J Paleolimnol (2008) 39:163–177
DOI 10.1007/s10933-007-9112-3

ORIGINAL PAPER

Seismic stratigraphy of Lago Puyehue (Chilean Lake District): new views on its deglacial and Holocene evolution

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Received: 2 October 2006 / Accepted: 29 April 2007 / Published online: 27 July 2007

Abstract Prior to the collection of a series of sediment cores, a high- and very-high-resolution reflection seismic survey was carried out on Lago Puyehue, Lake District, South-Central Chile. The data reveal a complex bathymetry and basin structure, with three sub-basins separated by bathymetric ridges, bedrock islands and interconnected channels. The sedimentary infill reaches a thickness of >200 m. It can be sub-divided into five seismic-stratigraphic units, which are interpreted as: moraine, ice-contact or outwash deposits (Unit I), glacio-lacustrine sediments rapidly deposited in a proglacial or subglacial lake at the onset of deglaciation (Unit II), lacustrine fan deposits fed by sediment-laden meltwater streams in a proglacial lake (Unit III), distal deposits of fluvially derived sediment in an open, post-glacial lake (Unit IV) and authigenic lacustrine sediments, predominantly of biogenic origin, that accumulated in an open, post-glacial lake (Unit V). This facies succession is very similar to that observed in other glacial lakes, and minor differences are attributed to an overall higher depositional energy and higher terrigenous input caused by the strong seismic and volcanic activity in the region combined with heavy

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This is the *second* in a series of eight papers published in this special issue dedicated to the 17,900 year multi-proxy lacustrine record of Lago Puyehue, Chilean Lake District. The papers in this special issue were collected by M. De Batist, N. Fagel, M.-F. Loutre and E. Chapron.

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precipitation. A long sediment core (PU-II core) penetrates part of Unit V and its base is dated as 17,915 cal. yr. BP. Extrapolation of average sedimentation rates yields an age of ca. 24,750 cal. yr. BP for the base of Unit V, and of ca. 28,000 cal. yr. BP for the base of Unit IV or for the onset of open-water conditions. This is in contrast with previous glacial-history reconstructions based on terrestrial records, which date the complete deglaciation of the basin as ca. 14,600 cal. yr. BP. This discrepancy cannot be easily explained and highlights the need for more lacustrine records from this region.

Keywords Seismic stratigraphy · Lake · Deglaciation · Holocene · South America

Introduction

Glacial lakes contain in their sedimentary infill an important record of the evolution in sediment-production and -transport processes that have affected the lake's drainage basin from the onset of deglaciation to the present. However, the sediments that have accumulated in these lakes are often extremely thick -up to several hundreds of meters- and this strongly complicates the study of their complete record through sediment coring. Most often, therefore, the sedimentary infill of glacial lakes is investigated through a combination of sediment coring and high-resolution reflection seismic profiling. Previous studies, especially in northern North America (e.g. Eyles et al. 1991; Eyles and Mullins 1997; Lønne and Syvitski 1997; Syvitski and Lee 1997; Desloges and Gilbert 1998; Eyles et al. 2000; Mullins and Halfman 2001) and in the European Alps (e.g. Finckh et al. 1984; Van Rensbergen et al. 1998, 1999; Beck et al. 2001; Moscariello et al. 1998), have shown that seismic records from these lakes are characterised by a very typical succession of seismic facies that highlight the evolution of the sedimentary environment from sub- or proglacial, over glaciolacustrine and fluviolacustrine to the present-day open lacustrine conditions, and this has led to the definition of a sort of general "type stratigraphy" for glacial lakes (Van Rensbergen et al. 1998).

In recent years, Lago Puyehue, a glacial lake at the piedmont of the Andes in the Lake District of South-Central Chile, has been the subject of an interdisciplinary study of its sedimentary infill through a combination of sediment cores and seismic profiles (De Batist et al. 2007). The objectives of the seismic investigations in this study were two-fold:

- to determine the most suitable location (e.g. suitable sedimentary environment, continuous and undisturbed record) for the collection of the sediment cores;
- to construct a seismic stratigraphy for Lago Puyehue in order to determine and characterise the major steps in the deglacial evolution of the basin (especially for the earlier periods not covered by the sediment cores), but also to provide a basin-wide stratigraphic framework that will allow the different sediment cores to be correlated with each other.

Unlike the glacial lakes in the European Alps or in northern North America, Lago Puyehue is located in a geodynamically highly active region, characterised by active volcanism and high subduction-related seismicity. Both can strongly impact the landscape surrounding the lake, alter the sediment yield and sediment-transport pathways in the drainage basin, and influence the sedimentary environments in the lake. The question thus arises whether the glacial lake "type stratigraphy" can also be applied to glacial lakes in such a highly dynamic area, or whether in these environments the overprint of volcanism and seismicity becomes too strong.

The aim of this paper is (1) to present the first reflection seismic data from Lago Puyehue, (2) to develop a seismic stratigraphy for Lago Puyehue and to compare it to that of other glacial lakes, (3) to correlate the coring information with the seismic data, and (4) to reconstruct the depositional and deglacial history of the area of Lago Puyehue.

Study area

Lago Puyehue (40°40′ S, 72°28′ W) is one of the large glacial, moraine-dammed piedmont lakes that make up the Lake District in South-Central Chile (38–43° S, Campos et al. 1989). It is located at the western foothill of the Cordillera de Los Andes (Fig. 1) at an elevation of 185 m a.s.l., and occupies an overdeepened glacial depression. The lake is dammed at its western margin by a series of moraine

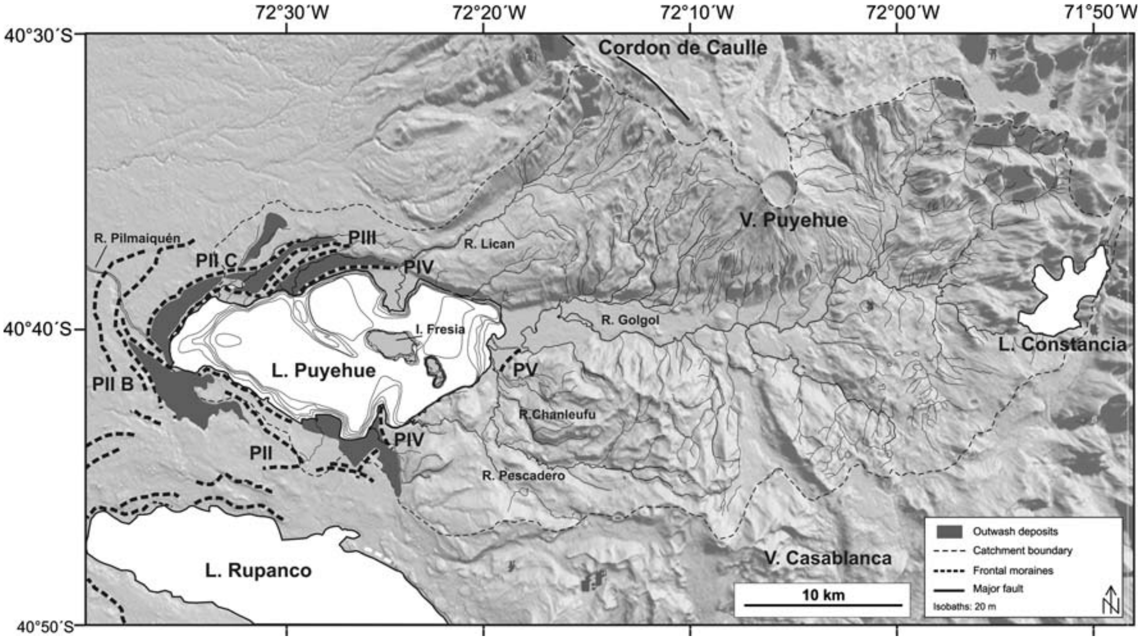

Fig. 1 Grey-shaded, SRTM-derived Digital Elevation Model (DEM) of Lago Puyehue and its catchment, with indication of drainage network, main rivers, volcanoes, and glacigenic geomorphological features (i.e. moraine ridges and outwash deposits, after Bentley 1997). Bathymetry of Lago Puyehue is based on Campos et al. (1989); bathymetry of Lago Rupanco is not included

belts (Laugenie 1982; Bentley 1997) that date from the last glaciation, which is known in the area as the Llanquihue glaciation (Heusser 1974).

Lago Puyehue has a surface area of 165.4 km^2 and a maximum depth of 123 m (Campos et al. 1989). Its bathymetry is complex, with several sub-basins separated by bathymetric sills and with a series of small bedrock islands in the centre (Fig. 1). The maximum depth of the lake is reached in the eastern sub-basin.

The catchment area covers 1,510 km^2, and extends far to the east from the lake (Fig. 1). It consists of Quaternary volcanic rocks, Pleistocene glacial and fluvioglacial deposits and isolated outcrops of Mesozoic and Cenozoic intrusions, and it is covered by several metres of post-glacial andosoils. The lake's main tributary is the Rio Golgol at its eastern margin (Fig. 1). Several smaller rivers also flow into the lake from the north, south and southeast. Rio Pilmaiquén forms the outlet of the lake, which cross-cuts several of the frontal moraine ridges (Laugenie 1982; Bentley 1997) before merging with the Rio Bueno and eventually flowing into the Pacific.

Lago Puyehue is surrounded by several active volcanoes (Fig. 1): i.e. Volcan Casablanca at about 20 km to the southeast of the lake (1,990 m a.s.l.) and Volcan Puyehue (2,240 m a.s.l.) and its fissural prolongation Cordon de Caulle at about 30 km to the east of the lake.

Material and methods

Reflection seismic profiles

In the austral summer of 2001–2002, a regional grid of 47 high-resolution and very-high-resolution reflection seismic profiles was acquired across the lake (Fig. 2). The high-resolution data were collected using a multi-electrode sparker (300 J, main frequency: 400–1,500 Hz) as seismic source, and a single-channel, high-resolution streamer as receiver, while the very-high-resolution data were acquired using a 3.5 kHz GeoAcoustics sub-bottom profiling system. A Simrad Shipmate GPS was used for positioning and navigation of the R/V Huala-II of the Universidad Austral de Chile (Valdivia, Chile). The seismic and positioning data were recorded digitally on an Elics Delph-2 system. Processing, which included signal deconvolution, frequency

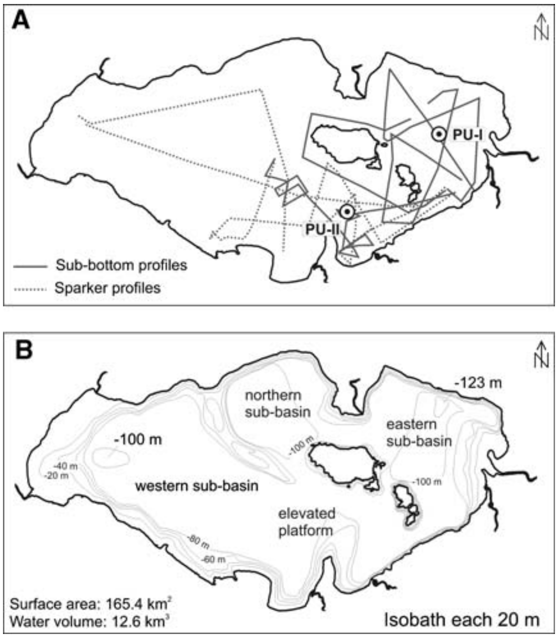

Fig. 2 (**A**) Location map of the seismic profiles (sparker and sub-bottom profiles) and of the PU-I and PU-II coring sites. (**B**) Bathymetry map, compiled by combining the seismic data with the data of Campos et al. (1989). The main morphological units are indicated

filtering and true-amplitude recovery, was carried out with Landmark ProMAX seismic processing software, and seismic-stratigraphic and structural interpretation and mapping was conducted on an SMT Kingdom Suite seismic interpretation system. Since the single-channel data do not provide information on seismic velocities, an average velocity of 1,600 m/s was used for time-depth conversions.

In total, 65 km of sparker profiles and 73 km of sub-bottom profiles were acquired (Fig. 2). The sparker data penetrate the entire sedimentary infill in the western part of the lake (>200 m thick) with a vertical resolution of <1 m. Elsewhere in the lake, penetration is restricted to ~20 m due to gas blanking. The sub-bottom profiles are predominantly located in the eastern part of the lake (Fig. 2). They penetrate the upper sedimentary infill to a depth of about 20 m with a vertical resolution of 25–30 cm.

Sediment cores and core analysis

The seismic data were used to select two sites for the collection of sediment cores (Fig. 2): the PU-I coring site (40°39.77′ S, 72°22.155′ W) is located in the deep eastern part of the lake at 122 m water depth and the PU-II coring site (40°41.84′ S, 72°25.341′ W) is located in the southern part of the lake at a water depth of 48 m. Cores were taken with the UWITEC piston corer of the Université de Savoie (Chambéry, France). The PU-II core has a total composite length of 1,122 cm; recovery in the PU-I core was restricted to only 236 cm.

The cores were scanned for magnetic susceptibility and gamma-density with a GEOTEK multisensor core logger on non-opened sections. Whole-core magnetic susceptibility was re-measured at higher resolution on open sections with a Bartington MS2E point sensor every 5 mm. Most subsequent analyses have focussed on the PU-II core, because of the quality of its record and its length. It was sampled for sedimentological, mineralogical and geochemical analysis (Bertrand et al. 2007), and for pollen and diatom studies (Vargas et al. 2007; Sterken et al. 2007).

Additionally, nine samples were used for bulk AMS ^{14}C dating. The ages and age-depth model are presented in Bertrand et al. (2007) and are internally consistent. Additional ^{210}Pb and ^{137}Cs datings were performed (Arnaud et al. 2006) and were similarly consistent with the age-depth model. The 1,122 cm long core spans the last 17,915 years. Large parts of it are annually laminated (Boës and Fagel 2007a, 2007b).

Results

Overall basin structure

The seismic data confirm the complex bathymetry and basin structure of Lago Puyehue (Figs. 1, 2). Three main sub-basins can be distinguished in the western, the northern and the eastern parts of the lake. The western sub-basin is the largest. It is completely separated from the northern sub-basin by a continuous bathymetric ridge, extending from the northern coast to Isla Fresia. In the south, the western sub-basin is bordered by a more or less isolated, elevated platform (PU-II coring site) that extends from the southern coast almost to Isla Fresia. A narrow passage connects the western sub-basin to the eastern sub-basin via a patchwork of interconnected deep channels that are flanked by bathymetric highs and smaller bedrock islands. The northern sub-basin is almost completely isolated. It is separated from the eastern sub-basin by the Rio Lican delta, which extends almost to Isla Fresia. Only a narrow connection between the two basins exists. The eastern sub-basin (PU-I coring site) is the deepest, despite the fact that it is located closest to the inflow of the Rio Golgol, the main tributary to the lake and main source of detrital input.

The sedimentary infill in the western sub-basin reaches a thickness of >200 m (Fig. 3). In the northern and eastern sub-basins acoustic penetration is restricted to ~20 m. The sedimentary cover on the southern platform is about 80 m thick.

Sparker data in the western sub-basin

The sparker data penetrate the entire sedimentary basin fill in the western sub-basin, down to the acoustic basement (Fig. 3). Five seismic-stratigraphic units, labelled Unit I to Unit V from old to young and separated by sequence boundaries (S1 to S5), can be distinguished within this basin fill.

The acoustic basement is marked by an irregular, high-amplitude reflection that marks the lower boundary of the acoustically-stratified sedimentary infill of the lake basin and below which no coherent seismic response is recorded. It is clearly visible in the westernmost part and close to basin margins of the western sub-basin, and in the vicinity of the

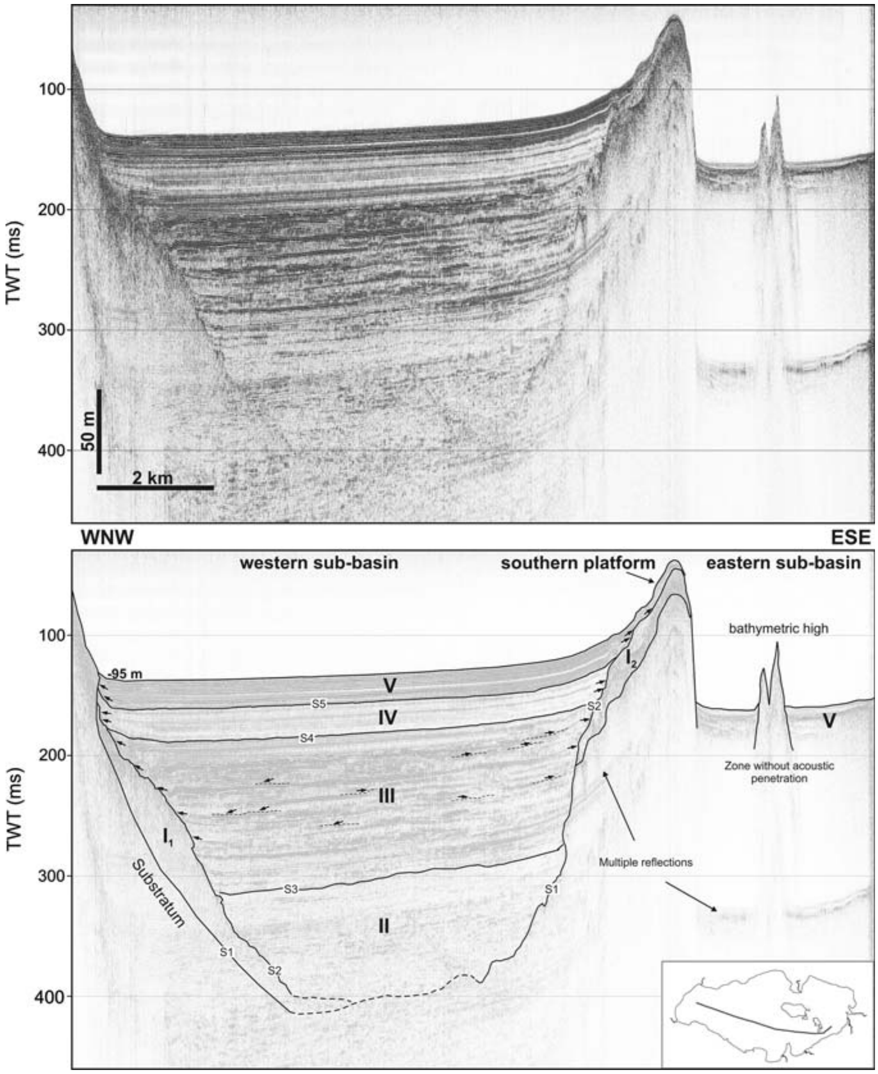

Fig. 3 Sparker seismic profile across the western sub-basin, the southern platform and part of the eastern sub-basin (see inset for location). Upper panel: un-interpreted section. Lower panel: interpreted section, with indication of substratum and seismic-stratigraphic units (Unit I to Unit V). Arrows in Units III, IV and V indicate onlapping and downlapping reflection terminations

islands (Fig. 3). It can not be traced below the central part of the basin due to interference with lake-floor reflection multiples.

Unit I is the oldest seismic-stratigraphic unit in the western sub-basin. It is characterised by a succession of two seismic facies: 1) a basal high-amplitude, chaotic facies that gradually changes higher up in the unit into 2) a facies consisting of lower-amplitude, discontinuous, irregular reflections. It occurs in two isolated sediment bodies: one in the western part and one in the southeastern part of the basin (Fig. 3). The western unit (Unit I_1) rests against the slope formed by the acoustic basement. It has a lenticular shape, thinning both towards the top and base of the slope, and reaches a maximum vertical thickness in its central part of 64 ms TWT (~51 m). The southeastern unit (Unit I_2) also forms an isolated, lenticular body perched on the top of the acoustic basement along the southeastern slope and extending under the southern platform (Fig. 4). The basal contact of Unit I (S1) is irregular and cannot be continuously traced throughout the basin due to interference with lake-floor reflection multiples. The upper boundary of the sequence (S2) is marked by a clear unconformity with the overlying, onlapping units (Unit II, Unit III and Unit IV).

Unit II fills the deepest part of the western sub-basin, and overlies the acoustic basement or Unit I. It reaches a maximum thickness of 102 ms TWT (~82 m). Although to a large extent hidden by lake-floor reflection multiples, the seismic facies of Unit II can be characterised as acoustically homogeneous: i.e. nearly transparent or consisting of only a few discontinuous, very weak reflections (Fig. 3). The upper boundary of the sequence is slightly undulating, with a few minor erosional incisions.

Unit III overlies Unit II in the deep part of the western sub-basin. It is the most voluminous seismic-stratigraphic unit of the entire basin infill. It reaches a maximum thickness of 128 ms TWT (~102 m) in the western part of the western sub-basin and is slightly thinner (117 ms TWT or ~94 m) in the eastern part. The seismic facies of Unit III consists of undulating, continuous or discontinuous, medium- to high-amplitude reflections that are characterised by a strong lateral variability in reflection amplitude. These reflections are separated by packages characterised by much lower reflection energy. The entire unit is affected by abundant erosional truncations and small-scale internal onlap and downlap terminations. The abundance of these internal erosive surfaces progressively decreases towards the upper part of the unit. The upper boundary of Unit III (S4) does not represent an unconformity, but has been defined as seismic-stratigraphic boundary as it marks a major change in acoustic facies with the overlying Unit IV.

Unit IV drapes Unit III. Its thickness reaches about 27 ms TWT (~22 m) in the centre of the basin and it gradually thins towards the basin margins. It is characterised by an acoustically well-stratified facies, with continuous, low- to medium-amplitude reflections. The upper boundary is an onlap surface for the overlying deposits.

Unit V reaches a maximum thickness of about 24 ms TWT (~19 m) in the centre of the basin and it gets thinner towards the basin margins, where some minor onlap against the underlying deposits can be observed. Its seismic facies is highly stratified with continuous, parallel, high-amplitude reflections.

Sparker data on the southern platform

The sparker data penetrate the sedimentary cover on the southern platform down to the acoustic basement (Fig. 4). Four seismic-stratigraphic units can be distinguished, but due to the fact that the platform is bounded by relatively steep slopes it is not possible to physically correlate all seismic-stratigraphic units from the western sub-basin with those on the platform, except for Unit I_2, Unit IV and Unit V. The fourth unit is tentatively correlated with Unit III based on its stratigraphic position and its seismic facies.

The acoustic basement and Unit I_2 have the same characteristics as in the western sub-basin (Figs. 3, 4).

Unit III overlies Unit I_2 and is characterised by a chaotic to poorly stratified acoustic facies with discontinuous, high- to medium-amplitude reflections, sometimes terminating in onlap or downlap on the irregular basal unconformity of Unit III (Fig. 4). It reaches a maximum thickness of 55 ms TWT (~44 m) in the deepest depressions. The upper boundary of Unit III marks a major change in acoustic facies with the overlying Unit IV.

The thickness of Unit IV is about 23 ms TWT (~18 m), and is relatively uniform across the platform. It is characterised by an acoustically-stratified facies, with continuous, undulating,

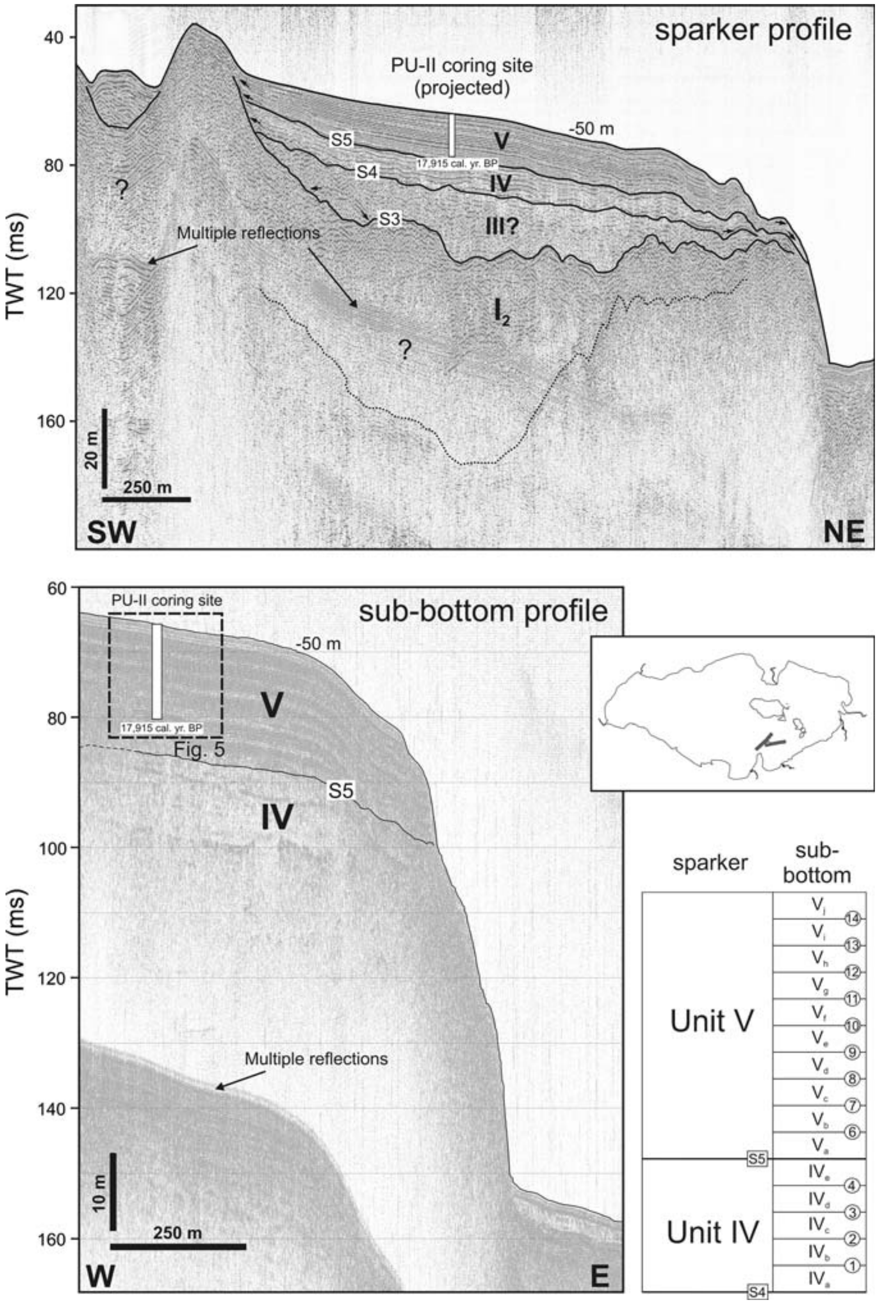

Fig. 4 Seismic profiles across (or very close to) the PU-II coring site on the southern platform. Upper panel: sparker seismic profile with indication of seismic-stratigraphy units. Lower panel (left): sub-bottom seismic profile. Lower panel (right): schematic table of the sparker versus sub-bottom seismic stratigraphy

low-frequency and medium-amplitude reflections (Fig. 4).

Unit V drapes Unit IV. It has a relatively uniform thickness of 35 ms TWT (~28 m). Two acoustically well-stratified seismic facies can be discerned within Unit V. The lower part is characterised by continuous, parallel, high-frequency and medium-amplitude reflections, while in the upper part the reflections are distinctly stronger. Both facies are separated by a high-amplitude reflection (Fig. 4).

Sub-bottom profiler data on the southern platform

The sub-bottom profiler data penetrate only the upper ~20 m of sedimentary cover on the southern platform, i.e. Unit V and the upper part of Unit IV

(Fig. 4). Due to the frequency and acoustic pulse characteristics, the seismic facies on the sub-bottom data are not entirely similar to those on the sparker data.

The upper part of Unit IV has a stratified to sometimes chaotic facies with low- to medium-amplitude reflections characterised by distinct lateral variations in amplitude. Unit V has a highly stratified seismic facies with continuous, parallel, high-frequency and medium- to high-amplitude reflections, separated by intervals in which the reflection amplitudes are weaker (Fig. 4). The succession of two seismic facies as observed on the sparker data is not evident on the sub-bottom profiles.

Based on the amplitude variations affecting both Unit IV and Unit V, it has been possible to sub-divide both units into a series of sub-units: five sub-units in Unit IV (named Unit IV$_a$ to Unit IV$_e$, from bottom to top) and ten sub-units in Unit V (named Unit V$_a$ to Unit V$_j$, from bottom to top). The sub-units are bounded by distinct, laterally continuous, high-amplitude reflections: reflections 1 to 4 in Unit IV and reflections 6 to 14 in Unit V (reflection 5 is equivalent to S5) (Fig. 4). These reflections can be used as marker horizons and allow a stratigraphic correlation to be made between the strata on the southern platform and those in the western sub-basin, even though it is not possible to trace these horizons on the sub-bottom profiler data across the steep slopes bounding the southern platform (Fig. 5).

PU-II core data versus seismic profiles

The PU-II core (Fig. 6), which penetrates the upper 3/4 of seismic-stratigraphic Unit V (i.e. sub-units V$_b$ to V$_j$, Fig. 5) and which spans the last 17,915 years (Bertrand et al. 2007), consists predominantly of finely-laminated to homogeneous brown silty sediment, mainly composed of diatoms, organic matter, amorphous clays, crystalline minerals and volcanic glasses (Bertrand et al. 2007). Diatom assemblages are dominated by *Cyclotella stelligera* and *Aulacoseira granulata* (Sterken et al. 2007). In addition to this background sedimentation indicative of calm- and open-water lacustrine conditions, the core comprises also 3 turbidite layers and 78 coarse-grained tephra

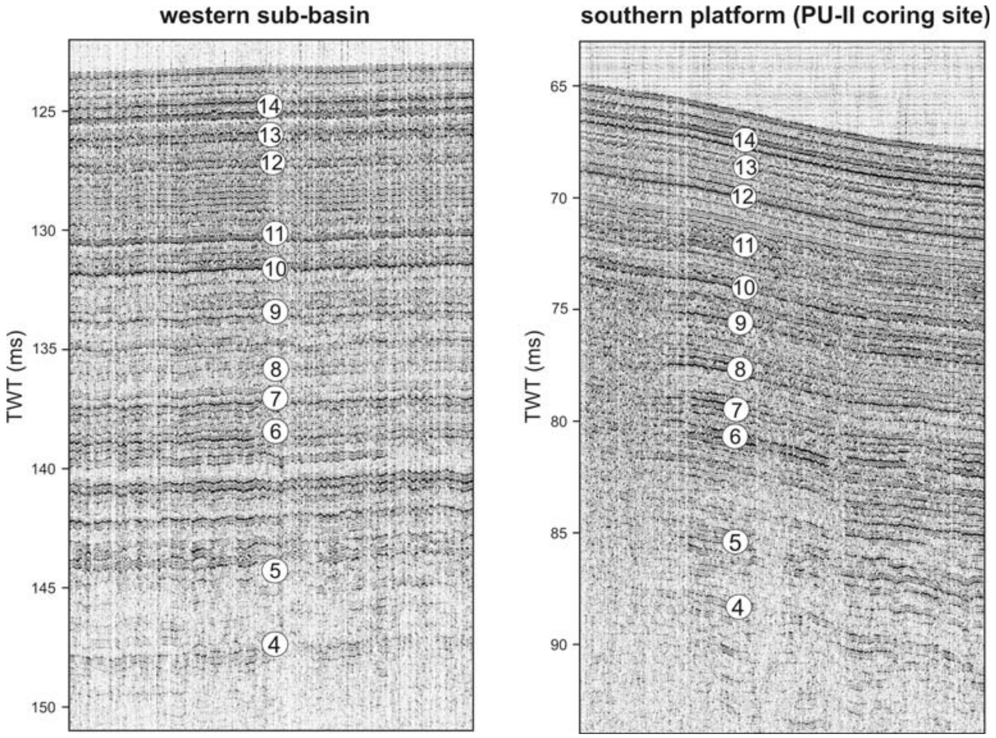

Fig. 5 Sub-bottom seismic profiles from the western sub-basin and the southern platform, with indication of the seismic-stratigraphic sub-unit boundaries

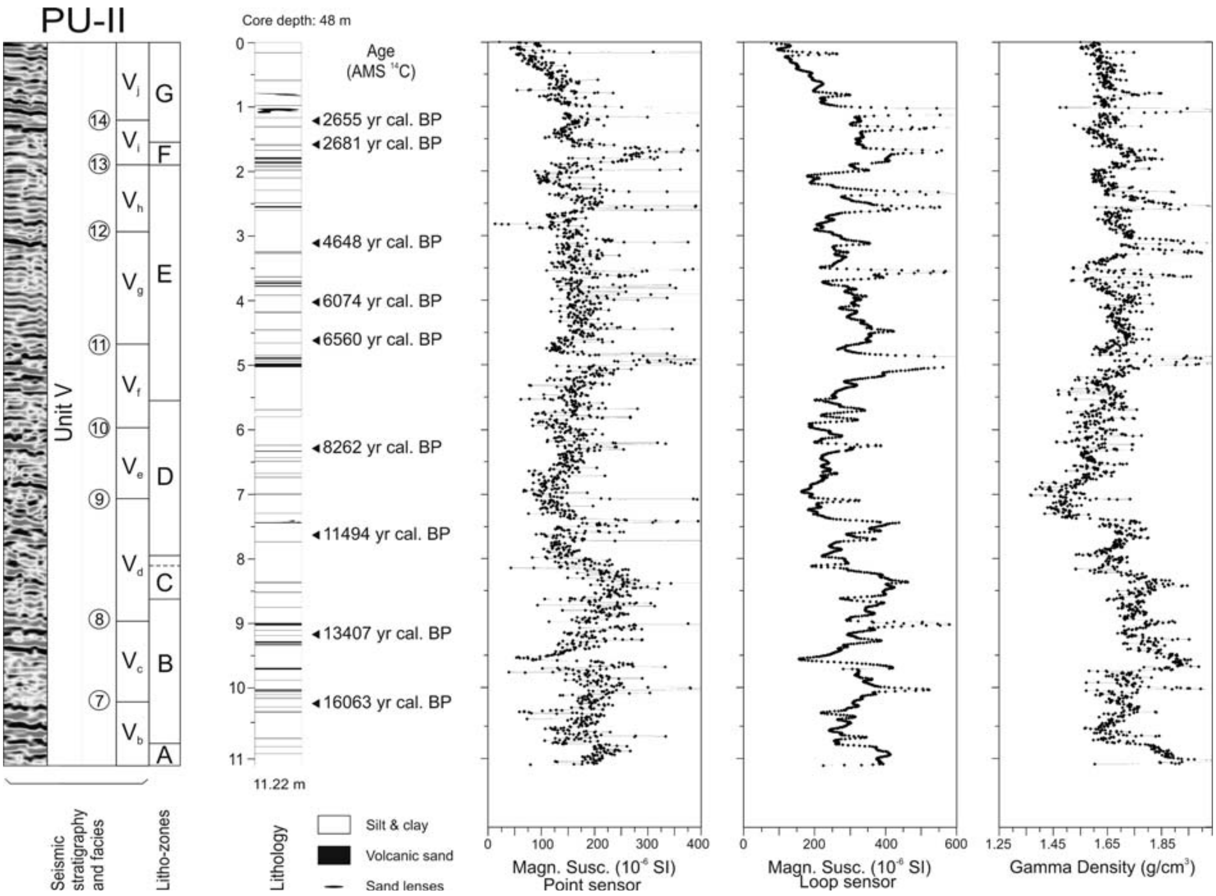

Fig. 6 Seismic stratigraphy versus lithology and physical properties (magnetic susceptibility and gamma density) of the PU-II core. Core lithology, AMS radiocarbon ages and sub-division in litho-zones is based on Bertrand et al. (2007)

layers (Bertrand et al. 2007). These intercalated tephra layers are embedded in a fine matrix and are generally less than 1 cm thick. They represent the bulk of the terrigenous supply to this part of the lake. Their total thickness is 52.3 cm (4.66 % of the total core length). Also, several ~1 cm thick grey or greenish clay layers often containing pumice pebbles were observed. Magnetic susceptibility (MS) data vary between 43 × 10^{-6} SI (9.5 cm) and 1,277 × 10^{-6} SI (233 cm). The higher values correspond to fall-out tephra layers, which are dominated by orthopyroxene minerals and characterised on the sub-bottom profiler seismic data by distinct strong reflections (Fig. 6).

Seven lithological zones have been identified in the PU-II core (Fig. 6), based on changes in paleoproductivity and in rates of detrital supply, and thus reflecting paleoclimatic evolution (Bertrand et al. 2007). They have been labelled A to G, from the base to the top (Bertrand et al. 2007). Some of the litho-zones correspond to seismic sub-units, but not all. The three oldest litho-zones (A, B and C, 800–1,122 cm, 11,800–17,915 cal. yr. BP) correspond to the interval of seismic Unit V_b to halfway Unit V_d. These litho-zones are characterised by a relatively high content of terrigenous material as indicated by high magnetic susceptibility (166–931 × 10^{-6} SI) and gamma density (1.571–1.995 g/cm^3) values. Litho-subzone C_1 (825–865 cm, 12,300–13,100 cal. yr. BP) represents the period with the most stable high values in magnetic susceptibility, followed by a relatively rapid decrease during litho-subzone C_2 (800–825 cm, 11,800–12,300 cal. yr. BP). Litho-zone D (580–800 cm, 7,800–11,800 cal. yr. BP) is characterised by low magnetic susceptibility (67.5 × 10^{-6} SI) and gamma density (1.368 g/cm^3) values, reflecting the high biogenic silica content of the sediment. Above this layer, an almost 3.5 m thick sedimentary package constitutes litho-zone E (195–580 cm, 3,400–7,800 cal. yr. BP). It is characterised by relatively low magnetic susceptibility values, which seems related to the large amounts of organic matter in the sediment (Bertrand et al. 2007), but these low values are frequently interrupted by peaks of high magnetic susceptibility values caused by tephra layers. Litho-zone F (150–195 cm, 2,900–3,400 cal. yr. BP) is marked by high magnetic susceptibility and gamma density values, also related to the concentration of tephra layers. The uppermost litho-zone G (0–150 cm, present to 2,900 cal. yr. BP) is dominated by high biogenic productivity and shows a progressive decrease in the petrophysical values towards the present-day very low values.

Seismic stratigraphy of Lago Puyehue

The sparker seismic data from the western sub-basin of Lago Puyehue reveal a sedimentary infill composed of five seismic-stratigraphic units, each with its own characteristic seismic facies (Fig. 3). The succession of these seismic facies throughout the infill reflects the evolution of the sedimentary processes in the lake basin through time.

A more or less similar 5-fold seismic stratigraphy has been observed in many other glacial lake basins, and this has led to the definition of a "type stratigraphy" for glacial lakes (Van Rensbergen et al. 1998), which consists of (from base to top):

- Unit/Facies 1: an assemblage of chaotic to irregularly stratified seismic facies units with irregular external form that overly the substratum = grounding-line deposits associated to sub-aqueous meltwater discharge in a sub- or proglacial lake;
- Unit/Facies 2: a thick, mostly reflection-free, basin-fill unit that ponds the central deep of the basin and that becomes discontinuously stratified towards the margins = a rapidly deposited glacio-lacustrine sediment fill in a proglacial or subglacial lake;
- Unit/Facies 3: an onlapping, stratified basin fill, with parallel, continuous, high- to medium-amplitude reflections, that ponds the central deep of the basin = lacustrine fans fed by meltwater streams in a proglacial lake;
- Unit/Facies 4: a basinward-downlapping fill with parallel, continuous, medium-amplitude, sub-horizontal reflections = steep, prograding fan deltas fed by alluvial fans in a post-glacial lake disconnected from the retreating glaciers;
- Unit/Facies 5: a sheet drape of concordant, low-amplitude, continuous reflections = authigenic lacustrine sediments deposited in post-glacial lake during a warmer climate.

Lago Puyehue's Unit I has all the characteristics of Unit/Facies 1 of the "type stratigraphy" of Van Rensbergen et al. (1998): it has a chaotic to irregularly stratified seismic facies and an irregular external form. Moreover, it occurs in the lake basin (i.e. Unit I_1 in western part and Unit I_2 on the southern platform) immediately adjacent to where moraine belts and outwash sediments have been identified and mapped onshore (Fig. 1, Laugenie 1982; Bentley 1997). For these reasons, this unit is interpreted to represent morainic, ice-contact or outwash deposits, associated to sub-aqueous meltwater discharge in a sub- or proglacial lake or even to sub-aerial accumulation.

Unit II in Lago Puyehue is also very similar to the reflection-free or discontinuously stratified, ponding basin-fill unit that has been described in the central deep of many glacial lake basins and also of several fjords (e.g. Eyles et al. 1991; Cai et al. 1997; Aarseth 1997) and that constitutes Unit/Facies 2 of Van Rensbergen et al. (1998). This unit is therefore interpreted as comprising glacio-lacustrine sediments that have been deposited very rapidly in a proglacial or subglacial lake at the onset of the deglaciation of the basin.

The facies characteristics of Unit III are quite similar to those described by Van Rensbergen et al. (1998) for Unit/Facies 3: a stratified, ponded basin fill, with parallel, continuous, high- to medium-amplitude reflections onlapping towards the basin margins. Based on this analogy, this unit is interpreted to represent lacustrine fan deposits that were fed by sediment-laden meltwater streams (i.e. underflows) in a proglacial lake. The highly dynamic character of this depositional environment is reflected in the strong lateral variability in reflection characteristics (i.e. amplitude, continuity) and in the presence of abundant internal erosional truncations and of small-scale onlap and downlap terminations. The upward decrease in abundance of these erosive surfaces suggests that depositional energy has gradually subsided during accumulation of Unit III. The sometimes very high reflection amplitudes in this unit indicate that these meltwater-generated underflow pulses may have delivered coarse-grained, sandy sediments to the central parts of the basin. This facies could be genetically related to the massive glaciofluvial outwash terraces that have been described onshore in between the moraine belts (Bentley 1996, 1997). As field data suggest that the glaciers retreated rapidly from the Andes in the Chilean Lake District at the end of the LGM (Lowell et al. 1995; McCulloch et al. 2000), the associated meltwater streams probably did not persist for a long time. Therefore, Unit III was probably deposited in a relatively short period of time, despite its considerable thickness.

Unit IV's well-stratified facies with continuous, low- to medium-amplitude, parallel reflections differs from that of Van Rensbergen et al.'s (1998) Unit/Facies 4. The latter comprises distinct basinward-downlapping geometries and is attributed to deposition in fan deltas that were fed by fluvially derived sediment in an open, post-glacial lake. Under such conditions, the inflowing rivers carried much less sediment than the meltwater streams of Unit III and underflow activity was consequently much reduced, except during seasonal or exceptional floods, which could explain the presence of sporadic higher-amplitude reflections in Unit IV and the slight basinward-thickening of the unit in the western sub-basin. The difference in facies as recorded in Lago Puyehue compared to the "type stratigraphy" of Van Rensbergen et al. (1998) could be attributed to the fact that most of the main inflowing rivers enter the lake either at its northern, eastern and southeastern margins, with the result that the more proximal, prograding fan delta deposits are probably restricted to those areas, while the western sub-basin and the southern platform receive only the finer, more distal fraction.

Lago Puyehue's Unit V is characterized by a highly stratified facies with continuous, parallel, high-amplitude reflections. It has a draping geometry on the southern platform, but a slightly marginward-thinning and onlapping geometry in the deeper western sub-basin. As such, it differs from Unit/Facies 5 of Van Rensbergen et al. (1998), which is described as comprising low-amplitude reflections in a purely draping configuration (i.e. also in the basin centre) and which is attributed to authigenic lacustrine sedimentation in an open, post-glacial lake. The lithology of core PU-II confirms that the sediments of Unit V on the southern platform have indeed accumulated mainly by suspension settling of fine-grained, silt-sized particles of predominantly biogenic origin. They do, however, still contain a terrigenous component and it is likely that this component is more important in the deep western sub-basin towards where it can be transported by sporadic flood-generated underflows. This could also explain the anomalously high reflection amplitudes of this open-lake deposit. Nevertheless, the sub-bottom profiler data illustrate that the Unit V strata in the western sub-basin are only slightly thicker than those on the southern platform, confirming that the main component in both environments is indeed suspension settling of fine-grained sediment.

Overall, the seismic stratigraphy of Lago Puyehue is thus quite similar to the "type stratigraphy" proposed by Van Rensbergen et al. (1998), suggesting that the sedimentary facies succession in the lake basin reflects the deglacial evolution of the lake depression and its drainage basin. Nevertheless, there are also some differences, which involve the upper units (i.e. Unit IV and Unit V). Where the "type stratigraphy" predicts a gradual decrease in depositional energy from terrigenous-input-dominated (Unit/Facies 3 and 4) to authigenic-production-dominated (Unit/Facies 5), in response to i) the disconnection of the lake from direct meltwater input as a result of retreat of glaciers higher up in the catchment, and ii) the stabilisation of sediment in soils in the catchment under the influence of warming climate, this effect seems to be less conspicuous in the Lago Puyehue infill than in that of most other alpine-type lakes, especially those in the northern hemisphere. We tentatively attribute this to the specific geodynamic setting: the high subduction-related seismicity in the region can generate landslides and reshape topography in the catchment, and the intensive volcanic activity repeatedly covers the entire catchment with thick layers of volcanic ash (e.g. Chapron et al. 2006; Volland et al. 2007). Both landscape-altering effects have major consequences for the sediment yield from the catchment. The stabilising effect that is normally exerted by the development of a post-glacial vegetational cover and of soil formation is strongly reduced by the continuous introduction of new, fresh and mobile sediment (volcanic ash, landslides in river valleys, etc.) in the catchment. Together with the natural high precipitation in this region, this leads to relatively high fluxes of terrigenous supply towards the lake, even in present-day interglacial conditions.

Age of the sedimentary infill and implications for the deglacial history

The base of the PU-II core was dated as 17,915 cal. yr. BP (Bertrand et al. 2007). According to the core's sedimentological characteristics (Bertrand et al. 2007) and diatom content (Sterken et al. 2007), Lago Puyehue was an open lake that was not in contact with glacier ice and that was disconnected from direct glacier meltwater input for the entire time interval covered by the core, i.e. at least since 17,915 cal. yr. BP. This is also supported by our interpretation of the seismic facies of seismic-stratigraphic Unit V as resulting from open-lake suspension settling. But, as the PU-II core only penetrates the upper 3/4 of Unit V on the southern platform and as the seismic facies of Unit V does not significantly change in its basal part (Fig. 4), the same open-lake conditions must have existed from the beginning of the deposition of Unit V. Extrapolating sedimentation rates from the base of the core yields an estimated age of ca. 24,750 cal. yr. BP for the base of Unit V. Moreover, Unit IV's seismic facies indicates that it also accumulated in open-water conditions, and probably even unit III was deposited when most of the lake was ice free, i.e. when it was a proglacial or ice-contact lake. By extrapolating the sedimentation rate of Unit V, the age of the base of Unit IV on the southern platform or of the onset of open-water conditions in Lago Puyehue can be estimated as ca. 28,000 cal. yr. BP, and the base of Unit III as several thousands of years older. These are maximum estimates as sedimentation rates were probably higher during deposition of Unit IV and significantly higher during deposition of Unit III than during deposition of Unit V.

The deglacial history of the Chilean Lake District has been intensively studied during the past decades by Mercer (1972, 1976), Porter (1981), Laugenie (1982), Lowell et al. (1995) and Denton et al. (1999). Bentley (1997) focussed in particular on Lago Puyehue and neighbouring Lago Rupanco and reconstructed glacier fluctuations using geomorphological and stratigraphic analysis and detailed radiocarbon dating of moraine ridges and outwash deposits. Up to five generations of moraine ridges (PI to PV on Fig. 1) are identified around Lago Puyehue. These are all attributed to the last cold phase of the last glaciation: i.e. the Llanquihue III phase (Porter 1981) or the Neo-Llanquihue phase (Laugenie 1982). Three of these moraine ridges (PI to PIII) delineate the western border of the lake; PIV marks an intermediate position about halfway the lake (i.e. linking with the southern platform in the south and with the bathymetric ridge between the western and northern sub-basins in the north); PV is located to the east of the lake. Radiocarbon dating yielded an age between 16,100 yr. BP (ca. 19,200 cal. yr. BP) and 12,200 yr. BP (ca. 14,600 cal. yr. BP) for the glacier stillstand or re-advance of PIII, and of >12,200 yr. BP (ca. 14,600 cal. yr. BP) for PV (Bentley 1997). So, according to the onshore evidence, deglaciation of the Lago Puyehue basin was only complete by ca. 14,600 cal. yr. BP. The chronology of glacier fluctuations in the Puyehue and Rupanco lake basins as reconstructed by Bentley (1997) is largely consistent with those derived for other lake basins in the area (e.g. Lowell et al. 1995).

Our derived age of 28,000 cal. yr. BP for the base of Unit IV –or for the onset of open-water conditions in Lago Puyehue- is difficult to reconcile with the consensus view of the deglacial history of the region. The discrepancy becomes even more pronounced if we take into consideration that Units IV and V make up only 18% of the total sediment thickness in the western sub-basin, and that there is thus a long additional history of sediment accumulation between the glacier advance forming moraine ridges PIII and the onset of open-water conditions. We are confident about our age model because it is based on a combination of multiple dating methods (AMS ^{14}C, ^{210}Pb and ^{137}Cs, varve counting) yielding consistent age values and sedimentation rates (Bertrand et al. 2007; Arnaud et al. 2006; Boës and Fagel 2007a, 2007b). Furthermore, paleoclimate trends that have been derived from the core (Bertrand et al. 2007; Sterken et al. 2007; Vargas et al. 2007; Boës and Fagel 2007b), and that were dated using our age-depth model, produce results that are consistent with other paleoclimate records from the area (e.g. Ariztegui et al. 1997; Moreno 1997, 2000; Moreno et al. 2001; Hajdas et al. 2003).

Our data represent the first fully continuous, high-resolution lacustrine record from the Chilean Lake District. Other existing data in the region are discontinuous or low-resolution terrestrial records, predominantly based on geomorphological and stratigraphic studies of deglacial sediment sequences and on palynological studies of peatbogs, and marine records with a temporal resolution that is lower than ours (e.g. Lamy et al. 2004). Other lacustrine data from Lago Puyehue or from other lakes in the region are therefore required to test the validity of our record and to resolve the apparent contradiction between the lacustrine and terrestrial records.

Conclusions

- Lago Puyehue is characterized by a complex bathymetry and basin structure. Three main sub-basins are separated by bathymetric ridges, bedrock islands, an elevated platform and narrow interconnected deep channels. This morphology highlights the influence of contrasts in bedrock lithology on glacial erosion.
- The sedimentary infill in the western sub-basin reaches a thickness of >200 m; the sedimentary cover on the platform is about 80 m thick. Elsewhere in the lake, acoustic penetration is restricted to ~20 m due to the presence of shallow gas.
- The sedimentary infill in the western sub-basin can be sub-divided into five seismic-stratigraphic units (Unit I to Unit V, from old to young). Four of these also occur on the platform, where the PU-II core has penetrated the upper 3/4 of Unit V. Based on seismic-facies interpretation and on comparison with a glacial-lake type stratigraphy, these five units are interpreted as: moraine, ice-contact or outwash deposits (Unit I), glacio-lacustrine sediments that have been rapidly deposited in a proglacial or subglacial lake at the onset of the deglaciation (Unit II), lacustrine fan deposits fed by sediment-laden meltwater streams in a proglacial lake (Unit III), distal deposits of fluvially derived sediment in an open, post-glacial lake (Unit IV) and authigenic lacustrine sediments, predominantly of biogenic origin, that accumulated in an open, post-glacial lake (Unit V).
- The observed facies succession is similar to the glacial-lake type stratigraphy that was originally defined for alpine-type glacial lakes (Van Rensbergen et al. 1998). Minor differences are observed in the upper units (Unit IV and Unit V), which are characterised by a higher depositional energy and higher terrigenous content than what is generally observed in alpine-type glacial lakes. This can be explained by the high seismicity and intensive volcanic activity in the region, both of which affect the sediment yield from the catchment. Combined with the strong precipitation, this leads to relatively high terrigenous fluxes into the lake, even in present-day interglacial conditions.
- Extrapolation of sedimentation rates at the base of the PU-II core (which was dated as 17,915 cal. yr. BP) yields an age of ca. 24,750 cal. yr. BP for the base of Unit V, and of ca. 28,000 cal. yr. BP for the base of Unit IV or for the onset of open-water conditions in Lago Puyehue. This contrasts with glacial history reconstructions based on terrestrial records, which date the complete deglaciation of the basin as ca. 14,600 cal. yr. BP, in general agreement with other basins in the region. This discrepancy cannot be easily explained. New lacustrine records are required to test the validity of our record and to resolve the apparent contradiction between the lacustrine and terrestrial records.

Acknowledgments This study was carried out with support from the Belgian Science Policy Office, project "A continuous Holocene record of ENSO variability in southern Chile". M. Pino was supported through the Millenium Science Initiative, Nuclei FORECOS (MIDEPLAN) N° P04-065-F. We thank R. Brümmer (Universidad Austral de Chile, Valdivia, Chile), W. San Martin and A. Peña (EULA, Universidad de Concepción, Chile), K. De Rycker (RCMG, Belgium), X. Boës (University of Liège, Belgium) and C. Beck, M. Tardy, F. Arnaud and V. Lignier (University of Savoie, Chambéry, France) for their support and cooperation during the seismic and coring fieldwork in the austral summer of 2001–2002. We are also grateful to X. Boës, F. De Vleeschouwer, V. Renson and N. Fagel (University of Liège, Belgium) for lithological descriptions, AMS radiocarbon dating and for their help during high-resolution magnetic susceptibility measurements. We also thank H. Oberhänsli (GFZ Potsdam, Germany) and M. Sturm (EAWAG, Switzerland) for the use of the GEOTEK core logger and the Bartington magnetic-susceptibility point sensor, respectively. The ENSO-CHILE team is thanked for stimulating discussions and for sharing data and ideas. Finally, we thank the two anonymous reviewers and the Editor-in-Chief of JOPL for their constructive and encouraging comments to improve the manuscript.

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