Submarine landforms in the fjords of southern Chile: implications for glacimarine processes and sedimentation in a mild glacier-influenced environment

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ABSTRACT
Chilean fjords are the lowest latitude at which glaciers reach the sea today. High accumulation and mass throughput sustain tidewater glacier margins in this relatively mild climatic and oceanographic setting. 27,000 km² of swath bathymetry allow mapping of sea-floor landforms and inferences on glacimarine sediments and sedimentation. Tidewater glaciers are present in several fjords. Beyond retreating Tempano glacier, a terminal moraine marks the limit of probable Little Ice Age advance with smaller transverse ridges closer to the glacier. Beyond advancing Pio XI Glacier there are few signs of organised submarine landforms. Older moraine ridges along several fjords formed at still-stands during deglaciation. Elsewhere, meltwater-fed braided rivers connect the glacial and marine sedimentary systems. Swath imagery shows glaciﬂuvial and ﬂuvial deltas with small channels and chutes that develop into long and sinuous turbidity-current channels. Few iceberg ploughmarks and submarine slope failures were observed, but several ﬁelds of pockmarks were present. The fjords of Chile are dominated by sediment delivery from turbid meltwater which distributes ﬁne-grained debris widely, producing sorted and laminated ﬁne-grained ice-proximal wedges and draping ice-distal seismic architecture to give a predominantly smooth sea ﬂoor. Turbidity currents also transfer sediments to some ice-distal environments. The Chilean fjordlands represent the mildest climatic and oceanographic end-member of a continuum of glacier-influenced marine settings; similar to south-east Alaska in the northern hemisphere. Components of a landform-assemblage model for climatically mild meltwater-dominated fjords include ice-contact moraine ridges, glaciﬂuvial and ﬂuvial deltas, and turbidity-current channels. Full-glacial and deglacial streamlined subglacial landforms are likely to have been buried in many areas by subsequent glacimarine sedimentation.

1. Introduction

The fjordlands of Chile, at 42°–55°S, are one of the lowest latitudes in either hemisphere where glaciers either reach the sea today or deliver sediments via proglacial rivers. The Chilean glaciers are fed by ice draining west from basins of up to 1300 km² in the Northern and Southern Patagonian ice caps (total areas 4197 km² and 13,000 km², respectively; Rivera et al., 2007; Lopez et al., 2010). The ice caps are typical of many mountain ice masses, with glaciers having a large altitudinal range (3300–4000 m) with very high accumulation (several thousand mm yr⁻¹) and throughput of mass (Warren and Aniya, 1999; Lopez et al., 2010). Meltwater runoff and iceberg production are both important mechanisms of mass loss, with their relative significance varying widely between individual glaciers (e.g. Rignot et al., 1996; Warren and Aniya, 1999). The most northerly tidewater glaciers are Jorge Montt and Tempano glaciers, at 48°15′S and 48°43′S respectively. In a number of other Chilean fjords, where glaciers no longer extend to the sea, glaciﬂuvial systems deliver meltwater to adjacent fjord heads. The Chilean fjordlands were inundated by ice during the Last Glacial Maximum (LGM) about 20,000 years ago (Hollin and Schilling, 1981; Hulton et al., 2002); therefore, the sedimentary record in the fjord systems includes a Late Quaternary full-glacial and deglacial record in addition to the imprint of modern glacimarine processes (DaSilva et al., 1997; Araya-Vergara, 1999a; Boyd et al., 2008).

Few detailed studies of the sedimentary products or the glacial and marine processes that influence sedimentation in the fjordlands of Chile have taken place (e.g. DaSilva et al., 1997; Araya-
Vergara, 1999a,b, 2008, 2011; Boyd et al., 2008; Rodrigo, 2008; Fernandez et al., 2012). Given their relatively low-latitude position at the equatorward limit of modern glaciomarine environments, sedimentation would be expected to be dominated by meltwater-related processes (Dowdeswell et al., 1998); a setting similar to that of south-east Alaska in the northern hemisphere (e.g. Powell and Molnia, 1989; Cai et al., 1997).

In this paper, we examine an extensive dataset of swath-bathymetric imagery covering almost 27,000 km² of the Chilean fjordlands, from Golfo de Penas at 47°35'S to Europa Fjord at 50°17'S; a latitudinal range of almost 400 km (Fig. 1). The spatial coverage of the data allows us to investigate areas ranging from ice-proximal settings within a kilometre or two of present tidewater glacier margins (e.g. Eyre and Iceberg fjords), to locations over 100 km distal from fjord heads which are little influenced by modern glaciomarine processes. Ice has, however, retreated through the fjord system since the LGM leaving a record of Late Quaternary deglacial behaviour of the Patagonian Ice Cap. The range of submarine landforms observed in the fjords of Chile is influenced by modern processes and those relict features that record elements of the Late Quaternary deglacial behaviour of the Patagonian Ice Cap. The range of submarine landforms observed in the fjords of Chile is described and discussed. We discuss, therefore, the sea-floor landforms of the fjordlands of Chile in terms of both modern processes and those relict features that record elements of the Late Quaternary deglacial behaviour of the Patagonian Ice Cap. The range of submarine landforms observed in the fjords of Chile is described and interpreted in the context of glacial, oceanographic and sub-aqueous mass-wasting processes before the spatial pattern of glacial and glaciomarine landforms is described and discussed. Finally, the Chilean fjords are set within the continuum of glacier-influenced marine environments that ranges from the lowest latitudes at which glaciers reach the sea to the very cold glaciomarine system of East Antarctica (Dowdeswell et al., 1998).

2. Data sources and methods

Swath bathymetry of the sea floor in the fjordlands of southern Chile was acquired over an area of 26,838 km² between 2003 and 2008 by the Hydrographic and Oceanographic Service of the Chilean Navy (SHOA). Two sets of equipment were used for data acquisition. For water depths up to 200 m, an Atlas Fansweep system operating at 200 kHz was deployed. For deeper water, a medium-depth Hydroseep sweep system (MD2) with a frequency of 50 kHz was used. In each case, the ship speed for swath data acquisition was 8 knots, and tracks were acquired with a nominal 100% overlap. No sub-bottom profiler data are available from these cruises to provide information on shallow acoustic stratigraphy, although 3.5 kHz records from other cruises has been acquired from some fjords by, for example, Araya-Vergara (1999a,b, 2008).

Sea-floor data acquired using these swath-bathymetry systems were processed through the removal of anomalous pings and were normally gridded at a horizontal resolution of 20 m using CARIS HIPS and SIPS software, which was also used for image manipulation and display. The swath-bathymetric data have a vertical resolution of better than 2 m.

3. Tidewater glacier sedimentary systems

Tidewater glaciers draining westwards from the Southern Patagonian Ice Cap are present in several Chilean fjords. Swath-bathymetric imagery is available from two areas, Iceberg and Eyre fjords, to within a kilometre or so of the grounded margins of Tempano and Pio XI glaciers (Figs. 2 and 3). A period of relatively widespread glacier advance between the 17th and 19th centuries in much of Patagonia has been replaced typically by shrinkage since that time (Masiokas et al., 2009). Pio XI Glacier is an exception, however; it has been advancing through most of the 20th century and may experience periodic surges (Rivera et al., 1997a,b). Our swath coverage provides, therefore, imagery of the well-preserved sea floor close to the margins of both a retreating and an advancing tidewater glacier.

3.1. Retreating tidewater glacier: Tempano Glacier, Iceberg Fjord

The innermost 4 km of Iceberg Fjord, and the crevassed margin of Tempano Glacier, are shown in Fig. 2. The sedimentary Fjord floor is marked by several sets of features: a series of transverse ridges of varying height distributed across the fjord; a number of sub-parallel ridges orientated in the likely direction of past ice flow; and areas of flat, smooth sea floor. The outermost and largest transverse ridge is about 100 m high and is clearly asymmetrical, with a steeper ice-distal face (labelled LIA Mor in Fig. 2). A second large ridge has a similar long profile and is about 50 m high. The remaining ten or so transverse ridges are smaller, at about 10 m high (labelled TR in Fig. 2). Closer to the modern ice front, and extending northwards into a relatively shallow enclosed basin, is a series of lineations of up to about 0.5 km in length that trend first just north of west and then to the north (labelled L in Fig. 2). Where the lineations are slightly more irregular in appearance, this may indicate that they are partly composed of bedrock as well as streamlined sediments. The remainder of the floor of the inner fjord, between the transverse ridges and lineations, is mainly smooth and flat (Fig. 2).

The outermost transverse ridge (LIA Mor in Fig. 2) is interpreted as the terminal moraine of an ice advance that filled the inner fjord basin, probably at the time of the Little Ice Age advance that has been observed widely in southern South American glaciers (Harrison et al., 2007; Masiokos et al., 2009) and in higher-latitude regions (e.g. Dowdeswell, 1995). Its asymmetrical long profile and steeper distal face are typical of moraines marking the maximum recent advance of many northern hemisphere tidewater glaciers (e.g. Ottesen and Dowdeswell, 2009). Similarly, the sets of smaller transverse ridges closer to the glacier front (TR in Fig. 2) are typical of those deposited during still-stands or minor readvances superimposed on more general glacier retreat (e.g. Boulton, 1986; Ottesen and Dowdeswell, 2006). These smaller ridges are unlikely to have been deposited annually, however, given that retreat from the terminal moraine to the present ice margin has probably taken on the order of 100 years and only about ten ridges are observed (Fig. 2).

The lineations that trend first west and then north in the innermost part of the fjord (L in Fig. 2) are interpreted as streamlined landforms produced beneath actively flowing glacier ice (Clark, 1993; Ottesen and Dowdeswell, 2009). This interpretation confirms that the tidewater glacier was grounded in the deepest parts of the inner fjord, where water depths reach about 200 m. It also suggests that ice flow included a northward component, either due to Little Ice Age advance into the northern enclosed bay as well as westward to the terminal moraines described above, or when the ice had retreated from the area of transverse ridges to fill only the innermost fjord.

Finally, the smooth and flat areas of the sea-floor in Fig. 2, best developed between the transverse moraine ridges, but also present in the deep innermost fjord, are interpreted as sedimentary infill from the rainout of fine-grained debris transported from the tidewater glacier as a turbid plume of suspended sediment (e.g. Syvitski, 1989; Powell, 1990). Such turbid plumes are observed on modern satellite imagery of the tidewater glacier margin, and are typical of tidewater glaciers in regions where surface melting is a significant component of glacier mass loss (e.g. Pfriman and Solheim, 1989; Dowdeswell et al., 1998). Water penetrates to the glacier bed through crevasses, which are illustrated near the terminus of Tempano Glacier in Fig. 2, and debris entrained in basal conduits forms a buoyant plume when the subglacial streams exit from portals at the base of tidewater ice cliffs (e.g. Powell, 1990;
Mugford and Dowdeswell, 2011). The plume then spreads out at the fjord surface under the influence of wind, tide and stream discharge (e.g. Syvitski, 1989; Dowdeswell and Cromack, 1991; Cowan, 1992). Fine-grained sediments rain-out from the plume to form a smooth drape over the fjord floor, deposited at a rate that decreases with distance from the plume source at the ice margin (e.g. Elverhøi et al., 1980; Ottesen and Dowdeswell, 2009). Beyond the terminal moraine, about 5 km further down Iceberg Fjord, the sea-floor is largely smooth, with sediment appearing to drape minor topographic features (Fig. 4A). This suggests that fine-grained suspended sediments continue to be deposited more distally, although probably at a slower rate than in the inner fjord.
3.2. Advancing tidewater glacier: Pio XI Glacier, Eyre Fjord

The sea-floor of inner Eyre Fjord, beyond about a kilometre from the modern ice front of Pio XI Glacier, shows few signs of an organised set of submarine landforms (Fig. 3). The largely flat surface is broken by a number of irregular hummocks up to 14 m high. In addition, there are several local areas where short ridges running both across- and along-fjord intersect in a rudimentary rhombohedral pattern. These rather chaotic positive-relief features give way to a smooth sea-floor down fjord (Fig. 3).

The observed 5 km advances of Pio XI Glacier during the 20th century (Rivera et al., 1997a, b) may have covered and reworkedgeomorphic evidence of earlier retreat linked to regional Little Ice Age cooling (Masiokos et al., 2009). The overall rather flat sea-floor observed proximal to the present ice front is likely to be a product of deposition of fine-grained material from turbid meltwater plumes (e.g. Syvitski, 1989; Powell, 1990). Isolated hummocks and ridges are probably produced by a previous surge of the glacier, given that deformed medial moraines on the modern glacier surface imply episodic surge activity (Meier and Post, 1969; Rivera et al., 1997a; Rignot et al., 2003). It should be noted, however, that the characteristic assemblage of superimposed submarine landforms, including streamlined lineations, terminal moraines, rhombohedral moraines and small transverse ridges, observed at the margins of many Svalbard surge-type glaciers (Solheim and Pfirman, 1985; Ottesen and Dowdeswell, 2006; Ottesen et al., 2008), is not observed in Eyre Fjord. In fact, the fjord floor is largely smooth through the inner fjord, with streamlined lineations...
that appear to be part-bedrock and part-sediment protruding through a fine-grained drape at about 15 km from the ice front (Fig. 4B). This interpretation is confirmed by the presence of draping and ponded sediments in 3.5 kHz records reported by Araya-Vergara (1999a). In the absence of chronological control, it is assumed that the lineations illustrated in Fig. 4B are linked to a significantly earlier, probably full-glacial phase of glacial activity in the Chilean fjords.

DaSilva et al. (1997) reported, based largely on seismic-reflection data from Canal Baker (48°S), that the inner fjords of central Chile contained 200–400 ms-thick acoustically laminated ice-proximal sediments that may relate to deglaciation from the LGM. They also noted that this has been augmented by the continuing input of fine-grained sediment from turbid meltwater where Holocene tidewater glaciers remain at fjord heads. Short piston cores sampled interbedded sands and muds at the head of Canal Baker beyond the terminus of Jorge Montt Glacier (DaSilva et al., 1997). These acoustic and sedimentary characteristics were suggested to be similar to those of tidewater glacier influenced Baffin Island fjords in the Northern Hemisphere (Stravers and Syvitski, 1991; Gilbert, 1992).

4. Glaciﬂuvial sedimentary systems: deltas and turbidity-current channels

In a number of locations where glaciers draining west from the Southern Patagonian Ice Cap do not reach the sea, braided rivers or sandurs fed by ice cap meltwater connect the glacial and marine sedimentary systems. Examples include Occidental Glacier (448 km²), which reaches outer Iceberg Fjord via an 11 km-long braided channel (Fig. 5), and Bernado Glacier (710 km²) where a 2 km-long braid plain links it with Bernado Fjord (Fig. 6). In each case, braided channels reach the sea across the top of glaciﬂuvial deltas that are about 1.5 km wide in Iceberg Fjord (Fig. 5) and almost 2 km wide in Bernado Fjord (Fig. 6).

Swath bathymetry of the delta faces in the two fjords shows series of small submarine channels and narrow chutes (Figs. 5 and 6), whose modern activity is presumably dependent on shifting spring and summer discharge from varying parts of the subaerial braided plain. The dissected slopes of the delta fronts are about a kilometre in length, beyond which the sets of submarine channels and chutes appear to organise into a single major submarine channel (Figs. 5 and 6). These fjord-floor submarine channels are sinuous and extend for a number of kilometres along the relatively ﬂat ﬂoors of Iceberg and Bernado fjords (Figs. 5 and 6). The submarine channel in outer Iceberg Fjord is at least 15 km long, up to about 50 m-deep, and with an average width of 275 m (maximum 400 m, minimum 150 m). The channel in Bernado Fjord extends about 10 km, and has a width and depth of 100 m and about 50 m, respectively. A proﬁle along the thalweg of the submarine channel in Bernado Fjord, with a slope of over 100:1, is shown in Fig. 6.

The submarine channel systems in Iceberg and Bernado fjords are interpreted to be formed by dense underﬂows or turbidity currents that are likely to be produced intermittently by one or

Fig. 3. Swath-bathymetry of the innermost 4 km of Erye Fjord (located in Fig. 1C). The Fjord coastline and tidewater margin of Pio XI Glacier are shown on the aerial photograph.
both of two processes (Syvitski et al., 1987). First, glaciﬂuvial meltwater ﬂow and the delivery of relatively coarse-grained sedi-
ment from the braid plain, which will vary both diurnally and seasonally with glacier melt rate, may cause turbidity-currents to form. Secondly, slope failures that translate into turbidity currents may occur on glaciﬂuvial delta fronts, which are areas of high and very variable rates of sediment delivery where the deposited material is likely to be relatively unstable on the delta front slope. The time-dependent variability of sediment delivery from glaci-
ﬂuvial braided river systems has been discussed thoroughly by, for example, Church and Gilbert (1975). The dissected nature of meltwater-fed delta fronts has been reported from a number of northern hemisphere fjords in, for example, British Columbia, Baffin Island and Spitsbergen (e.g. Prior et al., 1981; Syvitski et al., 1987). The presence of sinuous turbidity-current channels, similar those imaged in Figs. 5 and 6, is also characteristic of many northern hemisphere fjords that are fed by highly variable discharge from glaciﬂuvial braided rivers (e.g. Prior et al., 1986; Syvitski et al., 1987).

An additional submarine channel is mapped in Penguin Fjord (50° S). Its most distal 4 km is observed on swath imagery, but its extent towards the tidewater glaciers at the fjord head is unknown, since our bathymetric data end about 13 km from the ice front. It is not clear, therefore, whether this channel differs from those observed in Iceberg and Bernado fjords in extending close to a tidewater glacier terminus rather than to a glaciﬂuvial braided river system. Similar turbidity-current channels have been noted on recently acquired swath-bathymetry data from several Greenland fjords where marine-terminating glaciers are present (J.A. Dowdeswell, unpublished data).

5. Glacial and deglacial landforms

5.1. Retreat moraines

In several Chilean fjords, large sedimentary ridges are present across fjord axes (Figs. 2 and 7). In the 50 km-long Europa Fjord there is one ridge at the fjord mouth where it enters the 250 m-deeper Canal Wide. Three other sedimentary ridges are spaced about 8 km apart in the inner half of the fjord; two are illustrated in Fig. 7. Elsewhere, prominent sedimentary ridges of similar dimensions are located where relatively shallow tributary fjords enter the deeper and 40-km long Farquahar-Bernado Fjord system and in Ringdove Fjord (49°42′S).
These large transverse ridges are characteristically asymmetrical in long profile, with a steeper down fjord slope. They often extend the full width of the fjord and are more than a kilometre in along-fjord length (Figs. 2 and 7); no seismic data are available from this study to quantify their internal structure. Their steeper, outer-fjord slopes are sometimes dissected by small channels or chutes of up to a few hundred metres in length and a few metres wide. There are also some lobate features on the distal side of these ridges that...
grade into the relatively smooth fjord floor, whereas others appear to override fjord-floor sediments (Fig. 7). The latter may reflect relatively recent slope failure, whereas the former may represent subsequent partial burial by rain-out of fine-grained debris. Araya-Vergara (1999a) also suggests that downslope remobilisation processes may be operating on the steeper sides of these ridges, based on 3.5 kHz records.

The large transverse ridges, found along and at the mouths of several Chilean fjords, are similar in dimensions to the large ice-proximal terminal moraine in inner Iceberg Fjord (Fig. 2). These ridges are interpreted to be moraines that formed at the termini or retreating margins of grounded tidewater glaciers that extended further into the Chilean fjord system during the LGM and subsequent deglaciation. The ridges therefore mark former ice-front positions, and formed at either maximum or, more likely, still-stand positions during more general retreat; deglaciation in fjords where these retreat moraines are located was therefore episodic rather than catastrophic (Dowdeswell et al., 2008). Glasser et al. (2009) described cross-valley moraines of similar dimensions in subaerial locations around the Northern Patagonian Ice Cap.

The interpretation of these large transverse ridges as retreat moraines is supported by the location of several of them at the mouths of fjords; points where water deepens by tens to hundreds of metres immediately distal of the ridges. In addition, Araya-Vergara (1999a) shows interpreted 3.5 kHz profiles from Europa Fjord, where he maps both morainal banks and other ridges where acoustic penetration is limited. The rate of mass loss from tidewater glaciers by iceberg production is known to increase with water depth due to increasing buoyancy (e.g. Brown et al., 1982; Pelto and Warren, 1991; Venteris, 1999; Benn et al., 2007); thus, retreat into shallower water would decrease iceberg production and lead to a still-stand at such so-called ‘pinning points’. The size of moraine ridge would be a function of the rate of sediment supply to the ice margin and the duration of a still-stand — probably on the order of decades to centuries for sedimentary ridges that are likely to be tens of metres thick (DaSilva et al., 1997). The lobes on the steeper, ice-distal sides of the moraines ridges, illustrated in Fig. 7, are interpreted to be the morphological expression of debris flows of relatively rapidly delivered and unstable glacial debris (e.g. Ottesen and Dowdeswell, 2006; Ottesen et al., 2008).
Grounding-zone wedges (GZW) also mark pauses in glacier retreat during deglaciation on many high-latitude shelves (e.g. Mosola and Anderson, 2006; Dowdeswell et al., 2008). They form where still-stands during retreat allow sediment build-up at the glacier grounding-zone by the continuing delivery of deforming basal debris, at time-scales ranging from decades to centuries (e.g. Powell and Domack, 1995; Dowdeswell and Fugelli, 2012). GZW, which can be up to tens of metres thick and several kilometres or more in length (Dowdeswell and Fugelli, 2012), are most easily identified from sub-bottom profiler or seismic records, as their surface expression is often relatively subdued (e.g. Ó Cofaigh et al., 2013). We do not identify any GZW in the fjords of Chile, nor are such features reported from the seismic investigations of DaSilva et al. (1997) or Boyd et al. (2008). It appears that relatively well-defined moraine ridges, produced at the margins of grounded tidewater glaciers, provide the main record of still-stands during deglaciation of the fjords of Chile. Floating ice shelves or glacier tongues, where vertical accommodation space for sediment build-up is limited beyond the grounding-zone (Dowdeswell and Fugelli, 2012), may thus have been limited or absent in the fjords of Chile during deglaciation. Our lack of sub-bottom stratigraphic data must be borne in mind, however, as a caviat to this conclusion.

5.2. Streamlined lineations

Streamlined sea-floor lineations, with their long axes orientated along-fjord, are observed in several areas of our swath-bathymetric data from the fjords of Chile. A clear example of a set of streamlined lineations, probably formed of predominantly sedimentary material with some protruding bedrock, is from Eyre Fjord (Fig. 4B). We have observed a number of other occurrences of similar sets of features in, for example, Canal Wide (at about 49°45'S), Paso del Indio (at about 49°08'S), and Canal Messier (at about 48°50’S and 48°20’S). Some of these sets of lineations appear as streamlined bedrock protruding above the flat, sedimentary fjord floors.

These streamlined features are interpreted as a product of active glacier flow, formed subglacially, sometimes in a deformable sedimentary substrate (e.g. Clark, 1993; Dowdeswell et al., 2004; Ó Cofaigh et al., 2005a) or as glacially sculpted bedrock features (Ottesen and Dowdeswell, 2009; and Evans, 2010). Their orientation is indicative of the direction of past glacier flow; however, the sense of flow can only be obtained if landforms attenuated in the flow direction are present (e.g. drumlins, crag-and-tails; Benn and Evans, 2010), and such attenuated forms were not observed in Chilean fjords. Similar subglacially produced streamlined landforms, both sedimentary and bedrock, are commonly observed in fjord systems in, for example, Spitsbergen and in deep troughs that cross-cut many high-latitude continental shelves (e.g. Canals et al., 2000; Evans et al., 2006; Ottesen and Dowdeswell, 2009). It is possible that, if produced beneath past glaciers prior to deglaciation of the fjords of Chile, many such features have been largely buried by post-glacial sediments delivered relatively rapidly by turbid meltwater plumes from glaciers which undergo strong summer melting and high mass throughput (Warren and Aniya, 1999; Lopez et al., 2010).
5.3. Iceberg ploughmarks

The tidewater glaciers of the Chilean fjords lose mass by both surface-melting and runoff and through the production of icebergs (e.g. Rignot et al., 1996; Warren and Aniya, 1999). In many fjord and shelf systems where glaciers reach sea level and icebergs are calved, the keels of these icebergs make contact with and plough furrows in the sea floor (e.g. Woodworth-Lynas et al., 1991). We observed almost no iceberg-keel ploughmarks on the sedimentary floors of the fjords of Chile. This is interpreted to be for two reasons; first, the fjords are for the most part hundreds of metres deep; and, secondly, the closely spaced crevasses typical of the grounded margins of Chilean tidewater glaciers (illustrated on Tempano Glacier in Fig. 2) result in the production of large numbers of small icebergs of irregular size (e.g. Warren and Aniya, 1999) – a similar situation to that in many Alaskan and Spitsbergen fjords today (e.g. Ovenshine, 1970; Dowdeswell, 1989; Dowdeswell and Forsberg, 1992). This contrasts with the smaller numbers of very large tabular and deep-keeled icebergs produced from floating ice shelves and outlet-glacier termini in Greenland and Antarctica (Dowdeswell et al., 1992; Dowdeswell and Bamber, 2007). Thus, very few deep-keeled icebergs are available to plough and rework sea-floor sediments in the fjord systems of Chile.

6. Other submarine landforms

6.1. Fluvial deltas

Along the sides of several Chilean fjords, rivers draining fluvial catchments have depocentres at their marine margins that have built out into relatively deep fjord waters. Two examples of these fluvially fed depocentres in Eyre Fjord are shown in Fig. 8. Submarine chutes and channels are sometimes observed on the relatively steep seaward fronts of these depocentres (Fig. 8A); other depocentres have a more uniform lobate morphology (Fig. 8B). These marine depocentres are interpreted as fluvial deltas, fed from rivers draining relatively high-relief catchments in the mountainous hinterland of the Chilean fjordlands. Some of the delta-fronts appear from swath bathymetry to be dominated by down-slope sediment-transfer processes that are confined laterally in well-defined channels and chutes (Fig. 8A). Turbidity currents are most likely the dominant form of down-slope transport on these deltas. On other delta-fronts with more lobate relief, mass-wasting processes in the form of sediment slumps and slides probably predominate (Fig. 8B). Evidence that these deltas are active today, and continue to build outwards into the Chilean fjords, is indicated by the sharp contact between the deposite and the smooth fjord floor shown in Fig. 8B, where the delta front appears to be overriding fjord-floor sediments. A small fan/delta, which appears to be located at the marine margins of a fluvial drainage basin, has also been reported from swath bathymetry of Ainsworth Fjord, south of our study area at 54°23’S (Boyd et al., 2008).

6.2. Slope failures

There appear to be rather few clear examples of submarine slope failures on the swath bathymetry of the Chilean fjords that we have examined, although our recognition of more subdued features is likely to be inhibited by the lack of any sub-bottom acoustic data. Poorly defined lobes close to the steep walls of, for example, Europa Fjord probably represent limited down-slope mass-wasting. Most down-slope mass transfer, however, appears to be linked either to turbidity-current channels or to lobate slumps on glaci-fluvial and fluvial deltas (Fig. 8) and on the front-face of large glacier-derived moraine ridges (Figs. 2 and 7). These locations are sites of present or past delivery of sediments at relatively high rates from fluvial, glacifluval and glacial systems. Fjord walls beyond these areas of high sediment input do not appear to be locations for sustained mass-wasting due, presumably, to the lack of a sediment source. Further south in Chile, swath-bathymetric data from Ainsworth and Marinelli fjords also show evidence of only very restricted slumps and slides along the fjord margins (Boyd et al., 2008). In Aysen Fjord, north of our study area at about 45°20’S, submarine slope failures have been reported by Araya-Vergara (2011).
6.3. Crater-like pockmarks

Sets of crater-like structures, numbering tens of individual features sometimes orientated in linear strings, are observed in three areas in water depths of less than about 160 m within the sedimentary sea-floor of the Chilean fjords (Fig. 9); between 48°57′ and 49°02′S, and 49°04′ to 49°05′S in Angostura Inglesa and at about 49°11′S in Paso del Indio. The depths and widths of over 80 individual craters from two of these areas are plotted in Fig. 10. Median crater depth is between 3 and 5 m and median diameter is between 40 and 60 m. A sharp cut-off in minimum observed diameter at about 30 m probably reflects the resolution of the swath-bathymetry system (Fig. 10), implying that some smaller craters may have gone undetected. In addition, the craters show few signs of infilling, suggesting that they either formed relatively recently or that sedimentation rates in this part of the fjord system are very low.

These crater-like features are interpreted as pockmarks, probably produced from the escape of shallow gas from the sediments underlying these areas of the Chilean fjords. Pockmarks are found in many shallow continental-shelf settings throughout the world, including some observations from high-latitudes (e.g. Hovland, 1981; Solheim and Elverhøi, 1985). Chaotic reflectors in seismic records from Marinelli Fjord, further south at 54°18′S, have been interpreted as potential indicators of shallow gas by Boyd et al. (2008).

6.4. Distribution of submarine landforms in the fjords of Chile

The distribution of sedimentary submarine landforms identified in the almost 27,000 km of swath-bathymetric imagery we have examined from the fjords of Chile is shown in Fig. 11. Three main types of landform predominate: ice-contact moraine ridges; glaci-fluvial and fluvial deltas; and turbidity-current channels. Associated with these landforms are debris-flow lobes on the ice-distal faces of moraine ridges, and channels, chutes and debris-flow lobes on the steep faces of glaci-fluvial and fluvial deltas. Much of the fjord system, especially with increasing distance from tidewater glacier margins, is devoid of major sedimentary landforms, with the exception of occasional streamlined features and pockmarks. Here, the sea floor is mainly relatively smooth where sediments predominate, with bedrock outcrops providing additional topography which we do not plot in Fig. 11 except where they appear to be glacially sculpted.

Fig. 9. Swath-bathymetric examples of crater-like pockmarks on the relatively flat floor of two Chilean fjords. (A) Angostura Inglesa (located in Fig. 1B). (B) Paso del Indio. Note also the streamlined bedrock landforms on the left of the panel (located in Fig. 1C).
7. Discussion

7.1. Climatic and oceanographic setting of Chilean fjords

The tidewater glaciers of the Chilean fjordlands reach the sea at a lower latitude than any other ice masses in the world today. The regional climate of the fjordlands is typified by relatively cool summers and mild winters, with January temperatures around 11 °C and July means of 2 °C (Miller, 1976). Mean annual air temperature is between about 6° and 8 °C, varying with latitude across the study area (Hulton et al., 2002). Precipitation is also very high. On the west side of the Northern Patagonian Ice Cap, for example, precipitation is 3700 mm yr⁻¹, rising to 6700 mm yr⁻¹ at 700 m-elevation (Harrison et al., 2007). It is the high accumulation and mass throughput of Chilean glaciers that enables some to reach sea level at tidewater termini even in these relatively mild climatic conditions.

Although the fjords of southern Chile are adjacent to the Pacific Ocean, the bathymetry of the many channels that connect the inner fjords to the ocean margin is crucial to fjord oceanography (Pickard, 1971; Palma and Silva, 2004; Hromic et al., 2006; Sievers, 2008; Sievers and Silva, 2008). Coastal sills ranging from about 60 m to

Fig. 10. Histograms of the size-frequency distribution of pockmark geometry in two Chilean fjords. (A) Angostura Inglesa (Fig. 1B). (B) Paso del Indio (located in Fig. 1C). The histograms are for pockmark width and depth in each area, measured from swath-bathymetric data, with n indicating the number of individual pockmarks measured for each histogram.
150 m prevent ocean waters deeper than this from entering the inner fjord systems, even though the fjords themselves are up to about 1300 m deep in Messier Fjord. The fjords are, therefore, dominated by the inflow of Subantarctic Water (SAAW), which has a typical temperature of about 9°C and salinity of 33–34.2 ppt. The SAAW is slightly colder north of the 50 m-deep Angostura Inglesa (English Narrows) than to the south (8.3–8.5°C and 8.8–9°C, respectively) (Palma and Silva, 2004). In the inner fjords, SAAW mixes with colder fresh water that comes from rivers, coastal runoff and glacial meltwater to form a surface layer of Modified Subantarctic Water (MSAW) some tens of metres in thickness that flows outward from fjord heads in a classical fjord circulation (Syvitski et al., 1987), with SAAW flowing inward at depth, and filling most of the deep inner-fjord basins.

These relatively high water temperatures mean that the predominantly small and irregular icebergs calved from tidewater glacier margins will melt rapidly once they drift beyond the cold glacial meltwater close to the terminal ice cliffs and the cooler
MSAW in some glacier-influenced inner fjords. Iceberg and marginal ice-cliff melt rates in excess of 0.5 m day$^{-1}$ are predicted for marine water temperatures of about 9 °C using the equations of Weeks and Campbell (1973) and Russell-Head (1980). This relative rapid melting means that iceberg rafting of debris and ploughing of the sea floor by iceberg submarine keels are restricted largely to ice-proximal locations in the fjords of Chile.

7.2. Seismic and sedimentary facies in Chilean fjords

Although our marine-geophysical data from the Chilean fjord-lands are restricted to swath-bathymetric observations, several studies have obtained seismic records and core material from the region. Marine-seismic investigations by DaSilva et al. (1997) in Canal Baker (48°S), near the northern limit of our study area, show two principal acoustic facies. The first facies, present on the records obtained closest to the tidewater margins of Jorge Montt Glacier and extending about 60 km down fjord, is an acoustically laminated facies that is wedge-shaped in architecture and thins away from the sediment source. Cores collected from this facies consist of interbedded sands and muds. The second acoustic facies, found further seaward in the fjord, is semi-transparent in seismic character and draping in its form. It is composed of interbedded massive to stratified muds with occasional pebbles; the sediments are often bioturbated. The first facies grades into, and is sometimes interbedded with the second.

These acoustic and sedimentary facies were interpreted as ice-proximal and ice-distal glacimarine, respectively, by DaSilva et al. (1997), reflecting fined-grained and slower sedimentation with increasing distance from debris sourced from the Patagonian ice caps both today and during neoglacial association with Little Ice Age and earlier glacier advances (Maslokas et al., 2009). Similar acoustic facies have been reported from 3.5 kHz records from several Chilean fjords by Araya-Vergara (1999a), which he interpreted as ponded glacimarine sediment. The processes of glacimarine transport and delivery of sediments are likely to be mainly by turbid meltwater plumes derived from tidewater glaciers and glacioluvial systems. The rarely observed pebbles are presumably derived by iceberg-rafting of debris of all grain sizes. Relatively similar seismic- and litho-facies have also been reported from Marinelli and Ainsworth fjords to the south of our study area (Boyd et al., 2008). Here, radiocarbon dates allowed the calculation of sedimentation rates of tens of millimetres per year and about 0.5 mm yr$^{-1}$ for ice-proximal and ice-distal sediments, respectively (Boyd et al., 2008). Sedimentation rates are likely to be much higher than this as tidewater glacier margins are approached (e.g. Powell and Molnia, 1989).

The acoustic and sedimentary characteristics of glacimarine sediments reported from Canal Baker and the Marinelli Fjord area of the Chilean fjordlands (DaSilva et al., 1997; Boyd et al., 2008) are similar to observations from northern hemisphere fjords in southeast Alaska (Powell and Molnia, 1989; Cowan and Powell, 1990; Cai et al., 1997), Spitsbergen (e.g. Elverhøj et al., 1980; Dowdeswell and Dowdeswell, 1989; Sexton et al., 1992; Svensen et al., 1992) and Canadian Baffin Island (e.g. Syvitski, 1989; Gilbert et al., 1990; Stravers and Syvitski, 1991; Gilbert, 1992). In all these areas, glacimarine sedimentation beyond sandy to gravelly ice-contact fans, formed in the few hundred metres closest to the subglacial channels emerging at tidewater glacier margins (e.g. Powell, 1990), is usually of sorted and sometimes laminated fine-grained debris derived from turbid meltwater (e.g. Elverhøj et al., 1980; Gilbert, 1992). This is supplemented by the occasional delivery of coarser-grained iceberg-rafted debris (e.g. Dowdeswell and Dowdeswell, 1989; Gilbert, 1990).

Some bays in the South Shetland Islands, offshore of the western Antarctic Peninsula and about 1500 km south of the Chilean fjords, also contain over 100 m of Holocene infill that is derived largely from fine-grained meltwater-plume sedimentation, although deltas and submarine channels have not been observed here (Milliken et al., 2009). The strong environmental gradient across Bransfield Strait to the colder Antarctic Peninsula is reflected in much lower Holocene sediment thicknesses, typically of only a few metres, attributed to reduced meltwater discharge and fine-grained sediment delivery (Griffith and Anderson, 1989, 1999). Thus, differences between ‘temperate fjords’, such as those of Chile and south-east Alaska, and those of colder glacier-influenced environments include reduced meltwater and fine-grained sediment inputs (Griffith and Anderson, 1989; Anderson, 1999), together with the absence of submarine deltas and channels. The latter may reflect a lack of any direct fluvial influence and the increasingly limited delivery of sediment-laden meltwater from the base of tidewater glaciers in progressively colder conditions.

7.3. Meltwater- and iceberg-dominated fjord sedimentary systems

Having noted the similarities in seismic and sedimentary observations between the Chilean fjords and several relatively mild northern hemisphere locations at which glaciers reach the sea, it is useful to consider just where the fjordlands of Chile sit on the continuum of marine environments in which glaciers and ice-sheets enter marine waters. It is notable that locations such as south-east Alaska, the sub-Antarctic South Shetland Islands, Spitsbergen and Canadian Baffin Island are all relatively mild compared with, for example, fjord and shelf settings in North and Northeast Greenland and much of Antarctica (excluding the relatively warm western Antarctic Peninsula). In these much colder locations, water temperatures of less than zero degrees Celsius are not uncommon, with mean annual air temperatures also consistently below freezing. Here, glacier and ice-sheet mass loss is mainly by iceberg production and, sometimes, basal ice-shelf melting (e.g. Jenkins and Doake, 1991), instead of meltwater runoff (e.g. Dowdeswell et al., 1998; Siegert and Dowdeswell, 2002). Terrigenous sedimentation in these much harsher glacial and glacimarine settings is therefore dominated by debris transfer by icebergs, which transport and deliver sediment of all grain sizes to the glaciomarine environment, in contrast to the fine-grained and sorted debris derived from meltwater plumes. Fjord and shelf sediments in these colder, iceberg-dominated glacimarine settings are often diamicitic (e.g. Dowdeswell et al., 1994a,b, 1998) and, in the coldest waters offshore of East Antarctica, icebergs may even traverse the inner shelf without melting to release diamicitic material; in these areas sedimentation is by very slow rain-out of predominantly biogenic debris (e.g. Domack, 1988).

In addition, the rate of sediment delivery to many high-latitude fjord and, especially, more distal continental-shelf environments is very slow once ice sheets have retreated, sometimes hundreds of kilometres, to their interglacial position (e.g. Canals et al., 2000; Dowdeswell et al., 2004, 2010; Mosola and Anderson, 2006). This explains, in part at least, why landforms produced beneath active full-glacial ice sheets are often well-preserved in many high-latitude sea-floor settings, where they remain largely unburied and unmodified in areas of low Holocene sedimentation which are below wave-base. An exception is where these landforms are reworked by the ploughing action of deep-keeled icebergs (e.g. Dowdeswell et al., 1993, 2010; Ó Cofaigh et al., 2005b; Evans et al., 2006).

These cold, iceberg-dominated glacimarine environments contrast with the fjordlands of Chile, which are dominated by sediment delivery from meltwater that is produced mainly by strong surface ablation in summer and routed via the glacier bed before entering marine waters as a rising plume of high suspended-
sediment content that distributes fine-grained debris widely over the adjacent fjord system. This form of meltwater-dominated sedimentation is reflected in the ice-proximal wedges and draping ice-distal seismic architecture of the Chilean fjords, the sorted and often laminated fine-grained nature of the sediments (DaSilva et al., 1997; Boyd et al., 2008), and the predominantly flat and relatively smooth floor of most Chilean fjords. The latter are broken mainly by isolated moraine ridges that record still-stands in ice retreat; elsewhere continuing sedimentation of fine-grained meltwater-derived debris during the Holocene has probably contributed to the burial of many of the streamlined landforms produced under full-glacial conditions at the glacier bed. The draping of sea-floor topography by fine-grained sediments raining out of fjord waters can be seen clearly in Fig. 4A. An important exception to this is the sea floor close to the margins of Chilean tidewater glaciers that have retrograded only recently from Little Ice Age maxima; here a more diverse set of moraine ridges and streamlined bedforms remains visible on swath-bathymetric imagery close to the modern margin of Tempano Glacier in Iceberg Fjord (Fig. 2).

We can, therefore, plot the position of the Chilean fjordlands on a continuum of climatic and oceanographic settings from the mildest to the coldest parts of the Earth at which glaciers and ice sheets reach the sea (Fig. 12) (Dowdeswell et al., 1998). In the southern hemisphere, the fjords of southern Chile represent one end of this continuum; their northern hemisphere equivalents are the fjords of south-east Alaska where mass-turnover and meltwater production from the adjacent glaciers are of a similar order of magnitude. In addition, rainwater sometimes provides an increment of runoff in these areas (Cowan et al., 1988). Slightly colder environments, with lower glacier mass-turnover and, hence, meltwater production from the adjacent glaciers are of a similar order of magnitude. In the addition, rainwater sometimes provides an increment of runoff in these areas (Cowan et al., 1988). Slightly colder environments, with lower glacier mass-turnover and, hence, meltwater production from the adjacent glaciers are of a similar order of magnitude.

7.4. Landform assemblage model for mild meltwater-dominated fjords

The assemblage of glacial, glacifluvial and glacimarine landforms found in the fjords of Chile is summarised in the schematic model in Fig. 13. The three main component landforms of the landform-assemblage model for such climatically mild meltwater-dominated fjords are given below.

(A) Moraine ridges mark the locations of still-stands during ice retreat down fjords (Fig. 7), including the limit of recent ice advance during the Little Ice Age (Fig. 2). The ridges are oriented transverse to past ice-flow, are asymmetrical with steeper ice-distal sides, and sometimes have debris-flow lobes on their ice-distal flanks. Smaller moraines ridges, located inside Little Ice Age moraines, mark ice retreat over the past century or so (Fig. 2).

(B) Glaciﬂuvial and ﬂuvial delta are formed from sediment delivered by braided rivers from terrestrial glaciers or ﬂuvial catchments (Figs. 5, 6 and 8). They have small channels and chutes, and sometimes debris-flow lobes, on their submarine faces.

(C) Sinuous and relatively deep turbidity-current channels are set within the predominantly smooth fjord floor (Figs. 5 and 6).

It should be noted that both glaciﬂuvial and ﬂuvial deltas, together with turbidity-current channels, remain active today in the fjords of Chile, whereas the glacial component of the landform-assemblage model is often relict. Apart from these landforms, the sedimentary sea floor of Chilean fjords is predominantly smooth. Bedrock ridges may break through to the surface but, where underlying topography is present, it is often draped by subsequent fine-grained sedimentation from meltwater plumes that gradually bury any pre-existing relic landforms and smooths out irregularities.

When this landform-assemblage model for the fjords of Chile is compared with the morphology of the sea floor in fjords and cross-shelf troughs from other glacier-influenced marine environments, it is clear that subglacially produced landforms (e.g. drumlins, crag-and-tails, mega-scale glacial lineations) are largely absent in the Chilean case (Figs. 11 and 13). Only within a few kilometres of modern tidewater glacier margins, between moraine ridges marking the limit of Little Ice Age advance and the modern tidewater glacier terminus, are smaller transverse moraine ridges found (Fig. 2). In Spitsbergen fjords and cross-shelf troughs, for example, mega-scale glacial lineations and other sedimentary landforms produced by active subglacial processes are common where fast-flowing ice streams drained the interior ice sheet (Ottesen et al., 2005, 2007). In inter ice-stream locations, where ice flux was lower, series of transverse moraine ridges of various sizes predominate (Ottesen and Dowdeswell, 2009). Only in a few Spitsbergen fjords, such as Magdalenefjorden on the relatively mild west coast, do smooth sea-floor basins and sediment-draped submarine topography predominate (Ottesen and Dowdeswell, 2009). In colder high-polar glacimarine environments, streamlined sedimentary landforms, moraine ridges and grounding-zone wedges, formed in subglacial and ice-contact positions during the LGM and deglacial period between about 20,000 and 10,000 years ago, are characteristic submarine landforms on swath-bathymetric imagery of Greenland and Antarctic continental shelves (e.g. Canals et al., 2000; Dowdeswell et al., 2004, 2010; Ó Cofaigh et al., 2005b; Mosola and Anderson, 2006; Dowdeswell and Fugelli, 2012).

Subglacial and ice-contact landforms, similar to those observed in higher-latitude fjords and shelves, are likely to have been formed at the base and margins of Chilean glaciers under full-glacial and deglacial conditions. High rates of snow-accumulation and ice-surface melting on glaciers draining the Andian mountains led, however, to rapid meltwater and fine-grained sediment delivery into the relatively low-latitude Chilean fjords from both tidewater glaciers and glaciﬂuvial drainage systems after deglaciation. Most pre-existing glacial landforms on the fjord floor, with the exception of major retreat moraines (Figs. 2 and 7) and protruding streamlined bedrock (Fig. 4B), are likely to have been buried and obscured by this subsequent glacimarine and glaciﬂuvial sedimentation.
It is predominantly submarine landforms which remain in an active process environment today, for example turbidity-current channels, which are observed on our swath-bathymetric imagery.

South-east Alaska provides a likely northern-hemisphere equivalent to the fjordlands of Chile, with similarly high precipitation and glacier melt rates. In Alaskan fjords, sedimentation derived predominantly from glacial meltwater reaches rates of more than a metre per year close to the margins of modern tidewater glaciers and is transported to more ice-distal locations by plumes of suspended sediment (e.g. Powell and Molnia, 1989); this would be quite sufficient to bury most subglacial and ice-contact landforms produced by LGM ice sheets or during subsequent deglaciation beneath a relatively smooth cover of draping fine-grained glacimarine debris. It is noteworthy that the turbidity-current channels that are observed in Alaskan and British Columbian fjords remain active today (Syvitski et al., 1987), precluding burial by rain-out of fine-grained glaciﬂuvial and ﬂuvial sediments. In addition to deposition from meltwater, sediment gravity ﬂows that are sometimes sourced from steep fjord walls have also been reported to infill the floors of Alaskan fjords (Cowan et al., 2010). Tides are a further mechanism for the redistribution of fine-grained sediments in many Alaskan fjords (Cowan et al., 2010), through both the generation of strong currents and their effects on the time-dependent behaviour of meltwater plumes. Glacier Bay is macrotidal, with a tidal range exceeding 4 m in its inner arms that generates currents of about 2.5 m s⁻¹ where fjords narrow (Hooge and Hooge, 2002). This compares with tides of 1.66 m and 2.05 in Canal Messier and Canal Wide in our Chilean fjord study area (Fierro, 2008). Strong currents, especially where fjords narrow, may also be a mechanism for sediment reworking and redistribution in Chilean fjords.

8. Summary and conclusions

The Chilean fjords are at the lowest latitude in either hemisphere where glaciers reach the sea today. High accumulation and mass throughput sustain tidewater glacier margins in what are relatively mild climatic and oceanographic conditions. Swath bathymetry of almost 27,000 km² of sea floor in the fjordlands of southern Chile (42–55° S) was acquired between 2003 and 2008, allowing mapping of sea-floor landforms and inferences to be made on the nature of glacimarine sediments and sedimentation. Tidewater glaciers draining the Southern Patagonian Ice Cap are present in several fjords. The sea floor beyond retreating Tempano Glacier has an outermost terminal moraine marking the limit of ice advance during the Little Ice Age (Fig. 2). Sets of smaller transverse ridges closer to the glacier were deposited during still-stands or minor readvances in ice retreat. Streamlined lineations in the

![Fig. 13. A schematic landform-assemblage model for meltwater-dominated fjords subject to relatively mild climatic and oceanographic conditions, such as the fjordlands of southern Chile. The inset shows the efflux of a subglacial meltwater channel at the tidewater glacier terminus and the plume of turbid sediment and ice-proximal fan produced beyond the channel mouth.](image-url)
innermost fjord were produced beneath active ice. By contrast, beyond advancing Pio XI Glacier there are few signs of organised submarine landforms (Fig. 3). Isolated hummocks and ridges are probably the product of a previous glacier surge. Predominantly smooth and flat areas of the sea-floor beyond the two tidewater glaciers are interpreted as sedimentary infill from rainout of fine-grained debris from turbid meltwater (Fig. 4).

Older ridges are also located along and at the outer mouths of several Chilean fjords (Fig. 7), and are interpreted to be moraines formed at retreating margins of grounded tidewater glaciers during still-stands in deglaciation; deglaciation is inferred to be episodic rather than catastrophic (Dowdeswell et al., 2008).

Where glaciers do not reach the sea, meltwater-fed braided rivers connect the glacial and marine sedimentary systems. Swath imagery shows glacialfluvial and fluvial deltas with series of small channels and narrow chutes (Figs. 5 and 6). Beyond the delta-fronts are sinuous turbidity-current channels extending for kilometres along flat fjord floors (Figs. 5 and 6).

Relatively few other sedimentary landforms were imaged. Some streamlined sea-floor lineations were observed (Fig. 4B), but are largely buried by rapid post-glacial sediment delivery except where forming sculpted bedrock highs. Almost no iceberg-keel ploughmarks were observed, probably due to a combination of relatively deep water, the restricted keel-depth of most tidewater-glacier-derived icebergs, and rapid melting in mild water. Examples of submarine slope failures were restricted mainly to lobate slumps on delta fronts (Figs. 6 and 8). In addition, sets of crater-like pockmarks provide potential indicators of shallow gas in a few locations (Figs. 9 and 10).

The fjords of Chile are dominated by sediment delivery from turbid meltwater produced by ice-surface ablation and snowmelt that enters marine waters from tidewater glaciers and glacialfluvial systems and distributes fine-grained debris widely over the adja-
cent fjord systems. This meltwater-dominated sedimentation is reflected in the sorted and often laminated fine-grained nature of the sediments (DaSilva et al., 1997; Boyd et al., 2008), the ice-proximal wedges and draping ice-distal seismic architecture, and the predominantly flat and relatively smooth floor of most Chilean fjords.

The Chilean fjordlands represent the mildest climatic and oceanographic end-member of a continuum of glacier-influenced marine settings (Fig. 12). Their northern hemisphere equivalent is south-east Australia. Slightly colder environments, with lower glacier mass-turnover and, hence, meltwater production, are the fjords of Spitsbergen and Baffin Island. By contrast, the waters offshore of East Antarctica represent the most extreme glacialmarine environment, where even icebergs do not melt in the frigid waters (Fig. 12).

A landform-assembly model for climatically mild meltwater-dominated fjords is given in Fig. 13. Three main types of landform predominate (Figs. 11 and 13): ice-contact moraine ridges; glacialfluvial and fluvial deltas; and turbidity-current channels. Full-glacial and deglacial streamlined subglacial landforms are likely to have been buried and obscured by subsequent glacialmarine sedimentation; it is predominantly submarine landforms where sedimentary processes remain active today, such as turbidity-current channels, that are observed on our swath-bathymetric imagery of otherwise relatively smooth sedimentary fjord floors.

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