set.

A scatter plot of the thickness and length of 40 grounding-zone wedges is shown in Figure 10A. The data are derived from the identification and interpretation of grounding-zone wedges on seismic records from the Norwegian and Antarctic continental shelves, as well as from Greenland. A least-squares regression fit to these data gives a correlation coefficient, R, of 0.73, which is significant at a 95% level of probability; the slope and fit of the regression line imply that thickness and length scale approximately linearly. Note that the dimensions of three of the grounding-zone wedges from the Greenland margin are very large, at more than 150 m thick and up to almost 50 km long (Fig. 10A). Detailed examination of the seismic profiles in these cases suggests that they are composite features, which may have experienced several phases of buildup. The histogram in Figure 10C shows the distribution of sediment thickness in the 40 wedges; the median value is 75–100 m.

It is more difficult to analyze the lateral width of grounding-zone wedges from our grid of seismic lines from the Greenland shelf. Modern Antarctic ice streams typically have widths of a few tens of kilometers (e.g., Bentley, 1987). Using swath-bathymetric data sets from the Norwegian-Barents-Svalbard margin, Ottesen et al. (2005a) mapped the locations of former ice streams draining westward from the 2500-km-long margin of the late Weichselian Eurasian ice sheet. The estimated width of 18 former ice-streams ranged between ~10 km and 140 km, with a mean of 40 km. In an initial reconstruction of the form and flow of the Late Ordovician ice sheet that extended across northern Africa at ca. 440 Ma, Le Heron and Craig (2008) used seismic lines and satellite imagery to map seven major ice streams; the average width was ~90 km. These studies provide a maximum likely constraint on the lateral widths of grounding-zone wedges on paleoshelves. Where fast-flowing outlet glaciers flow though confining mountain chains, as is the case in Greenland today, the width of individual glaciers is often 10–20 km (e.g., Rignot and Kanagaratnam, 2006). Thus, the typical width of grounding-zone wedges, and the predominantly line-sources of sediment delivery they represent, appears to be a few tens of kilometers; only a few modern and paleo–ice streams record a lateral extent of greater than ~90 km.

In summary, a typical grounding-zone wedge produced at the grounding zone of a fast-flowing ice stream or outlet glacier might be, say, 5–20 km long and 50–100 m thick, with a lateral width of a few tens of kilometers and an asymmetric long profile. There is, however, considerable variability about these values in the dimensions of individual wedges (Fig. 10).

DISCUSSION: IMPLICATIONS FOR PAST ICE-SHEET FORM AND FLOW

The presence of grounding-zone wedges on continental shelves, modern or ancient, implies that the grounding zone remained relatively stable for a period of time that was sufficient to build a sedimentary depocenter with a volume of between about ten and several hundred cubic kilometers. Fluxes of 10^2 m^3 m^{-1} yr^{-1} have been estimated for the delivery of diamictic subglacial sediment to the grounding zone of a modern West Antarctic ice stream (Engelhardt and Kamb, 1997; Anandakrishnan et al., 2007). This suggests that grounding-zone wedges of the dimensions indicated in Figure 10 might take decades to centuries to build up, depending on the precise rate of till delivery to the grounding zone and the thickness of this subglacial deforming layer, which Anandakrishnan et al. (2007) estimated may be a few tens of centimeters.

There are several further implications to the presence of grounding-zone wedges. First, grounding-zone wedges mark the locations of halts or stillstands during ice-sheet retreat across continental shelves. Grounding-zone wedges grow seaward by the continued delivery of basal sediments from the flow of active ice; the prograding reflectors we have imaged support this view (Fig. 7). Alley et al. (2007) pointed out that sediment delivery to the grounding zone is itself a mechanism for ice-shelf stabilization in that wedge growth will tend to counteract the processes of ice-sheet thinning and sea-level rise, which are major causes of destabilization during periods of deglaciation. Grounding-zone wedges are therefore indicators of periods of ice-sheet marginal stability, although retreat across a shelf between grounding-zone wedges may be rapid. A series of grounding-zone wedges thus records the episodic retreat of ice during deglaciation; where grounding-zone wedges are present on Arctic and Antarctic shelves, the implication is that ice-sheet retreat was not by a single catastrophic collapse across the entire shelf (Dowdeswell et al., 2008a; Ó Cofaigh et al., 2008).

Secondly, grounding-zone wedges also indicate that a floating ice shelf is or was probably present, extending beyond the grounding zone itself (Fig. 1A). The wedges imply little about the length of such a floating margin; it could be a few hundred meters in length or represent a huge former ice shelf. The relatively subdued geometry of grounding-zone wedges does suggest, however, that upward accommodation space is limited by the roof of the water-filled cavity into which they may prograde; this restricts the development of pronounced ridges of higher amplitude (e.g., Powell, 1984; Lønne et al., 2001).

Finally, several other, often smaller-scale glacial landforms are produced at the grounding zones of glaciers, especially those that end in ice cliffs rather than floating ice shelves (Fig. 1A). These landforms include both transverse moraine ridges and channel-fan complexes (e.g., Powell, 1984, 1990; Sexton et al., 1992; Seramur et al., 1997), although the occurrence of channels in particular is dependent, in part, on the supply of surface-derived meltwater as well as that produced by basal melting and strain heating; the ice-surface source becomes more limited with increasing latitude (Siegert and Dowdeswell, 2002). Submarine ridges include morainal banks (e.g., Powell, 1984; Cai et al., 1997), terminal-moraine ridges (e.g., Lønne et al., 2001; Ottesen et al., 2007; Ottesen and Dowdeswell, 2006, 2009), and small transverse moraine ridges (e.g., Boulton, 1986; Shipp et al., 2002; Ottesen and Dowdeswell, 2006; Todd et al., 2007), sometimes known as De Geer moraines (Hoppe, 1959; Lindén and Möller, 2005). These topographic features often have marked ridges with low width-to-height ratios (<10:1), in contrast to the much wider and more subdued grounding-zone wedges. This may relate, in part at least, to the absence of the constraint to vertical growth provided by overlying ice when ice shelves are present, usually in relatively cold polar climatic and oceanographic settings where there is also a high ice flux to compensate for mass loss by iceberg production (Thomas, 1979). Some of these smaller ridges are also likely to include a significant component of ice push in their formation, in order to produce the low width-to-height ratios that they exhibit.

SUMMARY

Grounding-zone wedges form where temporary halts during ice-sheet retreat across high-latitude shelves allow sediment buildup at the grounding zone by the continued delivery of deforming basal debris from fast-flowing ice streams. About 30 major grounding-zone wedges were identified on 2-D seismic-reflection profiles of the NE and NW Greenland shelves (Fig. 2B). Some wedges are located close to the seafloor, covered by a thin veneer of sediment, and are probably of late Weichselian age; others are found on paleoshelf surfaces, buried beneath tens to hundreds of meters of prograding glacier-derived sediments. Several grounding-zone wedges on the Greenland shelf occur on topographic highs in the underlying bathymetry that provided pinning points in relatively shallower water, reducing iceberg calving (Figs. 4A and 5).

Grounding-zone wedges have a characteristically asymmetric shape in the direction of ice flow with a relatively steeper ice-distal side (Figs. 3A and 4). Typical grounding-zone wedges produced at the grounding zone of a fast-flowing ice stream or outlet glacier might be ~5–20 km long and 50–100 m thick, with a lateral width of a few tens of kilometers. The geometry of 40 grounding-zone wedges from the margins of Greenland, Norway, and Antarctica shows considerable variability about these values (Fig. 10).

Grounding-zone wedge dimensions are controlled by the flux of deforming sediment, the duration of a stillstand, the shape of the marginal cavity, and the width of the ice stream delivering the sediments; the latter may be controlled by trough geometry where a cross-shelf trough is present. Grounding-zone wedges probably take decades to centuries to build up, depending on the rate of till delivery to the grounding zone and the thickness of the subglacial deforming layer (Anandakrishnan et al., 2007). Evidence for active ice flow during deposition is provided by streamlined lineations observed on swath-bathymetry of grounding-zone wedge surfaces (Fig. 1B). It is presumably the presence of a floating ice shelf beyond the grounding zone that restricts vertical accommodation space for sedimentation and prevents the formation of the relatively high-amplitude ridges observed beyond the grounding zone of tidewater glaciers (e.g., Powell, 1984; Cai et al., 1997).

Grounding-zone wedges usually have a seismically transparent and sometimes chaotic pattern, probably resulting from delivery of diamictic debris derived from a subglacial deforming layer when subglacial water pressure is high and dilatancy occurs. Within grounding-zone wedges, offlapping reflectors represent progradation into an ice-roofed cavity at the ice-distal margin. Downlapping reflectors probably represent phases of sedimentation during minor ice retreat or oscillations at the wedge location. Truncations at the grounding-zone wedge base represent erosion during grounding-zone wedge initiation, whereas internal truncations may result from sediment deformation through changes in ice-sheet loading and the imposed stress field.

Erosional channels are present within some grounding-zone wedges (Fig. 8). They are not topographically controlled, implying that meltwater flows under high pressure in subglacial channels (Röthlisberger, 1972; Shreve, 1972). V-shaped incisions suggest high-energy meltwater flow. Channels are not ubiquitous within grounding-zone wedges from the Greenland shelf and may, in some cases, represent nonsteady meltwater release events, perhaps due to supraglacial or subglacial lake drainage. In climatic settings where ice-sheet mass loss is dominated by meltwater runoff, grounding-zone wedges are likely to contain a greater proportion of sorted sediment than in the Greenland shelf examples.

Simple schematic models of the architectural elements, reflectors, and terminations observed in grounding-zone wedges, together with the inferred locations of sand and gravel, are provided in both long profile and cross section (Fig. 9). Grounding-zone wedges are likely to contain mainly subglacially derived diamictic debris, but the observed architectural complexity suggests that their sedimentology includes sorted sediments in internal channels and ice-distal turbidity flows.

Grounding-zone wedges are important indicators of past ice-sheet dynamics in the geological record and allow former positions of the grounding zone to be identified. They represent episodic rather than catastrophic ice-sheet retreat (Dowdeswell et al., 2008a). Sediment delivery to the grounding zone is a mechanism for ice-shelf stabilization because wedge growth will tend to counteract the processes of ice-sheet thinning and sea-level rise, preventing or postponing rapid ice-sheet collapse (Alley et al., 2007).

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