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Detailed seismic stratigraphy of Lago Puyehue: implications for the mode and timing of glacier retreat in the Chilean Lake District

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ABSTRACT: Lago Puyehue is a glacigenic lake in the Chilean Lake District (40°S) with a complex deglaciation history. A detailed seismic–stratigraphic study of its sedimentary infill indicates a much earlier retreat of the glacier from the Lago Puyehue basin than the neighbouring glacier from the Lago Rupanco basin. Because of their close proximity, Rupanco meltwater streams played an important part in the depositional processes of Lago Puyehue. A timing discrepancy between the in-lake ages of a sediment core and the outer-lake ages of moraine deposits (re)opens the discussion on the timing of deglaciation in the Southern Hemisphere. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS: Lago Puyehue; Chilean Lake District; seismic stratigraphy; lake sediments; deglaciation.

Introduction

The piedmont of large mountain ranges affected by Pleistocene glaciations (such as the European and Southern Alps, Rocky Mountains, Patagonian Andes) is often marked by the occurrence of deep, elongated lakes. These are glacial lakes scoured into older sediments and bedrock, in places to depths well below sea level. The lakes formed near the basal equilibrium line of the large Pleistocene ice caps where maximum ice flux and circulating meltwater at the glacier base create maximal erosion (Menzies, 1995). The overdeepened glacial lakes are characterized by their fast and voluminous infill during and after deglaciation. The sedimentary processes active today and in the past and three-dimensional sedimentary facies associations of such lakes have been studied in detail in the European Alps (e.g. Van Rensbergen *et al.*, 1998, 1999; Girardclos *et al.*, 2005) and in North America (e.g. Eyles and Mullins 1997; Eyles *et al.*, 2000; Hofmann *et al.*, 2006). Research on the Southern Hemisphere versions of these lakes, however, remains basic and fragmentary.

The Chilean Lake District, which extends from 39°15′S to 43°20′S in south-central Chile, was host to several piedmont glaciers during cold phases in the Pleistocene. These outlet glaciers emanated from the northernmost part of the Last Glacial Maximum Patagonian Ice Sheet (Glasser *et al.*, 2008). Such mid-latitude mountain glaciers are believed to react sensitively to both medium- and long-term climate change (Häberli, 1994). Following deglaciation a completely altered Chilean landscape was left behind, characterized by the presence of a series of medium-sized to large, deep glacigenic lakes. Despite the many geomorphological, sedimentological and palaeoclimatological studies carried out in the region (Porter, 1981; Laugenie, 1982; Bentley, 1996; Andersen *et al.*, 1999; Denton *et al.*, 1999b), the palaeoclimatic archives preserved in these glacigenic lakes have received little attention. Nevertheless, lacustrine studies could provide – like their marine counterparts – continuous, high-resolution sediment records but in which environmental control is often far more amplified than in the oceanic sediments (Scholz, 2001). In combination with high-resolution reflection seismics, which is a very powerful technique for lake-basin studies as it allows a non-destructive and non-invasive, quasi three-dimensional exploration of the complete sedimentary lake infill, a full deglaciation history can be reconstructed.

With this in mind, we selected the glacigenic Lago Puyehue (40°S) for a detailed investigation of its sedimentary infill (Fig. 1). Our study was performed on a long sediment core, PU-II, from a key location in the lake, which was selected using the available seismic data at that time (Fig. 2). The results of the multi-disciplinary sediment core investigation showed changes in climate and regional environment in the lake and its catchment since the retreat of the Puyehue glacier out of the basin (De Batist *et al.*, 2008; Bertrand *et al.*, 2005, 2008; Boës and Fagel, 2008; Charlet *et al.*, 2008; Sterken *et al.*, 2008; Vargas *et al.*, 2008). The core bottom age of 17 915 cal a BP (Bertrand *et al.*, 2008), however, contradicts previous work of Bentley (1997), which states that the Puyehue glacier had not retreated out of the lake basin before 14 600 cal a BP, while sedimentological and diatom analyses of the lake sediment indicate an ice-free lake by 17 915 cal a BP (Bertrand *et al.*, 2008; Charlet *et al.*, 2008; Sterken *et al.*, 2008). This disagreement is complicated even further by the fact that most glacigenic lakes can contain up to hundreds of metres of sediment in their basin, deposited over a rather short time span, i.e. from deglaciation to present (Eyles and Mullins, 1997; Van Rensbergen *et al.*, 1998, 1999; Charlet *et al.*, 2008). Consequently, the majority of sediment core studies literally just scrape the surface of the story buried in the lake basin. Charlet *et al.* (2008) made a first attempt to unravel the complete history of sediment distribution and transport in the Puyehue lake basin based on analysis of the exploratory seismic data available at that time. The few available profiles did not cover every region of the lake basin and the lack of sufficient profile intersections prevented a reliable assessment of the thickness distribution of the different seismic units throughout the basin and the identification of sediment depocentres. This also hampered a good reconstruction of the behaviour of the retreating glacier and of the associated sedimentary processes. Therefore, the

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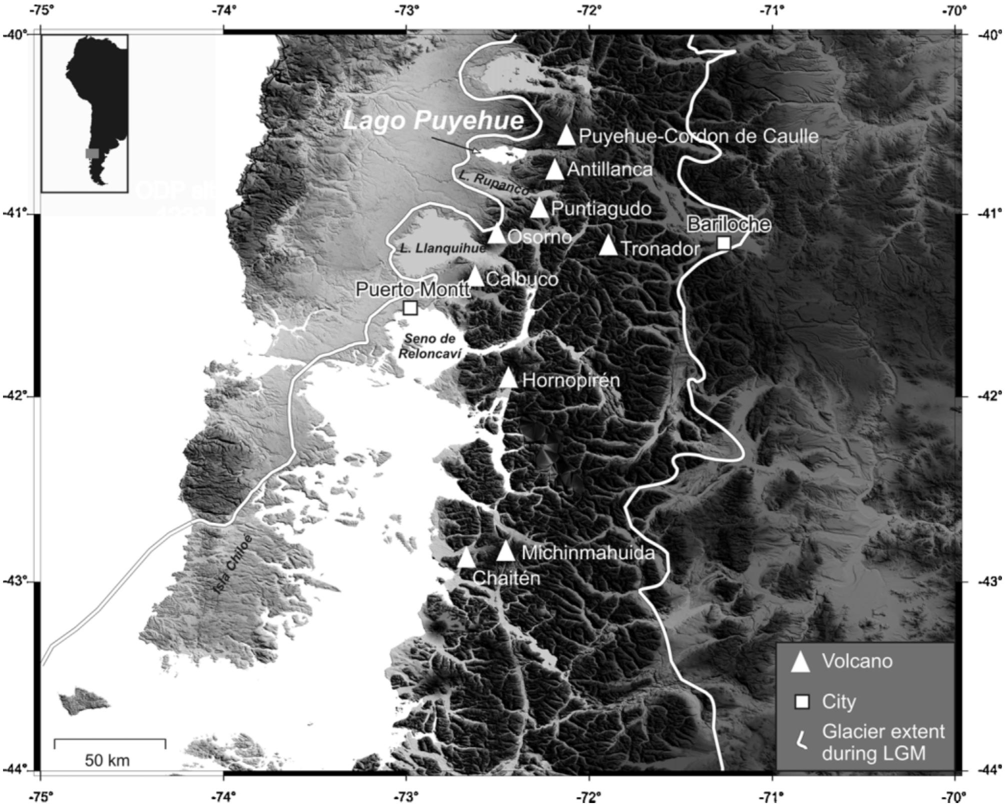

Figure 1. Location of Lago Puyehue, the study site and the extent of the glaciers during the Last Glacial Maximum (LGM); after Porter (1981).

decision was taken to return to Lago Puyehue and to perform a more detailed seismic survey in order to better understand the processes behind the complete sedimentary infill of the lake basin since the start of deglaciation and subsequently find a possible explanation for the age discrepancy between the lake core and the land-based studies. An exploratory survey was also performed in Lago Rupanco, south of Lago Puyehue (Fig. 1), as interaction between the two systems had already been pointed out by Bentley (1996, 1997).

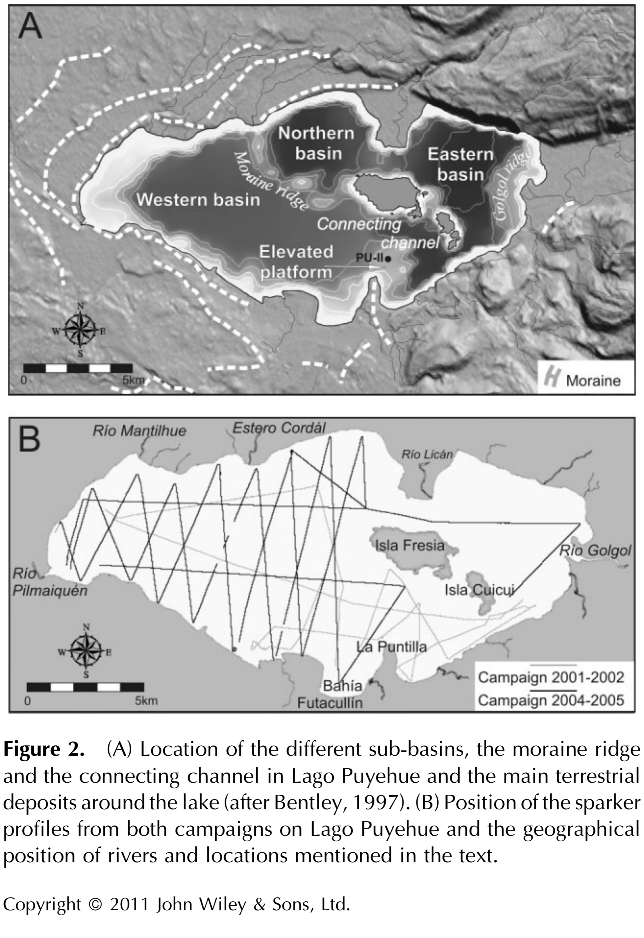

Figure 2. (A) Location of the different sub-basins, the moraine ridge and the connecting channel in Lago Puyehue and the main terrestrial deposits around the lake (after Bentley, 1997). (B) Position of the sparker profiles from both campaigns on Lago Puyehue and the geographical position of rivers and locations mentioned in the text.

Study area

Lago Puyehue (40°40′S, 72°28′W) is one of the medium-sized (ca. 20 km in length), moraine-dammed glacigenic lakes of the Chilean Lake District (Fig. 1). It is located at the foot of the Cordillera de los Andes in close proximity to the active Casablanca, Puyehue and Cordon de Caulle volcanoes. The lake itself is located at 185 m a.s.l. and has a maximum depth of 126 m. It is characterized by a complex bathymetry, with three sub-basins (a northern, eastern and western sub-basin) and an elevated platform in the south (Charlet *et al.*, 2008) (Fig. 2A). This division into several sub-basins has largely been created by the presence of a large subaqueous ridge, hereafter called ‘subaquatic moraine ridge’, which connects a lateral moraine on the northern shore with a series of bedrock islands in the centre of the lake (Campos *et al.*, 1989; Bentley, 1996; Charlet *et al.*, 2008). The western and eastern sub-basins are connected via a deep-water depression, here named ‘connecting channel’, that passes between Isla Fresia and the southern elevated platform. The only outlet, Río Pilmaiquén, connects the lake system via the Río Bueno with the Pacific Ocean. The main tributaries – Río Golgol and Río Licán – are located in the eastern part of the basin and transport sediment from the glacially scoured valleys into the lake (Laugenie, 1982) (Fig. 2). Another subaqueous ridge (‘Golgol ridge’), which links up with a small moraine on the eastern shore, is present in the far east of the basin, just west of the mouth of the Río Golgol.

The neighbouring Lago Rupanco (40°50′S, 72°26′W) is also a moraine-dammed glacigenic lake, but it is significantly larger than Lago Puyehue (ca. 40 km in length). It is located at 118 m a.s.l. and has a maximum depth of 274 m.

Currently, the lake and catchment systems of Lago Rupanco and Lago Puyehue are completely separated. However, when both lakes were covered by glaciers there was a certain degree of interaction between them, as evidenced by a series of intersecting moraine limits and ice-marginal meltwater channels at the western lakeshores of Lago Rupanco and Lago Puyehue (Bentley, 1996, 1997). A reconstruction of the advance and retreat history of the former Rupanco and Puyehue glaciers demonstrated a discordant behaviour, with the Rupanco glacier lagging retreat of the Puyehue glacier (Bentley, 1997).

Methods

High-resolution reflection seismic data were collected in two phases. A first exploratory survey was carried out in the austral summer of 2001/2 (Charlet *et al.*, 2008). Only 64 km of seismic profiles was collected during this survey (Fig. 2B). This was followed by a second, more detailed survey during the austral summer of 2004/5 (Fig. 2B), during which an extra 140 km of profiles was recorded and special care was taken to ensure enough profile intersections were obtained. In total, 204 km of sparker profiles was collected in Lago Puyehue during these two surveys. During the second survey, we also collected one sparker profile in Lago Rupanco.

A 'Centipede' multi-electrode sparker (300 J, main-frequency: 400–1500 Hz) was used as seismic source and a single-channel high-resolution streamer as the receiver. Both were towed at the surface, about 20 m behind the *Huala-2*, the research vessel of the Universidad Austral de Chile (Valdivia). Navigation and positioning of the equipment was done with a SIMRAD GPS. The positioning data and seismic signals were recorded digitally with an ELICS Delph-2 system, after analog bandpass filtering to remove noise with frequencies lower than 200 Hz and higher than 2300 Hz.

Penetration of the acoustic signal varies between the different sub-basins of Lago Puyehue. In the western sub-basin and on the elevated platform, data quality is excellent and the entire sediment infill is imaged, but data quality is very poor in the eastern sub-basin, where penetration is limited due to gas blanking. In the northern sub-basin, penetration of the acoustic signal is of good quality in only two seismic windows located in its western and eastern corners. The vertical resolution of these seismic data is in the range 50–75 cm (Rayleigh criterion). As a result of the greater data density in the western sub-basin and on the plateau, the distribution of several seismic units could be mapped in these regions, which was impossible with the data previously collected and presented by Charlet *et al.* (2008). However, a less dense seismic grid and gas blanking still prevented mapping of the seismic units in the eastern and northern sub-basins.

Seismic–stratigraphic interpretation was achieved through use of the KINGDOM SUITE^{TM} 7.5 package. The seismic stratigraphy of Lac Annecy (Van Rensbergen *et al.*, 1998) and Lac Le Bourget (Van Rensbergen *et al.*, 1999), both located in the western French Alps, was used as a generic model for the deglacial infill of a deep glacigenic lake.

For the bathymetry, time-to-depth conversion of the seismic data was done using a velocity of 1470 m/s in the water column, based on the known water depth at coring points located close to seismic profiles. For the sedimentary infill, time-to-depth conversion was done using a velocity of 1750 m/s. This velocity is used as an average (Eyles and Mullins, 1997), and is based on seismic-velocity studies carried out in several glacial lakes, showing that velocities in such environments generally vary between 1500 m/s in the uppermost deposits and 2100 m/s deeper in the sedimentary sequence (Finckh *et al.*, 1984).

Results: seismic units and seismic facies

The sedimentary infill of the lake basin can be subdivided into six seismic units, based on seismic–stratigraphic criteria, but also on seismic–facies characteristics. The acoustic basement shows no acoustic stratification or internal structures and is excluded from this discussion.

Unit I

This bottom unit is characterized by a chaotic seismic facies with generally low amplitudes and discontinuous reflections. It is separated from the acoustic basement and from the overlying unit II by clear unconformities, the upper unconformity having a strongly undulating morphology. Unit I can be further subdivided into two sub-units: (i) sub-unit Ia, with commonly weaker reflection amplitudes, present in the western part of the lake basin; and (ii) sub-unit Ib, with higher amplitude reflections, present on the subaquatic moraine ridge, on the elevated platform and in the northern sub-basin. The ridge itself shows a faint internal westward prograding structure in its upper part, but the majority of the ridge is reflection-free. Unit I appears to be truncated in the connecting channel between Isla Fresia and the elevated platform as it is not present below unit II (see Fig. 5 below). Just to the east of the elevated platform, in Bahía Futacullín, a small depression filled with horizontally stratified sediments is covered by unit I. The reflection characteristics of these sediments most closely resemble those of unit Ib, although the reflections are less chaotic and the boundaries of unit Ib are smoother. On the southern margin of the western sub-basin, unit I is characterized by gently dipping, parallel reflections (Fig. 3). In contrast to the general lack of continuity in the reflections of this unit observed elsewhere, here they can be followed over some distance, although they are sometimes interrupted by vertical acoustic wipe-outs. This deposit cannot be physically correlated to defined deposits of unit I; its interpretation as unit I is based on its similar stratigraphic position. The distribution of unit I is characterized by two depocentres: one in the westernmost part of the western sub-basin and one in the central part of the sub-basin (see Fig. 6). The central depocentre has a ridge shape, and is connected to the subaquatic moraine ridge. Both depocentres are flanked in the east by a zone of erosion or non-deposition. In general, unit I is of variable thickness. The maximum thickness [ca. 150 ms two-way travel time (TWT), or 130 m] is recorded in the far eastern part of the western sub-basin. In Lago Rupanco, unit I is very similar to the same chaotic facies in Lago Puyehue. Again a clear unconformity separates this unit from the acoustic basement. The Rupanco unit I has more internal structure than its Puyehue counterpart (see Fig. 8).

Unit II

Unit II consists of a facies with slightly undulating, low-amplitude reflections. These reflections are not continuous, but those in the lower part of the unit are less interrupted than those higher up. Unit II is the thickest unit in the western sub-basin with a clear unconformable lower boundary and probably a conformable upper boundary, although the latter is strongly overprinted by the first lake-floor multiple (Figs 4 and 5). The sedimentary deposits are concentrated in the deepest part of the basin, between the depocentres of unit I. This causes a smoothing of the topography previously created by unit I (Fig. 6). Unit II has a maximum thickness of 190 ms TWT (160 m). The same can be said about unit II in Lago Rupanco (Fig. 8).

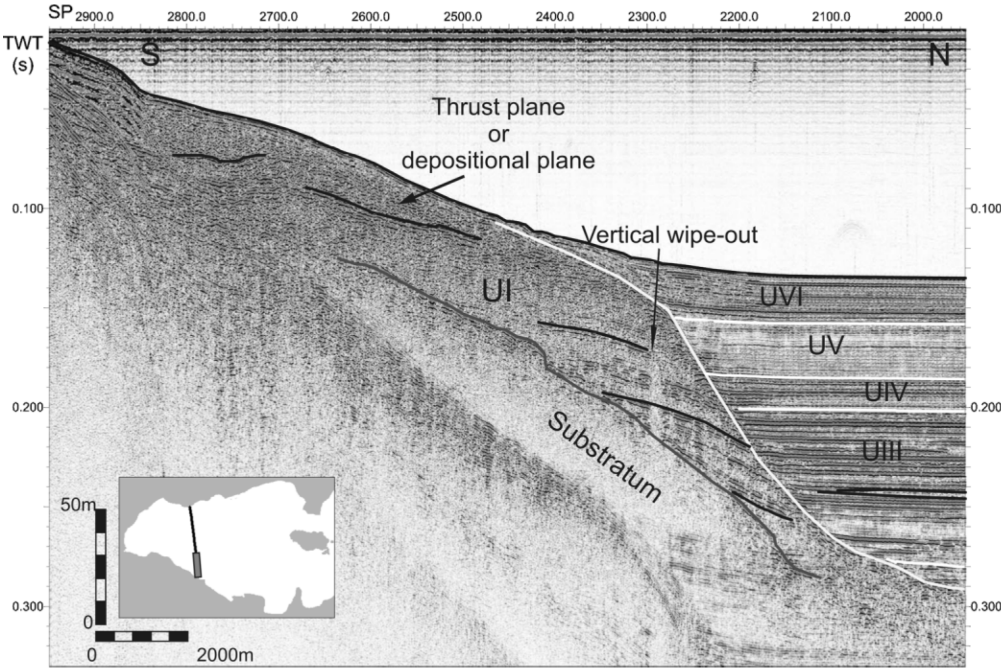

Figure 3. Seismic profile of the southern border of the western sub-basin highlighting the layering visible in unit I. Location of profile shown in inset.

Unit III

Separated from the other seismic units by a lower and upper seismic–stratigraphic boundary, unit III is characterized by relatively continuous, undulating reflections with amplitudes that vary laterally. In this unit, seven large, acoustically chaotic, wedge-shaped sub-units are present. These structures dip down and pinch out away from the subaquatic moraine ridge (Fig. 4). These wedges have internally weaker amplitudes, for the most part lack any visible internal structure and have erosional bases. In the connecting channel there is a level of erosional surfaces overlain by undulating reflections and vertical wipe-out structures. The largest depocentre is located in the north-west close to the present-day inlet of the Estero Cordàl and a smaller one is found in the connecting channel. In the former depocentre, unit III is maximally 85 ms TWT (75 m) thick (Fig. 6). A seismic unit with similar characteristics as those of unit III, with the exception of the absence of chaotic wedges, is present in the northern sub-basin (Fig. 4). This unit is absent in Lago Rupanco (Fig. 8).

Unit IV

This seismic unit is a transitional one that has the combined characteristics of both underlying unit III and overlying unit V. It resembles unit V because of the presence of parallel,

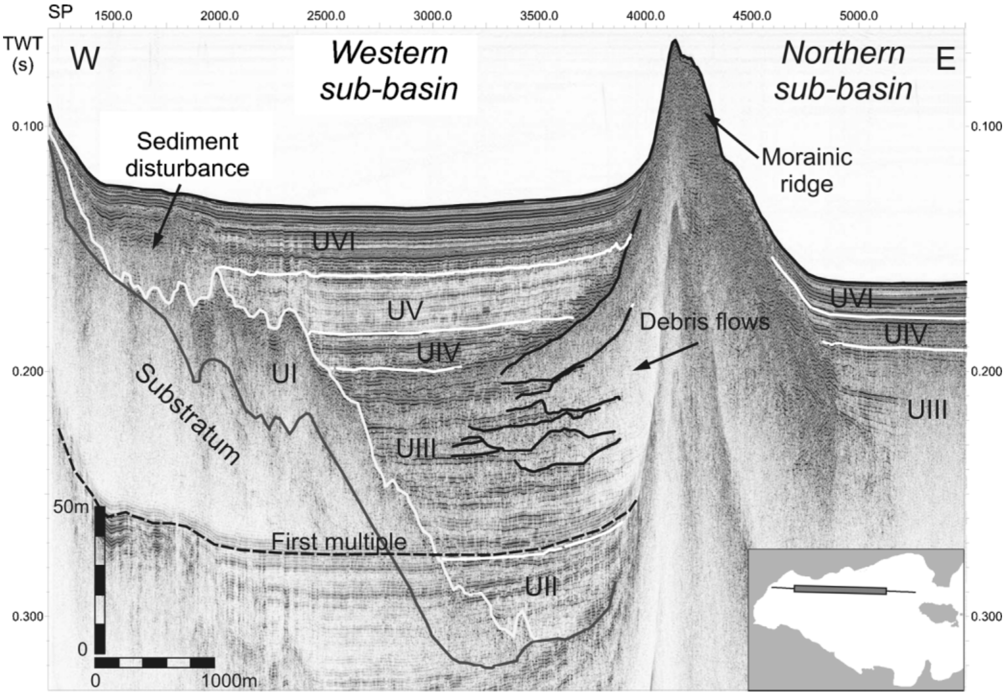

Figure 4. West–east seismic profile showing the western and northern sub-basins. The six different seismic units (units I–VI) are identified along with several debris flows derived from the moraine ridge during the deposition of unit III. Low penetration in the northern sub-basin prevents the imaging and identification of the depositional units below unit III. Unit V is lacking in the northern sub-basin. Location of profile shown in inset.

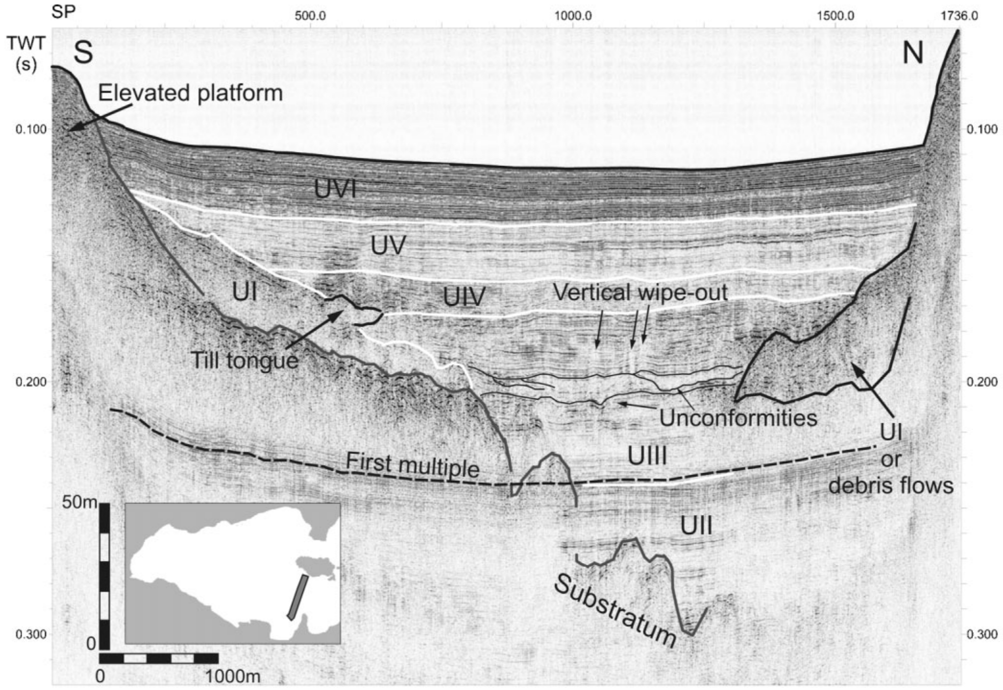

Figure 5. Cross-section of the connecting channel between the western and eastern sub-basins. Seismic units I–VI are defined as well as several other labelled phenomena probably related to a fluctuating ice terminus – till tongue, unconformities and vertical wipe-outs – are visible.

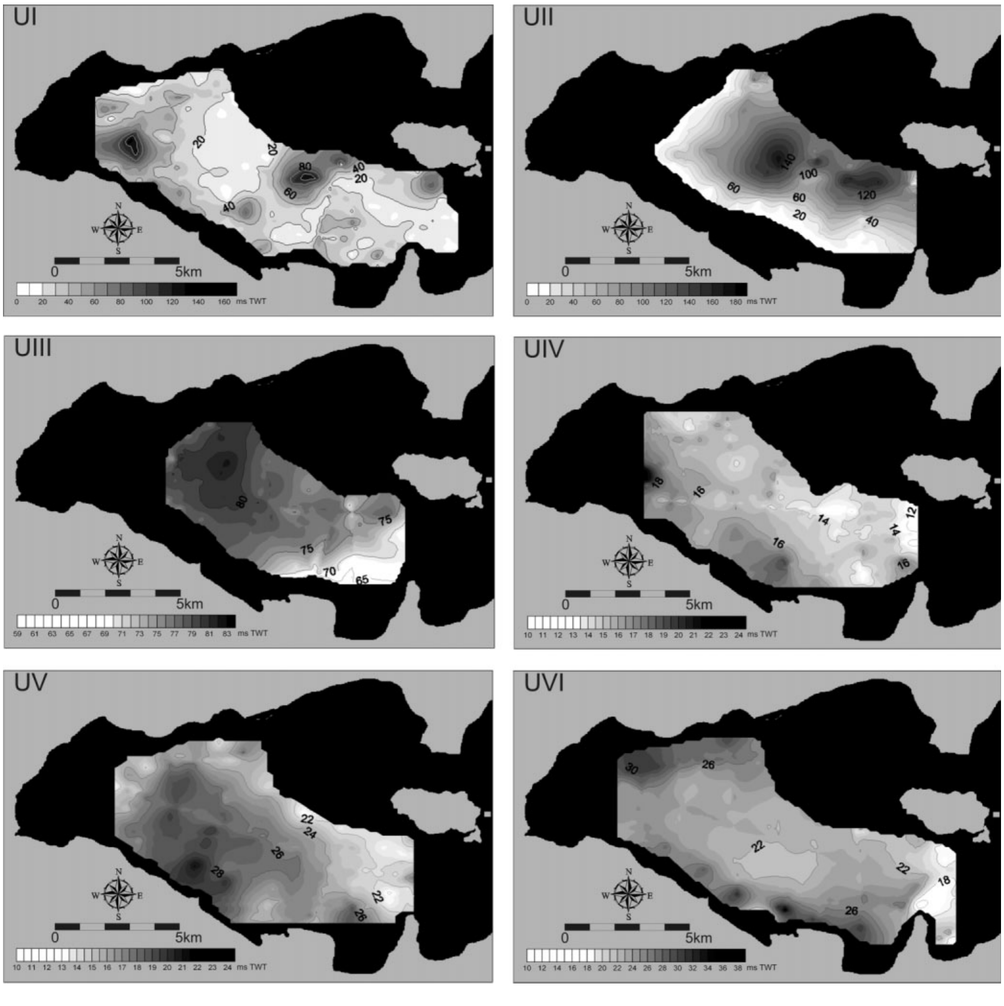

Figure 6. Isopach maps in ms TWT of the different seismic units identified in the lake infill.

subhorizontal, continuous reflections, but the amplitude of these reflections is more consistent with those observed in unit III (Figs 3– 5). Where the unit is thickest (25 ms TWT or 20 m), the reflections themselves are stronger than observed elsewhere, but have poorer continuity. These thicker zones are located in small areas in the south and in the far west of the western sub-basin (Fig. 6). A unit with the same seismic characteristics as unit IV is present in the eastern sub-basin, but only at the western side. The eastern side of this sub-basin is characterized by the presence of a chaotic, high-amplitude facies, sometimes showing discontinuous acoustic stratification. In the connecting channel a slight intrusion of the unit I seismic facies appears between the sediments of unit IV (Fig. 5). This unit is absent in Lago Rupanco (Fig. 8).

Unit V

The transition from unit IV to unit V is manifested only by a change in the average reflection amplitude from strong in unit IV to weaker in unit V. Unit V also occurs on the elevated platform (Fig. 8), but the reflections here are weaker and more chaotic than observed in the western sub-basin. Unit V reflections are locally less continuous in the western sub-basin on the north side close to the Río Mantilhue and Estero Cordàl river inlets. The disturbance not only covers unit V but extends also into the lower part of unit VI (Fig. 4). The main depocentres of unit V are located in the south of the western sub-basin, in Bahía Futacullín and in the connecting channel where this unit reaches its maximum thickness of 32 ms TWT (30 m) (Fig. 6). This unit is absent in the northern sub-basin as well as in Lago Rupanco.

Unit VI

Unit VI is the uppermost unit identified in Lago Puyehue. It consists of high-amplitude, continuous, parallel reflections that are parallel with the lake-floor topography (Figs 3–5). This unit is the only one visible in all three sub-basins and on the elevated platform. Unit VI is thickest at the lake margins (40 ms TWT or 35 m), especially close to the river mouths (Fig. 6). In Lago Rupanco, due to the lack of sufficient data it is impossible to divide the upper part of the seismic data into different units IV, V and VI. The upper part of the sedimentary sequence consists of high-amplitude, continuous parallel reflections which onlap against the unconformity of unit I. Only the upper 10 ms of the reflections in this unit are really draped over the lake-floor topography (Fig. 8).

Other structures

A prograding foreset configuration present on the southern basin slope off a river inlet west of Bahía Futacullín cannot be linked seismic–stratigraphically to any of the other seismic–stratigraphic units, because of its isolated location. The top of the deposit is located approximately 50 ms TWT (38 m) below the present lake level.

Interpretation: seismic units and seismic facies

Acoustic basement

The basement in the region consists predominantly of volcanic and sedimentary rocks with some intrusions of Miocene diorite (Laugenie, 1982; Dorsch, 2003). The latter forms the two islands (Isla Fresia and Isla Cuicui) (Fig. 2) and probably also the basement of La Puntilla and the Río Licán delta.

Unit I

Unit I in both Lago Puyehue and Lago Rupanco closely resembles the bottom facies described from many glacial lakes and fjords in Europe and North America (Lønne and Syvitski, 1997; Syvitski and Lee, 1997; Van Rensbergen *et al.*, 1998, 1999; Eyles *et al.*, 2000) and which is generally interpreted as an ice-contact deposit. The two depocentres are most likely the product of two small glacier readvances, associated with a fast ice flow, eroding the pre-existing sediments and then rapidly dumping sediment at the glacier edge (Dahlgren *et al.*, 2002), followed by rapid glacial retreat, preventing new deposition in the eroded zones. The parallel reflections on the southern margin of the western sub-basin could be caused by glacial thrusting with possible incorporation of pre-Llanquihue lacustrine sediments. Such sediments have the optimal characteristics for the creation of thrust surfaces, because of their low permeability and susceptibility to deformation (Bentley, 1996; Turbek and Lowell, 1999). Moraines with a basal thrust fault and repeated internal thrusting have been reported by Schlüchter *et al.* (1999) around Lago Llanquihue. However, it cannot be completely ruled out that these sediments are undeformed, well-stratified pre-Llanquihue lacustrine deposits, which were – for some reason – preserved during the last glaciation, or even that they represent local occurrences of sedimentary bedrock. Whatever the origin of the structures, the sediments certainly experienced fast and strong compaction that resulted in fluid expulsion, which is represented by vertical wipe-outs, similar to observations made in Lac Le Bourget (Chapron *et al.*, 2004). The deposit on top of the small basin in the Bahía Futtaculín might represent an ice-contact deposit, but could also have a pyroclastic or lahar origin given its proximity to the Casablanca volcano (Fig. 1).

Unit II

Based on its stratigraphic position, low-amplitude facies and seismic similarities to other glacigenic lakes (Syvitski and Lee, 1997; Van Rensbergen *et al.*, 1998, 1999), this unit is interpreted to represent glaciolacustrine sediments deposited in a sub- or proglacial lake by suspension settling out of meltwater plumes (Stravers and Powell, 1997). Any initial stratification was probably disrupted after deposition by grounding ice(bergs) (Van Rensbergen *et al.*, 1998) or by a restabilization of the glacier, causing it to touch solid ground again, but not enough to cause strong erosion or deformation. The erosion of the underlying unit I in the connecting channel could indicate that this narrow trough acted as a meltwater channel, although this transport route alone would not have caused the levelled infill and geomorphological smoothing of the unit I surface. This interpretation is valid for both Lago Puyehue and Lago Rupanco.

Unit III

The deposition of this unit is strongly linked to the moraine ridge. Not only is the main depocentre located in front of the ridge, but seven large, acoustically chaotic, wedge-shaped sub-units, interpreted here as debris-flow deposits, appear to have carried a large quantity of the unit III material from the moraine ridge into the western sub-basin. Other depocentres are associated with the connecting channel, which probably continued to function as a meltwater tunnel as it did during the deposition of unit II, and with the inlet of the current Estero Cordál, which was most likely the inlet of a large meltwater river. The disrupted sediments observed in the connecting channel may indicate minor glacier fluctuations, causing disturbance by the movement and pressure of grounding ice.

The unit III deposits in the northern sub-basin have the same seismic–facies characteristics as unit III in the western sub-basin, but they were deposited at the start of the deposition of unit IV in the western sub-basin. The northern unit III deposits are associated with a meltwater stream(s) coming from the Licán outwash fan and breaching the lateral moraine at the northern border of the basin during a period when the ice had receded from the moraine ridge.

Unit IV

Like unit III, unit IV is probably an outwash deposit created by sediment-loaded meltwater plumes (Seramur *et al.*, 1997). However, the location of the depocentres indicates a southern rather than a northern source. At this time the Río Pilmaiquén outlet must have functioned as an inlet, implying a lower lake level or blockage of the current outlet. If the lake level was indeed significantly lower, then the prograding delta deposit on the southern lake margin might be linked to this depositional facies.

In the northern sub-basin, unit IV indicates a return to a slower and less pulsed sedimentation pattern, but it is not clear if the deposition of this facies was synchronous in the western and northern sub-basins. The small intrusion of unit I seismic facies into unit IV might represent a till-tongue, indicating a local and small readvance or floatation of the glacier (King *et al.*, 1991). Similar features have also been observed in glacial lakes Le Bourget and Annecy (Van Rensbergen *et al.*, 1998, 1999).

Unit V

The transition between unit IV and unit V can be explained by a reduction of the sediment load in the lake water, indicating that sediment transport occurred mainly by rivers and no longer predominantly by melting ice in direct contact with the lake (Van Rensbergen *et al.*, 1999). The main depocentres in the lake correlate well with two delta deposits exposed on land, but this association would require the lake level to have been at least 10 m above its current level. The disturbed sediments at the inlets of Río Mantilhue and Estero Cordàl and the higher amplitude reflections on the elevated platform probably indicate a period of higher sediment input. A reduction in the average reflection energy within unit VI implies that the river influence decreased during the deposition of this unit.

Unit VI

Unit VI represents a facies of mainly autochthonous, lacustrine sediments. This interpretation is supported by the sediment cores taken in the eastern sub-basin and on the elevated platform (Bertrand *et al.*, 2005, 2008), which demonstrate that recent lake sediments are thinly laminated silts consisting of diatoms, organic material, amorphous clays, minerals and volcanic glass. This facies is relatively undisturbed, except for a few earthquake-triggered mass-wasting deposits (Moernaut *et al.*, 2007), and can be tracked across the entire lake basin. This implies that the lake must have been entirely ice-free during deposition of unit VI, an interpretation consistent with the diatom assemblages in the PU-II sediment core (Sterken *et al.*, 2008). River influence is low in the western and northern sub-basins and on the elevated platform because of the large distance between these areas and any river inlet. This is not the case for the eastern sub-basin, where most sediment is delivered by the Río Golgol and Río Licán. Here sedimentation is a combination of suspension-settling, as in the other basins, homopycnal flows at the end of the winter season (Chapron *et al.*, 2007) and sporadic hyperpycnal flows primarily associated with flood events (Moernaut *et al.*, 2007; Charlet *et al.*, 2008; Chapron *et al.*, 2007).

The upper unit IV/V/VI in Lago Rupanco probably represents a gradual change from deposition due to sediment-loaded meltwater outwash plumes into autochthonous deposited lacustrine sediments.

Other structures

The prograding foreset can be interpreted as a prograding river delta (D'Agostino *et al.*, 2002). As the top of this deposit is currently located at ca. 40 m below the present lake level, and the wave base in most lakes does not stretch deeper then ca. 5 m (Van Daele *et al.*, in press) this delta was most likely formed in a period when the Puyehue lake level was at least 35 m lower. The formation of this delta might be linked to the deposition of unit IV.

Mode of glacier retreat

Based on modelling studies, Hubbard (1997) concluded that the Puyehue glacier had a short response time of 1000 years to reach equilibrium after a climatic shift and was thus sensitive to climatic fluctuations. An ice-sheet model of the entire southern South American ice sheet demonstrates a rapid deglacial retreat (Hulton *et al.*, 2002), fully in agreement with such fast-response behaviour. Glaciers, however, not only respond to climate but also to local and internal factors such as topography, mechanisms of glacier flow and basal hydrology (Oerlemans, 1989), which hamper the identification of the climatic signal recorded in the traces left by glacier fluctuations. Moreover, it is important to note that in this volcanically active region geothermal effects might also have played a role.

Unit I was essentially deposited during the glacial maximum (i.e. the period with maximum expansion of the glacier), while the first signs of retreat resulted in the creation of the two smaller ridges. The creation of the moraine ridge in the centre of the lake basin was probably already initiated at the end of this phase. A moraine ridge several metres high can be produced in a single seasonal event (Powell, 1991). The recurrence of this moraine formation process during several seasons and over-consolidation of the ridge sediments could have led to the creation of the massive ridge structure (with a height of more than ca. 150 m) observed here. The likely presence of a sill in the bedrock (i.e. the diorite intrusions) could have created a pinning point for the increasingly unstable glacier, as has been documented for several marine glaciers (Powell, 1991; Seramur *et al.*, 1997). Finally, the Puyehue glacier was no longer grounded in the western sub-basin and at that time unit II was deposited either in subglacial or in proglacial conditions (Fig. 7). The more disturbed upper part of unit II could have been created by ice calving and iceberg scouring or by glacier restabilization. Such a calving process would also explain the different behaviour between the Puyehue and Rupanco glaciers. Climate is considered to be the dominant control mechanism on calving behaviour (Aniya *et al.*, 1997), but calving dynamics can sometimes reverse the trend expected from climatic control (Warren and Aniya, 1999). If the onset of calving creates a proglacial lake, glacier retreat can even accelerate (Warren and Aniya, 1999; Warren and Kirkbride, 2003). The lake geometry, especially in a deep basin, also increases the sensitivity of a glacier to calving losses and deep water may even delay ice advance (Cutler *et al.*, 2001). As all these factors affect calving behaviour, it is difficult to separate the climatic influence from local glacier behaviour.

During the deposition of unit III, the glacier's grounding line and snout was probably located at the large moraine ridge

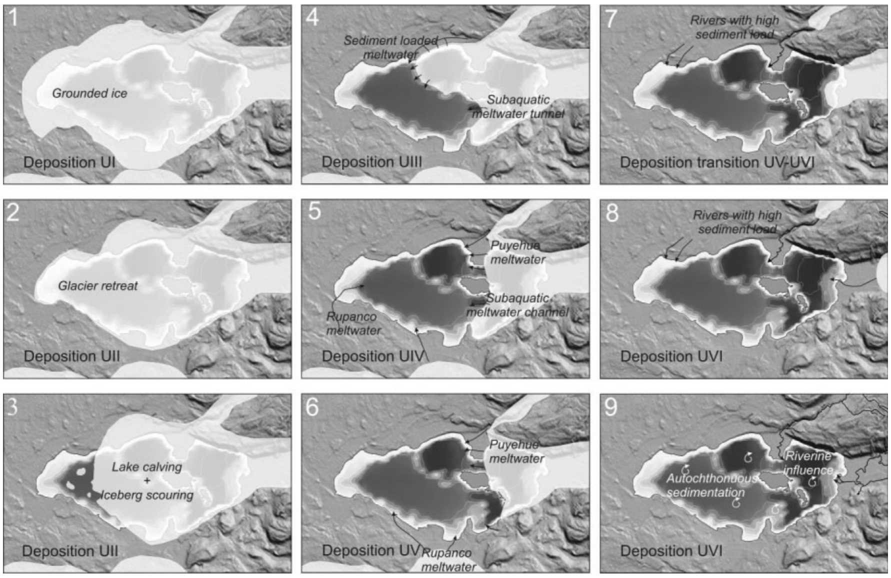

Figure 7. Reconstruction of the mode of deglaciation of the Puyehue glacier shown on a digital elevation model of the lake surroundings and the modern lake bathymetry. Terrestrial terminations are based on Bentley (1997).

(Fig. 7), which explains the occurrence of the debris-flow wedges in front of the moraine ridge. Ice terminus movements can often cause instability of morainal bank deposits, introducing sediment failure and debris flows (Lønne and Syvitski, 1997; Stravers and Powell, 1997). This process could have been particularly active where the large ridge prevented the glacier from readvancing beyond this self-created barrier (Benn *et al.*, 2003). The strong seismic activity in the region has also been a source of several slope failures in Lago Puyehue, as documented by Moernaut *et al.* (2007). However, none of these earthquake-triggered mass-movement deposits is of the same magnitude as the chaotic wedges in unit III.

Sediments thus entered the proglacial lake in the western sub-basin either as debris flows, derived from the moraine ridge, or as meltwater streams with a high sediment load. The channel that connects the western and eastern sub-basins probably still functioned as a meltwater channel, as it did during the deposition of unit II. The sediment disruptions in unit III within this channel indicate possible terminus fluctuations as does the small till tongue at the boundary between unit III and unit IV. The location of the Puyehue ice terminus during deposition of unit IV is uncertain. The depocentre location of unit IV indicates that Rupanco meltwater probably flowed into Lago Puyehue, indicating that the Puyehue glacier had already retreated (i.e. to the moraine ridge) out of that area of the lake basin, but that the Rupanco glacier still remained at its last maximum position, covering Lago Rupanco entirely. This is completely in agreement with the scenario proposed by Bentley (1997). Meltwater from the Rupanco glacier flowed into Lago Puyehue via the present-day outlet. However, Lago Puyehue probably had a significantly lower lake level. Subsequently, the lake level must have risen to allow the creation of the delta deposits, currently exposed on land, which correlate well with the depocentres of unit V and which Bentley (1997) links to meltwater streams from the Rupanco glacier. Thus, the positions of the deltas described by Bentley (1997) indicate that the Puyehue glacier had retreated beyond these deposits and that again Rupanco meltwater was responsible for sediment deposition in the western sub-basin of Lago Puyehue. The position of the depocentres at that time is best correlated with a possible advance of a Rupanco ice lobe south of Bahía Futacullín, as also proposed by Bentley (1997) based on onshore morphological and sedimentological observations.

In the northern sub-basin subglacial sedimentation processes were replaced by glaciolacustrine sedimentation as soon as the Puyehue glacier had started to retreat from the moraine ridge. The eastern subaqueous ridge, the Golgol ridge, just outside the Río Golgol delta probably represents the glacier's last stable position before fully retreating from the lake basin prior to the deposition of unit VI.

The initiation of deposition of unit VI indicates a totally ice-free lake with a predominantly autochthonous lacustrine sedimentation in the entire water basin, although there would

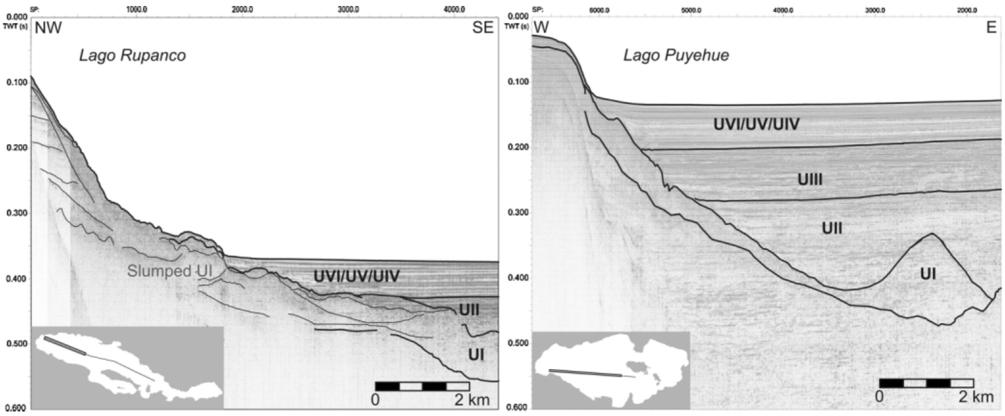

Figure 8. Seismic profiles contrasting the sediment infills in Lago Rupanco and Lago Puyehue. Lago Rupanco is a deep lake (ca. 280m) with a thin sediment infill (ca. 90m) in contrast to Lago Puyehue which is a much shallower lake (ca. 100m) but with a thicker sediment infill (ca. 240m).

still have been a significant riverine influence in the eastern sub-basin. For at least a short while during deposition of unit VI a glacier was probably still present in the lake catchment. There is sediment disturbance at the inlets of Río Mantilhue and Estero Cordàl that had already started during deposition of unit V, implying a higher sediment load in the river water, most likely caused by sediment-loaded glacial meltwater. But as many studies and models have indicated (McCulloch *et al.*, 2000; Hulton *et al.*, 2002), the retreat of the glacier from the catchment was probably rapid and present-day depositional conditions were achieved quickly.

The overall effect of the differential behaviour of the Rupanco and Puyehue glaciers (i.e. the maximum extent of the Rupanco glacier occurring at the same time as the retreat of the Puyehue glacier) is already obvious from the general lake basin geometries and the thicknesses of the basin infills. The water depth of Lago Puyehue (ca. 100 m) is much less than that of Lago Rupanco (ca. 280 m), but the sedimentary infill of Lago Puyehue is almost three times as thick as that of Lago Rupanco (Fig. 8). The proglacial unit III is also lacking in Lago Rupanco, indicating that this proglacial lake phase with a semi-stable Puyehue glacier pinned on the moraine ridge half-way in the lake is typical for Lago Puyehue, but is not representative of glacier behaviour in this region.

Timing of glacier retreat

Dating this series of events is difficult. Only one in-lake data point, the PU-II sediment core, is available for Lago Puyehue (Betrand *et al.*, 2008) and none for Lago Rupanco. Bentley (1997) provides ^{14}C dates for the moraines around both lakes. The discrepancy between both age models creates an impasse. The PU-II sediment core has a base-of-core age of 17915 cal a BP (Bertrand *et al.*, 2008). The sedimentological and geochemical characteristics (Bertrand *et al.*, 2008) and the diatom assemblages in the core (Sterken *et al.*, 2008) indicate open-lake conditions with no direct contact with glacier ice during the entire time interval represented by this core. The core itself penetrates only three-quarters of unit VI (Fig. 9). If we use the same seismic velocity obtained from the correlation between the core and the seismic profile, the remaining quarter represents still over 3 m of uncored sediment. The seismic data indicate no change in facies between the cored and the uncored part of this unit, implying that the depositional environment did not change (Charlet *et al.*, 2008; present study). Depending on the seismic velocities and sedimentation rates used, an extrapolated age for the lower boundary of unit VI has been estimated at 23 600 cal a BP by Moernaut *et al.* (2007) or at 24 750 cal a BP by Charlet *et al.* (2008). This age window for open-water conditions in Lago Puyehue contradicts strongly with Bentley's (1997) chronology, which places the Puyehue glacier still at the western margin of the lake basin at 23 150 cal a BP and estimates Lago Puyehue to have been ice-free only by 14 100 cal a BP. Even if we do not attach too much significance to the extrapolated ages obtained by Moernaut *et al.* (2007) and Charlet *et al.* (2008), the age of ice-free lake conditions of the multiproxy core study of PU-II at 17 915 cal a BP (Bertrand *et al.*, 2008; Sterken *et al.*, 2008) disagrees with the ice-free lake age of the geomorphological study (Bentley, 1997).

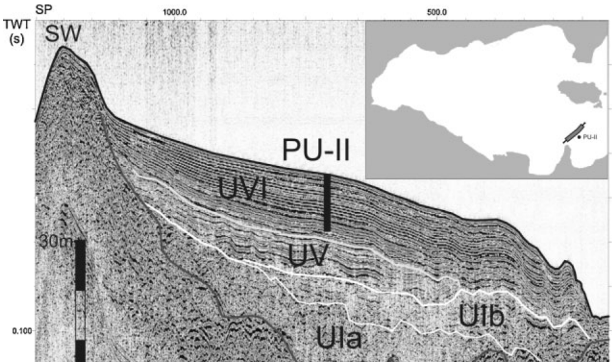

Figure 9. Seismic profile close to the PU-II coring site on the elevated platform. Location of profile shown in inset. Characterization of the three seismic units present on the platform. The projection of the core on the profile demonstrates that the core base does not reach the lower boundary of unit VI.

Conclusions

The seismic stratigraphy of Lago Puyehue reveals a complex deglacial history in this region. Bentley's (1997) earlier assumptions about the mode of deglaciation and the asynchronous behaviour of the Rupanco and Puyehue glaciers are largely supported by our findings. However, the combination of our new data with existing geomorphological information allows a better and more detailed reconstruction and understanding of the deglaciation of the Puyehue basin than previously possible. There are, however, significant discrepancies between the geomorphologically dated glacial advances (e.g. Bentley, 1996, 1997) and the dates of the Puyehue glacier retreat based on the continuous sedimentary record of the PU-II core. Both chronologies, the PU-II core (Bertrand *et al.*, 2008) and the dated moraines (Bentley, 1997), have their flaws, but this timing conundrum does point towards some imperfections in the current deglaciation history of the Chilean Lake District. More in-lake core studies should be performed to see if these age discrepancies also exist in other Chilean lakes.

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