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Geophysical evidence of multiple glacier advances in Lago Fagnano (54°S), southernmost Patagonia

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ABSTRACT

The Island of Tierra del Fuego, at the southernmost extreme of Patagonia, is located in one of the most extensively glaciated areas of the Southern Hemisphere outside Antarctica during the late Pleistocene. The Lago Fagnano region, at ~54°30′S and ~68°W, has experienced several phases of glacier growth and retreat since the Last Glacial Maximum (LGM). We illustrate these phases using combined geomorphological, geophysical and coring surveys in Lago Fagnano itself, a ~105 km-long, E–W-oriented glacio-tectonic basin. We identify and map a complex set of submerged frontal, central and lateral moraines covered by lacustrine sediments using seismic stratigraphic analysis of multi-channel profiles imaging the sub-lake floor. We then combine these geophysical data with field observations and regional maps of similar structures around the lake to reconstruct the spatial behavior of the Fagnano paleo-glacier since the LGM. We interpret the preserved frontal moraines as having formed during at least 20 re-advance stages of the glacier within a long-term deglaciation interval post-LGM. Preliminary tephrochronological dating of a ~7.5 m long core indicates a step-wise deglaciation pattern comprising a final glacier re-advance stage at ~11.2 ka BP.

1. Introduction

Among the physical systems on Earth linked to climate change, glaciers are one of the most responsive to climate fluctuations through time. During the Quaternary, glaciers have generally followed global temperature changes paced by Milankovitch cycles (Hays et al., 1976). Perhaps the best example of this periodicity is the transition from the Last Glacial Maximum (LGM), when glaciers covered most of southernmost South America (Fig. 1A), to the current interglacial, with only limited glacial coverage there. In this paper, we use geophysical profiles and core data to examine glacial features in the geological record of a lake in southernmost Patagonia, on the island of Tierra del Fuego, to provide clues as to timing and causes of abrupt Quaternary climate changes in the Southern Hemisphere.

Although precise dating of the LGM in Tierra del Fuego is still lacking, the best estimate is that it occurred between 18 and 20 ka (Rabassa et al., 2000). During the LGM, Patagonian glaciers expanded and formed a continuous ice field extending from ~35°S to ~56°S (Caldenius, 1932) (Fig. 1A). Since then, glaciers have generally waned in response to millennial and centennial climate oscillations, but have also expanded locally during periodic intervals of regional humidity increases (Fig. 1B; Kaplan et al., 2008). The Island of Tierra del Fuego is located at the southernmost extreme of this former ice field and only ~900 km north of the Antarctic Peninsula, thus providing an ideal location to study high-latitude Southern Hemisphere environmental changes during the Quaternary, bridging between known Patagonian climate records and their Antarctic counterparts.

Lago Fagnano, lying along 54°S in the southernmost part of Tierra del Fuego, is a ~105 km long and 5–10 km wide lake that occupies a half-graben pull-apart basin developed along the transcurrent South American Plate-Scotia Plate boundary (Fig. 2A; Klepeis, 1994; Menichetti et al., 2008; Tassone et al., 2008). This lake basin has also been intensely affected by repeated glaciations (Bujalesky et al., 1997; Rabassa et al., 2000; Coronato et al., 2002, 2009). The lake-floor morphology is composed of a deeper (~200 m) basin in the east and an elongated, shallower (~120 m) basin in the west, separated by a 30 m-deep sill (Fig. 2A). The geographic setting and

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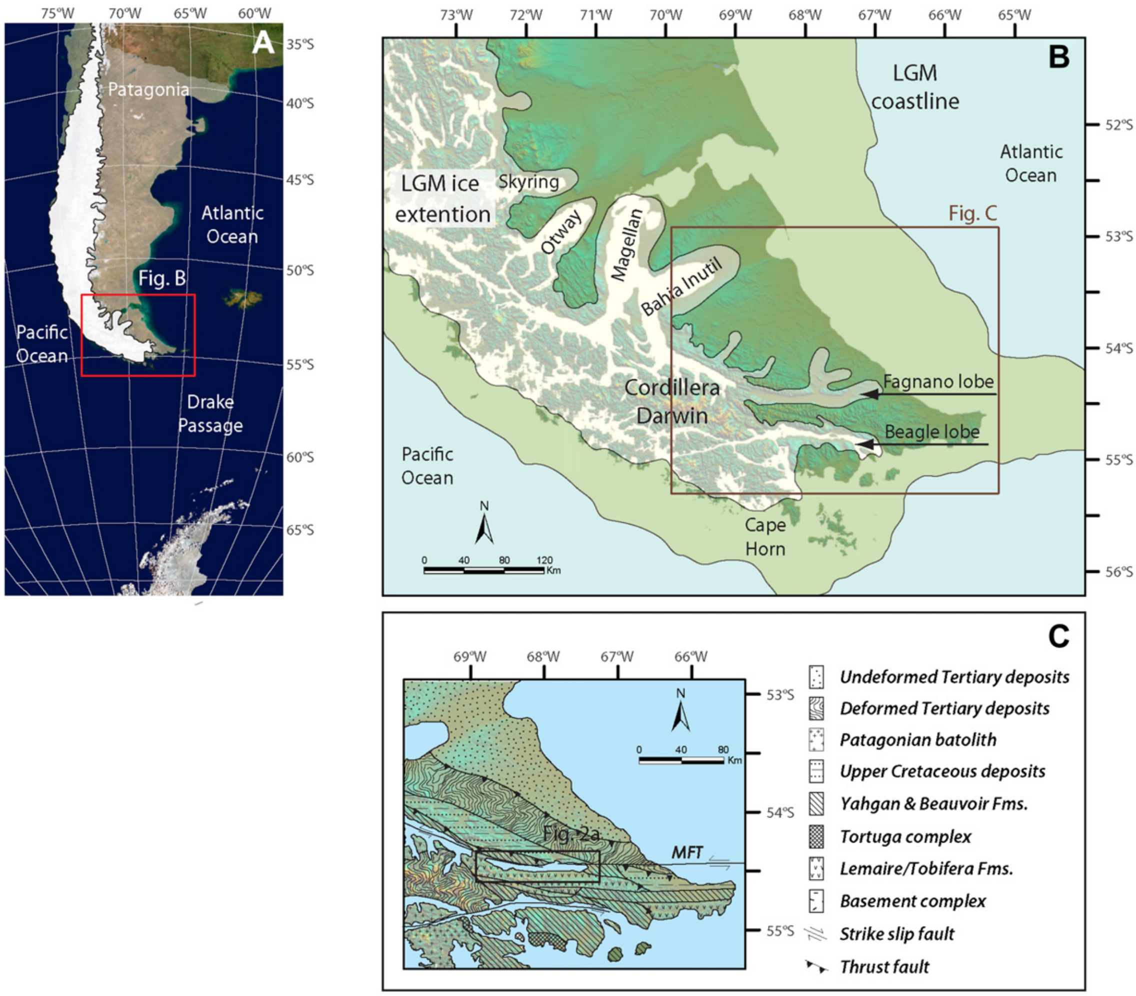


Fig. 1. A) Location map of Patagonia, the southernmost part of South America. The white area denotes the maximum extension of ice during the LGM (after Singer et al., 2004). B) Shuttle Radar Topographic Mission (SRTM; Farr et al., 2007) map of the Island of Tierra del Fuego, with the major physiographic units recognized during the LGM. White areas represent the maximum extension of ice (note: the Fagnano ice lobe occupied the entire area which is now Lago Fagnano) and pale green areas represent the exposed continental shelf as a result of lowered sea-level during the LGM (modified from Coronato et al., 2009). Note that the Fagnano (ice) lobe occupied the entire area now occupied by Lago Fagnano during the LGM. C) Simplified geologic sketch of the eastern half of Tierra del Fuego Island, adapted from Olivero and Martinioni (2001). MFT stands for Magallanes-Fagnano Transform fault. Location of Fig. 2A is shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

morphology of these basins make Lago Fagnano suitable for examining the sediment record of post-LGM glacier fluctuations. In this study, we analyze geophysical, sedimentological and geomorphological evidence from Lago Fagnano for multiple glacier advances into the Fagnano basin since the LGM. Then, we compare our multi-proxy evidence with other regional glacier reconstructions (e.g., Coronato et al., 2009) in an attempt to constrain the timing of these glacial fluctuations. Finally, we use our observational data and interpretations to speculate about ice-induced climate changes in southernmost South America during the Quaternary.

2. Approach

Over 800 km of single-channel high-resolution 3.5 kHz (pinger) and 1 in^3 airgun multi-channel seismic (MCS) profiles were acquired simultaneously using a small, versatile research vessel, the *Neecho*, in the Argentinean portion ($\sim$87%) of Lago Fagnano in 2005 (Fig. 2A). The pinger survey provides seismic stratigraphic information about subsurface sediments to depths of up to several tens of meters, while the airgun profiles image deeper sedimentary deposits and in places the basin's basement morphology. Parameters used for processing the data are explained in Waldmann et al. (2008). We interpreted the seismic data using Kingdom Suite™ software developed by Seismic Micro-Technology, Inc. We assumed an average water column velocity of 1430 m/s and 1500 m/s for the sedimentary infill.

Based on interpretation and mapping of the seismic data, we sited and recovered a series of 18 piston cores up to 8 m in length using a Kullenberg-type coring system on the *Neecho*. Methods used to document the petrophysical, sedimentological and geochemical properties of the cores have been previously described (Waldmann et al., 2008). We also performed radiocarbon analyses on terrestrial organic material found in two sedimentary cores from both the eastern and western sub-basins (Fig. 2A), using the AMS ^{14}C method (for detail on radiocarbon methodology, see Bonani et al. (1987). Three radiocarbon ages (two retrieved from the eastern core and only one from the western core) were calibrated using OxCal v3.10 (Bronk-Ramsey, 2005). Additional geochemical fingerprinting performed by ICP-MS measurements were accomplished on a tephra layer from the same core (Waldmann et al., in press) in order to identify its possible origin. We conducted these chronological analyses to attempt to assess the magnitude and timing of some of the glacier advances in the Fagnano region. Results from both lacustrine

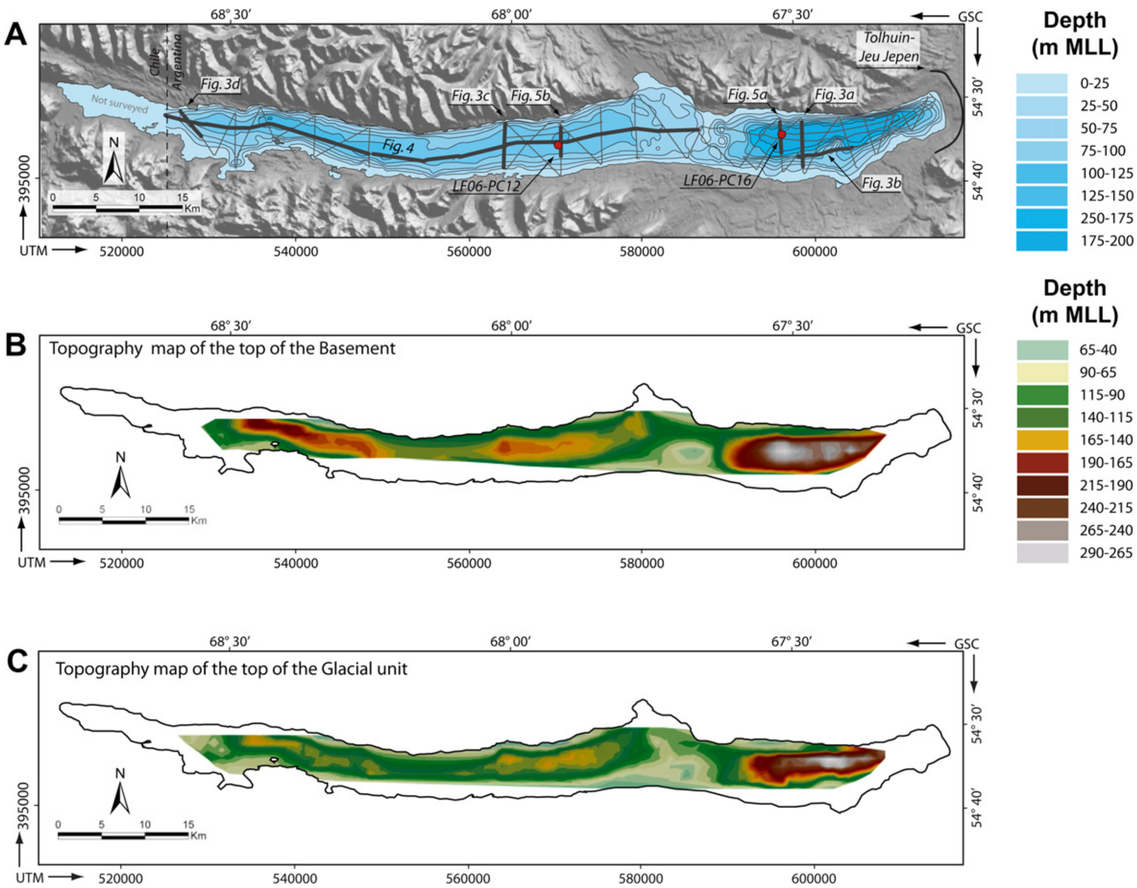


Fig. 2. A) Bathymetry of Lago Fagnano with 25-m contour interval (modified from Lodolo et al., 2003) plotted over a SRTM map with the entire seismic grid collected for this study. Thicker lines and the red dots indicate, respectively, the locations of seismic profiles and sedimentary piston cores presented in this article. Geographical system coordinates (GSC) are shown (right and top), along with UTM coordinates (left and bottom). Depth is denoted in meters below mean lake level (MLL) and is converted from two-way traveltime. The Tolhuin-Jeu Jepen moraine (Coronato et al., 2005) is marked by a solid black line. B) Topographic map of interpreted basement beneath Lago Fagnano; legend on the right indicates contoured depth interval, assuming water velocity of 1430 m/s and sediment velocity of 1500 m/s. Note the deeper structure of the eastern sub-basin and the sill that separates it from the shallower western sub-basin. C) Topographic map of the top of the interpreted glacial unit beneath Lago Fagnano; legend in Fig. 2B. A prominent terminal moraine on top of the sill dividing the two sub-basins is well-defined; see Fig. 4 for seismic profile across this moraine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

geophysical and terrestrial geomorphological surveys around the Fagnano basin were combined in order to reproduce our presumed paleo-glacier fluctuations over a Shuttle Radar Topographic Mission (SRTM; Farr et al., 2007) map of this region using ESRI©-based GIS software (Fig. 2).

3. Regional and environmental settings

Tierra del Fuego weather is currently dominated by annual fluctuations of cold, sub-polar winters and mild summers, coupled with precipitation increases brought by the Southern Hemisphere Westerlies (SHW) (Kutzbach et al., 1993; Rosenbluth et al., 1995; Wyrwoll et al., 2000). The positioning of this wind belt is controlled by the strength and latitudinal location of the subtropical anticyclone in the Southeast Pacific and the circum-Antarctic low-pressure belt (Rogers and van Loon, 1982; Lamy et al., 2001). The SHW are the main provider of humidity/precipitation to Tierra del Fuego from the southern Pacific Ocean (Strub et al., 1998; Klinger et al., 2003). Variability in the position and/or intensity of the SHW since the LGM has influenced precipitation and temperature changes throughout Patagonia (Villa-Martinez and Moreno, 2007; Moy et al., 2008; Waldmann et al., in press). Because glaciers are sensitive to such precipitation and temperature changes (Douglass et al., 2005), knowledge of the timing and magnitude of glacier advance and/or retreat provides a proxy tool for determining SHW fluctuation history. Glacier advance/retreat history can be further applied to assess a variety of proposed mechanisms of latest Pleistocene–Holocene climate change.

The timing of the LGM in Tierra del Fuego has been suggested as spanning between 18 and 20 ka (Rabassa et al., 2000). During this period, as was also the case with other ice bodies throughout Tierra del Fuego, the former Fagnano glacier originated from the main ice-cap to the west, at Cordillera Darwin (Fig. 1B; Coronato et al., 2002, 2005). The Fagnano glacier flowed eastwards, reaching a total length of $\sim$130 km before eventually draining into the Atlantic Ocean through four main outwash plains (Coronato et al., 2005). In what is now the western basin of Lago Fagnano, however, this glacier was confined to a relatively narrow zone, building an alpine-type landscape characterized by multiple tributary glaciers (Coronato et al., 2009). A basement promontory, which now divides the lake into its two sub-basins (Fig. 2B), bifurcated the Fagnano glacier into three main lobes (Coronato et al., 2005). At its maximum extent, ice covered an area of $\sim$4000 km^2, with an eastward slope of 8° and a total ice volume of $\sim 54 \times 10^5$ m^3 (Coronato et al., 2009). Although prominent frontal moraines formed during the LGM have not been recognized (Coronato et al., 2005), eroded remnants of interpreted lateral and basal moraines have been mapped $\sim$30 km east of the present eastern end of Lago Fagnano (Coronato et al., 2002). Basal and lateral moraines, as well as isolated drumlins, are most frequent along the southern coast of the lake (Coronato et al., 2009).

During the Lateglacial (15–∼12 ka), the Fagnano glacier retreated, along with most of its southern Patagonian equivalents (Heusser, 1998; Sugden et al., 2005), although with unknown timing of the different intermediate positions. Based upon our new data from Lago Fagnano summarized below, we suggest that this long retreat period also encompassed short intervals of increased humidity, likely caused by southward SHW shifts towards Lago Fagnano latitudes, causing glacier re-advances with associated deposition of geographically and topographically distinct terminal moraines.

The mid-Holocene (∼6 ka BP) marks the onset of the Neoglacial in Tierra del Fuego (Unkel et al., 2008; Waldmann et al., in press). During this interval, the Fagnano glacial lobe advanced again, but the ice was probably confined only to the high-mountain region of Cordillera Darwin to the west, as was and is the case for other regional glaciers (Fig. 1B; Planas et al., 2002; McCulloch et al., 2005b; Boyd et al., 2008). The present Lago Fagnano basin probably was not affected directly by glacial ice during this period.

In this paper, we use our new seismic and core data from Lago Fagnano to constrain some of these re-advance and/or stillstand stages of the Fagnano glacier during the Lateglacial period, the sedimentary record of which remains preserved only because of the continued presence of the lake.

4. The Lago Fagnano geological setting

4.1. Structure and seismic stratigraphy of the Lago Fagnano basin

The new MCS data image the Lago Fagnano sedimentary succession, and in places underlying acoustic basement, to depths of >150 m (Waldmann et al., 2008, in press). On the basis of distinctive seismic facies, similar to those recognized in other alpine lacustrine environments (Finckh et al., 1984; Mullins et al., 1996), Waldmann et al. (in press) interpret three major seismic stratigraphic units (Fig. 3): a bedrock/basement complex, overlain by ice-contact/glacial deposits, which in turn are buried in part by glacio-lacustrine and lacustrine successions infilling topographic lows. The top of presumed basement is an irregular surface developed on older Andean metasedimentary units (Fig. 1C), probably representing erosion by successive advances and retreats of the Fagnano glacier (Fig. 2B); similar basal erosional surfaces are observed within other similar high-latitude glaciated regions (Rise et al., 2006; Ottesen et al., 2008; Hjelstuen et al., 2009).

The eastern sub-basin of Lago Fagnano (Fig. 2B), deeper than its western equivalent, suggests either that it has experienced amplified tectonic subsidence or more glacial erosion. While those possibilities cannot be differentiated with our data, we suggest that continuing strike-slip movement along the Magallanes–Fagnano plate boundary (Cunningham, 1993) coupled with glacial erosion may have shaped this sub-basin, although we observe no major seismic evidence for such movement.

The interpreted glacial infill of the Fagnano basin, which is sandwiched between the underlying basement unit and the overlying glacio-lacustrine and lacustrine sediments, has a complex relief with crests reaching variable thicknesses of 10–100 m (Figs. 2C, 3 and 4). This composite unit, labeled G, is generally acoustically semi-transparent to chaotic, bounded by continuous to discontinuous high-amplitude reflections. The seismic properties of this unit, coupled with its complex local structural relief and variable thicknesses, suggest that the observed crested morphologies are moraines, although we cannot differentiate seismically whether they represent terminal, central or lateral structures, other than by their general orientation relative to the suspected east–west paleo-ice flow direction (Fig. 1B). Moreover, the seismic data do not allow us to discern if the interpreted moraine structures were formed during glacier re-advances or stillstands, as they have little diagnostic internal structure (Fig. 3A and B). The moraine structures are identified in a wide range of depths, between ∼50 and ∼150 m depth below the present lake level, and occur both in the central parts of the basin (e.g., moraines labeled B10 and B11; Fig. 3C) and near the basin shoulders (e.g., moraine labeled C10; Fig. 3D). Continuous, high-amplitude, sub-parallel intra-glacial unit reflections are occasionally recognized in several moraines (e.g., labeled G1–G3, from oldest to youngest horizons; Fig. 3B). We interpret this seismic architecture as superposition of stacked moraines constructed during repetitive advances and retreats of the Fagnano glacier. Similar structures have been interpreted in Arctic Canada and Greenland to be formed by shearing of sub-glacial debris onto glacier surfaces, as a result of sub-glacial meltwater activity at the confluence of two or more glaciers (Evans, 2009).

4.2. Seismic stratigraphy of the glacio-lacustrine infill of Lago Fagnano

Within both eastern and western sub-basins of Lago Fagnano, the interpreted glacio-lacustrine and lacustrine sedimentary sequences have partially buried ice-contact/glacial morphologies, providing further information about the regional depositional conditions. As a result, the lake basin is a valuable archive of sedimentation not found elsewhere, since these suspected moraine morphologies have mostly been erased on land by ensuing wind and rain erosion during the Holocene (Coronato et al., 2009).

Seismic stratigraphic analyses of the high-resolution pinger/3.5 kHz data in the eastern sub-basin (Waldmann et al., in press) reveal three major units (EA–EC) within the interpreted glacio-lacustrine unit (Fig. 5A). The oldest unit, EA, ponds within underlying morphology, reaching thicknesses of up to 50 m (Waldmann et al., 2008). EA is characterized by a transparent to semi-transparent chaotic seismic facies, with occasional internal medium-energy parallel-continuous reflections. In contrast, overlying unit EB is characterized by discrete bands of equally-spaced, continuous, medium-to-high amplitude reflections separating transparent subunits reaching a total thickness of up to 6 m. Topmost unit EC drapes the entire sequence and is characterized by intercalations of thinly-spaced, high-amplitude internal reflections, with low-amplitude to transparent intervals that get thicker eastwards while becoming more chaotic, reaching thicknesses up to 10 m.

The seismic facies succession in the western sub-basin does not resemble the succession in the eastern sub-basin; we therefore reconstruct it independently and label it differently. We once again recognize three seismostratigraphic units, but we name them WA–WC, from the lowermost to the topmost, respectively (Fig. 5B). Unit WA comprises a package of low-amplitude reflections with medium continuity. Only the top of unit WA is imaged by the 3.5 kHz data, while the base is beyond seismic penetration at a sub-lake level depth of more than 155 m. WA reflections are identified only up to 10 m below the unit's top, before the 3.5 kHz signal energy fades. In contrast, overlying seismostratigraphic unit WB thickens to ∼12 m, draping underlying topography, and is characterized by thinly-spaced, high-amplitude, parallel-continuous reflections that gradually alternate upward to lower amplitudes. The uppermost seismic unit WC is characterized by low-amplitude reflections occasionally intercalated with semi-transparent intervals and medium-to-high-amplitude internal reflections. Overall, unit WC is ∼5 m thick, draping the inherited topography.

4.3. The glacio-lacustrine sedimentary record of Lago Fagnano

We calibrated the seismic sequences and the different seismic facies described in both eastern and western sub-basins using the

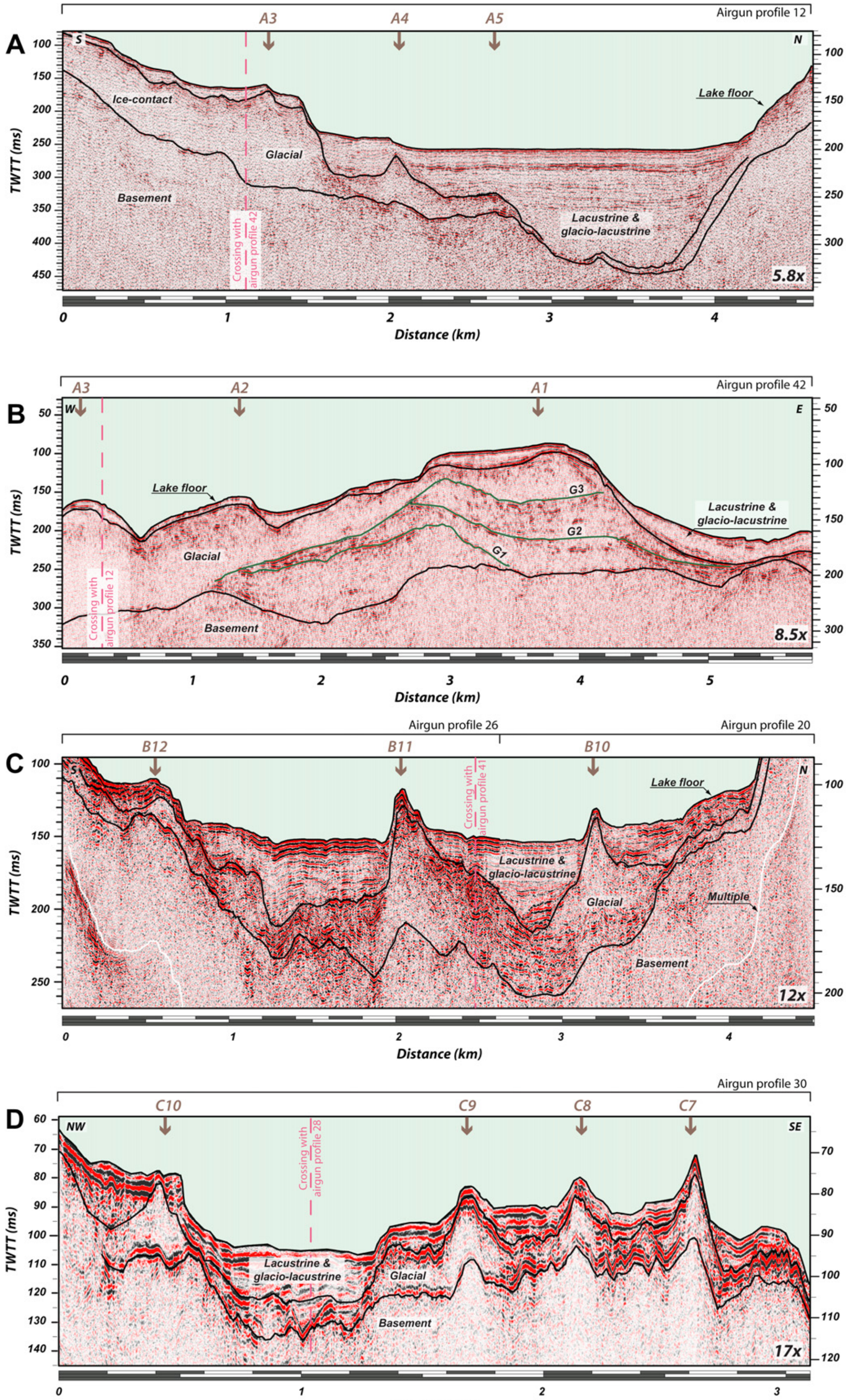


Fig. 3. A) North–south multi-channel seismic profile 12 crossing the eastern sub-basin (see Fig. 2A for location). Note U-shaped valley morphology caused by glacial erosion, with an interpreted lacustrine and glacio-lacustrine sedimentary infill >120 m thick. Three interpreted lateral moraines of the main Fagnano glacier (A3, A4 and A5) can be recognized. (Note: numbering scheme for moraine structures does not necessarily follow the relative age of the moraines, but instead denotes the geographical arrangement – A: easternmost sub-basin; B: central part of the western sub-basin and C: westernmost part of the western sub-basin). Pink dashed line marks the location of crossing profile 42 (Fig. 3B). B) East–west multi-channel seismic profile 42 crossing the eastern sub-basin. Along this profile, the interpreted glacial unit, G, reaches its maximum thickness of ∼100 m. Several glacier

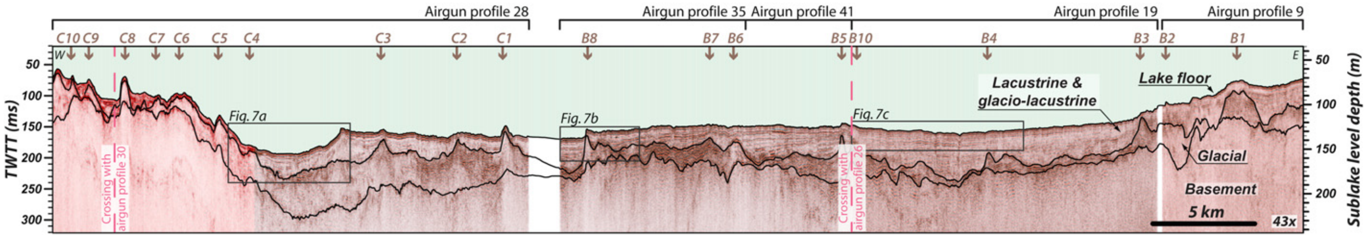


Fig. 4. East–west multi-channel seismic profile crossing the entire western sub-basin for >60 km (see Fig. 2A for location). Sediment depth is given in milliseconds of two-way traveltime (TWTT) and converted to sub-lake level depth (m), based on a *P*-wave velocity of 1430 m/s for water and 1500 m/s for sediment. Three main units are recognized, interpreted and mapped: an acoustic basement (Andean metasedimentary units) with an eroded upper surface, ice-contact/glacial deposits and glacio-lacustrine infill. We interpret topographic highs of the glacial unit as moraines of various types; these are marked by brown arrows and labeled correspondingly. B and C labels stand for distinct groups of interpreted moraines, arranged geographically with C presumably being younger than B. Pink dashed lines mark the location with crossing profiles 26 and 30, Fig. 3C and D, respectively. Locations of panels shown in Fig. 7 are also indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

petrophysical properties and sedimentary characteristics of two cores, one in the eastern sub-basin and one in the western sub-basin (Fig. 2A). Piston core LF06-PC16 was retrieved from a water depth of 196 m, penetrating almost all of seismic sequence EC and recovering almost 7.5 m of lacustrine sediments (Fig. 5C). The lithology consists of alternating pale-brown silty clay to clay. Laminations 0.5–1.0 cm thick gradually change upward to uniform alternations of brown silty clay laminae 0.5–2.0 mm thick and dark-green to black, organic material-enriched laminae. Variations of the measured petrophysical properties, density and magnetic susceptibility, mimic the seismic reflection pattern, allowing a precise core-to-seismic correlation. Small variations in both petrophysical values appear to be linked with layers consisting of brown, rather homogenous mud of variable thickness up to 20 cm interpreted as turbidites. We further interpret a very high magnetic susceptibility value at 4.8 m depth as marking the Hudson H1 tephra, dated to 7570 $\pm$ 120 ka (Stern, 2008). Waldmann et al. (in press) have geochemically fingerprinted by ICP-MS this tephra, confirming its source.

The seismic stratigraphy of the western sub-basin was corroborated with composite core LF06-PC12 (Fig. 5D). This 7.5 m long core was retrieved from 127 m water depth and penetrated the uppermost part of the seismic sequence WB and the entire WC. Four lithological units appear in the core (Waldmann et al., in press). The oldest recovered lithology, coinciding with the topmost part of seismic sequence WB, consists of light brownish clay, with laminae $\sim$1–1.3 cm thick and relatively low bulk density and magnetic susceptibility values. The overlying lithologies consist of 2–3 mm thick brown clay laminae, alternating with slightly coarser and lighter-colored laminae of clay and silt. These laminae gradually vary upward to an alternation of fine black and brownish laminae, similar to the sedimentary package described for core LF06-PC16 in seismic unit EC (Fig. 5A and C). Some 1–2 cm thick, well-rounded slate clasts are disseminated within the laminated sediments at $\sim$4.5–5.0 m depth, signifying dropstones. The H1 tephra was retrieved at only 1.4 m depth, suggesting a lower sedimentary rate when compared to the eastern sub-basin.

We determined three radiocarbon ages from both piston cores; these dates were further calibrated using the web-based CalPal share-ware converter tool (http://www.calpal-online.de/) (summarized in Table 1). Unfortunately, potential contamination by old or "dead" carbon sources within the watershed and/or by remobilization and deposition of older lacustrine sediments is possible (Moy et al., submitted for publication), so we treat the ages as maximum for their corresponding stratigraphic levels.

5. Fagnano glacier fluctuations since the LGM

The majority of glacial and climate reconstructions in southern South America are based on information gained from exposed mountain glaciers (Porter, 2000; Kaplan et al., 2004, 2008; Douglass et al., 2005; Glasser et al., 2008) and pollen records (Markgraf, 1993; Villa-Martinez and Moreno, 2007; Borromei and Quattrocchio, 2008), making this study of glacier advances/still-stands registered in the seismic stratigraphy of a lacustrine basin unique to this region. We identify the different moraines by: 1) geographical arrangement of the different morphologies within the basin, 2) orientation of the crests (see Fig. 4) in relation to the reconstructed movement axis of the Fagnano paleo-glacier ($\sim$E–W), and 3) comparison and correlation to similar structures previously mapped on land in the vicinity of Lago Fagnano (Coronato et al., 2002, 2005, 2009). We suggest that these moraines were deposited by the former Fagnano glacier and its tributaries, mostly during re-advance intervals within a longer post-LGM retreat period. Our interpreted lateral and central moraines run parallel to semi-parallel to the main basin axis, or $\sim$E–W, for several tens of kilometers. In contrast, interpreted terminal moraines are curved structures that cross the lake basin for shorter distances of 0.5 km–5 km (Fig. 6). Yet, our interpretation is limited by the existing seismic profile coverage. Using this map and the limited data from the two lacustrine cores, we also attempt to assess the relative ages of some of these moraines, as a primary proxy for post-LGM ice movements in southernmost Patagonia.

The easternmost identified post-LGM advance or stillstand of the Fagnano glacier occurred when the ice temporarily expanded to build a prominent terminal moraine that currently delimits the easternmost boundary of the lake, the Tolhuin-Jeu Jepen moraine (Coronato et al., 2009; Fig. 2A). Coronato et al. (2009) have

overriding stages are interpreted within the glacier unit and are labeled G1, G2 and G3. Pink dashed line marks the location of crossing profile 12 shown in Fig. 3A. C) North–south multi-channel seismic profiles 20 and 26 crossing the central part of the western sub-basin (see Fig. 2A for location). Three topographic highs of the interpreted glacial unit are >50 m thick and marked with brown arrows labeled B10, B11 and B12; we interpret these highs as the crests of central moraines (see also Fig. 5). D) Northwest-southeast multi-channel seismic profile 30 crossing the westernmost part of the western sub-basin (see Fig. 2A for location). Pink dashed line marks the location of crossing profile 28 shown in Fig. 4. Brown numbered arrows (C7–C10) indicate bathymetric highs of the glacial unit G, which we interpret as submerged moraine crests, representing ice-stillstand positions during the post-LGM recession. In this case, the ordering of C7 through C10 indicates relative age, with C7 being the oldest and C10 the youngest. On all seismic sections, depth is given both in milliseconds of two-way traveltime (TWTT) and converted to sub-lake level depth (m) based on a *P*-wave velocity of 1430 m/s for water and 1500 m/s for sediment (see also Fig. 2B, C). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

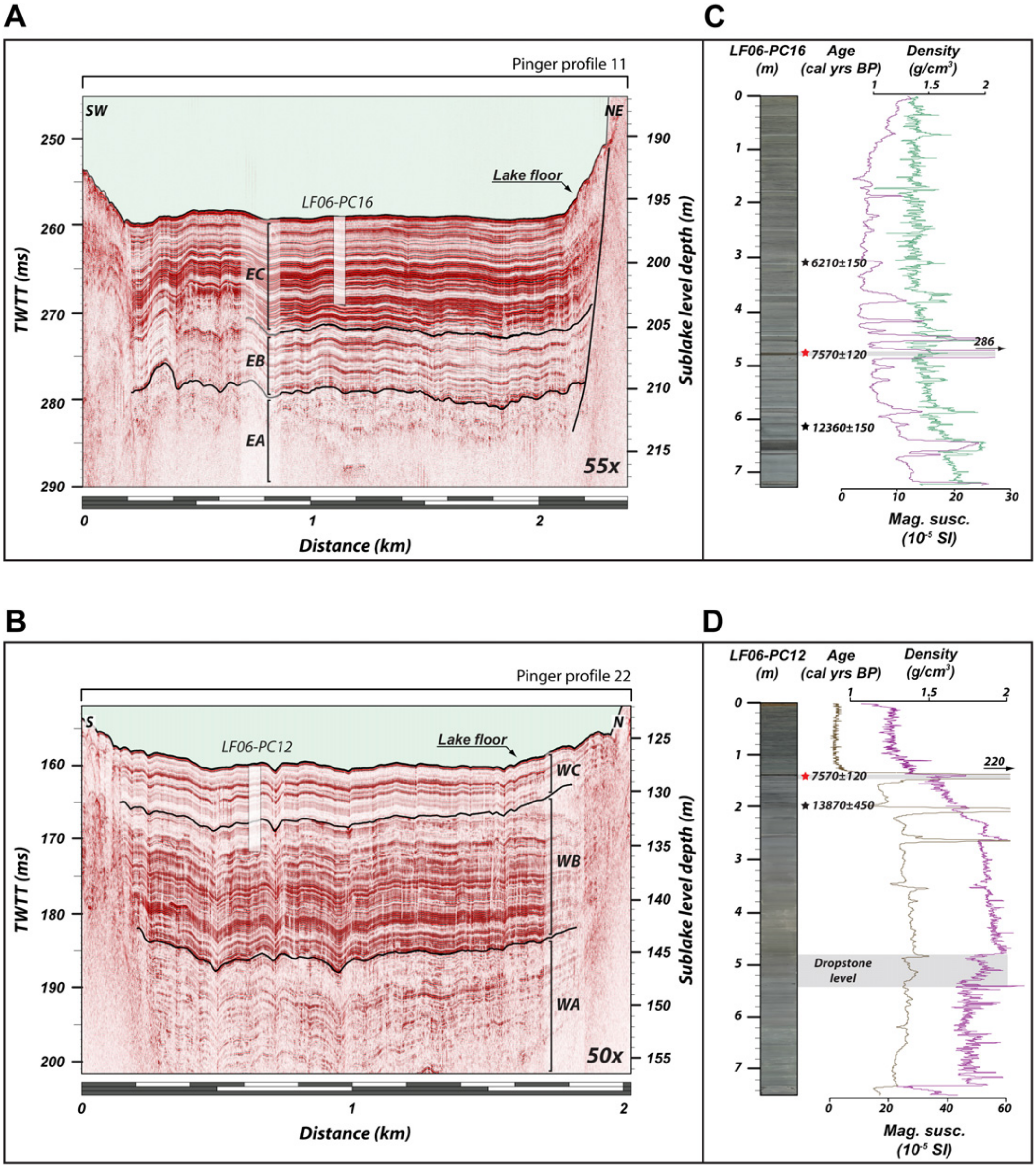


Fig. 5. North–south single-channel 3.5 kHz seismic profiles across the eastern sub-basin (A) and the western sub-basin (B) (see Fig. 2A for location). Sediment depth is given in milliseconds of two-way traveltime (TWTT) and converted to sub-lake level depth (m) based on a *P*-wave velocity of 1430 m/s for water and 1500 m/s for sediment. Piston cores location are marked and labeled respectively. Letters indicate seismic stratigraphic units defined by Waldmann et al. (in press) and further discussed in the text. Note the equally-spaced, semi-transparent reflectors of the EB unit that probably stand for sequences of interpreted proglacial turbidites or of small slides reflecting sediment pulses released by the retreating Fagnano glacier to the basin during deglaciation. Refer to the text for further discussion. Cores LF06-PC16 (C) and LF06-PC12 (D) retrieved in the eastern and western sub-basins, respectively, are shown along with the petrophysical properties of the sediments (bulk density and magnetic susceptibility). Note the large increase of both petrophysical parameters at the tephra level. Radiocarbon dating depths are marked by black stars, red stars mark the depths of the Hudson H1 tephra previously dated to 7570 ± 120 (Stern, 2008) and geochemically fingerprinted (Waldmann et al., in press). Refer to text for further discussion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

suggested that this major advance or stillstand probably occurred during an early stage of the Lateglacial, comparable to the ~20 ka glacier advances in the Inutil Bay and Magellan Strait regions ~200 km to the north (McCulloch et al., 2005b). This assumption is based on ages from peat bogs and by correlating deglaciation processes in the two regions (Coronato et al., 2009). Subsequent to this early advance, the Fagnano glacier retreated to a series of frontal positions (labeled A1–5, Fig. 6) within what is today the eastern Fagnano sub-basin (Fig. 2A). Exposed lacustrine sediments surrounding the easternmost part of the lake have been dated to Marine Isotope Stage (MIS) 2 (Bujalesky et al., 1997) suggesting slightly higher lake stands at this time in the past. Within the eastern sub-basin, a series of five elongated crested topographic highs (labeled A1–A5) are arranged in a SW–NE direction (Figs. 3A, B and 6). We interpret these morphologies as representing a sequence of lateral moraines or as central moraines formed by the conjunction of the Fagnano glacier lobe flowing from the W with other glaciers advancing from the SW, e.g., the Santa Laura and Escondido paleo-glaciers (Coronato et al., 2009; Fig. 6).

The southern slope of this part of the lake is characterized by a relief of >120 m (Fig. 2A); onshore, this slope abuts a relatively flat area of >60 km^2. This sharp break in slope may have allowed multiple inflowing glaciers from the SW to interfere with the E-movement of the Fagnano glacier. This hypothesis is supported by the presence of

Table 1
Radiocarbon and calibrated ages retrieved from cores LF06-PC16 and LF06-PC12 recovered from the eastern and western sub-basin, respectively. Calibration was calculated using the web-based *CalPal* share-ware converter tool (http://www.calpal-online.de/).

Sample	Laboratory number	Depth (cm)	Dated material	^{14}C age (yrs BP)	^{13}C (%)	Cal. Age (yrs BP)
PC16-C15	ETH-35343	318	wood	5445 ± 125	−20.4	6213 ± 149
PC16-C23	ETH-35453	612	wood	10435 ± 75	−28.4	12358 ± 149
PC12-C1	ETH-35629	200	wood	11820 ± 305	−30.9	13873 ± 446
PC12-T1		140	tephra	6850 ± 150[a]	n.a.	7570 ± 120

[a] Stern (2008).

a sequence of E–W-oriented stacked moraines in MCS profile 42 (Fig. 3B), as well as by the formation of a small drumlin field along the southern shores of the lake, which is parallel to the postulated main Fagnano ice flow direction (Fig. 6; Coronato et al., 2009). Previous studies have shown that the occurrence of drumlins is associated with decreased ice flow velocities, due either to the reduction in volume of transported ice or to shear strain changes caused by the differential velocity of two ice bodies flowing side by side (Aario, 1977; Clark and Walder, 1994; Ò Cofaigh et al., 2002).

The main lobe of the Fagnano glacier continued to retreat to a stillstand or re-advance position at the interpreted basement saddle currently observed between the two sub-basins (Fig. 2A). The sequence architecture of the easternmost sub-basin represents a succession comparable to those deposited in glacially elongated basins following deglaciation in other Alpine lacustrine settings (Van Rensbergen et al., 1999; Chapron et al., 2002). While we interpret unit EA (Fig. 5A) as a succession of glacially-derived sediments deposited in a proglacial lacustrine environment, unit EB may also represent a sequence of mass-flow deposits, released either by successive proglacial delta collapses or outbursts of turbid meltwater plumes. This hypothesis is based upon a comparison of our data with documented large prehistoric lake outburst floods, such as those resulting from natural dam collapses (e.g., Carter et al., 2006; Strasser et al., 2008). Furthermore, we interpret a prominent ~50 m thick frontal moraine, labeled B1, on top of the shallow sill (Figs. 4 and 6) as the position of the Fagnano glacier front at this time. B1's prominently curved morphology, and its ~5 km length and substantial thickness, coupled with our seismic stratigraphic interpretation of the eastern sub-basin units EA and EB, all suggest that the Fagnano glacier may have occupied this inter-basin divide (Fig. 2A) for an extended period. During this time interval, a negative ice budget may have prevailed, reducing the glacier mass by increased ablation, while enhancing sediment accumulation in the eastern sub-basin (Benn and Lehmkuhl, 2000).

Once the Fagnano glacier withdrew from this sill, it probably retreated rapidly, leaving remains of several central moraine structures, B10-12 (Fig. 3C), that run parallel to the lake axis for >5 km (Fig. 5). During this retreat, the Fagnano glacier likely behaved as a fast-flowing outlet glacier from the Cordillera Darwin, restricting its flow and volume to the narrow western Fagnano sub-basin. During this ablation interval, some interpreted terminal moraines were also built, B2–B8 (Fig. 4), suggesting that re-advances/stillstands of the Fagnano lobe occurred, probably related to temporary return of colder and/or wetter conditions to the region.

Multiple glacier re-advances/stillstands ensued within the westernmost basin, leaving behind a number of semicircular crested structures, C7–C12, that cross the lake basin (Fig. 6). We interpret these as terminal moraines similar to the nearby Chilena Moraine onshore (Coronato et al., 2009; Figs. 3D, 4 and 6). Another elongated rise, C13, can be traced along the southern flank of the lake basin (Fig. 6). We postulate that this topographic high may correspond to a lateral moraine or elevated basal till of which Martinez Island is an exposed remnant. Following the C7–C12

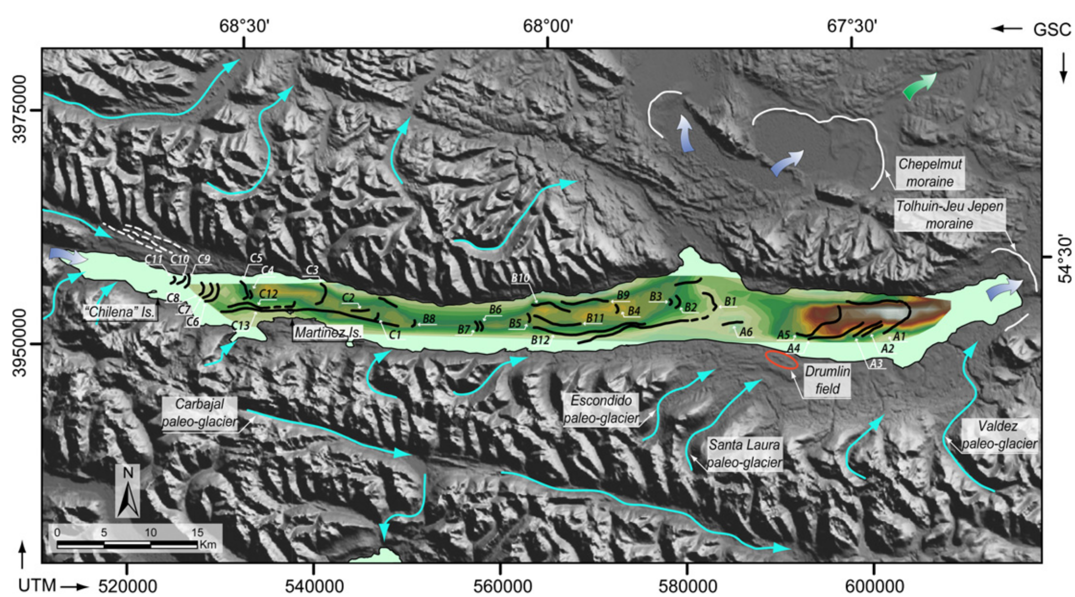


Fig. 6. A SRTM map (Farr et al., 2007) of the Lago Fagnano region, including a bathymetric map of the top of the glacial unit G (Fig. 3). Geographical system coordinates (GSC) are shown (right and top), along with UTM measurements (left and bottom). The black lines in the lake basin represent orientations of the different moraine structures as interpreted from the seismic profiles. The oldest moraines (labeled A) occupy the eastern sub-basin, while those in the western sub-basin are labeled B and C, with B presumably being older than C, assuming all represent a gradual post-LGM recession of the Fagnano glacier towards Cordillera Darwin to the west (Fig. 1B). Continuous white lines indicate moraine structures mapped on land (Coronato et al., 2005), while dashed white lines indicate moraine structures mapped for this study using the SRTM coverage. Paleo-glacier structures mentioned in the text are labeled. Thin blue arrows suggest principal paleo-glacier flow directions, and the thick gradient green arrow represents fluvial outwash (Coronato et al., 2009). Thicker gradient blue arrows indicate the main flow direction of the Fagnano glacier, and the red circle marks the location of several drumlins that are interpreted to indicate changes in the velocity of that glacier (Coronato et al., 2005). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

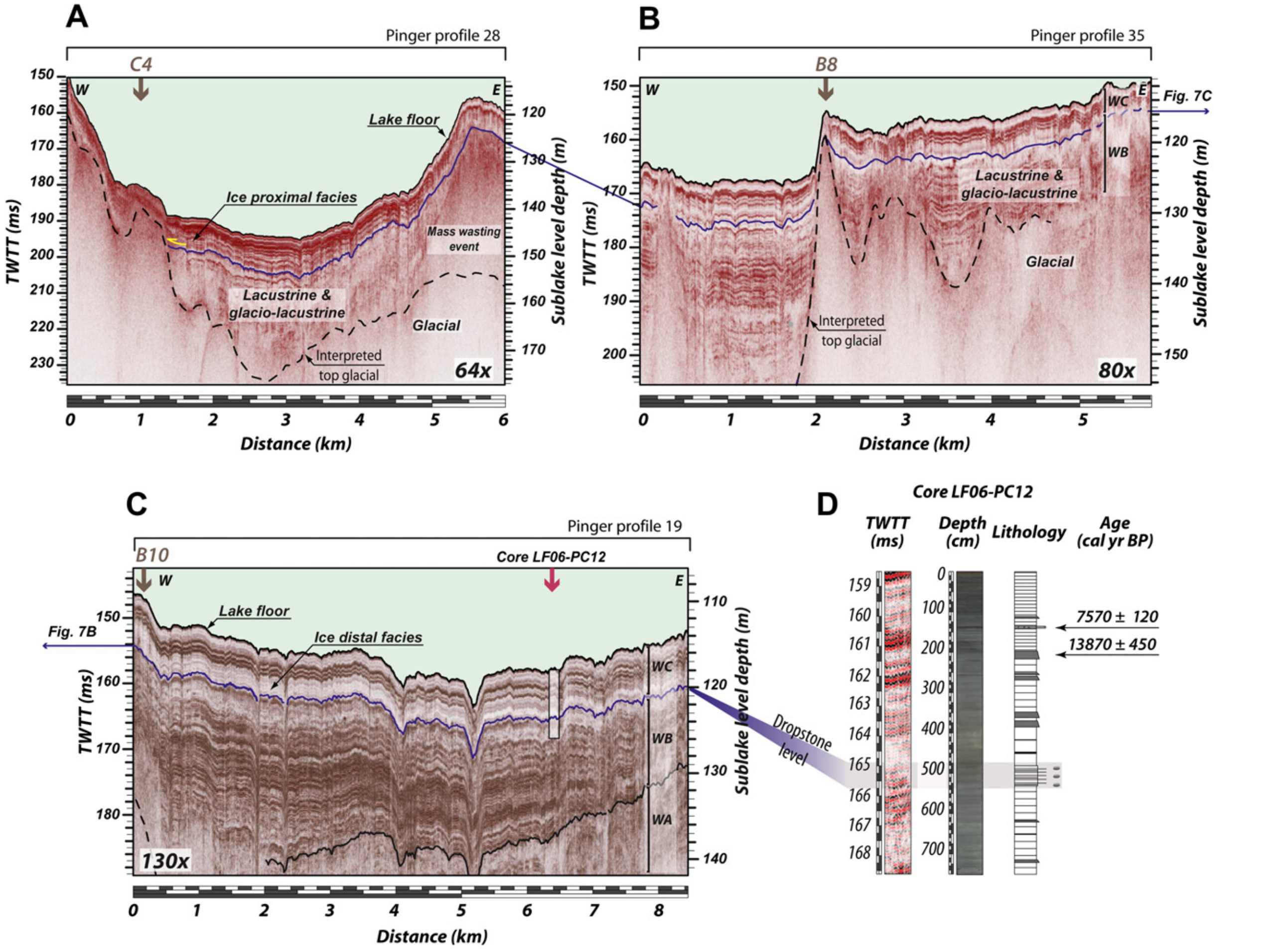


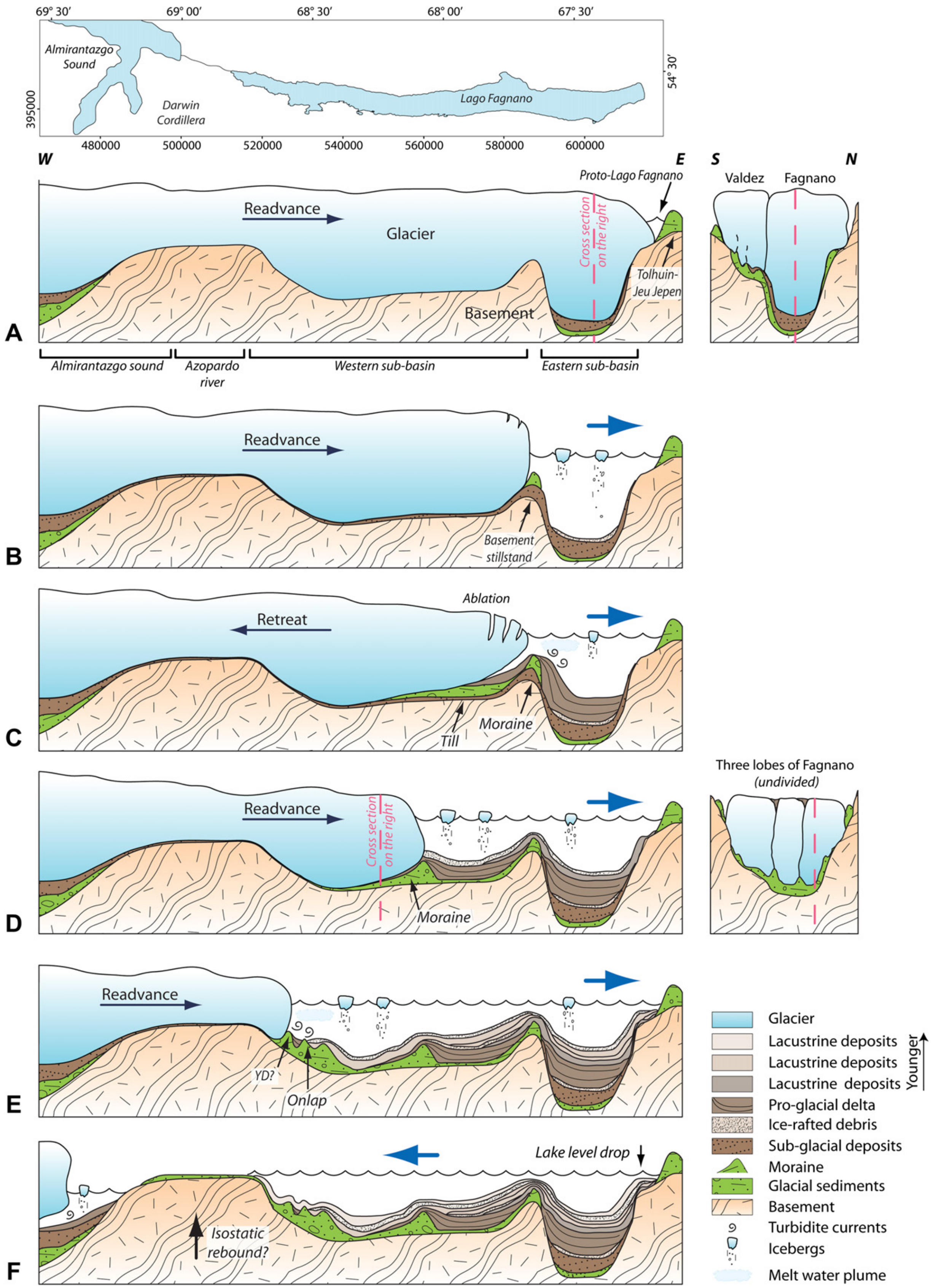
Fig. 7. West–east 3.5 kHz single-channel profiles in the westernmost (A), central (B) and easternmost (C) parts of the western sub-basin. For locations, see Fig. 4. Brown arrows stand for interpreted moraine crests. Dashed lines mark the top of the glacial unit, as interpreted in the longitudinal multi-channel profile (Fig. 4). Black line indicates the base of a sedimentary unit that drapes the interpreted moraine structures, while the continuous blue line indicates a dropstone-enriched level that appears to onlap the moraine structure in Fig. 7A. Three seismic stratigraphic units are recognized in the easternmost profiles (WC, WB and WA; following Waldmann et al., 2008). The location of core LF06-PC12 is highlighted and marked by a red arrow in Fig. 7C (see Fig. 2A for the geographical setting). D) Core LF06-PC12 with the dropstone unit highlighted and stratigraphic levels dated by radiocarbon and tephrochronology. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

re-advances/stillstands (Fig. 3D), the Fagnano glacier retreated westwards from the Fagnano basin, eventually opening a passage to the Magellan Strait and enabling drainage of the lake westwards, as it still does today. Lake level was lowered as a consequence, subaerially exposing the glacio-lacustrine sediments that are found currently in cliff exposures along the lake shores.

6. Estimating chronological constraints on moraine emplacement

By merging the information gathered from the 3.5 kHz seismic data with lithological and chronological analyses of the LF06-PC12 composite core, we propose a chronology for some of the interpreted moraine structures submerged below the glacio-lacustrine infill. Dropstones embedded within finely laminated clays at depths of ∼4.5–5.0 m in core LF06-PC12 (Figs. 2A, 5C and 7D) indicate the presence of a glacier carrying and shedding ice-rafted debris (IRD) into a proglacial Lago Fagnano. We think that the density contrast between the dropstone-rich horizon and the surrounding clay-rich, lacustrine material is denoted in the seismic profiles as a transition from high-amplitude reflections below to a semi-transparent unit with some low-amplitude reflections above (Fig. 7C). Occasional hyperbolic (point-source) reflections may originate from larger dropstone clastic material (probably larger than 5 cm, which is the minimum object size possible to visualize with a 3.5 kHz system (Van Rensbergen et al., 1999)). This change in geophysical properties marks the transition between seismic units WB and WC (Waldmann et al., in press); this transition can be correlated westwards from interpreted ice-distal facies (Fig. 7B and C) to interpreted ice-proximal facies (Fig. 7A). Similar architecture has been recognized in fjords in the Chilean part of Tierra del Fuego (DaSilva et al., 1997; Boyd et al.,

Fig. 8. Longitudinal depiction of the different advance/retreat stages that we interpret for the Fagnano glacier since the LGM. Vertical scale is exaggerated. Fig. 8A and D are further complemented by transversal cross sections. Note the existence of multiple ice lobes during different advance stages of the glacier, both in western and eastern sub-basins, as interpreted from the seismic profiles. During the early stages (Fig. 8A), part of the glacier was in direct ice-contact with the basement, while sub-glacial deposits were formed below distally. Fast sedimentation probably occurred in the westernmost sub-basin following glacier retreat to a stillstand, with enhanced contribution of ice-rafted debris (Fig. 8B). Ablation occurs during ensuing glacier retreat (Fig. 8C). Multiple terminal moraines were formed during a series of repeated glacier advances (Fig. 8D), including the suggested YD moraine (C4) in the westernmost part of the western sub-basin (Fig. 8E). Finally, the glacier retreated from the lake basin, the outflow of the lake changed direction from east- to westbound into the Almirantazgo Sound, while isostatic rebound with associated lake level lowering may also have occurred (Fig. 8F).



69° 30′
69° 00′
68° 30′
68° 00′
67° 30′
54° 30′
395000
480000
500000
520000
540000
560000
580000
600000
Almirantazgo Sound
Darwin Cordillera
Lago Fagnano
W
E
S
N
Proto-Lago Fagnano
Readvance
Glacier
Cross section on the right
Tolhuin-Jeu Jepen
Basement
Valdez
Fagnano
A
Almirantazgo sound
Azopardo river
Western sub-basin
Eastern sub-basin
B
Basement stillstand
Ablation
Retreat
C
Till
Moraine
D
Three lobes of Fagnano (undivided)
E
YD?
Onlap
F
Lake level drop
Isostatic rebound?
Glacier
Lacustrine deposits
Lacustrine deposits
Lacustrine deposits
Younger
Pro-glacial delta
Ice-rafted debris
Sub-glacial deposits
Moraine
Glacial sediments
Basement
Turbidite currents
Icebergs
Melt water plume

2008). The seismic stratigraphic level that includes dropstones can be traced seismically >40 km W of the coring site, until it onlaps an interpreted submerged moraine structure labeled C4 (Fig. 7A).

Radiocarbon dating carried out on a piece of wood retrieved at 2.0 m depth in core LF06-PC12 returned an age of 13,870 $\pm$ 450 cal yr BP (Fig. 7D). Yet, considering the questionable reliability of the radiocarbon ages, and since no other chronological markers are currently available (e.g., the Reclus R1 and the Mt. Burney MB1 tephras, dated to 14,810 $\pm$ 440 and 9400 $\pm$ 500 cal yrs BP, respectively, elsewhere in this region; Stern, 2008), we compute sedimentary rates below based solely on the H1 tephra. This tephra is found at 1.4 m depth in core LF06-PC12, with a known age of 7570 $\pm$ 120 cal yr BP.

The calculated sedimentation rate for the upper part of the LF06-PC12 core, above the H1 tephra level, is very low, ~0.18 mm/yr, probably suggesting decreased sediment input into the lake system due to glacier retreat, coupled perhaps with precipitation increase and augmentation of vegetation cover since the early Holocene (Borromei and Quattrocchio, 2008; Waldmann et al., in press).

We postulate different time-frames for the formation of moraine C4 by proposing different depositional rate scenarios for the sedimentary package constrained between the H1 tephra downwards to the dropstone level. Assuming a much higher sedimentation rate, ~1 mm/yr, similar to that calculated for other lacustrine settings abutting ice margins (e.g., Girardclos et al., 2005; Etienne et al., 2006; Chapron et al., 2007), the C4 moraine was created ~11,170 cal yrs BP, placing it close to the Younger Dryas chronozone (YD) (12,800–11,500 cal yrs BP) widely recognized in the Northern Hemisphere (Broecker et al., 1989).

Nevertheless, this calculated age for the C4 moraine would increase if ambient sedimentation rates were lower. For example, if we consider rates as low as ~0.6 mm/yr, the formation of the C4 moraine occurred at ~13,600 cal yrs BP, which would place its formation during the Antarctic Cold Reversal (ACR) interval (14,500–12,800 cal yrs BP), as recognized in the Vostok ice core paleo-temperature record (Blunier and Brook, 2001). However, we contend that rates as low as ~0.6 mm/yr are unlikely to occur in any lake abutting a glacier, as records elsewhere around the world confirm (e.g., Girardclos et al., 2005; Etienne et al., 2006; Chapron et al., 2007).

On the contrary, if sedimentation rates instead were as high as ~2 mm/yr, then the formation of the C4 moraine took place at ~9300 cal yrs BP, well within the Holocene. We consider such an age improbable, given the high content of organic matter characterizing the laminated sedimentary sequence beneath the H1 tephra in core LF06-PC16 from the eastern sub-basin, which suggests pervasive vegetative cover (Waldmann et al., in press). Such a lithology is unlikely in a lake adjacent to a calving glacier, where the environment was probably deprived of biota (Borromei and Quattrocchio, 2008). Indeed, the transparent to semi-transparent facies characterizing the lower part of seismic unit WC in the western sub-basin profiles (Figs. 5B and 7) suggest instead increased input of clastic material during C4 time, most likely from advancing glaciers in the watershed area.

The currently available core data in Lago Fagnano does not allow us to pinpoint whether the C4 moraine was formed during the ACR, the YD or another glacier advance interval. However, considering the different proposed sedimentation rates discussed above, we conclude that a rate of ~1 mm/y is reasonable for the dropstone level, given what we know about sedimentation rates in similar proglacial environments elsewhere. This assumption allows us to postulate that the C4 moraine formed most probably during the YD chronozone. If we further assume that the Tolhuin-Jeu Jepen moraine, which bounds the lake on the east (Fig. 5), corresponds to the LGM ice position (inferred to ~20–18 ka; Coronato et al., 2009), then the average deglaciation rate along the 75 km axis of Lago Fagnano from the Tohuin-Jeu Jepen moraine to the C4 moraine is 8.5–11 km/kyr. Similar magnitudes of deglaciation rates have been calculated for the Magellan and Bahia Inutil regions of southern Patagonia (~9 km/kyr; McCulloch et al., 2005b), for the Rhône glacier in Switzerland (~6–8 km/kyr; Winistörfer, 1977) and the Andfjord-Vågsfjord area in northern Norway (~16 km/kyr; Vorren and Plassen, 2002). We should add that much higher deglaciation rates have been measured in regions such as the Hardangerfjorden in western Norway (~300 km/kyr; Romundset et al., 2009), but these rates are calculated for the post-YD time interval and in the outer parts of the fjords, where deglaciation rates are frequently faster.

7. Paleoenvironmental implications

Widespread evidence for cold conditions in Tierra del Fuego has been previously reported for both the ACR and YD intervals (Heusser, 1998; Rabassa et al., 2000). Many authors have discussed the magnitude of both climatic events in southern Patagonia (McCulloch et al., 2000, 2005a, 2005b; Sugden et al., 2005; Kilian et al., 2007, among others), as well as their degree of synchrony (Blunier et al., 1998; Moreno et al., 2001; Turney et al., 2003). McCulloch et al. (2000) show that glacier advances in the Magellan Strait were driven by enhanced precipitation, which started ~14,200 cal yr BP and persisted until ~11,700 cal yr BP. They further suggest that this precipitation increase probably promoted glacial growth and/or stabilization in the region for a longer time period, postponing their final retreat into the early Holocene. Enhanced humid conditions at these latitudes were probably accompanied by displacement of the open steppe in favor of the *Nothofagus* forest (Villa-Martinez and Moreno, 2007; Borromei and Quattrocchio, 2008), which prevails today. We suggest that this humid period was also related to southward shift and/or strengthening of the SHW wind belt during and after the deglaciation (Moy et al., 2008; Waldmann et al., in press, and references therein).

If we consider the C4 moraine to have formed during the YD, we thereby also suggest that enhanced precipitation may have occurred during the YD, accompanied by a temperature drop sufficient to increase accumulation of snow over ablation. Therefore, we suspect that final retreat of glaciers from the Tierra del Fuego's lowlands towards Cordillera Darwin occurred during later stages of the YD, following ACR weakening (Boyd et al., 2008), assuming that both events occurred in Tierra del Fuego.

During the final stage of deglaciation, the Fagnano glacier retreated westward from the western Fagnano sub-basin, clearing a drainage pathway from the lake to the Almirantazgo Fjord and eventually to the Magellan Strait. This complete change in lake drainage pattern is recorded by cessation of deposition from several fluvial outwashes in the San Pablo River east of Lago Fagnano (Coronato et al., 2005). Similar switches in drainage direction are also recorded further north, in the Magellan Strait and Bahia Inutil regions, where ice-dammed lakes emptied their water following the collapse of the Magellan glacier (Fig. 1B for location; McCulloch et al., 2005a). This regional hydrological drainage of lakes subsequent to the final retreat of glaciers is comparable, at a smaller scale, to the breakdown of the Laurentide ice-sheet in North America, which resulted in freshwater outburst releases through first the Mississippi River system and then the St. Lawrence Seaway (Teller et al., 2002), temporarily affecting the regional thermohaline circulation pattern in the North Atlantic Ocean (Clarke et al., 2004; Broecker, 2006). This study contributes some new information about the latest Pleistocene–early

Holocene deglaciation pattern in the southern part of Tierra del Fuego. Learning more about natural deglaciation patterns allows us to understand better the mechanisms behind climate change, especially in the context of present-day anthropogenically induced climatic warming and accompanying rapid glacier retreat worldwide.

8. Summary and conclusions

Geophysical and core data collected in 2005/2006 from Lago Fagnano permit us to recognize, for the first time, multiple advances/stillstands of the Fagnano glacier lobe, as evidenced by moraine crests preserved in the lake basin. These glacial features are poorly conserved outside the lake basin. Each glacial advance induced formation of terminal, central and/or lateral moraine structures, while overrunning previous morphologies along its path. These moraines have been for the most part submerged under ensuing glacio-lacustrine and lacustrine deposits, burying and preserving them beneath Lago Fagnano.

Data and interpretations of seismic stratigraphy, terrestrial geomorphology, and from lacustrine sediment cores dated by tephrochronology and radiocarbon techniques, provide a partial time-frame for at least one glacier advance within an overall retreat pattern in the Fagnano basin. Evidence for elongated moraine morphologies parallel and sub-parallel to the modern lake axis confirm the presence of at least two ice bodies, and probably more, coexisting concurrently, involving at least the Fagnano lobe in what is now the E–W lake basin, and the Valdez and Escondido glaciers southwest of the lake (Fig. 8A; Coronato et al., 2009). We interpret a series of elevated structures that transverse the lake basin as frontal moraines formed during multiple eastward advances of the Fagnano glacier during a general westward deglaciation pattern (Fig. 8B–E). The final deglaciation phase is characterized by complete retreat of ice from the basin, followed by a drainage switch of Lago Fagnano to the Almirantazgo Fjord and a concurrent lake level lowering (Fig. 8F).

One of the advance episodes of the Fagnano glacier during the last stages of deglaciation probably occurred during or soon after the YD interval (Fig. 8E). Our results indicate a step-wise deglaciation pattern of the Lago Fagnano basin, consistent with other studies in this part of Patagonia.

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