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Invited review

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 km^2 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 km^2 in the Northern and Southern Patagonian ice caps (total areas 4197 km^2 and 13,000 km^2, 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,b; 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-

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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 glacimarine 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 km^2 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 glacimarine processes. Ice has, however, retreated through the fjord system since the LGM leaving a record of Late Quaternary subglacial and ice-contact landforms. 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 glacimarine 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 glacimarine 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 km^2 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 Hydrosweep 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. Pfirman 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;